Vehicle Emissions Prediction Model (VEPM) Version 5.0 Development and User Information Report

Prepared for:

NZ Transport Agency and

Auckland Council

by:

K.Jones, M.Graham, S.Elder and R.Raine

Energy & Fuels Research Unit

Department of Mechanical Engineering

The University of Auckland

November 2011

c/- The University of Auckland
Private Bag 92019, AMC
Auckland 1142, New Zealand
www.uniservices.co.nz

Auckland UniServices Limited
Level 10, UniServices House,
70 Symonds Street, Auckland
+64 9 373 7522

CONTENTS

Glossary of Terms and Abbreviations

Average speed	the average speed for a transient driving cycle
ARC	Auckland Regional Council
cc	cubic centimetre
CO	Carbon monoxide
CO_2	Carbon dioxide
COPERT	Computer programme to calculate emissions from road transport
EMEP/EEA	European Monitoring and Evaluation Programme/European Environmental Agency
EPA	US Environmental Protection Agency
EPEFE	European Program on Emissions, Fuels and Engine Technologies
Euro	European vehicle emissions legislation
FC	Fuel consumption
g/km	grammes per kilometre
HC	Total Hydrocarbons
JCAP	Japan Clean Air Program
kg	kilogramme
km/h	kilometres per hour
L	litre
m/m	"by mass"
MoT	Ministry of Transport
NAEI	National Atmospheric Emissions Inventory
NH_3	Ammonia
NIWA	National Institute for Water & Atmospheric Research Ltd
NO_X	Oxides of nitrogen, including nitric oxide, nitrogen dioxide and nitrous oxide
NZTA	New Zealand Transport Agency
N_2O	Nitrous oxide
PM	Particulate matter
ppm	parts per million
TRL	Transport Research Laboratory
TSP	Total suspended particulates
t	tonne
VEPM	Vehicle Emissions Prediction Model
VKT	Vehicle kilometres travelled
v/v	"by volume"

Introduction

The Vehicle Emissions Prediction Model (VEPM) was developed for the Auckland Regional Council and released as version 3.0 in 2008. The purpose of developing VEPM was:

- To have a model that could be used to predict emissions factors for vehicles that could be found in the New Zealand fleet for typical road, traffic and operating conditions.
- To have a simple emissions prediction model suitable for air quality assessment projects on a regional and national basis.

This original version was based on emissions factors obtained primarily from the UK National Atmospheric Emissions Inventory (NAEI) database, which was based on emissions factors measured during the late 1990's and early 2000's.

In 2009 the ARC felt that VEPM should be updated to reflect the latest data available on emissions factors and also on the NZ vehicle fleet. This decision was supported by the NZ Transport Agency and, jointly, the ARC (now Auckland Council) and NZTA funded the development of VEPM 5.0.

This report is in two parts. The first part covers the process that has been undertaken in the development of VEPM 5.0 and the technical changes that have been made to produce VEPM 5.0. The second part provides users with guidance on its use, limitations and general information relating to vehicle exhaust emissions.

Part 1: Development of VEPM 5.0

1.1 Survey of Users and Non-Users

Prior to commencing the update of VEPM a survey was undertaken of air pollution practitioners in NZ, including both users and non-users of VEPM. A total of 30 people were interviewed, representing 12 individual organisations, and covering 3 classes of organisation; consultants, local and central government agencies and researchers/ consultants.

In summary, the findings of the survey were:

- All the consultants were using VEPM for estimating emissions for air quality assessments or mechanical design for roading or construction projects.

- VEPM was being used in preference to the NZ Traffic Emissions Rates (NZTER) tool due to NZTER's perceived inefficiencies and lack of traceability.

- VEPM was frequently being used for link lengths significantly shorter than the minimum 1km recommended by the developers of VEPM. In many cases these short links also included intersections.

- Users (particularly consultants) recognised that VEPM wasn't designed to predict emissions around intersections but needed such a tool.

- All VEPM users found the model to be user friendly.

- Most users obtained their fleet, vehicle trip and speed data from traffic modellers, generally within their own organisation. Few independently checked this information.

- Several users wanted more detailed speed profile data, ie. shorter speed/distance intervals.

- All the consultants expressed concern about the fleet data. This included:
  - ➢ Lack of current data
  - ➢ The accuracy of the projected fleet out to 2030 and beyond.

- All parties supported the proposal to update VEPM by the inclusion of the latest available emission factors.

- Preferred additions to VEPM were (in order of most requested and highest ranked):
  - ➢ Inclusion of the effect of gradient
  - ➢ $PM_{2.5}$ (particle size + count for NIWA)
  - ➢ Ability to deal with very large runs automatically (both input and output)
  - ➢ Provide advisory information around secondary inputs.

From the survey and previous discussions with the ARC and NZTA a number of recommendations were made and accepted:

- Review latest available international literature on emissions factors and update VEPM accordingly.

- Include factors for Euro 5/V[1] and 6/VI based on latest available information.
- Include effect of gradient.
- If possible, include $PM_{2.5}$ as output instead of PM_{10}.
- Update the fleet profile data to the latest available and ensure this is updated on a regular basis.
- Provide the ability to load multiple input data sets, conduct runs automatically, and output in summary form.
- Investigate the accuracy of VEPM for link length shorter than the 1km recommended minimum, including intersections.
- Investigate the effects of variations in actual speed within an average with regard to potential errors in emissions factor prediction.
- Investigate the effects of gradient on emissions factors on a regional basis.

1.2 Review of Latest Information on Emissions Factors

When VEPM was originally developed, a review was undertaken of all the information available worldwide on emissions factors for light and heavy, petrol and diesel vehicles. From this review the decision was made to base VEPM on the most up-to-date, relevant to NZ, data available at the time from a number of different sources. Table 1.1 shows the sources of emissions factors for the various components of VEPM 3.0.

Table 1.1: Sources of emissions factors for VEPM 3.0

Factor	Vehicle Class	Source (s)
Hot running	Light duty gasoline and diesel	NAEI (2001)
Hot running	Heavy duty (diesel)	COPERT III
Hot running	Japanese domestic imports (light duty)	NAEI (2001) based on NAEI/JCAP equivalent emissions factors
Cold start	All light duty	COPERT III
Fuel correction	All gasoline and diesel	EPEFE
Degradation	European gasoline	COPERT III
Degradation	Japanese domestic imports	JCAP
Degradation	Light duty diesel	European Auto-Oil study
Degradation	Heavy duty diesel	Euro Auto-Oil study + EPA M6.HDE.001
Catalyst removal	Light duty gasoline	NAEI (2001)

---

[1] In this report Arabic numerals are used for emissions standards for passenger cars and light duty vehicles and Roman numerals for heavy duty vehicles.

For the update of VEPM a similar worldwide review was undertaken, looking at developments/new data for each of the above Factors.

Since VEPM 3.0 was released there have been two major developments relating to the models primarily used in VEPM:

- The UK Transport Research Laboratory (TRL) had been commissioned to undertake a review of the methodology used in the NAEI, and

- COPERT III had been updated to COPERT 4

In addition, the US Mobile6 model had been replaced by MOVES2010 (Motor Vehicle Emission Simulator). However, for the reason that Mobile6 was not considered for VEPM, namely that the US fleet composition bears little relativity to the NZ fleet, MOVES was considered to be similarly non-applicable.

1.2.1 Hot Running (Light duty)

The overall outcomes and conclusions of the TRL study [1] for hot exhaust emissions were:

- New emissions factors were developed for road vehicles in the UK using data from other European test programmes. For light duty vehicles, factors were developed for pre-Euro 1 to Euro 4 from test data and for Euro 5 and 6 using scaling factors.
- Emissions factors were developed for methane, 1,3 butadiene, benzene, nitrous oxide, ammonia, polycyclic aromatic hydrocarbons and nitrogen dioxide.
- Low level blends of biodiesel (<10%) are not expected to have any effects on emissions.
- Ethanol/gasoline blends reduce CO, HC and PM emissions but vehicles with new technologies show smaller reductions compared to older technologies.

A significant difference between the new factors and those used in 2001 NAEI database and in VEPM 3.0, is the form of the polynomial, derived from the regression curve fitted to the data. The new polynomial follows the form:

$$E_{hot} = k(a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6)/x$$

where:
E_{hot} is the emissions factor in g/km
x is the average speed in km/h
a, b, c, d, e, f and g are coefficients determined from the statistical analysis.

Another significant difference between the 2001 NAEI database and the 2009 work is that the factors for 2009 were normalised to an accumulated mileage of 50,000km for each vehicle type, whereas the 2001 factors were developed from vehicles of different mileages.

The final significant difference is that in the 2001 database there was only one class of light goods vehicle, whereas in the 2009 version there are three classes: ≤1305 kg, >1305 kg to ≤1760 kg and >1760 kg to ≤3500 kg.

COPERT 4 includes the following changes relative to COPERT III:

- New emissions factors for Euro 4 diesel passenger cars
- New scaling factors for Euro 5 and 6 passenger cars and light duty vehicles

- Hybrid vehicle fuel consumption and emissions factors.
- New N_2O/NH_3 emissions factors for passenger cars and light duty vehicles.

1.2.2 Hot Running (Heavy duty)

In VEPM 3.0, COPERT III was chosen over NAEI because it contained four weight classes for heavy duty vehicles as opposed to two in NAEI. The new TRL developed heavy duty factors retained the same two classes.

