Emissions Estimation Technique Manual

for

Aggregated Emissions from Paved and Unpaved Roads

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EMISSIONS ESTIMATION TECHNIQUE MANUAL:
AGGREGATED EMISSIONS FROM PAVED AND UNPAVED ROADS

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1.0 Introduction

1.1 The NPI

The National Pollutant Inventory (NPI) was established under a National Environment Protection Measure (NEPM) made by the National Environment Protection Council (NEPC) under Commonwealth, State and Territory legislation on 27 February 1998. This Measure is to be implemented progressively through the laws and administrative arrangements of each of these participating jurisdictions (i.e. State and Territory Governments).

The NEPM and an associated Memorandum of Understanding for the NPI, which have been published as a single document by the NEPC, provide more details on the purpose and structure of the NPI, and the arrangements for implementation of the NEPM that have been agreed by the jurisdictions. Users of this Manual should read this publication if they are unfamiliar with the NEPM or the NPI.

1.2 Purpose and Scope of the Manual

The NPI will be developed as an internet database designed to provide information on the types and amounts of certain chemical substances being emitted to the air, land and water environments. If the NPI is to achieve its aim of communicating useful and reliable information to the community, industry and governments on pollutants present in our environment, the emissions estimation techniques (EETs) used to generate inputs to the NPI need to be consistent, and the process for developing these techniques needs to be transparent. This Manual has been developed, reviewed and finalised in this context.

The NEPM contains a list of substances for which emissions will be reported on an annual basis to the Commonwealth Government, which will then compile and publish the NPI. The aggregated emissions (AE) manuals, of which this is one, have been prepared to assist State and Territory Governments in preparing these submissions, and to facilitate consistent reporting between these jurisdictions.

State and Territory Governments will also be compiling and submitting emissions data based on annual inputs from reporting facilities. These facilities are primarily industrial enterprises which use (or handle, manufacture or process) more than specified amounts of certain polluting substances, burn more than specified amounts of fuel, or consume more than certain amounts of energy. These amounts or “thresholds” (which are clearly defined in the NEPM) govern whether an industrial facility is required to report and what substances it is required to report on, and industry handbooks are being developed to help industries to prepare the information for these reports.

The AE manuals complement these handbooks, and are intended to enable Governments to estimate emissions from non-industrial activities (e.g. transportation, domestic and commercial activities) and emissions from

industry which are not reported because the relevant thresholds are not exceeded.

Annual submissions are also to be prepared and submitted in conformance with the NPI Data Model and Data Transfer Protocol. For emissions to the air environment, this Protocol only requires jurisdictions to submit data on emissions into the particular airsheds that are listed in the Protocol, and not to the rest of each jurisdictional area. For example, in Victoria, emissions data are only required for the Port Phillip and Latrobe Valley Regions. In addition, emissions data are required to be submitted on a gridded basis, with each jurisdiction determining a grid domain and grid cell size appropriate to its needs and responsibilities (e.g. for air quality modelling purposes).

Therefore, in addition to recommending and providing details and examples of appropriate emissions estimation techniques (EETs) for the relevant NPI substances, this Manual provides guidance on the spatial allocation of emissions and the use of area-based surrogates for accurately distributing the activities or sources in question.

1.3 Application of the Manual

Each of the AE manuals provides details of:

- the NPI substances that are expected to be emitted from the relevant aggregated source type;
- the origins or sources of the emissions, and the processes that may generate them;
- the impacts of any control equipment or procedures on those emissions;
- the broad approaches that may be employed in the estimation and spatial allocation of emissions;
- details of emission factors to be used in the estimation of emissions; and
- a series of illustrative sample calculations for each estimation technique.

Each of the manuals also contains a section on “Uncertainty Analysis”, which provides information and guidance to users on the reliability of the various estimation techniques, problems and issues associated with their development and application, and recommendations for their improvement. In preparing the AE manuals it has been recognised that some jurisdictions already undertake detailed emissions inventories on a regular basis, based on relatively sophisticated methodologies. For these jurisdictions the manuals offer techniques which represent commonly available best practice for emissions estimation in Australia (i.e. techniques of high quality which can be employed by larger or more experienced jurisdictions with an acceptable expenditure of time and effort). The most recent developments in inventory methodology in Australia and overseas have been considered in selecting and documenting these techniques.

