Effect of speed on greenhouse gas emissions from road transport - a review

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Executive summary

Addressing climate change requires transformational and fundamental changes to the transport system. The *Climate Change Response Act* sets a domestic target for Aotearoa to reduce net emissions of all greenhouse gases (GHGs) (except biogenic methane) to zero by 2050.

Modelling to estimate GHG emissions is often undertaken to help decision-makers understand the impacts of transport policies and specific projects. In New Zealand, the standard vehicle emissions model is the Waka Kotahi Vehicle Emissions Prediction Model (VEPM)[1]. VEPM uses a well-established 'average speed' approach to calculate hot exhaust emissions. This means that emission factors are expressed as a function of the mean speed over a complete driving cycle of several kilometres. However, such average-models do have some limitations, and it is important that these limitations are understood when estimating the effects on emissions of changes in speed.

This document presents a review of the average-speed modelling approach, with the aim of improving the understanding of the limitations and uncertainty of average-speed models like VEPM. The focus of the review is on GHG assessments, especially in relation to speed effects. Specific recommendations for VEPM users are developed.

The review also aims to improve understanding of the likely emission impacts of some common speed related interventions. These include traffic calming, intersection design and speed limit changes.

Key findings

Appropriate application of VEPM

Overall, our review finds that average-speed models such as VEPM are valid over a network of roads within an urban area larger than approximately a half square kilometre. However, they can only predict one emission rate for a given average speed. Whereas in reality, trips having different operational[2] characteristics (and different emission levels) can have the same average speed. All the types of operation associated with a given average speed cannot be accounted for using a single emission factor. This is a particular problem at low-medium average speeds, for which the range of possible operational conditions is great. This means that, at a local scale (e.g. for an individual intersection or road link) VEPM might significantly underestimate or overestimate emissions, but on average VEPM emission estimates are expected to be valid.

Although different modelling approaches can theoretically provide more detail and accuracy compared with average-speed models such as VEPM, these models have their own limitations and may not improve the accuracy of assessments compared with an average-speed model.

Our review concludes that VEPM continues to be the most appropriate tool for greenhouse gas emission and air quality assessments in New Zealand due to reasons of practicality, cost, and consistency.

[1] https://www.nzta.govt.nz/roads-and-rail/highways-information-portal/technical-disciplines/air-quality-climate/planning-and-assessment/vehicle-emissions-prediction-model/

[2] In this report the term 'vehicle operation' refers to a wide range of parameters which describe the way in which a driver controls a vehicle (e.g. average speed, maximum speed, acceleration pattern, gear-change pattern), as well as the way in which the vehicle responds (e.g. engine speed, engine load).

Recommendations for VEPM users

Specific recommendations for VEPM users have been developed based on relevant conclusions throughout this review as follows.

Using VEPM for local scale assessment (spatial resolution)

- It is recommended that VEPM continue to be used to estimate vehicle emissions for GHG and air quality assessments in New Zealand, including local scale assessments.
- For local scale air quality assessments, where the spatial resolution of emissions can be of more relevance (compared with a greenhouse gas assessment), it is particularly important that users understand the limitations of VEPM.

Temporal resolution of speed data for assessments with VEPM

- 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.
- Using VEPM with higher resolution speed data (i.e. less than 1 hour) is generally not recommended.

*Using VEPM to assess impacts of speed limit changes**

- It is appropriate to use VEPM to estimate the impact of speed limit changes on GHG emissions for speed limits above 60 km/h.
- VEPM can also be used to assess impacts of speed limit changes at speeds below 60 km/h, although:
    - the limitations of the model predictions should be made clear, and
    - the limitations of the model should be considered in any conclusions or recommendations based on the assessment.

*note: other key findings about the effects of speed limits on emissions are provided later in the executive summary

Recommendations for all VEPM assessments

- While changes in speed can impact emissions, it is important for any assessment of speed related impacts to be considered in the wider context of policy outcomes. For example, road safety measures might reduce vehicle speed and potentially increase emissions per vehicle, but these measures might also contribute to mode shift and reduction in vehicle kilometres travelled. Wider impacts of interventions, such as mode shift, are often not adequately captured in traffic modelling.
- It is also important to acknowledge that emission impacts of speed changes will become less significant over time with the increasing prevalence of electric, hybrid and microhybrid vehicles[3,4].

[3] For example, *Te hau mārohi ki anamata*, Aotearoa New Zealand's first emission reduction plan (MfE 2022) contains a target to increase zero emission vehicles to 30% of the light vehicle fleet by 2030.
[4] Emission factors in VEPM account for the projected uptake of electric and hybrid vehicles in the fleet. However, the potential impact of micro hybrids is not yet reflected in VEPM CO_2 emission factor projections

Traffic calming

- Traffic calming measures can increase vehicle accelerations and decelerations, which can in turn increase GHG and harmful emissions. Implementation of traffic calming generally increases emissions per vehicle on affected roads. However, our review concludes that:
    - the overall impact of traffic calming on GHG emissions and harmful air pollutant emissions would be small (emissions are likely to increase by less than 10%)
    - It is unlikely that traffic calming measures will result in poor local air quality even in the vicinity of traffic calming measures.
- Design which encourages reduced, steady speed along the whole stretch of road (minimising the amount of vehicle acceleration and deceleration) would help to minimise the emission impacts of traffic calming measures.

Intersection treatments

- There is a significant amount of literature considering the impacts of various intersection treatments on emissions. Our review focused on two common themes from literature: replacement of intersections with roundabouts, and improved signal timing and coordination. The review focused primarily on GHG emissions.
- There is general consensus in the literature that improving traffic flow across intersections can reduce GHG emissions in the vicinity of the intersection. However, the effects of studies are site specific and depend strongly on local factors such as the traffic volume on different branches of the intersection and the frequency of stops.
- Similarly, studies suggest that improved signal timing and coordination can reduce GHG emissions on affected road segments.

Reduction in speed limits from 50 km/h to 30 km/h

- Average-speed models such as VEPM typically predict an increase in emissions with reduction of average speed (below about 60 km/h). However, research shows that speed limit reductions in urban areas don’t necessarily cause increased emissions in the real world.
- Overall, we conclude that reduction of speed limits in urban areas will not significantly impact GHG emissions on affected roads (less than 10% change in GHG emissions on affected roads and across the affected network) and the absolute change in GHG emissions at the regional or national level is likely to be negligible.
- The discrepancy between modelled and real-world impacts is because VEPM can’t account for differences in specific driving patterns at a given average speed. Average-speed models like VEPM assume typical driving conditions for the average speed – which means more acceleration and deceleration due to stop-and-go driving at lower average speeds. However, reduced speed limits don’t generally increase the amount of stop-and-go driving and can make vehicles move more smoothly with fewer accelerations and decelerations.
- We conclude that VEPM may overestimate the impact of speed limit changes on GHG emissions at low speeds (below 60 km/h).

(micro hybrid vehicles will also reduce the impact of speed changes because these vehicles are equipped with stop-start technology which minimises emissions penalties at lower average speeds).

Reduction in speed limits from 100 km/h to 80 km/h

- Our review concludes that speed limit reductions in the 100 km/h to 80 km/h range will reduce GHG emissions by a small amount (less than 10%) at high speeds (80 km/h to 100 km/h).
- Average speed models are widely used to estimate the emissions impact of speed limit changes on motorways. There is less variability in vehicle speed and operation at higher average speeds, which means that average speed models are expected to be more reliable for assessment of speed limit changes compared with lower speeds. Overall, we conclude that VEPM will provide a reasonable estimate of the impact of speed limit changes on GHG emissions for speed limits above 60 km/h.

Contents

Glossary of terms and abbreviations

AADT	Annual Average Daily Traffic
AQEG	The Air Quality Expert Group – an expert committee to the UK Department for Environment Food and Rural Affairs.
CH_4	Methane, a greenhouse gas
CO_2	Carbon dioxide, a greenhouse gas
CO_2-e	Carbon dioxide equivalent, a way to express the impact of each different greenhouse gas in terms of the amount of CO_2 that would create the same amount of warming
COPERT	The European Computer Programme to calculate Emissions from Road Transport
GHG	Greenhouse gas
g/km	Grams per kilometre
HAPINZ 3.0	Health and Air Pollution in New Zealand study (2016 base year)
km/h	Kilometre per hour
MBCM	The Waka Kotahi Monetised Benefits and Costs Manual
MSM	Auckland's transportation forecasting model, the Macro Strategic Model
NO_X	Nitrogen oxides, including nitric oxide and nitrogen dioxide
NO_2	Nitrogen dioxide, an air quality pollutant
N_2O	Nitrous oxide, a greenhouse gas (not to be confused with NO_2 which is an air quality pollutant)
PΔP model	Australian power based instantaneous vehicle emissions and fuel consumption model
PEET	The Waka Kotahi project emissions estimation tool
PM	Particulate matter

PM_{10}	Particles smaller than 10 micrometres
$PM_{2.5}$	Particles smaller than 2.5 micrometres
VEPM	Vehicle Emissions Prediction Model, developed by Waka Kotahi to predict air emissions and fuel consumption for the New Zealand fleet
VKT	Vehicle kilometres travelled
VOC	Volatile organic compound

1. Introduction

1.1 Purpose

Reduction of emissions to reach climate change targets requires transformational and fundamental changes to the transport system.

Modelling to estimate greenhouse gas (GHG) emissions is often undertaken to help decision-makers understand the impacts of transport polices and specific projects. In New Zealand, the standard vehicle emissions model is the Waka Kotahi Vehicle Emissions Prediction Model (VEPM)[5]. VEPM uses a well-established 'average speed' approach to calculate exhaust emissions. This means that emission factors are expressed as a function of the mean speed over a complete driving cycle of several kilometres. However, such average-speed models do have some limitations, and it is important that these limitations are understood when estimating the effects on emissions of projects and policies.

This document presents a review of the average-speed modelling approach, with the aim of improving the understanding of VEPM's applicability to GHG assessments, and to improve the understanding of VEPM's limitations with respect to assessing the impacts of projects and policies. The likely emission impacts of some common speed related interventions are also investigated, including changes in intersection design, implementation of traffic calming measures and changes in speed limits.

The review focusses primarily on hot exhaust emissions of GHGs. However, recommendations for VEPM users are generally applicable to assessment of GHGs and harmful air pollutants.

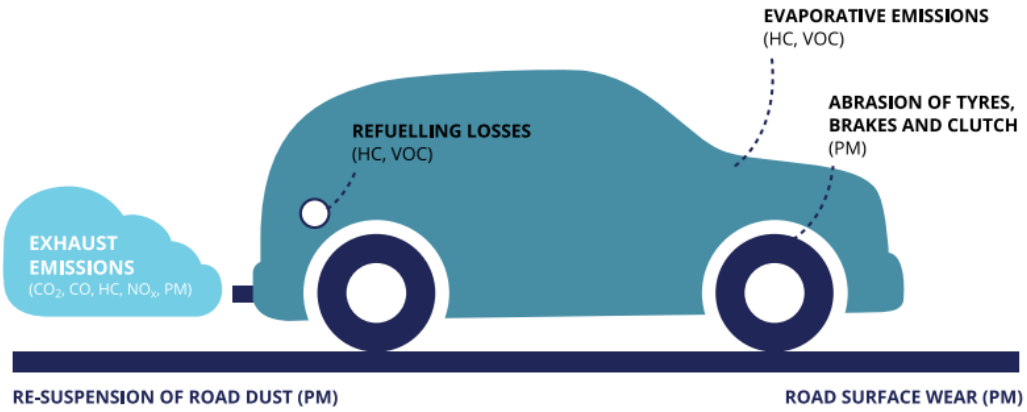
1.2 Background

1.2.1 What are vehicle emissions?

Vehicles are an important source of both GHGs (which impact globally) and harmful air pollutants (which impact locally and regionally). Vehicles generate different types of pollutants as shown in Figure 1.

[5] https://www.nzta.govt.nz/roads-and-rail/highways-information-portal/technical-disciplines/air-quality-climate/planning-and-assessment/vehicle-emissions-prediction-model/

Figure 1: Different types of emissions from internal combustion engine vehicles. Abrasion emissions, road surface wear and re-suspension of road dust are the only emissions from electric vehicles.



Source: EEA (2016)

Note: CO_2=carbon dioxide; CO=carbon monoxide; NOx=nitrogen oxides; PM=particulate matter; HC=hydrocarbon; VOC=volatile organic compounds.