The COPERT 4 update includes new heavy duty vehicle and bus methodology (emissions factors, load factor corrections (COPERT III assumed a fixed 50% load) and road gradient factors)

1.2.3 Cold Start

COPERT 4 includes the latest developments on cold start factors but the factors have not changed from version III.

The TRL recommendation was that NAEI should adopt the COPERT 4 methodology for cold start emissions.

1.2.4 Fuel Correction

COPERT 4, and TRL's recommendations for NAEI, continues to use the EPEFE studies as the basis for the correction of hot emissions factors for different fuel compositions. The correction equations have not changed.

The specification of NZ gasoline was revised in 2008, but the new specification is still more or less within the range of EPEFE tested fuels. The range of specifications of the gasoline tested in the EPEFE study and New Zealand regular gasoline are shown in Table 1.2.

Table 1.2: Comparison of EPEFE gasoline against NZ regular gasoline specification

	EPEFE gasoline	**NZ regular gasoline pre-2002 limit**	**NZ regular gasoline 2002 limit**	**NZ regular gasoline 2004 limit**	**NZ regular gasoline 2006 limit**	**NZ regular gasoline 2008 limit**
NZ limit effective date	N/A	N/A	September 2002	1 January 2004	1 January 2006	1 July 2008
Sulphur (ppm)	30-400 ±10	500	350	350	150	50
Aromatics (% v/v)	20-50 ±2.5	48 max	42 max pool avge	42 max pool avge	42 max pool avge.	42 max pool avge
Oxygenates	0%	0.1% m/m max.	1.0% v/v max.	1.0% v/v max.	1.0% v/v max.	1.0 v/v max.
Olefins (% v/v)	6 ±2.7	Not regulated	Not regulated	25 max.	18 max.	18 max.
E100 (%)	35-65 ±2.5	45-67	45-70	45-70	45-70	45-70
E150 (%)	90 ±2	Not regulated	Not regulated	75 min.	75 min.	75 min.

The specification of NZ diesel was similarly revised in 2009. The range of specifications of the diesel tested in the EPEFE study and New Zealand diesel are shown in Table 1.3.

Table 1.3: Comparison of EPEFE diesel against NZ diesel specification

	EPEFE diesel	NZ diesel pre-2002 limit	NZ diesel 2002 limit	NZ diesel 2004 limit	NZ diesel 2006 limit	NZ diesel 2009 limit
NZ limit effective date	N/A	N/A	September 2002	1 January 2004	1 January 2006	1 January 2009
Sulphur (ppm)	450 ±50	3000 max.	Northland and Auckland: 1000 max pool avge Rest of NZ: 2200 max pool avge	500 max. pool. avge	50 max.	10 max.
Density (kg/m^3)	828-855	810-860	820-860	820-850	820-850	820-850
Aromatics (% m/m)	1-8	Not regulated	Not regulated	Not regulated	11 max	11 max
Cetane number	50-58 ±1	45 min.	47 min.	49 min.	51 min.	51 min.
T95 (°C)	320-370	Not regulated	370 max.	370 max.	360 max.	360 max.

1.2.5 Degradation

COPERT 4 has retained the same mileage degradation factors as COPERT III for Euro 1 and 2 passenger cars and light duty vehicles.

For Euro 3 and 4 vehicles the capacity classes have been changed from <1.4L, 1.4-2.0L and >2L, to <1.4L and >1.4L, and the factors have also been changed. The model assumes that the degradation factor is constant above 160,000km.

COPERT 4 does not include degradation factors for heavy duty vehicles.

The TRL study [2] developed degradation factors for cars and light duty vehicles from the database of emissions measurements compiled during the project. However, the authors were of the opinion that more data was required to make the results robust. The database of heavy duty emissions measurements was too small to allow any factors to be developed.

The JCAP study finished in 2006 and there has been no further release of data since then.

1.2.6 Biofuels

<u>Biodiesel</u>

The TRL study [3] concluded that, while the use of biodiesel decreases exhaust emissions of CO, HC and PM, and increases emissions of NO_x, blends of biodiesel with diesel in a proportion of less that 10% are not expected to have any significant effect on emissions.
The EMEP/EEA guidebook [4] lists the effects of biodiesel on emissions as shown in Table 1.4.

Table1.4: Effect of biodiesel blends on diesel vehicle emissions

Pollutant	Vehicle type	B10	B20	B100
CO	Passenger car	0.0%	-5.0%	
	Light duty vehicles	0.0%	-6.0%	
	Heavy duty vehicles	-5.0%	-9.0%	-20.0%
HC	Passenger car	0.0%	-10.0%	
	Light duty vehicles	-10.0%	-15.0%	
	Heavy duty vehicles	-10.0%	-15.0%	-17.0%
NO_X	Passenger car	+0.4%	+1.0%	
	Light duty vehicles	+1.7%	+2.0%	
	Heavy duty vehicles	+3.0%	+3.5%	+9.0%
PM	Passenger car	-13.0%	-20.0%	
	Light duty vehicles	-15.0%	-20.0%	
	Heavy duty vehicles	-10.0%	-15.0%	-47.0%
CO_2	Passenger car	-1.5%	-2.0%	
	Light duty vehicles	-0.7%	-1.5%	
	Heavy duty vehicles	+0.2%	0.0%	+0.1%

Table 1.5 shows the results of a study by the University of Auckland [5] on two buses using a tallow based biodiesel. Bus A was built to Japan 94 emission specifications and Bus B to a pre-Euro specification. The figures are for a combined series of part and full load steady speed tests.

Table 1.5: Change in emissions

Pollutant	Vehicle	B20	B40
CO	Bus A	-29%	-26%
	Bus B	+34%	-13%
HC	Bus A	-15%	-15%
	Bus B	-12%	-27%
NOx	Bus A	+1.4%	+4.2%
	Bus B	-8.2%	-8.2%
PM	Bus A	-14%	-8.2%
	Bus B	-18%	-20%
CO_2	Bus A	-2.6%	-3.3%
	Bus B	-1.2%	-3.2%

There is good correlation between the guidebook heavy duty vehicle and University figures for B20 fuel for HC, PM and CO_2.

The difference between the guidebook and University figures for NO_X may be due to the source of the biodiesel. Both overseas and NZ tests indicate that NO_X emissions from a tallow based biodiesel are lower than from soy or rape based biodiesels.

Ethanol

The TRL study concluded that ethanol/petrol blends reduce CO, HC and PM emissions but vehicles with new technologies show smaller reductions than vehicles with older technologies.

No emissions correction factors could be found for biodiesel or ethanol, primarily, it appears, due to the low proportion of biodiesel in biodiesel/petroleum diesel blends and the low uptake of biofuels in general at this point in time.

1.2.6 Hybrid Vehicles

The TRL study did not include any factors for hybrid vehicles on the basis that very little data was obtained for these vehicles. However, it was recommended that these should be included in future updates of UK emissions factors.

The EMEP/EEA guidebook [4] includes emissions factors for Euro 4 “full” hybrids of <1.6L capacity. The term “full” refers to hybrids that can start only powered by their electric motor.

1.3 Emissions Factors for VEPM 5.0

Based on the information obtained from the review, the sources of emissions factor data selected for VEPM 4.0 are shown in Table 1.6.

Table 1.6: Sources of data for VEPM 5.0

Factor	Vehicle Class	Source (s)
Hot running	Light duty gasoline and diesel	TRL/NAEI (2009)
Hot running	Heavy duty (diesel)	COPERT 4
Hot running	Japanese domestic imports (light duty)	NAEI based on NAEI/JCAP equivalent emissions factors
Hot running	Hybrids	COPERT 4
Cold start	All light duty	COPERT 4
Fuel correction	All gasoline and diesel	EPEFE
Degradation	European gasoline	COPERT 4
Degradation	Japanese domestic imports	JCAP
Degradation	Light duty diesel	European Auto-Oil study
Degradation	Heavy duty diesel	Euro Auto-Oil study + EPA M6.HDE.001
Catalyst removal	Light duty gasoline	TRL/NAEI (2009)

The following sections outline the differences in emissions factors between VEPM 5.0 and VEPM 3.0. Where factors/vehicle classes are not discussed, this indicates that the sources and factors have not changed. Details of the sources and development of unchanged factors can be found in [6].

1.3.1. Hot Running (Light duty)

<u>Pre-Euro, Euro 1 to 4.</u>

Coefficients for pre-Euro and Euro 1 to 4 passenger cars and light duty gasoline and diesel vehicles are as given in TRL Report PPR356 [1], Appendix D. For light duty vehicles the coefficients for type N1(III) vehicles (GVW >1760 to ≤3,500kg) were used in VEPM.

<u>Euro 5 and 6</u>

In VEPM 3.0 emissions factors for Euro 3 and 4 were modelled using scaling factors based on type approval limits applied to Euro 2 emissions factors. As noted in section 1.2.1, NAEI 2009 has taken a similar approach to modelling Euro 5 and 6, applying scaling factors for Euro 4 factors.

The type approval limits for Euro 4, 5 and 6 vehicles are shown in Table 1.7.

Table 1.7: Type approval limits for Euro 4, 5 and 6 vehicles

Level	Limits	Gasoline				Diesel			
		CO	HC	NO_X	PM	CO	$HC+NO_X$	NO_X	PM
Euro 4	g/km	1.0	0.1	0.08		0.5	0.3	0.25	0.025
Euro 5	g/km	1.0	0.1	0.06	0.005	0.5	0.23	0.18	0.005
Euro 6	g/km	1.0	0.1	0.06	0.005	0.5	0.17	0.08	0.005
Euro 5:4	Ratio	1.0	1.0	0.75		1.0		0.72	0.2
Euro 6:4	Ratio	1.0	1.0	0.75		1.0		0.32	0.2

However, Euro 5 and 6 vehicles have different durability requirements and different deterioration factors. These are shown in Table 1.8.