Where a more simplified methodology for emissions estimation of acceptable quality is available, it is recommended in the manual for the use of those jurisdictions which may, for the time being at least, lack the data, resources or

expertise to employ a more sophisticated approach, or not see the need for highly reliable estimates in that particular part of the inventory.

2.0 Emissions Covered by the Manual

2.1 NPI Substances

Field studies have found that paved and unpaved roads are a major source of atmospheric particulate matter within an airshed (USEPA 1997).

Road dusts emitted into the atmosphere may be categorised according to dust particle size as follows:

- particulate matter less than or equal to 2.5 μm (PM2.5);
- particulate matter less than or equal to 10 μm (PM10), which is a substance listed in Table 2 of Schedule A to the NEPM;
- particulate matter less than or equal to 15 μm (PM15); and
- particulate matter less than or equal to 30 μm (PM30), which is assumed to be equivalent to total suspended particulate matter (USEPA 1998).

A number of other NPI substances listed in Schedule A to the NEPM are found on roadways in trace amounts, and may form part of the particulate matter which is emitted from paved and unpaved roads. These substances are listed in Table 1.

Table 1: NPI Substances Typically Emitted from Paved and Unpaved Roads

Antimony and compounds	Manganese and compounds
Arsenic and compounds	Mercury and compounds
Cadmium and compounds	Nickel and compounds
Cobalt and compounds	Particulate Matter ≤10μm (PM10)
Copper and compounds	Selenium and compounds
Lead and compounds	Zinc and compounds

2.2 Emission Sources and Related Processes

2.2.1 Paved Roads

When a vehicle travels over a paved road, particulate emissions are generated by the suspension or resuspension of loose material on the road surface. The surface loading of this material is the main source of particulate emissions from roads, and is continually moved and removed via the processes listed in Table 2. Deposition processes lead to a constant supply of loose material accumulating on the road surface.

Particulate matter also arises from exhaust and other emissions directly associated with motor vehicles. These emissions are not covered in this manual.

Table 2: Removal and Deposition Processes for Paved Road Dusts

Removal	Deposition
Re-entrainment	Dustfall
Wind erosion	Litter
Displacement	Mud and dirt carryout
Rainfall runoff to stormwater drains	Erosion from adjacent areas
Street sweeping	Spillage

2.2.2 Unpaved Roads

When a vehicle travels on an unpaved road the force of the wheels on the road surface pulverises the surface material into fine particles. Tests have shown that fine particles are continually removed by traffic through re-entrainment to the atmosphere, leaving a higher percentage of coarse particles on the road surface (USEPA 1998). These fine particles are lifted by and dropped from the rolling wheels of vehicles, and the road surface is exposed to strong air currents in turbulent shear with the surface. The turbulent wake that is left behind the vehicle continues to act on the road surface after the vehicle has passed, resulting in further particulate emissions.

2.3 Emission Controls

2.3.1 Paved Roads

Because the surface loading is the major source leading to particulate emissions, control techniques for paved roads look at both preventing and removing road dusts. Measures that attempt to prevent material from being deposited onto the surface include the covering of truckloads and the paving of access areas to unpaved lots or sites. Mitigation measures that remove dust deposited on paved roads include activities such as vacuum sweeping, water flushing and broom sweeping.

It is important to note that street sweeping of kerb and channel areas may actually increase the loading on the travelled portion of the road. Redistribution of loose material from the kerb onto the travel lanes can actually produce a short-term increase in emissions (USEPA 1997).

2.3.2 Unpaved Roads

Measures available for controlling emissions from unpaved roads fall into the categories of vehicle restriction, surface improvement and surface treatment. Vehicle restrictions seek to limit traffic on the road or to lower the mean vehicle speed. Surface improvements are relatively permanent and include paving, the placing of gravel or slag, and grading to ensure larger aggregate is placed on the travelled portion of the road. On the other hand, surface treatments are not permanent and require periodic application. Wet suppression by road watering increases moisture content, which conglomerates particles and reduces the likelihood of their suspension. Chemical stabilisation treatment, on the other hand, attempts to change the physical characteristics of the road surface.