Internal combustion engines emit a range of pollutants via the exhaust. The mechanical abrasion of vehicle parts (most importantly tyres and brakes) and road surface wear also generate emissions. Abrasion is a key source of emissions of particulate matter and some heavy metals. Vapours can escape from vehicle fuel systems via evaporation and during refuelling, resulting in increased emissions of volatile organic compounds (VOCs).

1.2.2 Greenhouse gases

GHGs, also known as climate pollutants, are so-called because they contribute to global warming and climate change. The most important GHGs emitted by motor vehicles are:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)

GHGs can be short-lived with an atmospheric lifetime of days to ~15 years (e.g. methane), or long-lived with an atmospheric lifetime of more than 100 years (e.g. carbon dioxide). For ease of comparison, GHGs are typically expressed as carbon dioxide equivalents (CO_2-e), which is the mass of CO_2 which would have the equivalent global warming impact[6].

The *Climate Change Response Act* sets a domestic target for Aotearoa to reduce net emissions of all GHGs (except biogenic methane) to zero by 2050. Transport is responsible for approximately 39% of domestic CO_2 emissions and 17% of total gross GHG emissions. Road transport accounts for more than 90% of gross transport emissions[7].

[6] This report only considers direct emissions of CO_2-e from motor vehicles. Life cycle emissions from motor vehicles and transport infrastructure are not considered.
[7] Transport accounted for 16.7% of total gross greenhouse gas emissions (CO_2-e) in 2020, and road transport accounted for 15.3% New Zealand's Greenhouse Gas Inventory 1990-2020 snapshot | Ministry for the Environment

Te hau mārohi ki anamata, Aotearoa New Zealand's first emissions-reduction plan (MfE 2022), states that we need to largely decarbonise transport by 2050 to reach the emission-reduction targets. The plan has three focus areas to achieve these targets:

- Reduce reliance on cars, and support people to walk, cycle and use public transport.
- Rapidly adopt low emission vehicles.
- Begin work to decarbonise heavy transport and freight.

The plan sets out specific targets and outlines actions that will be undertaken in the first emissions budget period (2022-2025).

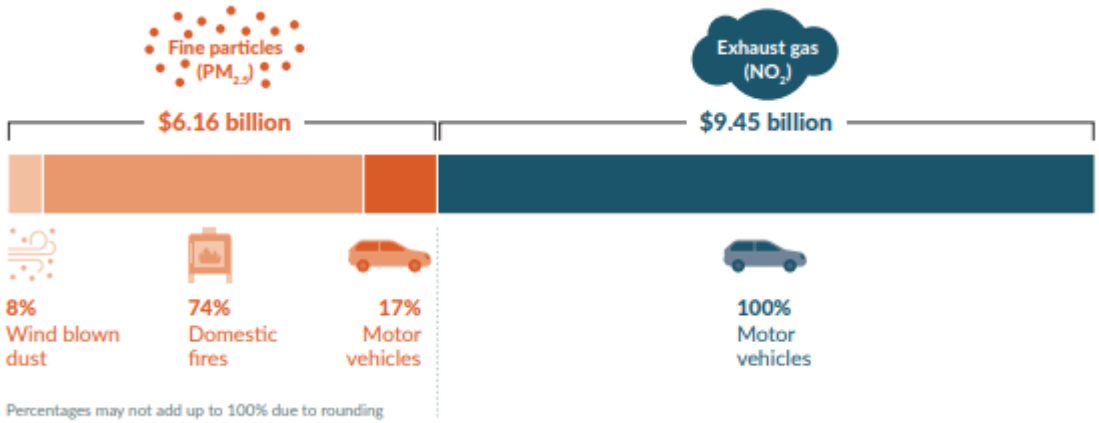
1.2.3 Harmful air pollutants

Harmful air pollutants are so-called because they can cause adverse human health effects. This review focuses on the two motor vehicle pollutants of most concern in New Zealand:

- Particulate matter – both particles smaller than 10 micrometres (PM_{10}) and those smaller than 2.5 micrometres ($PM_{2.5}$) – which arises primarily from diesel fuel combustion, brake/tyre wear and road dust.
- Nitrogen oxides (NO_X), in particular nitrogen dioxide (NO_2) – which are emitted from diesel and petrol fuel combustion.

As shown in Figure 2, the air pollution health impacts of motor vehicle emissions in Aotearoa New Zealand are considerable. Air pollution from motor vehicles is estimated to result in 2,247 premature deaths, nearly 9,400 hospitalisations, over 13,200 cases of childhood asthma and more than 330,000 restricted activity days each year in New Zealand. These health impacts result in an estimated social cost of more than $10.5 billion per year (Kuschel et al. 2022).

Figure 2: Social costs of health impacts from human made air pollution. The estimated social cost of health impacts from motor vehicle air pollution (NO_2 and $PM_{2.5}$) is more than $10.5 billion. Source: MfE[8]



1.2.4 Factors affecting vehicle emissions

The amounts of GHGs and harmful emissions produced by a particular vehicle depend on many factors including, for example:

[8] MfE_HAPINZ3_A4-infographic (environment.govt.nz)

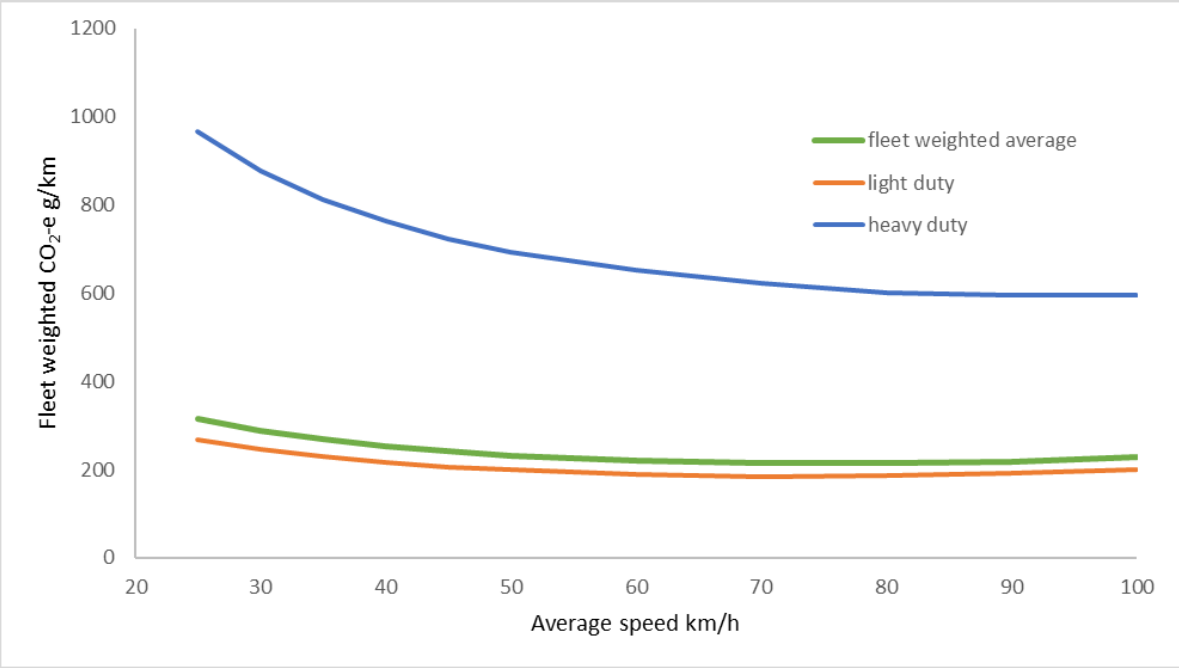
- Vehicle type:
    - fuel (e.g. petrol, diesel, hybrid, micro hybrid, electric)
    - Size and weight
    - Emission control technology (e.g. catalytic converter, diesel particulate filter)
    - Engine technology
- Vehicle maintenance (e.g. engine, emission control systems, AdBlue, tyre pressure)
- Road gradient
- Ambient temperature
- Use of auxiliary equipment such as air conditioning
- Vehicle operation (speed, acceleration, deceleration, gear, stopping and idling)
- Driving style
- Road layout
- Congestion

Effect of speed on emissions

Speed is one factor that can affect emissions. In general, harmful air pollutant and GHG emissions are lowest when a vehicle is travelling at steady speed, and emissions are increased when the amount of acceleration and deceleration is increased. This means, for example, that emissions tend to be higher in congested traffic and around intersections.

Figure 3 illustrates the effect of average speed on CO_2-e emissions predicted by VEPM. The emissions-speed curve has a distinctive shape, with high emission factors at low speed and somewhat higher emissions at higher speeds, with generally lower emission rates in the middle of the speed range. This is because, low average speeds generally represent stop-and-go driving, with high fuel use and emissions. However, at high speeds, higher engine loads and aerodynamic resistance can also require more fuel and generate more emissions.

Figure 3: Fleet weighted average CO_2-e predicted by the vehicle emission prediction model (VEPM 6.3) as a function of speed for 2022.



Effect of vehicle type on emissions

Although average speed affects emissions, the mix of vehicle types in the fleet is the most significant factor affecting average emissions from the fleet. Figure 4 and Figure 5 show NOx and CO_2-e emission factors as a function of speed for an average petrol hybrid car, petrol car, and diesel utility vehicle(ute) in the New Zealand fleet.

These comparisons show that the types of vehicles being driven on our roads can have a huge effect on emissions, which is much bigger than the relatively small effect of speed on emissions. This is especially true when we consider petrol hybrid vehicles, which have very low emissions even in stop-and-go traffic conditions, and electric cars which have no exhaust emissions.

Figure 4: Fleet weighted average NOx emission factors predicted by VEPM 6.3 as a function of speed for different vehicle types (for 2022 with all other settings at default)

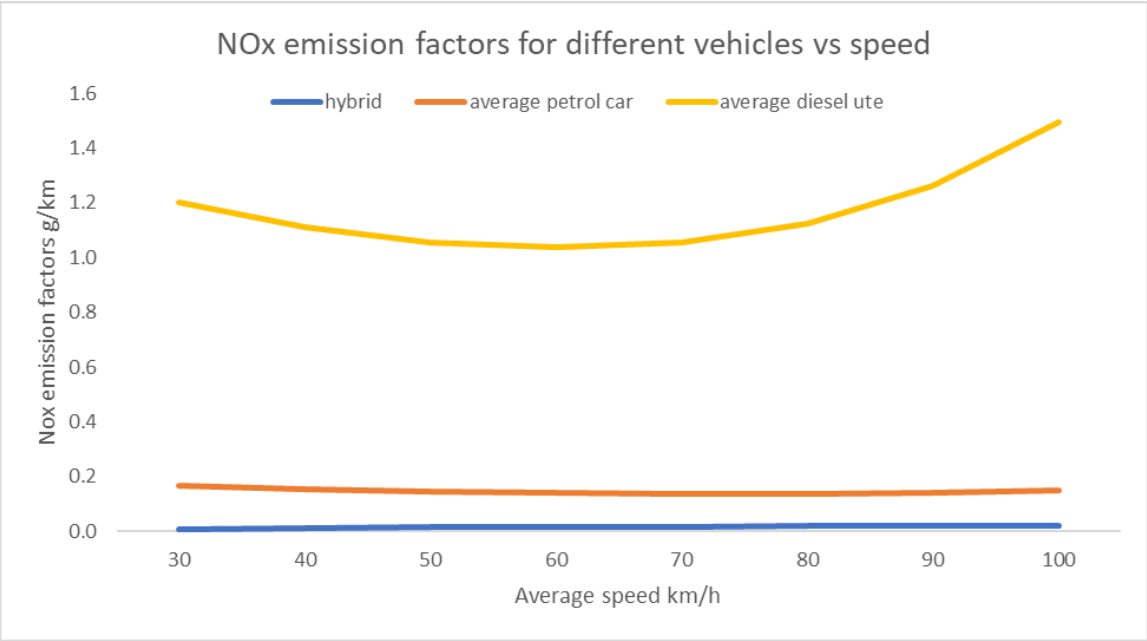
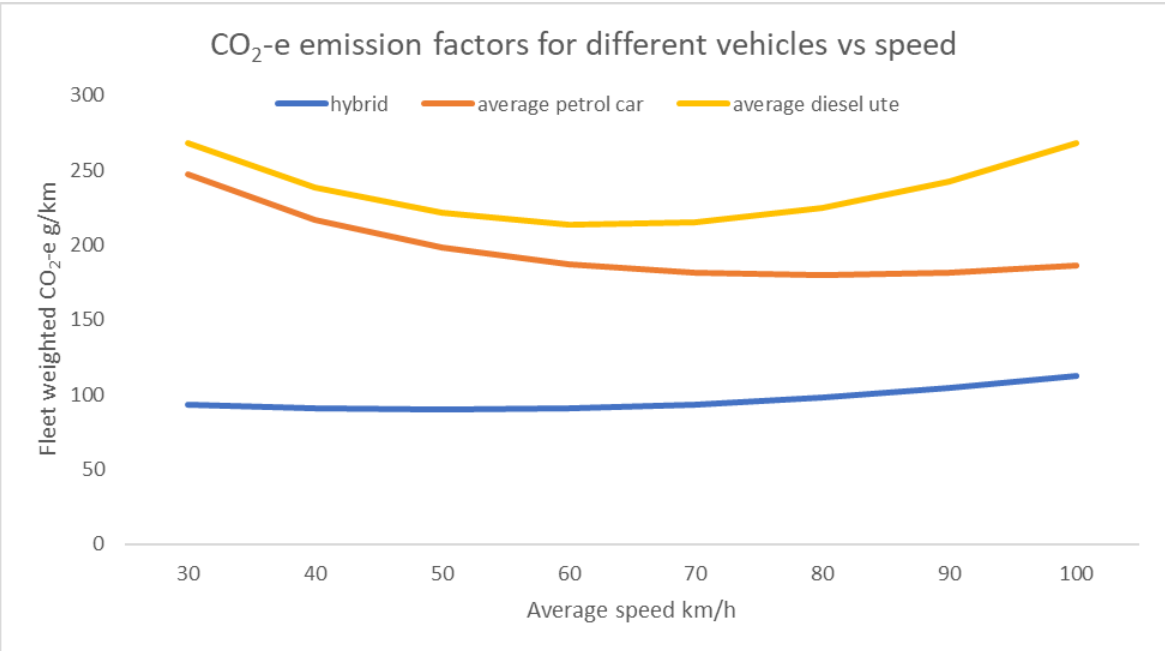