Table 1.8: Type approval durability and deterioration factors

Limits	Mileage km	Gasoline				Diesel			
		CO	HC	NO_X	PM	CO	$HC+NO_X$	NO_X	PM
Euro 4	80,000	1.2	1.2	1.2		1.1	1.0	1.0	1.2
Euro 5	160,000	1.5	1.3	1.6	1.0	1.5	1.1	1.1	1.0
Euro 6	160,000	1.5	1.3	1.6	1.0	To be determined			

These factors have been taken into account in the development of the scaling factors for Euro 5 and 6 vehicles relative to Euro 4 as shown in Table 1.9.

Table 1.9: Scaling factors for modelling hot running emissions from Euro 5 and 6 vehicles

Vehicle Categories	CO	HC	NO_X	PM
Gasoline passenger car, Euro 5, all engine sizes	0.822	0.897	0.594	
Gasoline passenger car, Euro 6, all engine sizes	0.822	0.897	0.594	
Diesel passenger car, Euro 5, all engine sizes	0.798	1.000	0.675	0.213
Diesel passenger car, Euro 6, all engine sizes	0.798	1.000	0.300	0.213
Gasoline light duty vehicles, Euro 5	0.822	0.897	0.590	
Gasoline light duty vehicles, Euro 6	0.822	0.897	0.590	
Diesel light duty vehicles, Euro 5	0.798	1.000	0.673	0.089
Diesel light duty vehicles, Euro 6	0.798	1.000	0.300	0.089

1.3.2 Hot Running (Heavy duty) and Gradient

Coefficients for pre-Euro to Euro V heavy duty vehicles, as used in COPERT 4, are given in the EMEP/EEA air pollution emission inventory guidebook 2009 [7].

In VEPM 3.0 the emissions factors for heavy duty vehicles were based on a zero road gradient and for a load factor of 50%. In VEPM 5.0, factors are included for road gradients of +6%, +4%, +2%, 0, -2%, -4% and -6%, and for load factors of 0%, 50% and 100%. The default condition is 0% gradient and 50% load.

In VEPM 3.0 the speed range was 10 to 100km/h. In VEPM 5.0, using the COPERT 4 data, the maximum speed varies with vehicle type, load and gradient. The maximum average speed for trucks at zero gradient is 86km/h, but at 6% gradient the maximum varies between 40 and 71 km/h.

As a result of these limited ranges of validity, care needs to be taken when using VEPM at the higher end of the speed range or for links that have significant gradients.

1.3.3 Degradation

Degradation rates for European Euro 3 and 4 gasoline passenger cars and light duty vehicles are given in Table 1.10.

As in VEPM 3.0 the emissions factor, corrected for degradation, is give by the equation

$$E_{actual} = s(m)E_{base}$$

where:
E_{actual} is the emissions factor showing the actual effect of degradation
E_{base} is the base or hot emissions factor (i.e. no fuel or cold start correction)
s is the degradation correction factor and is a function of the mileage travelled by the vehicle (m)

$$s(m) = \begin{cases} s(m=0) + m\dfrac{\partial s}{\partial m} & 0 \le m \le m^* \\ s(m=0) + m^*\dfrac{\partial s}{\partial m} & m \ge m^* \end{cases}$$

m^* = 160,000km

Table 1.10: Emissions degradation due to vehicle mileage for Euro 3 and 4 gasoline passenger cars and light duty vehicles

Vehicle category	$\frac{\partial s_{\text{CO}}}{\partial m}$	$s(m=0)$	$\frac{\partial s_{\text{HC}}}{\partial m}$	$s(m=0)$	$\frac{\partial s_{\text{NOx}}}{\partial m}$	$s(m=0)$
≤1.4L	7.129×10^{-6}	0.769	3.149×10^{-6}	0.891	0	1
>1.4L	2.67×10^{-6}	0.955	0	1	3.986×10^{-6}	0.932

In the absence of specific degradation rates for Euro 5 and 6 vehicles, VEPM 4.0 uses the above rates.

1.3.4 Hybrids

As the latest NZ fleet profile provided by the Ministry of Transport includes hybrid vehicles in its long term projections, emissions factors of CO, HC, NO_x and Fuel Consumption from the EMEP/EEA guidebook/COPERT 4 are included in VEPM 5.0.

The hot emissions factor for CO is given by the equation

$$E_{hot} = 3.293 \times x^{-1.165}$$

and the factors for HC, NO_x and FC are given by the equation:

$$E_{hot} = a + cx + ex^2$$

where x is the average speed in km/h and a, c and e are coefficients as shown in Table 1.11.

Table 1.11: Coefficients for calculating emissions factors for hybrid gasoline passenger cars

Pollutant	Engine capacity	a	c	e
HC	All	2.21E-03	44.44E-05	3.00E-07
NO_x	All	-1.00E-02	6.54E-04	-3.76E-06
FC	All	3.8E+01	-2.95E-01	2.99E-03

As noted in section 1.2.7 the test vehicles from which these coefficients were derived were all <1.6L engine capacity. However, in the absence of data from larger engine vehicles the above coefficients are used for all engine capacities at this stage.

This is a section of VEPM that should be updated on a frequent basis as it is a rapidly expanding sector of the vehicle market.

Emissions factors for newer technology vehicles, eg. plug-in hybrids, and larger engine capacity vehicles, should be included as they become available, and factors for existing vehicles should be updated as the database of measurements enlarges.

1.3.5 Vehicle Fleet

NZ vehicle fleet data (vehicle fleet profile and VKT) with projections to 2040 was supplied by the MoT [8].

Figure 1 shows the projected light passenger vehicle fleet by motive power type to 2040.

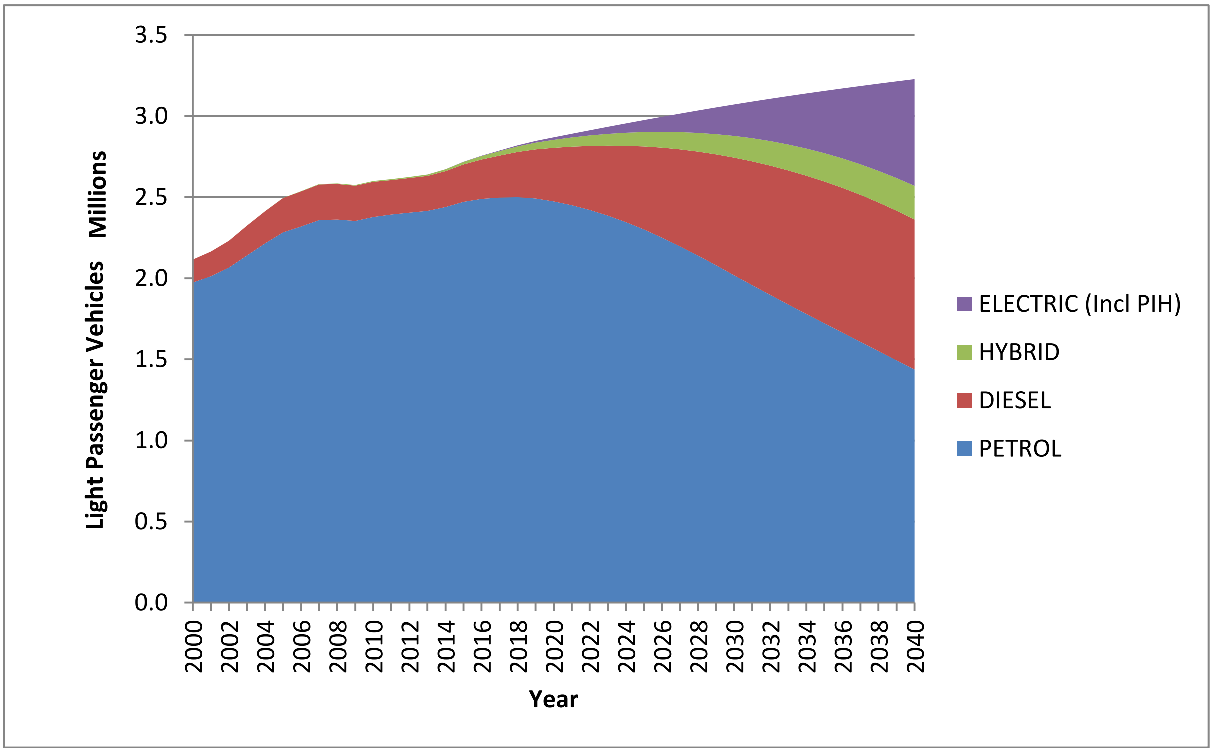


Figure 1: Projected light passenger vehicle fleet.

VEPM requires a detailed breakdown of kilometres travelled by the fleet in order to calculate emissions levels, by multiplying the emissions factors in g/km for each vehicle class by the kilometres travelled by that class for a defined period, eg. a year.

The VKT data used in VEPM is created by combining two sets of data – one is a fleet profile, giving the number of vehicles on the road within each category, and a table of average VKT per vehicle within each category; multiplying these two together gives a total VKT for each vehicle category.