3.0 Emissions Estimation Techniques

3.1 Approaches Employed

The recommended EETs for paved and unpaved roads employ empirical equations which are based on US tests and have been widely used for inventory development. These equations can be used to calculate emission factors for different particle size categories and, by combining these factors with data on vehicle kilometres travelled (VKT) in an airshed, total airshed emissions can be estimated.

For NPI purposes, emissions estimates are only required for one particle size category (PM10). However, TSP estimates are required for the calculation of emissions of the other substances listed in Table 1, which is achieved by multiplying TSP emissions by the weight fractions of these substances.

The EETs include the following steps:

- apply the empirical equations to calculate EFs for PM10 and TSP from paved and unpaved roads respectively;
- obtain total VKT data (on paved roads) for the airshed;
- estimate VKT for unpaved roads;
- multiply the EFs by the VKT data for paved and unpaved roads to derive estimates of total airshed emissions of PM10 and TSP;
- allocate airshed emissions of PM10 and TSP to grid cells; and
- speciate gridded TSP emissions into the relevant NPI substances.

3.1.1 Paved Roads

Equation 1: Calculation of emission factor for paved roads[a]

$$EF_{ip} = k_{ip} * (sL / 2)^{0.65} * (AW / 3)^{1.5}$$

where

EF_{ip} = Emission factor for particle size category i and paved roads, kg km^{-1}

k_{ip} = Empirical factor for particle size category i and paved roads

sL = Road surface silt loading, g m^{-2}

AW = Average weight of vehicles, tonnes

[a] USEPA (1997).

The factor k_{ip} varies with particle size category (see Table 3).

Table 3: Values of k_{ip} for Predicting Paved Road Dust Emissions

Particle Size Range	Emission Factor (kg km^{-1})[a]
PM10	0.0046
TSP	0.024

[a] USEPA (1997).

The values of sL and AW used in Equation 1 adjust emission factors for local conditions by characterising road surface and traffic conditions.

The use of locally relevant values for sL is strongly recommended. Field and laboratory procedures for determining surface material silt content and surface dust loading can be found in Appendices C.1 and C.2 of the USEPA AP-42 publication (USEPA 1998). If local values of sL cannot be obtained, an appropriate value may be selected from the default values in Table 4. However, use of the figures in Table 4 is not expected to produce better than an "order of magnitude" estimate of the emission factor.

Table 4: Default Values of sL for Public Paved Roads

	High ADT roads[a,b] (g m^{-2})	Low ADT roads[a] (g m^{-2})
Normal conditions	0.1	0.4
Worst case conditions[c]	0.5	3

[a] USEPA (1997). Excludes limited access roads. ADT means average daily traffic.
[b] Roads with at least 5,000 vehicles per day
[c] For conditions such as after storm or areas with substantial mud/dirt carryout

A value for AW can be estimated from data on the average weights of vehicles in various vehicle classes, and the distribution of total VKT between these classes (Equation 2). These data can be obtained from the ABS for a jurisdiction. A default value of 3.1 tonnes calculated by ABS for Australian vehicles (ABS 1996) can be used if data are not available.

Equation 2: Calculation of average vehicle weight

$$AW = \sum_{c} (W_c * F_c)$$

where

AW	=	Average weight of all vehicles in airshed, tonnes
W_c	=	Average weight of vehicles in vehicle class c, tonnes
F_c	=	Fraction of total airshed VKT by vehicle class c

VKT data are required to convert per kilometre travelled EFs into airshed emission estimates for PM10 and TSP. VKT data are also used in estimating and distributing motor vehicle emissions. Details of methods for obtaining these VKT data can be found in the AE Manual for Motor Vehicles. These VKT data are usually for paved roads only.

Total airshed emissions of PM10 and TSP for paved roads can be calculated by multiplying the total VKT for paved roads by the relevant emission factors.