Figure 5: Fleet weighted average CO_2-e emission factors predicted by VEPM 6.3 as a function of speed for different vehicle types (for 2022 with all other settings at default)



1.3 Vehicle emissions prediction model

VEPM is the main road vehicle emission model used in New Zealand. The model is used in policy analysis and assessments of environmental effects. Detailed information about VEPM is available on the Waka Kotahi website (www.nzta.govt.nz).

VEPM estimates emissions from vehicles in the New Zealand fleet under typical road, traffic and operating conditions. An important feature of the model is the ability to estimate changes in vehicle emissions in previous years (back to 2001) and future years (to 2050).

VEPM predicts emission factors for the New Zealand fleet based on the different vehicle types/technologies present and the VKT of each vehicle type. It includes default fleet profiles developed from national fleet data collected by Ministry of Transport, together with predictions of future fleet trends. Fleet-weighted emission factors are calculated by multiplying the emission factors in grams per kilometre (g/km) for each vehicle class by the proportion of kilometres travelled by that class for any given year.

VEPM emission factors can be adjusted for a range of variables including for example, gradient, temperature, fuel quality, heavy vehicle load and average speed.

VEPM predicts real-world average-speed emission factors. These emission factors are intended to represent typical emissions at a defined average speed for typical conditions (e.g. typical driving behaviour and typical levels of congestion for the defined average speed). So, for 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).

As with any model, there is some uncertainty in emission estimates from VEPM. The limitations of VEPM are discussed in section 2 of this review and the specific recommendations for VEPM users are summarised in section 7.

1.4 Assessment of greenhouse gas emissions in New Zealand

Transport policies and projects influence the quantity, composition, and speed of traffic on roads, and consequently GHG emissions[9]. The Monetised benefits and costs manual (MBCM) sets out the current Waka Kotahi procedure for assessing changes in GHG emissions from transport activities (Waka Kotahi, 2023). The procedure, shown in Figure 6, relies on VEPM emission factors. Emission factors from VEPM are calculated for each road link being assessed based on the average speed of traffic, which is often provided by traffic models.

[9] GHG emissions are also impacted by the construction, operation and maintenance of transport infrastructure across the infrastructure lifecycle. These emissions are not considered in this report.

Figure 6: Waka Kotahi MBCM procedures for assessment of changes in GHG emissions (Waka Kotahi, 2023)

Step	Action	
1	Determine the: • traffic composition • time period's total average travel time per vehicle (min).	
2	Convert the traffic composition vehicle classes into emission classes:	
	Emission class	**Vehicle classes** (Table A45)
	Light (vehicles less than 3.5 tonnes)	Passenger cars Light commercial vehicles
	Heavy (vehicles greater than 3.5 tonnes)	Medium commercial vehicle (MCV) Heavy commercial vehicle I (HCVI) Heavy commercial vehicle II (HCVII) Buses
3	Calculate average speed on the link road, either using a model, or according to the formula: *Speed (km/h) = 60 × length / TT* where: length = road link length (km) TT = time period total average travel time per vehicle	
4	Calculate the emission rates (g/km) for light and heavy vehicle types using average speed on the link road from step 3, and emission factors from latest VEPM version.	
5	Weight the calculated emission rates by vehicle flow composition (g/vkt): *= % light vehicles × light emission rate + % heavy vehicles × heavy emission rate*	
6	Multiply the weighted emission rates by the time period's total vehicle volume and the road's length to give the emission load (g).	

1.4.1 Greenhouse gas assessment tools

Project Emissions Estimation Tool

The project emissions estimation tool (PEET)[10] is a GHG emissions tool that has been developed by Waka Kotahi for use in the early stages of a project. The tool estimates emissions from construction, operation and maintenance of a project as well emissions associated with the use of infrastructure over time.

Emissions associated with project use are estimated using vehicle-kilometres travelled (VKT) and speed data, combined with emission factors from VEPM. PEET estimates the change in enabled emissions by comparing the predicted future traffic volumes with the project in place against the traffic volumes expected without the project in place. As a default, emissions are estimated based on annual average daily traffic and the average speed of vehicles along the route (however, any traffic model output could be used in PEET).

PEET has not been developed to provide for a detailed analysis of specific project elements, and is not a replacement for detailed emissions assessment for infrastructure design.

Tool to calculate emissions from traffic model outputs

A spreadsheet tool has been developed by BECA to calculate emissions using outputs from a traffic model[11]. The tool was developed for outputs from traffic models developed in SATURN software, although it is readily applicable to other model systems (BECA, 2022).

[10] Project Emissions Estimation Tool (PEET) | Waka Kotahi NZ Transport Agency (nzta.govt.nz)
[11] Traffic model emissions tool | Waka Kotahi NZ Transport Agency (nzta.govt.nz)

The BECA tool applies emissions rates from VEPM to each road link in the model based on the average traffic speed on that link. The tool makes use of both link and turn (intersection) data from the traffic model to determine the average speed of each link (that is, the average link speed includes intersection delays at the end of the link).

1.4.2 Transport modelling for greenhouse gas assessments

Waka Kotahi (2019) provides guidelines on the development of transport models, which are developed for various purposes and with various levels of confidence. There is no specific guidance to determine whether a transport model is suitable for assessing GHG impacts. This review specifically considers the impact of average speed estimated from traffic model outputs on emission estimates. However, it is important to note that the validity and consistency of GHG impact assessments based on traffic model outputs will be affected by a range of factors, including, for example:

- The timeframe of the assessment. Does the assessment look far enough into the future? Does the assessment consider cumulative emissions over the project lifetime?
- Uncertainty and limitations in traffic model outputs, especially projections.
- The geographic scope of the model. For localised models, are there impacts on the wider road network?
- The assumptions for the derivation of 24 hour (hourly diurnal profiles) and annual traffic data from the time periods included in the model.
- How well the road network in the traffic model represents the real-world road network. In strategic traffic models, for example, the road network is usually represented schematically, with 'straight line' connections between nodes. Therefore, when calculating GHG emissions, the real-world road lengths, and hence the total traffic emission rate for the full length of a given road (in g/h), can be underestimated.

The impact of these factors, and any other factors which might affect the validity and comparability of GHG impact assessments, are outside the scope of this review.

1.5 Specific aims of this review

This review aims to improve the understanding of VEPM's limitations and uncertainty with a focus on GHG assessments, especially in relation to speed effects.

Specific recommendations for VEPM users are developed for:

- The appropriate spatial resolution of assessments using VEPM, particularly considering whether VEPM represents good practice for local scale emission assessments.
- The appropriate temporal resolution of assessments using VEPM, particularly considering the appropriate time averages for deriving speed data from traffic models for assessment of GHG emissions.
- The review also aims to improve understanding of the likely impacts of some common speed related interventions on emissions. The review includes: A summary of literature reviews considering the likely effects of traffic calming measures and intersection design on emissions.
- Literature reviews considering the likely effects of speed limit changes and whether VEPM is appropriate for assessing the impacts of these speed limit changes.

1.6 Structure and content of this review

The remainder of this review is structured as follows:

- Section 2 briefly describes the basis of average-speed models like VEPM, and the limitations and uncertainty with respect to GHG emissions.
- Section 3 considers other types of models that are used to estimate vehicle emissions, including instantaneous (microsimulation) emission models and develops recommendations for appropriate spatial and temporal resolution of emission assessments based on VEPM factors.
- Section 4 considers emission impacts of intersection treatment and traffic calming measures.
- Section 5 considers GHG emission impacts of changing speed limits on urban roads.
- Section 6 considers GHG emission impacts of changing speed limits on state highways.
- Section 7 summarises recommendations for VEPM users.

The review covers a number of distinct themes. These themes are addressed in separate sections of the review, and conclusions are provided at the end of each section. The recommendations for VEPM users are based on conclusions from each theme where relevant.

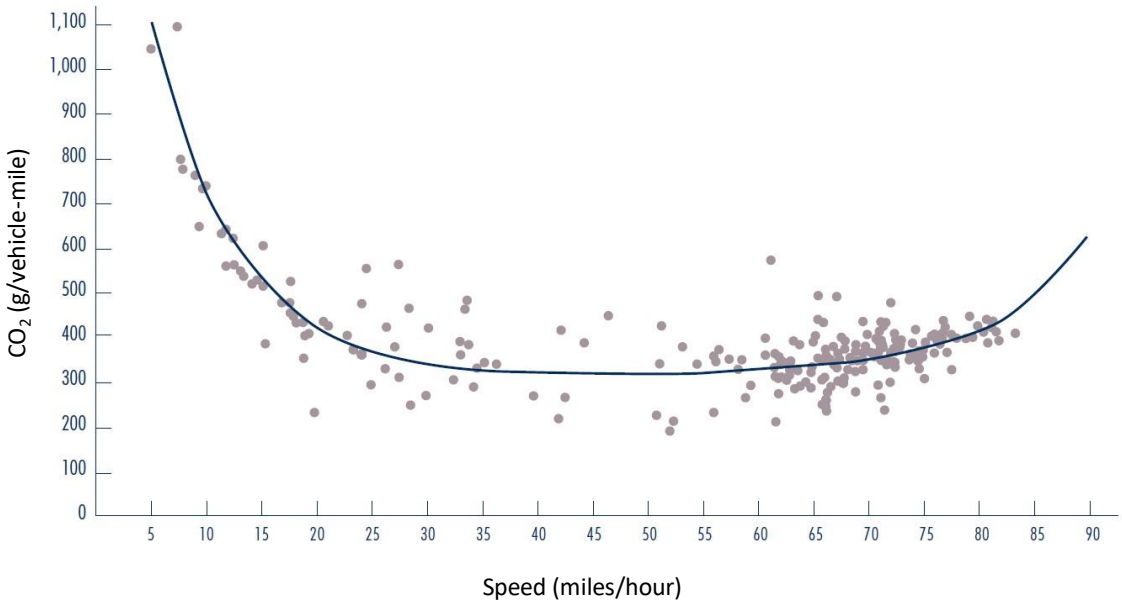
2. Improved understanding of VEPM's limitations

2.1. Average-speed models – principle of operation

In average-speed models, emission factors are defined as a function of average trip speed, based on polynomial regression or a similar approach. COPERT[12] is an example of a well-established average-speed model. These models are usually based on the results of laboratory tests in which a sample of vehicles is driven over several well-defined speed profiles (driving cycles) on a chassis dynamometer[13]. The laboratory tests use driving cycles that represent a wide range of real-world operating conditions, including different ranges of speed, acceleration, periods of idling, etc.