Previously the VKT data was available with a sufficiently detailed breakdown to assign VKT data directly to the appropriate vehicle emissions categories (broken down by vehicle type, fuel type, engine capacity, year of manufacture, whether the vehicle was sold new in NZ or a used import, and country of origin). The latest fleet data no longer contains a breakdown by country of origin – a factor of high importance for New Zealand's reasonably diverse fleet. The lack of this breakdown is particularly problematic for cars from the 70's to the late 90's, where there is considerable variation between the emissions levels of vehicles from different parts of the world.

The process used to establish a country of origin breakdown for the new fleet data follows in pseudo-code format:

```
For each vehicle type
  For each fuel type
    For each original market (NZ new vs used imports)
      For each fleet year
        For each year of manufacture
          Group Total Old = number of cars within this class before breakdown by country of origin (from old data)
          For each country of origin
            Country Total Old = sum of vehicles from this country in this group (from old data)
            Country Fraction = Country Total Old / Group Total Old
            For each engine size group
              Engine Group Total = number of vehicles in this engine size category (from new data)
              Engine & Country Group Total = Country Fraction × Engine Group Total
```

From 2010 all cars are categorised as equivalent to European origin, as it is expected that beyond this point the global standardising of emissions regulations means there is no longer a requirement to differentiate between the countries of origin.

2006 is the last year where recorded data for the fleet broken down by country of origin is available. The percentages from each country from this year onwards are assumed to remain the same, with the actual vehicle numbers slowly decreasing every year due to scrappage. For the years between 2006 and 2010, where new vehicles still require a break-down into country of origin but no data is available, the 2006 manufacture year breakdown is used.

Passenger Car and Light Duty Vehicle Size Categories

Fleet data from MOT is divided into engine size categories:

- <1350cc
- 1350-1600cc
- 1600-2000cc
- 2000-3000cc
- >3000cc

While the NAEI emissions factors are divided as:

- <1400cc
- 1400-2000cc
- >2000cc

The fleet data is grouped to match the emissions factors, so the <1400cc factors are applied to <1350cc vehicles, the 1400-2000cc factors are applied to the 1350-1600 and 1600-2000cc vehicles, and the >2000cc factors applied to the 2000-3000cc and >3000cc vehicles.

Hybrid and Electric Vehicles

MoT fleet data includes 3 new categories, hybrid, plug-in hybrid and electric vehicles. These have been included in VEPM 5.0 but tailpipe emissions are only estimated for hybrid vehicles. Plug-in and electric vehicles only contribute PM emissions from brake and tear wear to the model.

Heavy Vehicle Weight Categories

The EMEP/EEA guidebook includes a much more detailed breakdown of heavy vehicles – with many more weight classes, and a division by vehicle type (bus, coach, rigid truck, articulated truck/truck and trailer). As heavy duty vehicles are not divided by vehicle type in the MoT fleet data, the factors for rigid trucks were applied to all heavy vehicles. In future buses could be separated out from the fleet data and bus-specific emissions factors applied. The weight classes given in the guidebook, in the MT fleet data and in VEPM 5.0, are given in Table 1.12.

Table 1.12: Heavy vehicle weight categories

EMEP/EEA	Fleet Data	Classes in VEPM 4.0 (COPERT class used)
• <7.5t • 7.5-12t • 12-14t • 14-20t • 20-26t • 26-28t • 28-32t • 32t+	• 3.5-5t • 5-7.5t • 7.5-10t • 10-12t • 12-15t • 15-20t • 20-25t • 25-30t • 30t+	• 3.5-7.5t (<7.5t) – includes buses 3.5-7.5t • 7.5-12t (7.5-12t) – includes buses 7.5-12t • 12-15t (12-14t) – includes buses 12t+ • 15-20t (14-20t) • 20-25t (20-26t) • 25-30t (26-28t) • 30t+ (32t+)

The new weight categories no longer match the equivalencies drawn between Japanese and European vehicles. However, as the categories previously spanned a larger weight range, the equivalencies for a single class are now applied to all the new classes within that weight range, for example the equivalencies for the 12t+ class are now applied to all categories from above 12t (12-15, 15-20, 20-25, 25-30 and 30+).

Part 2: Notes on the Use of VEPM and other Information Relating to Exhaust Emissions

2.1 Characteristics of VEPM

VEPM is what is known as an Average Speed model, that is to say, the input data defining the vehicle operation is the average speed of the vehicle over the link or grid under consideration.

This type of model is ideally suited to the creation of emissions inventories (as was the original intention of VEPM) as it is scalable with ease from single highways to multi-road grids.

The emissions factors used in VEPM have been obtained from actual tests on a large number of vehicles of different types, sizes and technologies. The test cycles used were, in the main, representative of real on-road driving conditions, rather than the stylised cycles used for regulatory purposes. The cycles comprise of periods of idle, acceleration, cruise and deceleration, and simulate both uphill and downhill conditions. The emissions factors therefore cover a wide range of road speeds about the average.

As a result of this approach, low average speeds effectively represent conditions typical of congested urban routes with frequent intersections and traffic signals. Conversely, high average speeds represent free flowing rural or highway conditions.

2.2 Using VEPM 5.0

The procedure for using VEPM 5.0 is identical to that for version 3.0.

Changes in input parameters are:

- Year range is now out to 2040 (previously 2030)
- Optional inputs for heavy duty vehicles now include gradient: -6%, -4%, -2%, 0 (default), +2%, +4%, +6% and load: 0%, 50% (default) and 100%

The valid speed range for the particular heavy vehicle gradient and load condition is noted on the Input Sheet. If the conditions are changed the speed range will change.

VEPM 5.0 has the capability to undertake multiple calculations of different input conditions with a single run.

2.3 Link Lengths

When VEPM was originally developed the recommendation was that the minimum grid size (or single highway length) should be 1km.

It was noted during the survey conducted at the start of the upgrade programme (see Section 1.1) that many consultants were using VEPM for link lengths of considerably less than 1 km.

In order to investigate the accuracy of VEPM over these short distances a test programme was undertaken using a suitably instrumented vehicle driven repeatedly over a 1km length of mainly flat road in the Auckland CBD containing 9 intersections in one direction and 8 in the other.

From the data obtained from on-board instrumentation, three speed ~ time profiles were selected representing the lowest (7.5 km/h), highest (32 km/h) and one intermediate (15.5 km/h) average speed. All three profiles were then reproduced on the University of Auckland's transient chassis dynamometer. The fuel consumption/CO_2 and regulated emissions (CO, HC and NO_X) were measured over these profiles and compared with VEPM predictions based on the average speed for each profile.

Full details of the test programme are given in Appendix 1.

Figure 2 shows measured CO_2 emissions and predicted CO_2 emissions over an average speed range of 3 km/h to 50 km/h. Results are shown for the full 1 km route length and for a 100 m length with an intersection in the middle. Two runs were also done at steady speeds of 30 km/h and 50 km/h for reference.

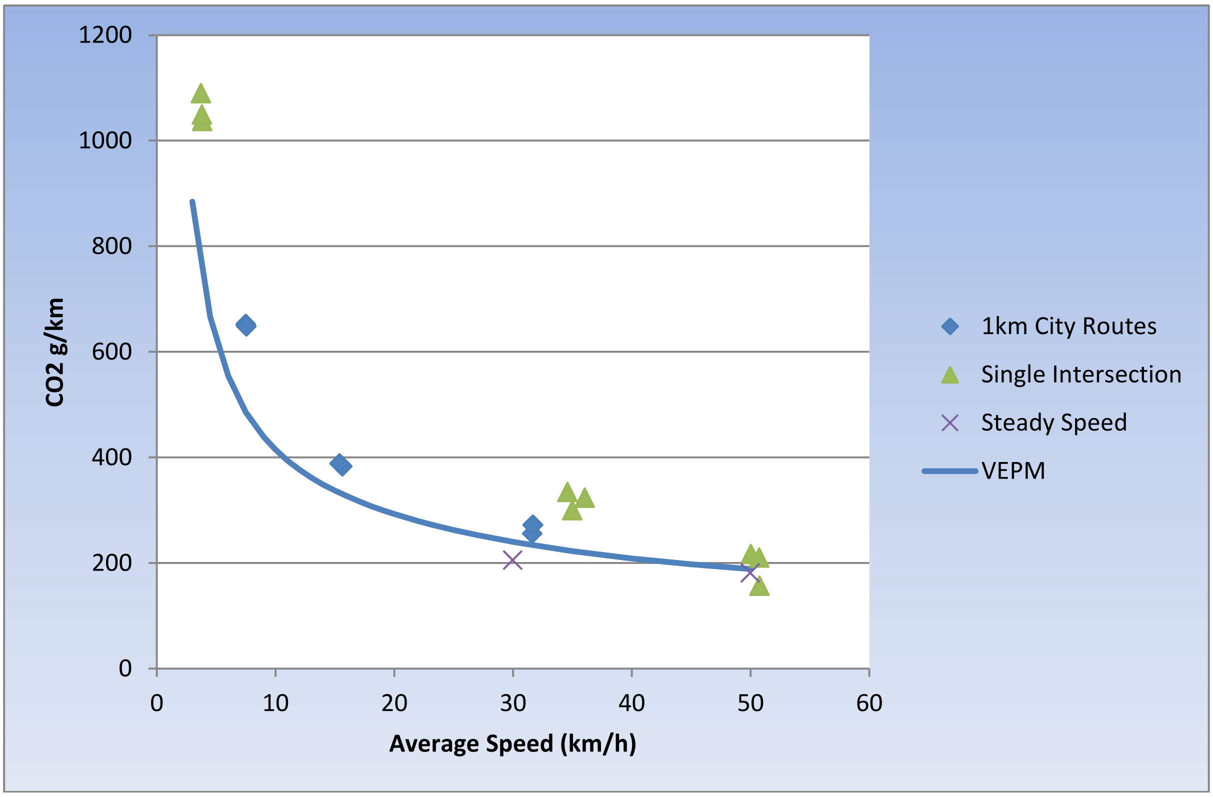


Figure 2: CO_2 emissions ~ average speed: predicted and measured

Taking into account that the test vehicle had a 3L engine, and VEPM uses aggregated emissions factors for engine sizes over 2L, both the full 1km route and the intersection figures show good agreement between measurements and predictions. On the basis of this test, albeit on only one vehicle, it would appear that VEPM can be used with equal confidence for regional size studies down to short link length studies.