Equation 3: Estimation of total airshed emissions from paved roads

$$E_{ip} = EF_{ip} * VKT_p$$

where

E_{ip} = Total airshed emissions from paved roads of particle size category i, kg yr^{-1}

EF_{ip} = Emission factor for particle size category i and paved roads, kg km^{-1}

VKT_p = VKT on paved roads in airshed, km yr^{-1}

3.1.2 Unpaved Roads

Equation 4: Calculation of emission factor for unpaved roads [a]

$$EF_{iu} = k_{iu} * (s / 12)^A * (AW / 3)^B / (M / 0.2)^C$$

where

EF_{iu} = Emission factor for particle size category i and unpaved roads, kg km^{-1}

k_{iu} = Empirical factor for particle size category i and unpaved roads

s = Surface material silt content, %

AW = Average weight of vehicles, tonnes

M = Surface material moisture content, %

A, B and C are empirical constants

[a] USEPA (1998).

Values for the factor k_{iu} and constants A, B and C are listed in Table 5. The use of locally derived values for s, AW and M is strongly recommended. If these are unavailable, the default values in Table 6 and Table 7 may be used. However, these values may only yield an emission factor of limited reliability.

VKT data for unpaved roads are usually not available and have to be estimated as a percentage of paved road VKT. The ratio of unpaved to paved roads may be difficult to obtain from road or traffic authorities. Some broad assumptions or professional judgements may be necessary to derive the ratio. For example, the ratio of unpaved to paved roads is about 0.01% in most urban areas.

Table 5: Empirical Constants for Predicting Paved Road Dust Emissions

	PM10[a]	TSP[a]
k_{iu}	0.733	2.82
A	0.8	0.8
B	0.4	0.5
C	0.3	0.4

[a] USEPA (1998).

Table 6: Default Silt Content Values for Publicly Accessible Unpaved Roads

Unpaved Road Surface Material	Mean Silt Content [s] [a] (%)
Gravel or crushed limestone	6.4
Dirt (i.e. local material compacted, bladed and crowned)	11

[a] USEPA (1998).

Table 7: Default Values for Average Vehicle Weight and Moisture Content for Publicly Accessible Unpaved Roads

Correction Parameter	Default Value
AW	3.1[a]
M	0.2[b]

[a] Calculated from ABS data (see Paved Roads under Section 3.1.1).
[b] Use of this default value for M is discouraged for dry conditions.

Total airshed emissions of PM10 and TSP for unpaved roads can be calculated by multiplying total VKT for unpaved roads by the relevant EFs.

Equation 5: Estimation of total airshed emissions from unpaved roads

$$E_{iu} = EF_{iu} * VKT_u$$

where

E_{iu} = Total airshed emissions of particle size category i from unpaved roads, kg yr^{-1}

EF_{iu} = Emission factor for particle size category i and unpaved roads, kg km^{-1}

VKT_u = VKT on unpaved roads in airshed, km yr^{-1}

3.2 Spatial Surrogates and Spatial Allocation

3.2.1 Paved Roads

VKT data for each grid cell are required to spatially allocate total airshed emissions of PM10 and TSP. Gridded VKT data are also used in estimating and distributing motor vehicle emissions. Details of methods for obtaining the

VKT data can be found in the AE Manual for Motor Vehicles. These VKT data are usually for paved roads only.

Equation 6: Allocation of emissions from paved roads to grid cells

$$E_{ijp} = E_{ip} * VKT_{jp} / VKT_p$$

where

E_{ijp} = Emissions of particle size category i from paved roads in grid cell j, kg yr^{-1}

E_{ip} = Total airshed emissions of particle size category i from paved roads, kg yr^{-1}

VKT_{jp} = VKT on paved roads in grid cell j, km yr^{-1}

VKT_p = Total VKT on paved roads in the airshed, km yr^{-1}

3.2.2 Unpaved Roads

Spatial VKT or traffic count data are usually not available for unpaved roads. In such instances, the emissions should be evenly distributed over an airshed (Eastern Research Group 1996). Equation 9 demonstrates how emissions should be allocated from unpaved road emissions.