Figure 7, adapted from Barth & Boriboonsomsin (2009), shows an example of the average-speed approach for CO_2 emissions (note that the distances are in miles, and the speeds are in miles per hour (mph)). Each point in the figure corresponds to a test result for a driving cycle, or sub-cycle, that has an associated average speed and emission factor. The figure is purely illustrative. It could represent one vehicle, or more typically it would represent a larger sample of vehicles that are taken to have similar charactistics (e.g. type, size, emission standard). In practice, the test results for multiple vehicles tend to be combined. In either case, there would tend to be some scatter in the resulting emission factors due to differences in the characteristics of driving cycles, as well as differences in vehicle emissions behaviour. The test results may also be taken from different laboratories, which adds further variability. The upshot is that driving cycles with similar average speeds can have quite different emission factors. Consider, for example, the wide range of emission factors between 25 mph and 30 mph in the example shown in Figure 7.

Figure 7: CO_2 emission factors vs average speed for individual driving cycles, and a corresponding average-speed emission function



Fitting a line to the data points results in a typical parabolic (often termed 'U-shaped') emissions-speed curve. Very low average speeds generally represent stop-and-go driving, with high fuel use and

[12] https://www.emisia.com/utilities/copert/

[13] In some cases, the underlying emissions data may be generated using another model.

emission factors. Reducing the speed will also tend to increase the proportion of time spent in lower gears, which in turn will tend to increase fuel consumption per unit distance. Conversely, when vehicles travel at high speeds, they demand high engine loads, and are faced with high aerodynamic resistance, which require more fuel. As a result, the emissions-speed curve has its distinctive shape, with high emission factors at both ends of the speed range, and lower emission rates in the middle of the speed range.

The average-speed modelling approach therefore involves averaging for at least three levels; each measurement point (see Figure 7) is an average for a given driving cycle, and the average-speed function is fitted across multiple driving cycles and vehicles.

Given enough data, different curves can be established for multiple vehicle types, and in some cases for different road types. In COPERT, emission factors are defined as a function of speed for vehicles typically represented in the European fleet. Vehicles are classified by category (passenger car, Light Commercial etc), type (petrol, diesel, hybrid, etc), emission standard and vehicle size.

2.2. VEPM emission factors

VEPM derives New Zealand-relevant factors based on average-speed emission factors from the European COPERT model. The COPERT methodology is published by the European Environment Agency (EEA, 2021). VEPM draws on several other emission models and data sources to account for some of the unique features of the New Zealand fleet. The VEPM technical report provides a description of how the COPERT factors are applied to the New Zealand fleet (Metcalfe & Peeters 2022).

2.3. Uncertainty

All emission models have an inherent uncertainty and evaluating this is a complex task. In the case of VEPM, this is compounded by the fact that the emission factors are based on test data from European vehicles.

We know that real world emissions from New Zealand vehicles are comparable with real world emissions from European vehicles (Kuschel et al. 2019). However, at a fleet average level, there are differences between the European and New Zealand vehicle fleets (Metcalfe et al. 2020). Understanding these differences and validating real-world CO_2 emission estimates from VEPM is an area of ongoing research.

At a fleet wide average level, VEPM generally underestimates fuel consumption somewhat (and therefore CO_2 emissions) compared with real world fuel consumption factors[14] (Metcalfe et al. 2022).

2.4. Limitations

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.

[14] For example, Metcalfe et al. 2022 found that fuel consumption estimated at a national level using VEPM underestimated petrol car fuel consumption by 12% and diesel car fuel consumption by 15%. However, national estimates of transport fuel consumption have been revised since the report was published, so these comparisons need to be updated.

However, average-speed models do have some limitations, including the following which are relevant here (Barlow & Boulter, 2009):

(i) An average-speed model can only predict on emission rate for a given average speed. Whereas in reality, trips having different operational[15] characteristics (and different emission levels) can have the same average speed. All the types of operation associated with a given average speed cannot be accounted for using a single emission factor. This is a particular problem at low-medium average speeds, for which the range of possible operational conditions is great. This has always been a shortcoming of average-speed models and has been one of the main reasons for the development of other types of model.

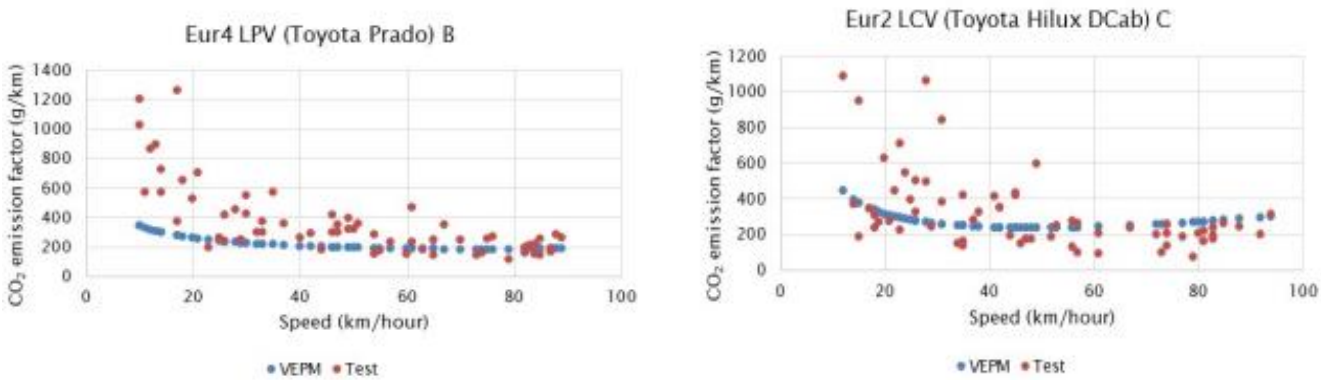
(ii) The shape of an average-speed function is not *fundamental*, but depends on, amongst other factors, the types of cycle and specific vehicles used in development of the functions, and the regression method. For example, each cycle used in the development of the functions typically represents a given real-world driving condition, but the actual distribution of these driving conditions in the real world will vary by time and location.

(iii) Average-speed models do not allow (in principle) for detailed spatial resolution in emission predictions, although this is less of a drawback for GHG calculations than for, say, local air quality modelling.

By their nature, average-speed models are therefore not best suited to the estimation of emissions from individual vehicles, or where an investigation of detailed vehicle operation is required. They are better suited to 'bulk', large-scale and generalised analyses.

This is illustrated by the results of a real-world emissions study undertaken in New Zealand (Kuschel et al. 2019). The study found that measured CO_2 emissions from individual vehicles compared reasonably well, on average, with the VEPM emission factor for the corresponding vehicle category. However, at any specific part of a real-world trip, emissions can be significantly different to the VEPM emission factor, as shown in Figure 3. This shows CO_2 emission test results at a 1-minute resolution compared with VEPM emission factors for two example vehicles.

Figure 8: Real world emission test results graphed at 1 minute resolution compared against VEPM predictions for CO_2 for two example vehicles (Kuschel et al. 2019).



[15] In this report the term 'vehicle operation' refers to a wide range of parameters which describe the way in which a driver controls a vehicle (e.g. average speed, maximum speed, acceleration pattern, gear-change pattern), as well as the way in which the vehicle responds (e.g. engine speed, engine load).

A recent report from the UK Air Quality Expert Group considers the limitations of various emission modelling approaches in some detail (AQEG). The report finds that, because average-speed models can only predict on emission factor at a given average speed, they are likely to underestimate emissions at some locations and overestimate emissions at other locations. Overall, the average speed approach is considered valid for a national inventory and over a network of roads within an urban area larger than approximately a half square kilometre, but less so at specific road links and junctions (AQEG 2021).

2.5. Conclusions

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. However, they can only predict one emission rate for a given average speed. This means that, at a local scale (e.g. for an individual intersection or road link) VEPM might significantly underestimate or overestimate emissions, but on average VEPM emission estimates are expected to be valid.

Section 3 of this review considers whether average-speed models are appropriate for local scale modelling. Specific recommendations for VEPM users are provided in section 7.

3. Appropriate spatial and temporal resolution of assessments using VEPM

This section of the review considers:

- Alternatives to average-speed models, in particular instantaneous models.
- Whether VEPM represents good practice for local scale emission assessments.
- The appropriate temporal resolution of assessments using VEPM, particularly considering the appropriate time averages for deriving speed data from traffic models for assessment of GHG emissions.

Conclusions are provided at the end of this section, and recommendations for VEPM users are summarised in section 7 of this review.

3.1. Alternatives to average-speed models

Various vehicle emissions models have been developed internationally with different levels of complexity for different uses. These can be classified by generic model type. The most common model types are shown in Table 1, together with their applications.

Table 1: The most common types of emission models and their applications

Type	Input data required to define vehicle operation	Characteristic	Typical application	Example
Aggregate	Area or road type	Simplest level, no speed or vehicle specific dependency	National inventories	COPERT (Europe and international)
Average speed	Average trip speed	Speed and vehicle type/ technology specific	National and regional inventories, local air quality assessments	COPERT (Europe) VEPM (New Zealand)
Traffic situation	Road type, speed limits, level of congestion	Driving pattern (speed, acceleration etc) and vehicle type/technology specific	Environmental impact assessment, area-wide urban traffic management assessment	HBEFA (Germany, Switzerland, Austria, Sweden, Norway, France)
Instantaneous/ microsimulation	Driving pattern, vehicle specific data – power, speed, emissions	Micro-scale modelling, typically 1 second intervals, individual vehicle specific	Developing emission factors, research, urban traffic management assessment	PHEM (EUROPE) PΔP (Australia)

Traffic situation models provide emission factors for a combination of traffic descriptors instead of average speed. For example, the Handbook of Emission Factors (HBEFA) is a traffic situation model that is used in several European countries. The HBEFA model provides factors for different road types (motorway, distributor, etc), levels of service, and speed limits.

The most detailed instantaneous emission models (also known as 'microsimulation' and 'modal' models) estimate vehicle emissions via engine or vehicle operating models at a resolution of one to several seconds. These models typically require detailed information on vehicle characteristics and vehicle movements (Smit et al. 2010). One application of these models is to provide emission factors

for other types of model. For example, in Europe PHEM has been used to develop emission factors for both COPERT and HBEFA.

3.2. Comparison of average-speed and instantaneous emission models

As discussed in section 2, average-speed models are best suited to large-scale and generalised analyses, such as regional or national emission inventories. Nevertheless, they have become the de facto standard method for estimating emissions resulting from a roading project in 'local' assessments, including near-road air quality modelling.

For research purposes, there has been an increasing tendency towards the use of microsimulation traffic and emission models to investigate air quality effects of localised traffic projects such as intersection treatments (Boulter 2023). It is therefore timely to consider whether VEPM represents good practice for assessment of emission impacts of projects with localised impacts, such as intersection changes.

In principle, instantaneous emission models can provide finer spatial and temporal resolution of emissions estimates and have the potential to provide more accurate predictions compared with average-speed models as they take into account more variables. However, a review of emission model validation studies found no evidence that more complex models perform systematically better in terms of prediction errors than simpler ones (Smit et al. 2010). A more recent review from the UK Air Quality Expert Group (AQEG) reached similar conclusions (AQEG 2021).

The AQEG recognises that average-speed emission factors are not intended to inform local scale assessments and considers whether instantaneous emission modelling approaches may be more valid for local scale assessments, at least conceptually. However, the AQEG finds that instantaneous models themselves have limitations, for example:

- They are usually based on tests on a limited number of vehicles.
- They require detailed traffic movement data, and so are often linked to traffic microsimulation models. The additional demands placed on traffic models, when compared with average-speed modelling, may add further sources of uncertainty.
- A key area of uncertainty for many microsimulation traffic models is their ability to predict acceleration profiles, which are closely linked with emissions.
- There are few studies in which emissions calculated from microsimulation traffic and instantaneous emission models have been validated against measurements.

Overall, the AQEG concludes that, particularly taking account of the increased requirement for predictive traffic data, microsimulation models may not improve simulations compared with a coarser resolution model.