The results for the other emissions were not as good as for CO_2, but this is a reflection of the variation in emissions that occurs between vehicles, as has been reported by other researchers, rather than of the fundamental accuracy of VEPM.

2.4 Speed Variation

Other than under motorway or rural conditions driving speeds are seldom constant. While the emissions factors used in VEPM are based on a wide range of real life driving conditions, comprising of accelerations, decelerations, cruise and idle, there have been questions over the accuracy of an average speed model when there are significant variations in speed around the average.

The programme described in section 2.3 also provides useful data from which some conclusions could be drawn as to the speed variation ~ average speed relationship.

Figure 3 shows the speed ~ longitude/distance profile for the various runs along the test route. As can be seen, the speeds varied widely over the route, with some runs having speeds varying from 0 km/h to 47 km/h. However, as illustrated in Figure 1, the measured CO_2 agreed well with the VEPM predictions over the whole average speed range.

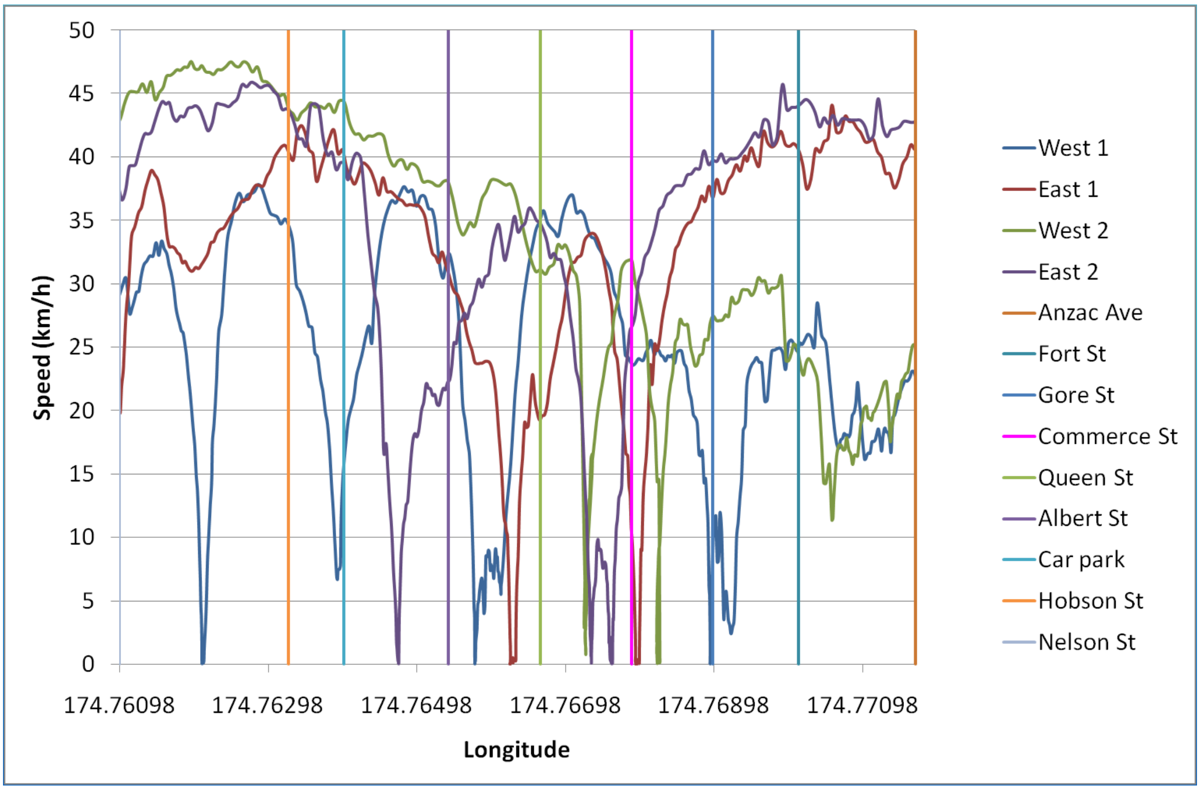


Figure 3: Speed ~ Longitude Profile for 1km Auckland CBD Test Route
(vertical coloured bars show intersections)

2.5 Particulate Matter

There is increasing interest in Particulate Matter (PM) of sizes smaller than the traditional PM_{10} that has been the reference figure for many years.

VEPM emissions factors include PM from two sources, exhaust and road/tyre wear, both of which are currently specified as PM_{10}.

The reality is that almost all PM from both gasoline and diesel exhaust is less than 1 micron, with the majority of particles from both fuels being in the 10nm to 100nm range.

Particles from road and tyre wear on the other hand, are substantially larger. The EMEP/EEA guidebook [9] gives the proportions of PM_{10}, $PM_{2.5}$, PM_1 and $PM_{0.1}$ as shown in Table 2.1.

Table 2.1: Size distribution of tyre and brake wear particles as proportions of Total Suspended Particulates (TSP)

Particle Size Class	Mass Fraction of TSP	
	Tyre Wear	Brake Wear
TSP	1.000	1.000
PM_{10}	0.600*	0.980
$PM_{2.5}$	0.420*	0.390
PM_1	0.060*	0.100
$PM_{0.1}$	0.048*	0.080

*denotes that 60% (by mass) of tyre wear particles are smaller than 10 micron, 42% are smaller than 2.5 micron, 6% are smaller than 1 micron and 4.8% are smaller than 0.1 micron.

This table does not include re-suspension of road dust.

In VEPM 5.0, exhaust PM is now denoted as $PM_{2.5}$ and tyre and brake PM is split into PM_{10} and $PM_{2.5}$ based on the proportions given in Table 2.1.

2.6 Effects of Changes in Gradient on Emissions

It was noted during the initial survey that some users of VEPM were assuming that, if the region over which they were assessing the emissions had a net zero change in elevation, the increase in emissions due to uphill sections within the region would be cancelled out by the effects of the corresponding downhill sections.

However, the characteristics of engine combustion are such that this assumption does not hold true.

For example, NO_x is only produced when the combustion temperature exceeds a threshold temperature, and is highly dependent on mixture strength. Consequently it would be expected that the increase in NO_x as a result of the increased power demand on an uphill section would be larger than the corresponding decrease on a similar downhill section.

This is illustrated in Table 2.2 which shows the emissions rates predicted using VEPM 5.0 for CO, HC, NO_x , PM and CO_2 for fully laden 15 to 20 tonne trucks (combined fleet) over four routes at 50 km/h average speed. The first route is a constant zero gradient, the others are an average zero gradient consisting of positive (uphill) gradients of 2%, 4% and 6%, followed by equal length corresponding negative (downhill) gradients.

Table 2.2: Emissions rates for a level road and different gradients

Gradient	Emissions rates g/km				
	CO	HC	NO_X	PM	CO_2
0%	1.46	0.46	5.00	0.22	679
+2%	2.00	0.47	8.80	0.29	1164
-2%	0.78	0.30	1.84	0.14	262
Average +2%/-2%	1.39	0.39	5.32	0.22	713
Difference wrt 0%	-5%	-15%	+6%	0	+5%
+4%	2.90	0.49	12.49	0.41	1735
-4%	0.42	0.19	0.73	0.10	111
Average +4%/-4%	1.66	0.34	6.61	0.26	923
Difference wrt 0%	+14%	-26%	+32%	+18%	+36%
+6%	3.82	0.53	15.97	0.54	2312
-6%	0.26	0.14	0.36	0.08	56
Average +6%/-6%	2.04	0.34	8.17	0.31	1184
Difference wrt 0%	+40%	-26%	+63%	+41%	+74%

The difference in NO_x between the level road and the positive gradients is clearly much greater than between the level road and negative gradients, with the difference increasing with increasing gradient/engine load.

The overall result of these characteristics is that assuming a nett zero gradient change for a region that contains significant changes in gradient could significantly underestimate the emissions of CO, NO_x, PM and CO_2, and overestimate HC, for heavy duty vehicles.

2.7 Idle Emissions Rates

The authors have frequently been requested for emissions rates for vehicles at idle for the purposes of estimating emissions concentrations, particularly at intersections.

These rates would normally be obtained empirically and quoted in g/min or g/h. However, it is possible to use VEPM to produce rates which, for the purposes of emissions concentrations studies, will be accurate enough.

The emissions factors used in VEPM are taken from different drive cycles for a wide range of average speeds. The lower the average speed, the greater the proportion of the cycle would have consisted of idle. Consequently, by calculating emissions rates down to low average speeds, an approximation of emissions rates at idle can be obtained.

The following gives examples of how this can be done.