Equation 7: Allocation of emissions from unpaved roads to grid cells

$$E_{iju} = (E_{iu} / A) * A_j$$

where

E_{iju} = Emissions of particle size category i from unpaved roads in grid cell j, kg yr^{-1}

E_i = Total airshed emissions of particle size category i from unpaved roads, kg yr^{-1}

A = Area of airshed, km^2

A_j = Area of grid cell j, km^2

3.3 Emission and Speciation Factors

Gridded annual TSP emissions from paved and unpaved roads can be separately speciated into gridded annual emissions of the NPI substances listed in Table 8 according to Equation 8.

Total annual emissions of a substance in a grid cell can then be obtained by summing the emissions for each road surface type (paved and unpaved).

Equation 8: Estimation of gridded emissions of an NPI substance from TSP emissions

$$E_{jkn} = E_{TSPjn} * WF_{kn}$$

where

E_{jkn} = Emissions of substance k from road type n (paved or unpaved) in grid cell j, kg yr^{-1}

E_{TSPjn} = TSP emissions in grid cell j from road type n, kg yr^{-1}

WF_{kn} = Weight fraction for substance k and road type n

Table 8: Speciation of TSP Emissions from Paved and Unpaved Roads

NPI Substance	Weight Fraction [WF_{kn}] [a]	
	Paved Roads	Unpaved Roads
Antimony and compounds	0.000013	0.000008
Arsenic and compounds	0.000015	0.000014
Cadmium and compounds	0.000019	0.000022
Cobalt and compounds	0.000116	0.000143
Copper and compounds	0.000161	0.000088
Lead and compounds	0.000951	0.000867
Manganese and compounds	0.000795	0.000973
Mercury and compounds	0.000016	0.000015
Nickel and compounds	0.000068	0.000065
Selenium and compounds	0.000002	0.000001
Zinc and compounds	0.000936	0.000605

[a] CARB (1991).

3.4 Sample Calculations

The sample calculations in this section relate to emissions of TSP and a single NPI substance (copper) for paved roads.

The calculations will need to be carried out for each NPI substance and for both road types to produce a gridded inventory of the total emissions of all substances.

Table 9: Sample Data for Calculation of Average Vehicle Weight[a]

Vehicle Class	Weight [W_c] (tonnes)	Fraction of Total VKT [F_c]
Passenger vehicles	1.15	0.743
Motorcycles	0.179	0.009
Light commercial vehicles	2.40	0.167
Rigid trucks	10.9	0.040
Articulated trucks	42.6	0.030
Other trucks	7.86	0.001
Buses	9.00	0.009

[a] ABS (1995).

Example 1: Calculation of average vehicle weight

Using Equation 2 and

Table 9

$$AW = \sum_{c} (W_c * F_c)$$

$$= 1.15 * 0.743 + 0.179 * 0.009 + 2.40 * 0.167 + 10.9 * 0.040 + 42.6 * 0.030 + 7.86 * 0.001 + 9.00 * 0.009$$

$$= 3.1 \text{ tonnes}$$

Example 2: Calculation of emission factor for TSP from paved roads

Using Equation 1 with the result from Example 1, and assuming a value for sL of 0.08 g m^{-2} and a value of 0.024 kg km^{-1} for TSP (Table 3)

$$EF_{ip} = k_{ip} * (sL / 2)^{0.65} * (AW / 3)^{1.5}$$

$$EF_{TSP,paved} = k_{TSP,\ paved} * (sL / 2)^{0.65} * (AW / 3)^{1.5}$$
$$= 0.024 * (0.08 / 2)^{0.65} * (3.1 / 3)^{1.5}$$
$$= 3.1 * 10^{-3} \text{ kg } KM^{-1}$$

Example 3: Estimation of TSP emissions to airshed from paved roads

Using Equation 3, the result from Example 2, and an annual airshed VKT on paved roads of 25 billion km

$E_{ip} = EF_{ip} * VKT_p$

$E_{TSP,paved} = EF_{TSP,paved} * VKT_{paved}$
$= 3.1 * 10^{-3} * 2.5 * 10^{10}$
$= 7.75 * 10^{7}$ kg yr^{-1}

Example 4: Allocation of TSP emissions from paved roads to a grid cell

Using Equation 6, the result from Example 3, and a cell VKT of 15 million km

$E_{ijp} = E_{ip} * VKT_{jp} / VKT_p$

$E_{TSP,cell,paved} = E_{TSP,paved} * VKT_{cell,paved} / VKT_{paved}$
$= 7.75 * 10^{7} * 1.5 * 10^{7} / (2.5 * 10^{10})$
$= 4.65 * 10^{4}$ kg yr^{-1}