The AQEG reviews several studies which compare air quality modelling based on average speed vs instantaneous models. At a localised scale, the AQEG concludes that average-speed models will under predict concentrations at some locations and over predict elsewhere, but there is no obvious bias on average between average speed and instantaneous models (AQEG 2021). This means, for example, that modelling based on average-speed emission factors might not accurately predict localised air quality hot spots. However, estimates of overall emissions from a road network average-speed and instantaneous modelling approaches would likely be similar.

3.3. Are average-speed models appropriate for local scale assessments?

In the UK, average-speed emission models are used for almost all predictive emissions modelling, including local scale assessments, assessments of road schemes, and the evaluation of policies and interventions.

As discussed in the previous section, the AQEG review acknowledges the limitations of average-speed models for local scale air quality assessments, however they conclude that instantaneous models have their own limitations and may not improve the accuracy of assessments. The AQEG review recommends that average-speed emissions models continue to be used for local scale assessments for reasons of practicality, cost, and consistency as follows:

- Practicality: Availability of traffic data: Instantaneous emission models generally require traffic data from a microsimulation traffic model. Microsimulation traffic models often focus on specific periods of the day, with the extension to 24 hour and annual periods required for emissions assessments being difficult. The spatial extent of microsimulation traffic models is also often smaller than the spatial extent required for an emissions assessment.
- Practicality: Availability of emissions factors: Instantaneous emission models do not contain data for all existing vehicles and cannot contain data for future vehicles, which means that they cannot estimate emissions for future years. In contrast, average-speed models tend to cover most current and future vehicle types.
- Cost: Detailed microsimulation traffic modelling can be prohibitively expensive for many types of local-scale assessment.
- Consistency: Virtually all modelling guidance in the UK refers to average-speed models, and consistency across applications simplifies policy development and planning processes. The additional costs and expected challenges associated with instantaneous emission models mean that they are seldom used.

3.3.1 Using VEPM for local scale assessments

The situation in New Zealand is similar to the UK – average-speed models are the de facto standard method for emissions estimation. We consider that the findings of the AQEG review are relevant in the New Zealand context. We recommend that VEPM continue to be used for local emissions assessments for the following key reasons:

- Practicality:
    - Microsimulation traffic models are not available for all projects. Where they are available, the traffic data from microsimulation models often doesn't cover the time period and spatial extent required for an emissions assessment. Making assumptions introduces additional uncertainty.
    - Instantaneous emission models do not usually contain data for all existing vehicles and cannot contain data for future vehicles, which means that they cannot estimate emissions for future years. In contrast, average-speed models tend to cover most current and future vehicle types.
    - There is currently no instantaneous emissions model available in New Zealand.

- **Cost:** The cost of detailed microsimulation traffic modelling is prohibitively expensive for many projects. Similarly, the cost of developing a New Zealand specific instantaneous emissions model would likely be significant.
- **Consistency:** In New Zealand, VEPM is recommended for all Waka Kotahi emission assessments and Waka Kotahi emission assessment tools and guidance are currently based on VEPM. Using another model for emission assessments could introduce inconsistency and additional uncertainty.
- **Accuracy**: Instantaneous emission models have their own limitations and may not improve the accuracy of an emissions estimate compared with an average-speed model (AQEG 2021, Smit et al. 2010, Boulter 2023).

3.4. Appropriate temporal resolution for speed data

Operational GHG assessments are undertaken using VEPM, with speed data often being derived from traffic models (microsimulation, SATURN models and regional transport models) in different ways, and over different time periods. Examples include:

- Emissions inventories at a regional level. These are often based on annual average daily traffic (AADT) and annual average or approximate speed data.
- Some detailed emissions inventories, and most assessments at a project level, utilise average traffic and speed for the time periods covered by the traffic model (typically morning peak, inter-peak, afternoon peak and overnight). Hourly traffic data – which is often derived from traffic model outputs over the four time periods – are also commonly used in emission estimates. Utilising traffic and speed data for peak and off-peak periods means that the effects of congestion during peak periods are captured in the emissions estimate. The emissions are aggregated to provide daily and annual emissions.
- Microsimulation models have been used to provide average traffic and speed data for 15-minute time periods.

The following sections consider whether these time averaging periods are appropriate, and whether different approaches could lead to inconsistency in results.

3.4.1 What temporal resolution is appropriate?

Average speed models such as VEPM are widely used for compiling national emissions inventories, as well as emission modelling at the street level.

Average-speed models are widely used with a temporal resolution of 24 hours or 1 hour. In most cases, we consider that it is appropriate for VEPM to be applied at a minimum temporal resolution of 1 hour.

For specific emissions assessments, the most appropriate temporal resolution will depend on the purpose of the assessment. Higher temporal and spatial resolution can be important for air quality assessments where short term exposures and exposure location are important.

For GHG assessments, temporal and spatial resolution of emissions are generally not important. However, it is worth considering whether greater temporal resolution of speed data might improve the accuracy of assessments. The effect of temporal resolution of speed data has been investigated

for Waka Kotahi by Tonkin & Taylor (2022, draft). Emissions were estimated for two busy Auckland roads based on 24-hour average speed, and based on AM peak, PM peak and inter-peak and off-peak speeds. The comparison found that CO_2 emissions based on 24-hour average speed were approximately 9.3% lower for light duty vehicles and 11.1% lower for heavy duty vehicles, compared with emissions estimated based on the AM peak, PM peak and inter-peak and off-peak speeds on a busy Auckland road. On another road, CO_2 emissions based on 24-hour average speed were approximately 21.2% lower for light duty vehicles and 28.8% lower for heavy duty vehicles, compared with emissions estimated based on the AM peak, PM peak and inter-peak and off-peak speeds.

As stated previously, VEPM generally underestimates fuel consumption (and therefore CO_2 emissions) compared with real world fuel consumption factors (Metcalfe et al. 2022). It is therefore possible that higher temporal resolution of speed data could improve the accuracy of CO_2 emission estimates somewhat. However, given the uncertainty and limitations of emissions models (discussed in Section 2), it is unlikely that a higher temporal resolution would significantly affect the accuracy or conclusions of a project level GHG assessment.

In most circumstances, an assessment based on daily average traffic and speed is considered appropriate for assessment of GHG emissions. However, it is recommended that 1-hour temporal resolution data should be used if good quality 1-hour data is already available as part of the assessment.

We understand that some assessments in New Zealand have been undertaken based on 15-minute resolution data derived from traffic microsimulation models. This is probably not unreasonable, but the results will not be directly comparable with other assessments, and the increased resolution is unlikely to improve accuracy of the assessment.

Using VEPM with higher resolution data (less than 15 minutes) would not be recommended because the averaging period could be shorter than the duration of some of the driving cycles used to derive emission factors in the average-speed model. The validity of applying average-speed emission factors at a resolution higher than the driving cycles they were derived from is subject to question (Lerj et al. 2021).

3.4.2 Will different approaches and averaging periods lead to inconsistency in results?

In locations where congestion effects are significant, different temporal resolution of speed data may lead to inconsistency in results. For example, the comparison discussed in the previous section found that fleet average emissions estimated based on 24-hour average speed were approximately 21.8% lower on one busy Auckland road, and 9.5% lower on another road compared with emissions estimated from AM peak, PM peak and inter-peak and off-peak speeds (Tonkin & Taylor, 2022, draft).

It will be important to ensure consistency in the methodology for estimating average speed if the results of GHG impact assessments need to be directly comparable.

3.5. The potential role of an instantaneous emission model in New Zealand

Instantaneous (microsimulation) emission models are currently used primarily in the development of emission factors and in research. There is no instantaneous emissions model available for New Zealand. We consider that there could be value in developing an instantaneous emission model to

address specific research or policy questions, and to provide New Zealand specific emission factors or adjustment factors for VEPM. For example, an instantaneous emissions model that is sufficiently representative of the NZ fleet could be used to develop:

- VEPM emission factors that explicitly account for heavier vehicles (e.g. utes) in the NZ fleet (compared with Europe)
- VEPM adjustment factors to account for the effect of rough road surfaces in New Zealand

Adaptation of the existing Australian PΔP model is likely to be the most cost-effective option to develop an instantaneous emissions model that is sufficiently representative of the New Zealand fleet. However, the likely cost of developing and validating an instantaneous emission model for New Zealand would need to be considered in the context of the potential emission benefits that might be gained from more detailed modelling.

It is unlikely that an instantaneous model would be recommended for use in routine assessments, at least in the short term. This may change in the longer term, as emissions data and modelling techniques continue to evolve and improve.

3.6. Conclusions

3.6.1 Use of VEPM for local scale assessments

VEPM produces average-speed emission factors, which generally are considered valid over a network of roads within an urban area larger than approximately a half square kilometre, but less so at specific road links and intersections.

In relation to the estimation of GHG emissions, where spatial information is of less relevance than for harmful air pollutants, and assessments are generally based on estimated changes in emissions (as opposed to absolute values), average-speed models represent good practice.

Although instantaneous models can theoretically provide more detail and accuracy compared with average-speed models such as VEPM, these models have their own limitations and may not improve the accuracy of assessments compared with an average-speed model.

Even for localised air quality assessments where spatial information is more important, it is recommended that VEPM continue to be used due to reasons of practicality, cost and consistency. However, it is important that users understand the limitations of VEPM.

3.6.2 Appropriate temporal resolution for VEPM

It is appropriate for VEPM to be applied at a temporal resolution of 24 hours for assessment of GHG emissions (where temporal and spatial resolution of emissions are less relevant than for harmful emissions). However, it is recommended that 1-hour temporal resolution speed data should be used if good quality data is available. Using VEPM with higher resolution data (i.e. averaging time periods shorter than 1 hour) is generally not recommended.

Estimation of GHG emissions with different temporal resolutions of speed data will potentially lead to inconsistency in results. It will be important to ensure consistency in the methodology for estimating average speed if the results of GHG impact assessments need to be directly comparable.

3.6.3 The potential role of an instantaneous emissions model in New Zealand

There could be value in developing an instantaneous emissions model that is representative of the New Zealand fleet for research, policy development and emission factor development. However, it is unlikely that an instantaneous model would be recommended for use in routine assessments, at least in the short term. The likely costs and benefits of developing an instantaneous model for New Zealand would need to be considered.

4. Effects of intersection treatment and traffic calming measures on emissions

Changes to road layout and design can impact vehicle speed and emissions. There is a significant amount of international research investigating these potential impacts.

This section briefly summarises the findings of two literature reviews (Gilbert & Boulter 2022, Boulter 2023) investigating the effects of traffic calming measures and intersection design on emissions.

4.1. Literature review

4.1.1 Methods used to assess impacts of traffic calming measures and intersection design

As discussed in section 2, average-speed models such as VEPM have limitations and are not well suited to the evaluation of traffic calming measures or the detailed comparison of intersection designs.

The literature reviews found that there is no standard methodology for assessment of localised emission impacts of traffic calming measures or intersection design. A range of methodologies have been used, including:

- Measuring emissions in situ by equipping vehicles with a portable emissions measurement system (PEMS).
- Instrumenting vehicles to measure driving patterns to develop driving cycles which are then used to measure vehicle emission in a laboratory.
- Instrumenting vehicles to measure driving patterns for use in an instantaneous emissions model.
- Using a traffic intersection model in combination with an emissions model.
- Using a microsimulation traffic model in combination with an instantaneous emissions model.

Because a wide variety of assessment methods and assumptions have been used, it is difficult to compare results across studies.

4.1.2 Traffic calming

This section summarises the available evidence about the effects of traffic calming on emissions and air quality. The literature review is reported in full in Gilbert & Boulter (2022).

Traffic calming is the use of physical measures to control vehicle speed and traffic volume, leading to improved road safety. Traffic calming measures typically involve a vertical and/or horizontal deflection of the vehicle path.

Traffic calming measures can increase vehicle accelerations and decelerations, which can in turn increase GHG and harmful emissions. The available literature suggests that the effects of traffic calming measures on emissions are complex and highly variable.

The literature review by Gilbert & Boulter (2022) summarises and collates the results of 9 studies in which the impact of traffic calming measures on emissions has been estimated, and in which clear,

quantitative results were provided. The literature review finds that traffic calming measures can significantly increase GHG and harmful pollutant emissions per vehicle on affected road segments. For example, the review finds that for the more severe vertical deflections, CO_2 emissions per vehicle kilometre increase by around 30% to 60% on the affected road. For harmful air pollutants the results reported in literature are much more variable.