Tables 2.3 and 2.4 show the 2011 fleet average CO and NO_X emissions factors and emissions rates from 10 to 25 km/h and Figures 4 and 5 show plots of the emission rates.

Table 2.3: CO emissions factors and rates at low speeds

Speed km/h	Emission factor g/km	Emissions rate g/h
25	6.11	153
20	7.01	140
15	8.46	127
10	11.32	113

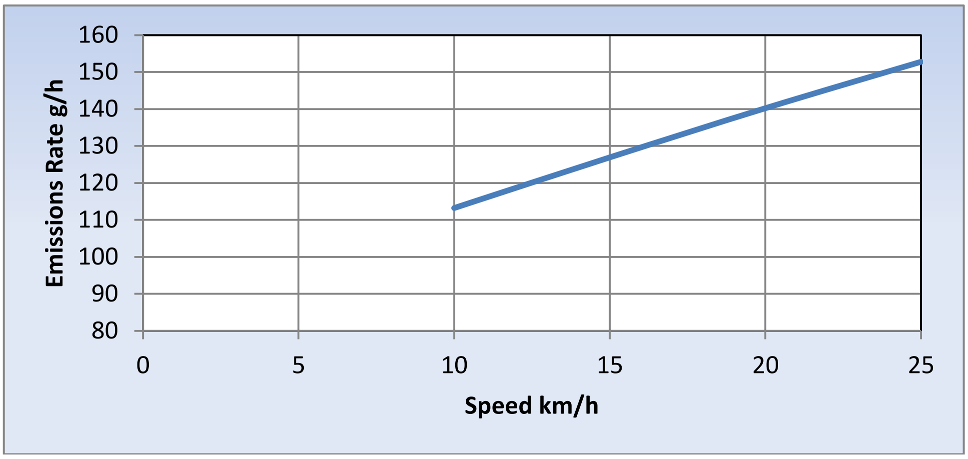


Figure 4: CO emissions rates at low speeds

Table 2.4: NO_X emissions factors and rates at low speeds

Speed km/h	Emission factor g/km	Emissions rate g/h
25	0.86	21.5
20	0.94	18.8
15	1.07	16.05
10	1.33	13.3

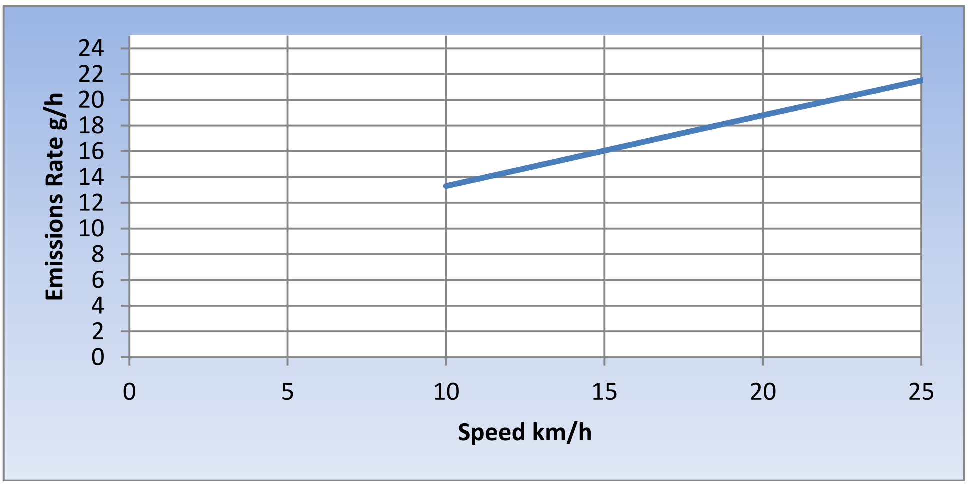


Figure 5: NO_X emissions rates at low speeds

Extrapolating the lines back to the zero speed axis will give approximate values for the idle rates, ie. 85 g/h for CO and 8 g/h for NO_X.

References

1. **P.G. Boulter, T.J. Barlow and I.S. McCrae.** Emissions factors 2009: Report 3 – exhaust emissions factors for road vehicles in the United Kingdom. TRL report PPR356, 2009.

2. **P.G. Boulter.** Emissions factors 2009: Report 6 – deterioration factors and other modelling assumptions for road vehicles in the NAEI. TRL Report PPR359, 2009.

3. **P.G. Boulter and S. Latham.** Emissions factors 2009: Report 5 – a review of the effects of fuel properties on road vehicle emissions. TRL Report PPR358, 2009.

4. **EMEP/EEA air pollution emission inventory guidebook 2009.** 1.A.3.b Road transport update 2010.

5. **N.M. Boeille.** Assessment of Bus Exhaust Emissions for Tallow Methyl Ester Biodiesel Blends. ME Thesis, The University of Auckland, 2006

6. **K.Kar, B. Baral and S Elder.** Development of a Vehicle Emissions Prediction Model. A report prepared for the Auckland Regional Council by the Energy and Fuels Research Unit, The University of Auckland, 2009

7. **EMEP/EEA air pollution emission inventory guidebook 2009.** 1.A.3.b Road transport annex HDV files.

8. **S.Wheaton.** Personal communication, 2011.

9. **EMEP/EEA air pollution emission inventory guidebook 2009.** 1.A.3.b.vi Road vehicle tyre and brake wear.

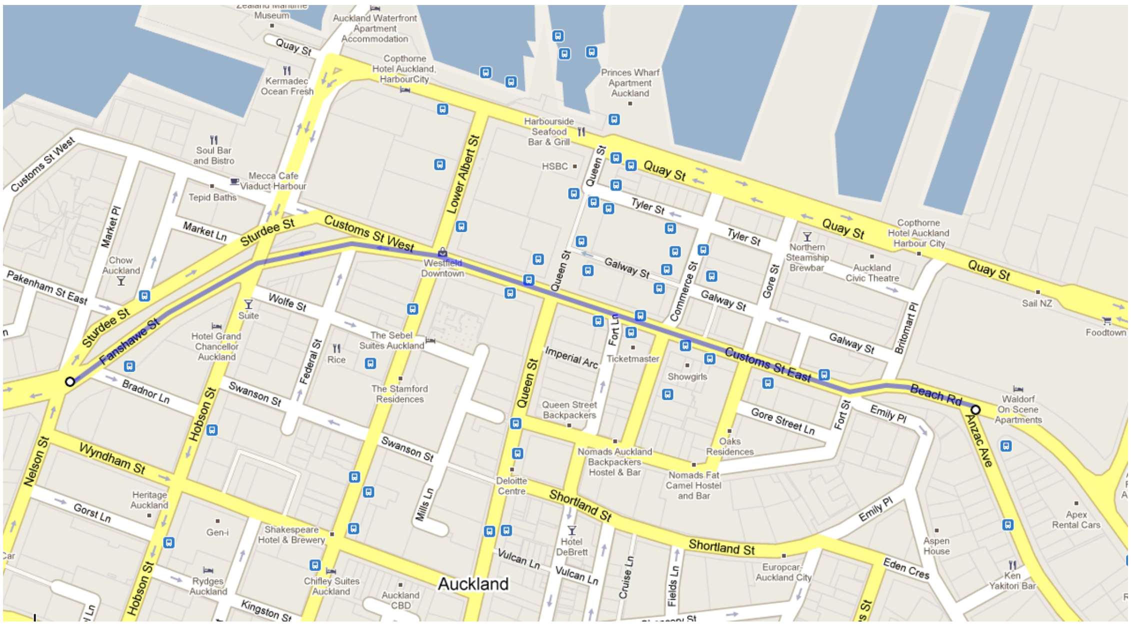
Appendix 1: Short Link Comparison Test Programme

Testing of fuel consumption and emissions from a 2010 Holden Commodore (a Euro IV-compliant vehicle) were performed in order to assess the accuracy of VEPM for short trip distances. The testing comprised of two stages:

1. With the vehicle fitted with GPS monitoring and recording equipment, driving repeatedly along a 1km route through Auckland City in order to establish the range of average speeds that could be obtained over such a trip, and to generate speed/distance profiles for this route.
2. Chassis dynamometer testing, where the same vehicle was run through three different drive cycles, matching recorded routes from the on-road testing. This was performed with the vehicle connected to a constant volume sampling emissions system and fuel flow measuring equipment.