Example 5: Estimation of annual emissions of copper in a grid cell

Using Equation 8, the result from Example 4, and the weight fraction for copper from paved roads from Table 8

$E_{jkn} = E_{TSPjn} * WF_{kn}$

$E_{copper,cell,paved} = E_{TSP,cell,paved} * WF_{copper,paved}$
$= 4.65 * 10^{4} * 0.000161$
$= 7.49$ kg yr^{-1}

4.0 Uncertainty Analysis

4.1 Data Reliability

VKT data for the inner areas of most airsheds should be highly reliable. However, there will probably be very little data for the outer areas of most airsheds, and traffic counts may be required to estimate VKT.

VKT figures for unpaved roads usually have to be estimated by professional judgement because of lack of data, and hence are of low reliability.

4.2 Reliability of Emission Factors and Speciation Profiles

4.2.1 Emission Factor Equations

The empirical expressions provided in the handbook have been developed by the USEPA after considerable field testing. Equation 1 was based on a regression analysis of numerous emission tests, and Equation 4 was developed from tests of traffic on uncontrolled and watered unpaved surfaces (USEPA 1998).

Equation 1 has a high reliability rating if it is applied within the range of conditions specified in Table 10.

Table 10: Source Conditions Used in Developing Equation 1[a]

Silt loading [sL] ($g\ m^{-2}$)	Average vehicle weight [AW] (tonnes)	Average vehicle speed ($km\ hr^{-1}$)
0.02 – 400	2.0 – 4.2	16 - 88

[a] USEPA (1997).

To sustain this rating for Equation 1 when it is applied to roads within an airshed, locally relevant sL parameters should be determined. If a default value is used, the reliability of the technique is assessed as medium to low.

Equation 4 has a medium to high reliability if applied within the range of conditions specified in Table 11.

Table 11: Source Conditions Used in Developing Equation 4 [a]

Silt Content [s] (%)	Moisture Content [M] (%)	Average Vehicle Weight [AW] (tonnes)	Average Vehicle Speed ($km\ hr^{-1}$)	Average Number of Wheels
1.2 – 35	0.03 – 20	1.5 – 290	8 - 88	4 – 7

[a] USEPA (1998).

To sustain this rating when applied to roads within an airshed, reliable values for s and M should be determined. If a default value is used for silt content or

moisture content, the reliability of the equation would be medium to low. If default values are used for both, the rating would be low to very low.

4.2.2 Speciation Profiles

The speciation profiles in Table 8 were based on composite results for paved and unpaved roads. Composite data does not take into account local conditions and therefore the reliability of these profiles is assessed as medium to low.

4.3 Problems and Issues Encountered

The task of estimating emissions is complicated by the sparseness of emission data for paved and unpaved roads and the year-to-year variation in weather conditions. The lack of unpaved road VKT data is another serious constraint for this EET.

It should also be recognised that, because road dusts are a major source of airshed particulate emissions, even a small error in the estimation may have a relatively large impact on the overall particulate emissions inventory.

4.4 Recommendations for Further Work

Equations 1 and 4 were developed for free flowing traffic at constant speeds on relatively level roads. It may be useful to conduct investigations of emissions under the actual types of traffic conditions that are usually found in airsheds.

5.0 Glossary of Terms and Abbreviations

ABS	Australian Bureau of Statistics
ADT	Average daily traffic
AE	Aggregated emissions
AW	Average weight
CARB	California Air Resources Board
EET	Emissions estimation technique
EF	Emission factor
GIS	Geographic information system
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NPI	National Pollutant Inventory
PM2.5	Particulate matter less than or equal to 2.5 µm
PM10	Particulate matter less than or equal to 10 µm
PM15	Particulate matter less than or equal to 15 µm
PM30	Particulate matter less than or equal to 30 µm
TSP	Total suspended particulates
USEPA	United States Environmental Protection Agency
VKT	Vehicle kilometres travelled

6.0 References

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