Overall, the review concludes that the effect of traffic calming measures will depend on the type and design of traffic calming measures. However, design which encourages reduced, steady speed along the whole stretch of road (minimising the amount of vehicle acceleration and deceleration) would help to minimise the emission impacts.

Although impacts of traffic calming on GHG emissions per vehicle on individual affected roads can be significant, the overall effect on emissions across the affected area is likely to be small (less than 10%) because:

- Traffic calming measures tend to be implemented on low-traffic residential roads, or on isolated segments of busy roads (for example in the vicinity of schools).
- Traffic calming can lead to some reduction in overall traffic volume and some diversion of traffic (onto roads without traffic calming).

Gilbert & Boulter (2022) discuss several assessments which demonstrate that the area wide impact of traffic calming schemes on emissions is likely to be small. One detailed modelling study assessed the impact of area wide traffic calming to reduce speed from 50 km/h to 30 km/h across a suburb of Montreal, Canada. Modelling estimated that greenhouse emissions from vehicles across the entire affected area would increase by 4% and NOx emissions would increase by 2%[16]. Two studies from the UK found similar results. A traffic calming scheme in Havant Hampshire was estimated to decrease area wide CO_2 emissions by 8%. Another scheme in Gloucester was estimated to increase area wide CO_2 emissions by 2%.

Several real-world monitoring studies in cities where traffic calming has been widely implemented have found no significant impact on measured ambient air quality. Even though traffic calming measures generally result in increased emissions on affected roads, the review concludes that traffic calming is unlikely to result in poor air quality (Gilbert & Boulter 2022).

4.1.3 Intersection treatments

This section summarises the available evidence about the effects of intersection treatments on emissions and air quality. The literature review is reported in full in Gilbert & Boulter (2022) and Boulter (2023).

There is a significant amount of literature considering the impacts of various intersection treatments on emissions. The review focused on two common themes from literature: replacement of intersections with roundabouts, and improved signal timing and coordination.

Replacement of intersections with roundabouts

The literature review by Boulter (2023) collates and summarises the results from 13 studies in which intersections (signalised or unsignalised) have been replaced with roundabouts, and in which clear,

[16] Ghafgazi (2013) estimated that traffic calming measures could increase emissions from vehicles on individual affected roads by up to 15% to 81%, which is comparable with estimates from other published studies.

quantitative results were provided. Because of the wide range of assessment methods and assumptions used in research it is difficult to compare results across studies. However, the literature review makes some general observations, which are summarised as follows:

- Replacing signalised or unsignalised intersections with roundabouts has typically led to an estimated reduction in CO_2 emissions around 10% to 30%.
- It appears that the greatest (proportional) benefits of roundabouts are in locations with low traffic volume or relatively free-flow conditions where queue lengths and delays can be reduced.
- On the other hand, some authors have found that the emission benefits of roundabouts can be less when traffic reaches capacity and that roundabouts can have higher emissions than intersections under high demand.
- Some authors also report that roundabouts can increase emissions compared with an intersection in low demand locations. For example, replacing an unsignalised intersection with a roundabout could increase emissions because of slowing the traffic.

Overall, the studies suggest that improving traffic flow across intersections can potentially reduce emissions in the vicinity of the intersection. However, the effects of studies are site-specific and depend strongly on local factors such as the traffic volume on different branches of the intersection and the frequency of stops.

Improved signal timing and coordination

The literature review by Boulter (2023) considers four studies relating to improved signal timing and coordination. These studies used microsimulation traffic and emission models to estimate potential emission reductions ranging from 1.5% to 40%. One author noted that signal coordination would tend to decrease travel times which may, in the long term, induce additional traffic potentially offsetting the original benefit.

4.2. Conclusions

Traffic calming

Traffic calming measures can increase vehicle accelerations and decelerations, which can in turn increase GHG and harmful emissions. Studies have generally shown that the implementation of traffic calming increases emissions per vehicle on the affected roads. However:

- The overall impacts of traffic calming on GHG emissions and harmful air pollutant emissions across an affected area would be small (emissions are likely to increase by less than 10%)
- It is unlikely that traffic calming measures will result in poor local air quality, even in the vicinity of traffic calming measures.

Design which encourages reduced, steady speed along the whole stretch of road (minimising the amount of vehicle acceleration and deceleration) would help to minimise the emission impacts.

Intersection treatments

There is a significant amount of literature considering the impacts of various intersection treatments on emissions. The review focused on two common themes from literature: replacement of

intersections with roundabouts, and improved signal timing and coordination. The review focused primarily on GHG emissions.

Overall, there is general consensus in the literature that improving traffic flow across intersections can reduce GHG emissions in the vicinity of the intersection. However, the effects of studies are site specific and depend strongly on local factors such as the traffic volume on different branches of the intersection and the frequency of stops.

Similarly, studies suggest that improved signal timing and coordination can reduce GHG emissions on affected road segments.

5. Reduced speed limits on urban roads

To make roads safer in some urban areas of New Zealand, speed limits are being reduced, for example from 50 km/h to 30 km/h on urban roads. Such a change will affect the following:

- The operation of vehicles on the affected roads. To estimate the impacts on GHG emissions *per vehicle* on the affected roads, it is necessary to understand:
    - The links between speed limits and speed (and more generally, vehicle operation).
    - The links between speed (and more generally, vehicle operation) and emissions, and how these are affected by local conditions (For the affected road(s), the result would be dependent on the local conditions (e.g. road surface, road gradient, road layout, traffic signals)).
- The volume and composition of the traffic on the affected roads. To estimate the emissions *from the traffic* on the affected roads, it is necessary to understand how the change in speed limit affects the numbers of different types of vehicle on those roads.
- The volume and composition of the *traffic on other roads* (and possibly vehicle operation). The change in speed limits may also have wider impacts on the road network which should be considered when evaluating GHG emissions.

Therefore, although quantifying the effects on GHG emissions of the reduction in speed limit seems straightforward in principle, it is rather difficult to generalise in practice, given that multiple factors would affect the outcome. This section examines the impacts on vehicle operation and the impacts on traffic more widely.

5.1. Vehicle operation

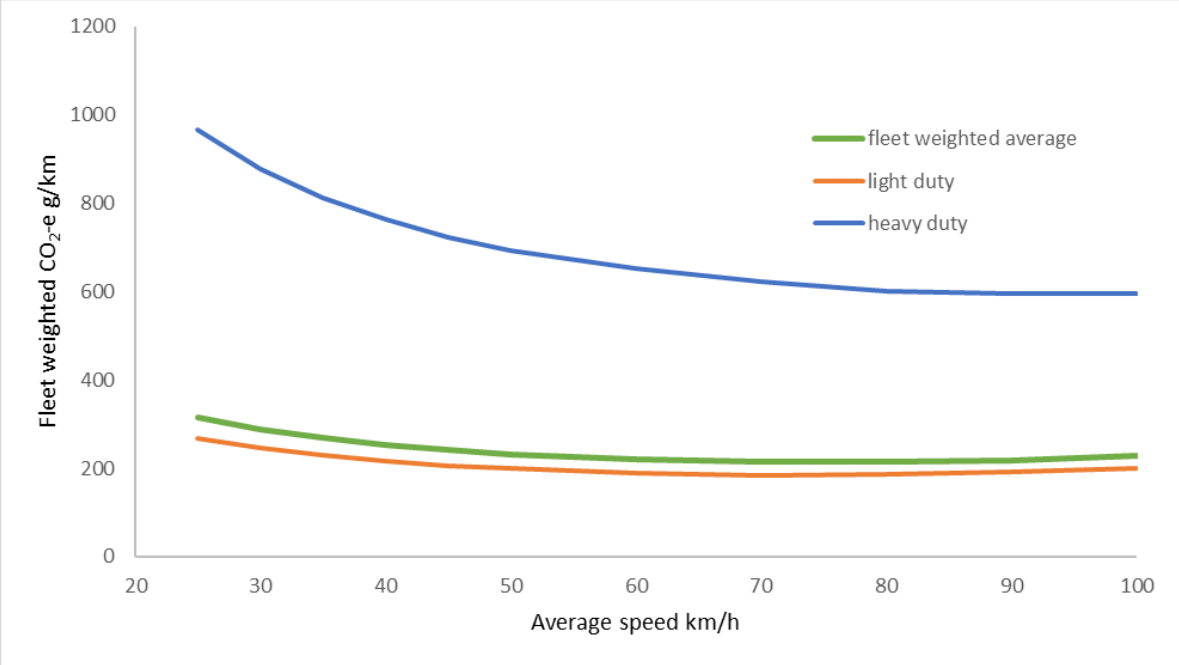
This review firstly considers the impacts of the change in speed limit on GHG emissions from individual vehicles, and only on the road that is affected by the speed limit.

5.1.1 Estimation using average-speed models

When using an average-speed model to estimate the change in emissions associated with the reduction in speed limit, it is necessary to determine the average speed before and after the change. As a first approximation, in this case, we can assume that the change in speed limit from 50 km/h to 30 km/h results in a change in average speed from 50 km/h to 30 km/h. In practice the actual average speeds will not be the same as the speed limits, and the values will vary from road to road.

Figure 4 illustrates the effect of speed on CO_2-e emissions predicted by VEPM. This shows fleet weighted average emissions predicted by VEPM 6.3 for 2022 for the entire fleet, and for light and heavy-duty vehicles separately.

Figure 9: fleet weighted average CO_2-e predicted by VEPM 6.3 as a function of speed for 2022.



Using VEPM for a typical New Zealand traffic mix, a reduction in average speed from 50 km/h to 40 km/h on a given road would result (on the affected road) in an increased in predicted CO_2-e emissions per vehicle-km of 9%, and a reduction in average speed from 50 km/h to 30 km/h would increase CO_2-e emissions per vehicle-km by 24%[17].

For comparison, we have estimated the effects of these speed changes using an average-speed model developed by the New South Wales Department of Planning and Environment for the NSW emissions inventory. With the New South Wales model reducing the average speed from 50 km/h to 30 km/h would increase CO_2-e emissions per vehicle-km by 5% to 14%, depending on the road type.

The main question here is whether the average speeds in VEPM (or any average-speed model) mean the same thing as the corresponding speed limits.

The underlying driving cycles measurements in average-speed models are essentially decoupled from speed limits. For example, a driving cycle with an average speed of 20 km/h may be derived using data for unconstrained conditions on a road with a 20 km/h speed limit, or it may be derived from congested conditions on a motorway. It is likely that fuel consumption and GHG emissions would tend to be different in these two cases. In practice, it is likely that the emission factors at the lower end of the speed range would be based on driving cycles for roads with speed limits in a similar range, but the point is that the speed limit is not modelled explicitly, and information on the actual real-world conditions that each driving cycle in the model represents is usually unavailable to the user.

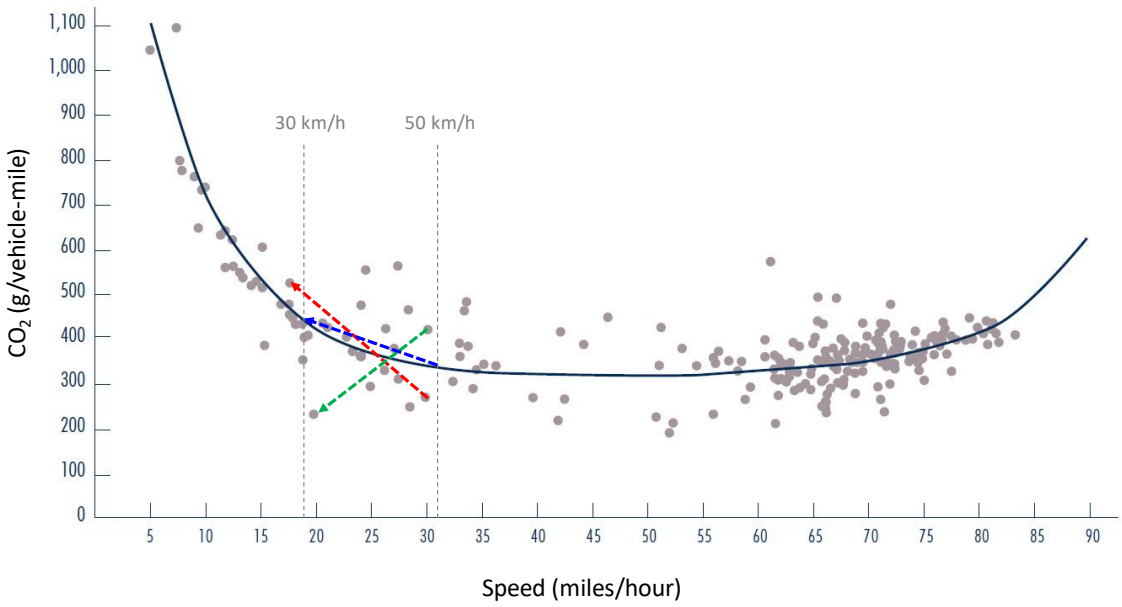
To illustrate this further, Figure 10 takes Figure 7 and shows some possible outcomes for a change in average speed from 50 km/h to 30 km/h. Again, it is possible that none of the driving cycles in the model are actually designed to represent speed limits at these values, but it is likely that some of them will. The blue line shows that the average-speed function would predict an increase in emissions (this is, in principle, what VEPM is doing). However, when considering individual data points in

[17] Estimated using VEPM6.3 for 2022 with all settings at default.

isolation, it is possible that one would conclude that there could be a larger increase in emissions (red line) or a reduction in emissions (green line).