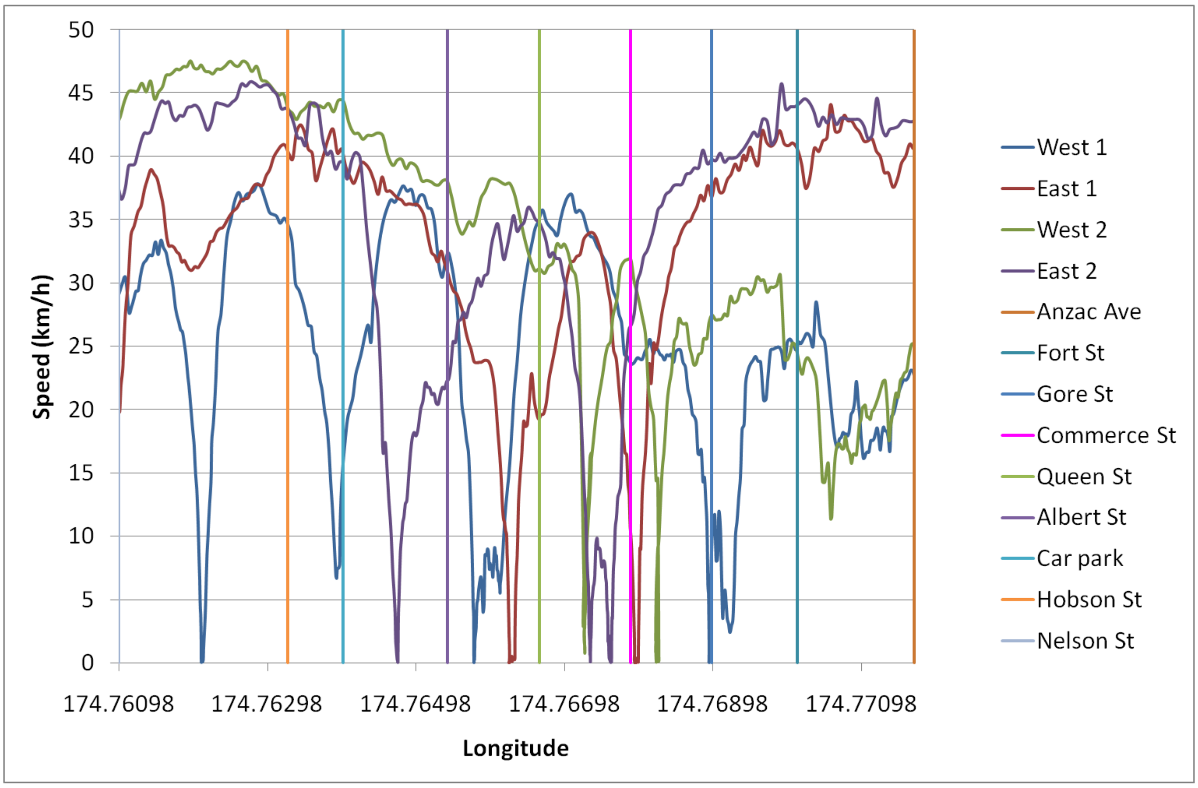
On-road Testing

The route for the on-road testing is shown in blue in the image below. The recorded route runs between the white dots. The route runs approximately East-West along Customs and Fanshawe Streets.

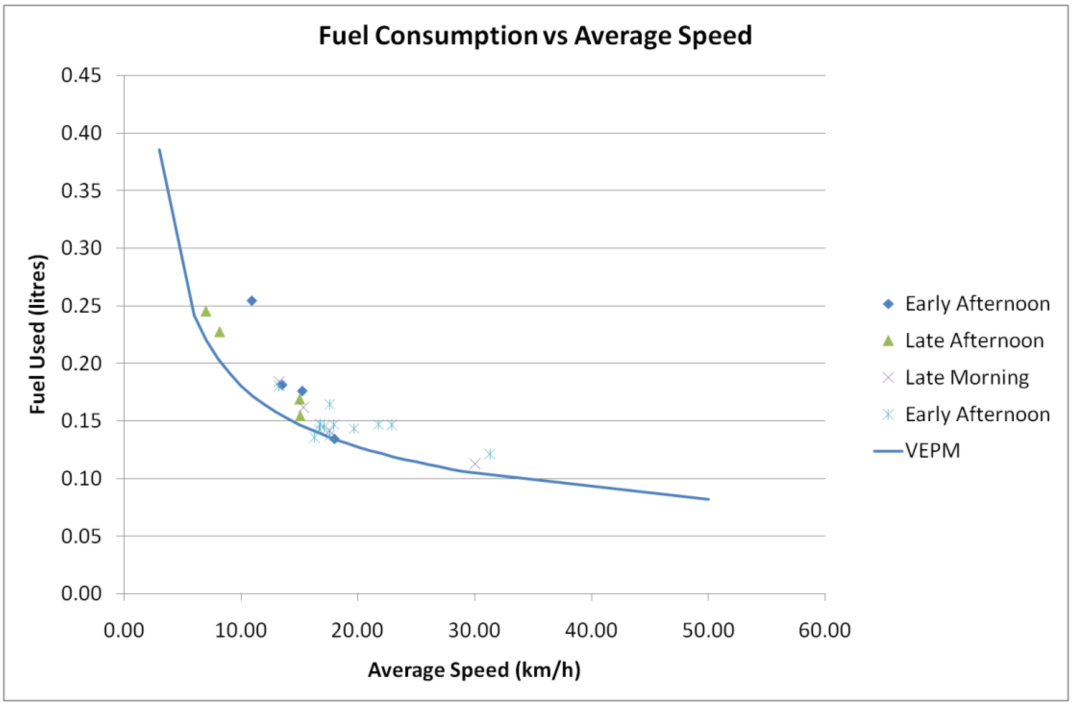


This route was chosen due to the large number of intersections and frequent congestion being expected to provide a large amount of variability in average speeds through the route.

From 24 passes along this route, average speeds ranging from 7 to 32km/h were obtained. A chart is shown below, plotting speed against longitude (effectively showing speed along the route) for one set of four passes.



The data logging equipment fitted to the car for this testing includes an OBD II (on board diagnostics) port scanner, which amongst other things, collects information from the vehicle's computer from which it can calculate approximate fuel consumption. Previous testing has shown an accuracy of around 5% for this calculated value versus actual fuel consumption. The fuel consumption over the 1km route for all runs compared with the predicted fuel consumption from the VEPM, are shown below. Note that the predicted values from the VEPM are simply the hot emissions values, with no fuel corrections, degradation, or warm-up corrections added.

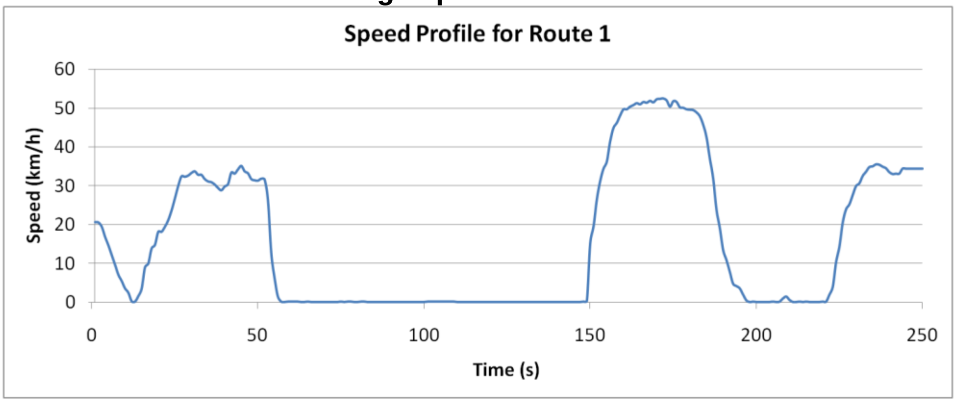


With the possible exception of one early afternoon run with an average speed around 10km/h, this shows a very good correlation between the VEPM and the actual results.

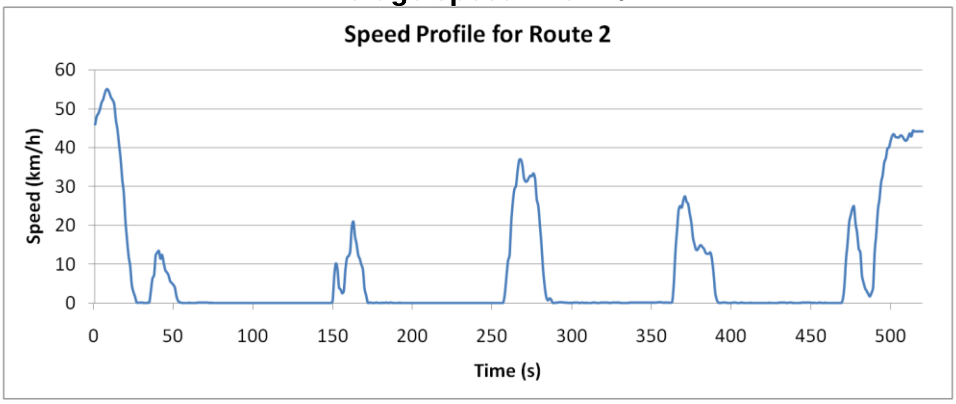
Dynamometer Testing

From the recorded speed/time profiles for all the trips, the fastest, slowest and one intermediate speed were selected for dynamometer testing. The testing consisted of running the test vehicle through the selected speed/time profile while recording fuel flow into the engine and collecting exhaust emissions for analysis after the runs. Each route was run three times to increase confidence in the results. The three selected speed/time profiles are shown below.