Without knowing all the characteristics of the driving cycles in the model, one cannot know which situation best represents the change in emissions associated with the change in speed limit. The user can only assume that *the emission function has been derived as an unbiased predictor of mean emission performance*, and in many situations this is a reasonable assumption. Where there is concern that the average-speed function is not properly characterising emissions on a *specific* road, this this should be investigated in more detail using real-world measurements of fuel consumption or GHG emissions. This would apply not only to the speed limits mentioned above, but in fact most speed limits; the underlying emission factors are variable aross the speed range.

Figure 10: Effects of changes in speed in an average-speed model



5.1.2 Literature review

There is a substantial amount of literature, going back several decades, on the impacts of reducing speed limits on emissions. We have therefore constrained the review to those studies from the last decade or so. Given that the aim is to understand model predictions, the review also excludes studies based on measurement. Various studies have also focussed on regulated pollutants such as NO_X and PM, without considering GHG emissions.

Int Panis et al. (2011) considered the effects of speed management policies in Europe on CO_2 emissions, noting that many urban streets have been converted into 30 km/h zones. The authors note that reducing the maximum speed is seen as beneficial to the environment due to the reduced fuel consumption and emissions, but add that the claims are often unsubstantiated. Emissions were calculated using the microsimulation model VeTESS, and the results were compared with those from an average-speed model (COPERT). The authors examined the relative change in emissions from light vehicles for a reduction in maximum speed on local roads from 50 km/h to 30 km/h. When using VeTESS, reducing the maximum speed to 30 km/h had a negligible impact on CO_2 emissions. With the

average-speed model, given the shape of the emission functions, slightly higher emissions were predicted for the 30 km/h maximum speed than the 50 km/h maximum speed.

By coupling a traffic microsimulation model with the VERSIT+ emission model, Madireddy et al. (2011) were able to investigate the effects of a reduction in the speed limit from 50 km/h to 30 km/h in a residential area of Antwerp, Belgium. It was estimated that overall CO_2 emissions from traffic would decrease by around 25%. This was attributed to the combination of traffic rerouting and a smoother traffic flow at the lower speed.

Modelling with an instantaneous emissions model in London has found that reduction of speed limits from 30 mph (48 km/h) to 20 mph (32 km/h) would not significantly affect CO_2 emissions in real-world driving conditions. Emissions increased by 2.1% for a Euro IV petrol car and decreased by 0.9% for a Euro IV diesel car. This is because the change in speed limit was found to change driving style, with less acceleration and deceleration on roads with lower speed limits (Williams, 2013).

Research on the effects of speed limits on emissions has been published on the web site Future Transport London[18]. This work does not appear to have been peer reviewed, and some of the wording of the report suggests that it should be treated with caution. For example, it is stated that, "… *the emissions were dominated by the energy required to accelerate the vehicle in stop-start traffic. This contrasts to many of the accepted models in the literature, which exclude the effect of stop-start traffic and consider only the 'cruise' portion of the journey*". This appears to be a misrepresentation of average-speed models (which do include the effects of stop-start traffic), or otherwise refers to very old models. They also note that, "*The existing literature on the relationship between speed and emissions is limited. "*. The findings of this review demonstrate that, this is clearly not the case. The effects on CO_2 were modelled using engine maps from the United States Environmental Protection Agency (USEPA). It is worth noting that only three vehicles were simulated in the study. Nevertheless, this study has been referenced in various other online sources, and so the results are included here. For a small hatchback, at a speed limit of 30 mph (48 km/h) CO_2 emissions were 21% higher than at a speed limit of 15 mph (24 km/h), and 22% higher than at a speed limit of 20 mph (32 km/h). For a diesel SUV, CO_2 emissions were 40% higher at a speed limit of 30 mph than at a speed limit of 15 mph, and 36% higher than at a speed limit of 20 mph. The authors did not consider the wider implications of speed limit changes on traffic on the road network.

In general, the international studies reviewed have estimated that speed limit changes in the 30 km/h to 50 km/h range will have a small impact on individual vehicle emissions (in the order of a few percent). This is consistent with the findings of a real-world travel time and fuel consumption investigation undertaken in New Zealand (Rowland and McLeod 2017). The investigation measured the impact of a speed limit change from 50 km/h to 40 km/h on three short urban routes for a typical petrol vehicle[19]. Each route was driven between 102 and 120 times. At the 40 km/h speed limit, average fuel consumption reduced by 5% and 3% on two routes, and was unchanged on the third route, compared with the 50 km/h speed limit. The results of testing on one type of vehicle can't be extrapolated to the whole fleet. However, the results are broadly consistent with the findings reported in international literature.

[18] https://futuretransport.info/urban-traffic-research/

[19] Each route used a different vehicle of the same model – Toyota Corolla, 2013, 1800cc.

5.2. Impacts on the road network

Where there is a change in the speed limit on a given road, it is likely that there will be impacts on some other roads. Where there is a change in the speed limit on multiple roads, there will probably be wider network implications.

It is possible that any changes in the speed limit on certain roads could be offset by (or compounded by) changes in emissions elsewhere. For example, reducing the speed limit on one road may reduce the traffic volume on that road, as some drivers decide to take an alternative route. The alternative route may be longer than the original route, and the emission factor would be, one imagines, closer that for the original speed limit. Some drivers may even decide to use a different means of transport.

A comprehensive evaluation of 20 mph speed limits in England has found that reduced speed limits could increase the use of active travel modes, thereby reducing GHG emissions. The evaluation found encouraging signs of a small (but significant) increase in use of active travel modes, based on self-reported evidence[20]. The evaluation concludes that the actual extent of mode shift is unclear but is likely to be small. Overall, the evaluation found that the net impact of 20 mph speed limits on GHG emissions was estimated to be small (Atkins, AECOM and Professor Mike Maher, 2018).

5.3. Discussion

The effects on GHG emissions of a reduction in the speed limit from 50 km/h to 30 km/h are dependent on multiple factors, including the type of model used to assess the effects (average speed or microsimulation), and it is difficult to draw generalised conclusions.

The increases in CO_2 emissions per vehicle-km predicted by VEPM are broadly representative of what one would expect from an understanding of average-speed models. Where microsimulation models (or other alternatives to average-speed models) have been used, the estimated change in emissions has ranged from a small increase in emissions from vehicles on the affected roads (a few percent) to a 25% overall reduction, which was attributed to the combination of traffic rerouting and smoother traffic flow at the lower speed. Given that these models have tended to focus on a small sample of vehicles, some bias is likely. Any reduction in emissions due to a lower speed limit is dependent on maintaining a smooth driving pattern at the lower speed. For roads with substantial traffic volumes, this is not a given. Nevertheless, some larger reductions in emissions have been predicted where the overall implications on traffic volume have been considered.

As noted in this review, the average speed is decoupled from the speed limit in average-speed models such as VEPM, and it is possible that the changes in driving patterns associated with these speed limits could lead to real-world outcomes that are different from those predicted by VEPM. Comparing the effects of speed changes predicted by VEPM with the effects predicted by other models reported in the literature suggests that VEPM might slightly overestimate the GHG impact of speed limit changes. This is because average-speed models like VEPM assume typical driving conditions for the average speed – which means more acceleration and deceleration due to stop-and-go driving at lower average speeds. However, reduced speed limits don't generally increase the amount of stop-and-go driving and can make vehicles move more smoothly with fewer accelerations and decelerations.

[20] In case study areas, 5% of residents surveyed said that they are walking more and 2% said that they are cycling more since the introduction of the 20 mph limits. Further changes may occur over time, as a result of the cumulative effect of other sustainable travel interventions or changes in individual circumstances.

Validating the likely impact of speed limit changes in New Zealand would be quite an extensive and time-consuming research project, involving, for example:

- In-situ measurements of fuel consumption and/or GHG emissions, for multiple vehicles before and after the introduction of new speed limits. Again, this is not so straightforward, as it would be desirable to have the tests on the same road, and this may be impractical. Conducting the tests on different roads with different speed limits would introduce some uncertainty into the outcome.
- Microsimulation traffic and emissions modelling. This type of modelling has not previously been undertaken in New Zealand so there are no suitable vehicle emission microsimulation data sets available. Some microsimulation emissions modelling has been undertaken in Australia, but this has tended to focus on a few vehicles.

Either of these detailed research projects would necessarily be limited to assessment of a few vehicles, which could introduce bias in the assessment.

On balance, it seems that the net overall changes in GHG emissions at the individual road or 'project level' are likely to be relatively small (less than around 10% on affected roads and across the affected network). Moreover, roads which have a 30 km/h speed limit often have a relatively low volume of traffic, and therefore the absolute change in GHG emissions at the regional or national level is likely to be negligible. The Auckland Forecasting Centre has undertaken modelling to test this conclusion (summarised in Metcalfe 2023). VEPM emission factors were used with the Auckland Macro Strategic Model (MSM) to estimate vehicle emissions across the Auckland land transport network for a range of speed management scenarios. The modelling confirmed that region wide speed limit reductions would increase emissions by less than 1 %, even though VEPM is likely to overestimate the impact of any emission increase due to speed limit reductions in urban areas. This provides a useful worst case estimate of the likely impacts of speed interventions in the Auckland region.

Further work could include investigation of HBEFA emission factors, which have been developed for roads with specific speed limits. HBEFA factors have recently been updated to include speed limits of 30 km/h and 40 km/h for road types "access residential", "local/collector" and "district connector/medium arterial" (Ericsson et al. 2021). HBEFA emission factors for specific vehicles on different road types and speed limits could be compared with VEPM emission factors for the same vehicle type.

5.4. Conclusions

Average-speed models such as VEPM, typically predict an increase in emissions with reduction of average speed (below about 60 km/h). However, research shows that speed limit reductions in urban areas don't necessarily cause increased emissions in the real world.

The discrepancy between modelled and real-world impacts is because VEPM can't account for differences in specific driving patterns at a given average speed. Average-speed models like VEPM assume typical driving conditions for the average speed – which means more acceleration and deceleration due to stop-and-go driving at lower average speeds. However, reduced speed limits don't generally increase the amount of stop-and-go driving and can make vehicles move more smoothly with fewer accelerations and decelerations.

Overall, we conclude that:

- reduction of speed limits in urban areas will not significantly impact GHG emissions on affected roads (less than 10% change in GHG emissions on affected roads and across the affected network) and the absolute change in GHG emissions at the regional or national level is likely to be negligible.
- VEPM may overestimate the impact of speed limit changes on GHG emissions at low speeds (below 60 km/h). Although our review focuses specifically on speed limit changes in the 30 km/h to 50 km/h range, this conclusion is considered applicable for any speed limit below 60 km/h.

6. Reduced speed limits on state highways

To make roads safer on some state highways in New Zealand, speed limits are being reduced, for example from 100 km/h to 80 km/h.

As discussed in section 5, speed limit changes could affect the operation of vehicles on affected roads as well as affecting traffic volume and composition on the wider network. In this section we focus on potential impacts of speed limit changes on average vehicle emissions on affected roads.

6.1. Estimation using average-speed models

As a first approximation, we assume that the change in speed limit from 100 km/h to 80 km/h results in a change in average speed from 100 km/h to 80 km/h. In practice the actual average speeds will not be the same as the speed limits, and the values will vary from road to road.

VEPM predicts a reduction in CO_2-e emissions per vehicle of 5% for a reduction in average speed from 100 km/h to 80 km/h[21].