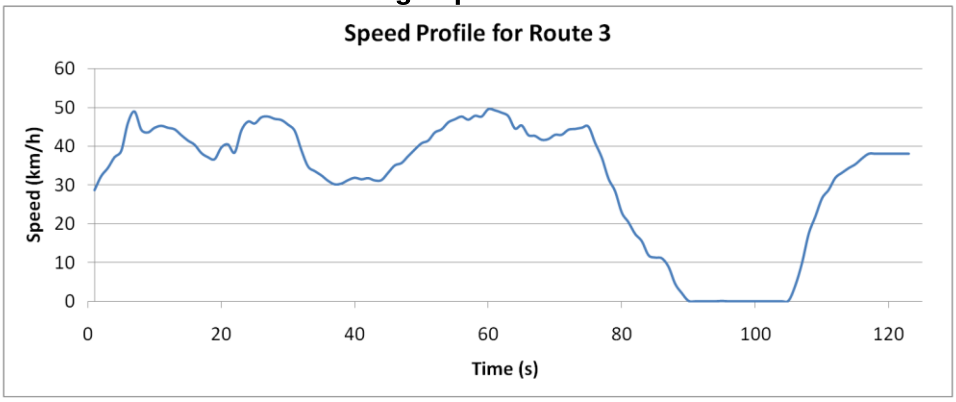
Average speed: 15.5km/h:



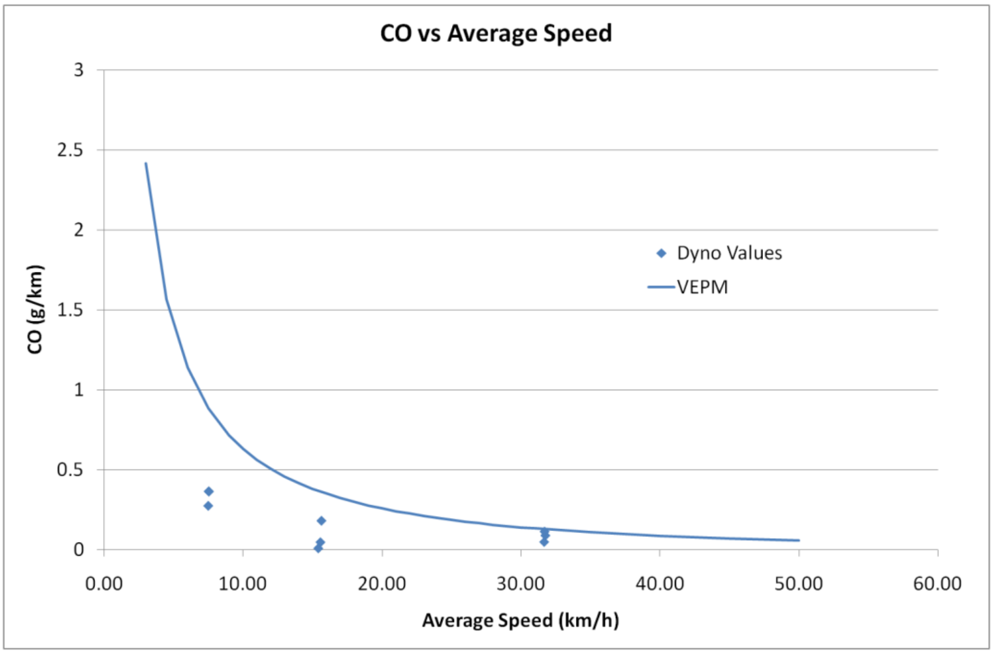
Average speed: 7.5km/h

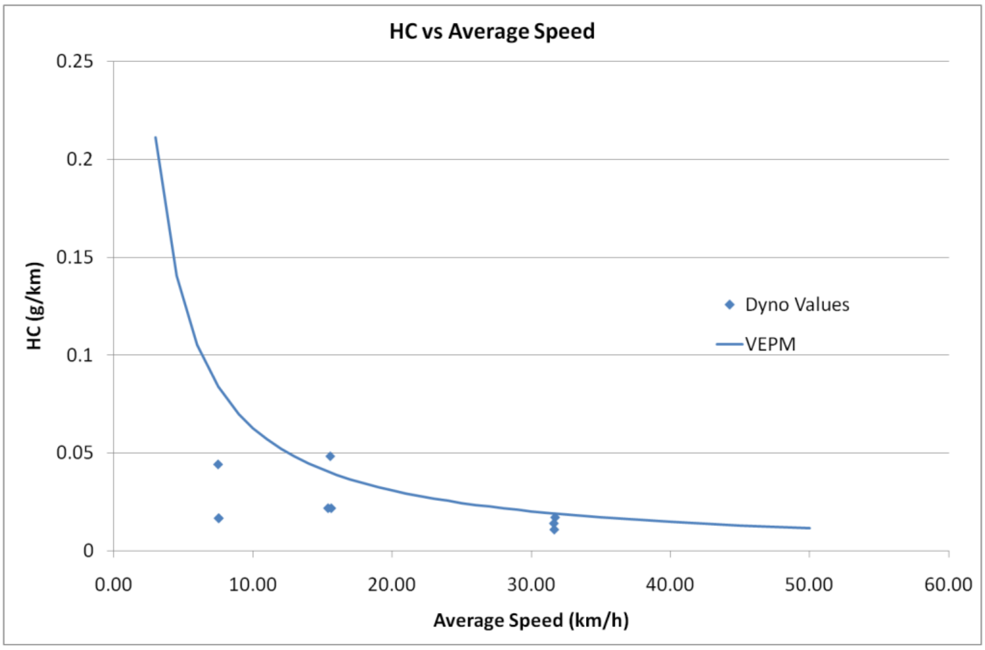


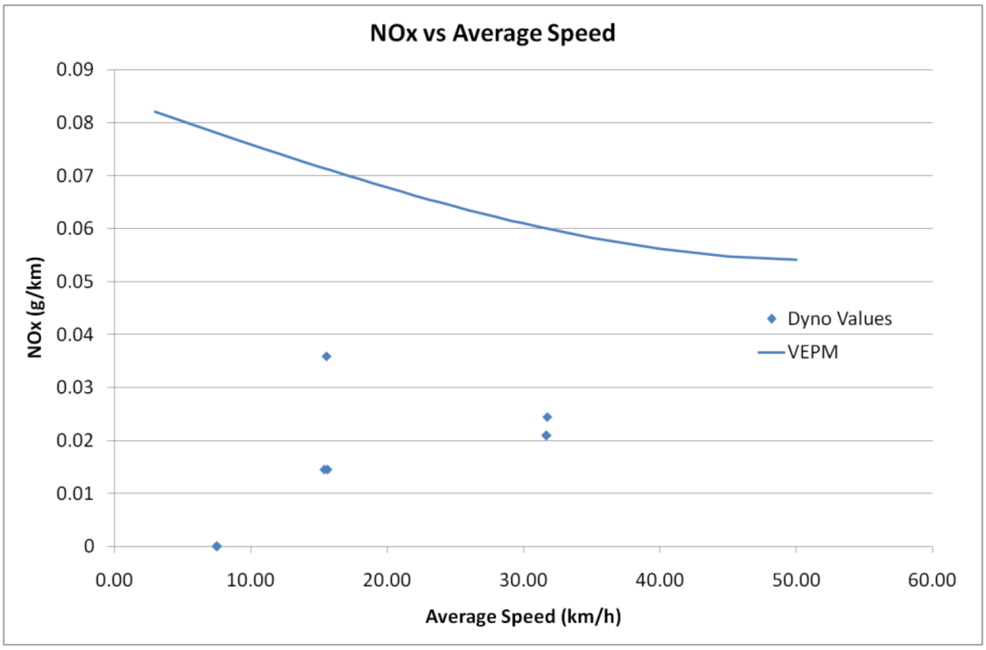
Average speed: 32km/h

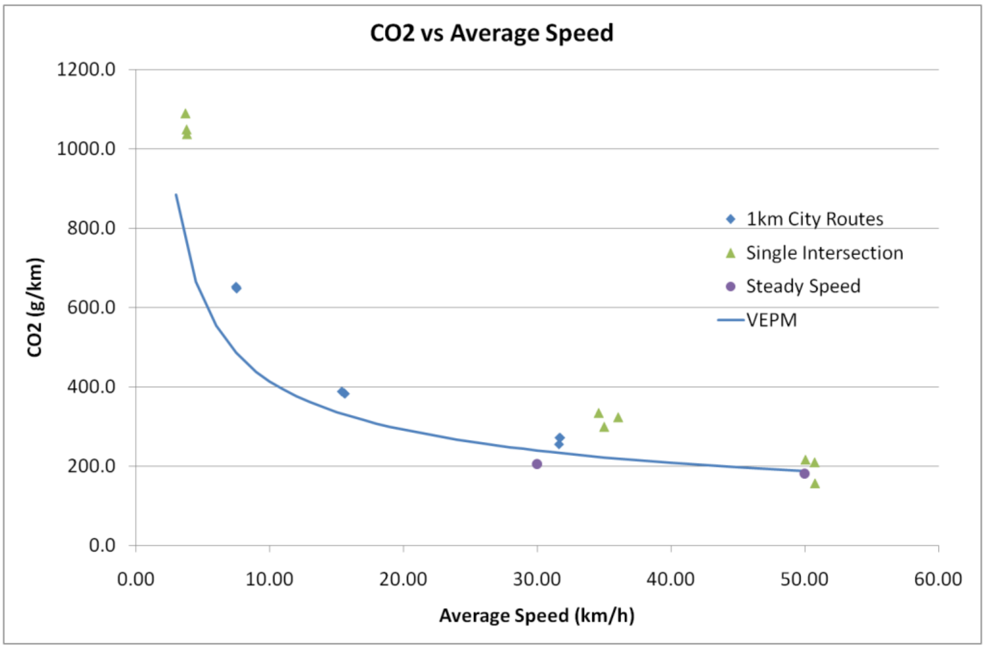


Results
The results for each of the tested emissions species are shown below.









Included in the CO_2 data are values for a 100m section of the routes, representing 50m on either side of an intersection. Values from previous steady-speed testing of the same vehicle at 30 and 50km/h are also included for additional reference. It can be seen that the CO_2 (and so fuel consumption) predicted by VEPM follows the same trend and has a very similar magnitude to the results, even when taken down to very short trip lengths.

The other emissions species do not show as good a correlation between the predicted and experimental results, with the error being worse at lower speeds. This is the same as has been found in numerous other international studies.