The limitations of average-speed models in relation to predicting the impacts of a 50 km/h to 30 km/h speed limit change (in section 4) are generally applicable here. However, there is less variability in speed at higher average speeds than at lower average 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. This means that the estimates of emission changes at higher speeds are likely to be more reliable than those noted for lower speeds in section 5[22].

6.2. Literature review

There is a substantial amount of literature, going back several decades, on the impacts of reducing motorway speed limits on emissions and fuel consumption. In the following paragraphs we have focussed on the more recent studies. Some of the information is taken from a literature review by ADEME (2014).

Baldasano et al. (2010) analysed the changes in emissions and urban air quality due to the introduction of a maximum speed limit of 80 km/h on motorways in the city of Barcelona, Spain. For the affected roads, the existing speed limit was mostly 100 km/h (63% of roads) or 120 km/h (20% of roads). The simulation year was 2008. The methodology combined the assimilation of traffic data from 125 measurement points with an emissions/air quality modelling system. Emissions were modelled using COPERT III. A combination of reduced speed and reduced congestion led to a predicted reduction in CO_2 emissions of 4% in the Barcelona Metropolitan Area. The predicted reduction in emissions on the affected roads only was 10%.

In a pilot study in the Netherlands, Otten and van Essen (2010) considered several scenarios which reduced the speed limit on all motorways from the existing limits of 120 km/h and 100 km/h. It was

[21] Estimated using VEPM 6.3 with all settings at default and assuming that heavy vehicles account for 10.7% of vehicle kilometers travelled based on Waka Kotahi VKT data for state highways in 2021/22. https://www.nzta.govt.nz/assets/userfiles/transport-data/VKT.xlsx

[22] We understand that speed limit changes on state highways tend to be implemented over long distances compared with speed limit changes in urban areas, which might affect small road segments. This would also tend to reduce the uncertainty in emission estimates.

found that a reduction in the speed limit to 80 km/h could potentially reduce CO_2 emissions from cars by up to 30% in the long term. This figure was obtained using detailed emission model data from TNO which found that the most favourable speed limit for minimising emissions was around 80 km/h. Less drastic reductions in the speed limit (to 100 km/h or 90 km/h) had smaller effects on CO_2 but, depending on the scenario, still led to a reduction of emissions from passenger cars on motorways of 8% to 21%, which equated 3% to 9% of all CO_2 emissions from passenger cars in the Netherlands.

The study by Int Panis et al. (2011) (referred to in section 4) considered the effects on truck emissions of reducing the speed limit on urban motorways in Belgium from 90 km/h to 80 km/h. It was determined that the change in speed limits would result in a 'realistic' reduction in speed from 86 km/h to 77 km/h. Emissions were calculated using the microsimulation model VeTESS, and the results were compared with those from an average-speed model (COPERT). In VeTESS, four specific truck models were simulated (all Euro II, ranging from 7.5 tonnes to 30 tonnes), and CO_2 emissions per vehicle were predicted to decrease by between 9% and 16%. In COPERT, four vehicle weight classes were considered: 3.5-7.5 tonnes, 7.6-16 tonnes, 16-32 tonnes and 32-40 tonnes. In this case, estimated CO_2 emissions per vehicle class decreased by between 5% and 14%. In both models, the larger emission reductions were observed for the lighter vehicles.

Chanut & Chevallier (2012) used three types of emission model to estimate the effects of reduction in speed from 90 km/h to 70 km/h on the A86 around Paris. It was found that estimated CO_2 emissions changed by between -4% and +4%, depending on the model type.

Cohen (2014) used a macro-scale traffic model (FREQ) in combination with an average-speed emissions model (COPERT III) to assess three motorways and one national road in the French city of Lille. It was found that a reduction in the speed limit from 110 km/h to 90 km/h led to a decrease in average daily speed of between 4 km/h and 17 km/h, depending on the road and direction of travel. The corresponding predicted changes in daily emissions of CO_2 were between -9.6% and +1.2%.

The regional association for air quality monitoring in Auvergne-Rhône-Alpes, France, estimated that a speed limit reduction from 90 km/h to 80 km/h reduced CO_2 emissions by less than 3% (ATMO Auvergne-Rhône-Alpes, 2018).

Cerema (2020) examined the effect of a French government measure to lower the speed limit on two-way rural roads from 90 km/h to 80 km/h. The authors noted that the 80 km/h measure resulted in a 3 km/h reduction in the average traffic speed. The effect of the measure on CO_2 emissions was estimated using COPERT 4 in combination with floating car measurements, taking into account the scale of the network to which the measure applied and the number of vehicle-kilometres travelled. It was calculated that the measure led to a reduction in CO_2 emissions of more than a million tonnes per year, although the percentage reduction from the baseline was not stated.

Gressai et al. (2021) investigated the effects of reductions in the speed limit on two urban motorways in Budapest, Hungary. The speed limits were relatively low for motorways both before the change (70 km/h) and after the change (60 km/h and 50 km/h). Traffic was simulated using a micro-scale model (VISSIM), and emissions were estimated using HBEFA version 3. The lower speed limits both led to an increase in estimated daily CO_2 emissions of 2%.

In a study for Transport Infrastructure Ireland, AECOM (2022) examined the effects of decreasing speed limits on motorways and national roads. Emissions were estimated using average-speed functions from COPERT 4 and the UK Emission Factor Toolkit. It was estimated that a 10 km/h reduction in the speed limit on motorways (from 120 km/h to 110 km/h) would equate to a reduction

in total GHG emissions (as CO_2-e) of less than 0.7%. Under the most extreme speed-limit change scenario tested, a 30 km/h reduction (from 100 km/h to 70 km/h) across all of national roads in Ireland equated to a 2.7% reduction in GHG emissions.

The German Environment Agency published a study to evaluate the consequences of a general speed limit on previously unrestricted motorways across the country (UBA 2020). Emissions of CO_2 were calculated using PHEM in conjunction with research data on speed. According to this study, the imposition of a 120 km/h speed limit would result in an annual CO_2 saving of 2.6 million tonnes (or 7%). A similar study by Kunkler et al. (2021) found that the introduction of a speed limit of 120 km/h on the German motorway network also resulted in a reduction in CO_2 emissions from the traffic on the network of around 7%. The corresponding CO_2 reductions for speed limits of 100 km/h and 80 km/h were 19% and 26%, respectively.

A New Zealand study (Rowland and McLeod 2017) investigated the impact of speed limit reductions in the 100 km/h to 80 km/h range on travel time and speed. The investigation measured the impact of a speed limit change from 100 km/h to 90 km/h and from 100 km/h to 80 km/h on three open road routes for a typical petrol vehicle[23]. Each route was driven between 40 and 42 times. At the 90 km/h speed limit, average fuel consumption reduced by 5% on one route and 7% on the other two routes, compared with the 100 km/h speed limit. At the 80 km/h speed limit, average fuel consumption reduced by 15% on one route and 14% on the other two routes, compared with the 100 km/h speed limit. The results of testing on one type of vehicle can't be extrapolated to the whole fleet. However, the results are broadly consistent with the findings reported in international literature and support the conclusion that emissions will reduce with a reduction in speed limits in the 100 km/h to 80 km/h range.

It is worth noting that intelligent transport systems (ITS) have the potential to lead to further reductions in CO_2 emissions, sometimes in conjunction with speed limits. For example, Samaras et al. (2016) quantified the effects of various approaches on CO_2 emissions, including variable speed limits, green navigation, urban traffic control, ecodriving and adaptive cruise control. This is a wide area of research, and beyond the scope of this review. However, it would be of value to assess the potential for CO_2 reduction through ITS in New Zealand.

6.3. Discussion

The effect on CO_2 emissions of lowering the speed limits on motorways and highways depends on the method of investigation and the speed limits before and after the change. Typically, where there has been an estimated reduction in emissions this has been less than 10%, and in some cases a small increase has been estimated. In average-speed models the emission functions tend to be quite flat in the range 60-100 km/h (see, for example, Figures 2 to 4). It is therefore unsurprising that the changes in CO_2 emissions in this speed range have been found to be quite small. Larger reductions may be possible in situations where a substantial reduction in speed could be achieved. This is most obviously the case in Germany, and for motorways on which the speed limit is not currently restricted. In these cases, the aerodynamic resistance at high speeds (well above New Zealand speed limits) can result in high emissions.

Average-speed models are widely used to estimate the impact of speed limit changes on motorways. A number of published studies have compared the results from average speed and more detailed modelling approaches. These have found somewhat different results using different models.

[23] Each route used a different vehicle of the same model – Toyota Corolla, 2013, 1800cc.

However, it isn't feasible to confirm whether one modelling approach produces more realistic results compared with another.

As discussed previously there is less variability in speed at higher average speeds than at lower average 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. This means that the estimates of emission changes at higher speeds are likely to be more reliable than those noted for lower speeds in section 5.

VEPM predicts an emission reduction of around 5% for a change in average speed from 100 km/h to 80 km/h. Overall, this is consistent with findings in literature and we consider it likely that speed limit changes from 100 km/h to 80 km/h will result in small reductions in CO_2 emissions from vehicles travelling on the affected roads, in the order of 10% or less.

6.4. Conclusions

There is a substantial amount of literature on the impacts of reducing motorway speed limits on emissions. Typically, where there has been an estimated reduction in emissions this has been less than 10%, and in some cases a small increase has been estimated.

Average-speed models are widely used to estimate the impact of speed limit changes on motorways.

There is less variability in vehicle speed at higher average speeds compared with lower average speeds. This means that the estimates of emission changes from average-speed models at higher speeds are likely to be more reliable than those noted for lower speeds.

For a typical state highway traffic mix, VEPM predicts an emission reduction of around 5% for a change in average speed from 100 km/h to 80 km/h. This is generally consistent with findings in literature.

Overall, we conclude that:

- Speed limit reductions in the 100 km/h to 80 km/h range will reduce GHG emissions by a small amount (less than 10%) at high speeds (80 km/h to 100 km/h).
- VEPM will provide a reasonable estimate of the impact of speed limit changes on GHG emissions. Although our review specifically focused on changes to speed limits in the 100 km/h to 80 km/h range, this conclusion is considered applicable for any speed limit above 60 km/h.

7. Recommendations for VEPM users

This review covers a number of distinct themes. These themes are addressed in separate chapters of the review, and conclusions are provided at the end of each section. The following recommendations for VEPM users are based on conclusions from each section where relevant.

Using VEPM for local scale assessment (spatial resolution)

- It is recommended that VEPM continue to be used to estimate vehicle emissions for GHG assessments and air quality assessments in New Zealand, including local-scale assessments.
- For local-scale air quality assessments, where the spatial resolution of emissions can be of more relevance (compared with a GHG assessment), it is particularly important that users understand the limitations of VEPM.

Temporal resolution of speed data for assessments with VEPM

- 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.
- Using VEPM with higher resolution speed data (i.e. less than 1 hour) is generally not recommended.

Using VEPM to assess impacts of speed limit changes

- It is appropriate to use VEPM to estimate the impact of speed limit changes on GHG emissions for speed limits above 60 km/h.
- VEPM can also be used to assess impacts of speed limit changes at speeds below 60 km/h, although:
    - the limitations of the model predictions should be made clear, and
    - the limitations of the model should be considered in any conclusions or recommendations based on the assessment.

Recommendations for all assessments

While changes in speed can impact emissions, it is important for any assessment of speed related impacts to be considered in the wider context of policy outcomes. For example, road safety measures might reduce vehicle speed and potentially increase emissions per vehicle, but these measures might also contribute to mode shift and reduction in vehicle kilometres travelled. Wider impacts of interventions, such as mode shift, are often not adequately captured in traffic modelling.

It is also important to acknowledge that emission impacts of speed changes will become less significant over time with the increasing prevalence of electric, hybrid and microhybrid vehicles[24,25].

[24] For example, *Te hau mārohi ki anamata*, Aotearoa New Zealand's first emission reduction plan (MfE 2022) contains a target to increase zero emission vehicles to 30% of the light vehicle fleet by 2030.

[25] Emission factors in VEPM account for the projected uptake of electric and hybrid vehicles in the fleet. However, the potential impact of micro hybrids is not yet reflected in VEPM CO_2 emission factor projections (micro hybrid vehicles will also reduce the impact of speed changes because these vehicles are equipped with stop-start technology which minimises emissions penalties at lower average speeds).

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