Building an Australian national motor vehicle inventory for air pollution population exposure assessment

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This paper explores the current state of play regarding national motor vehicle emission inventories in Australia and identifies the gaps and further work required. The overarching question is: "*do we need a national Australian MVEI at a high resolution, and if so, how could we achieve this?*"

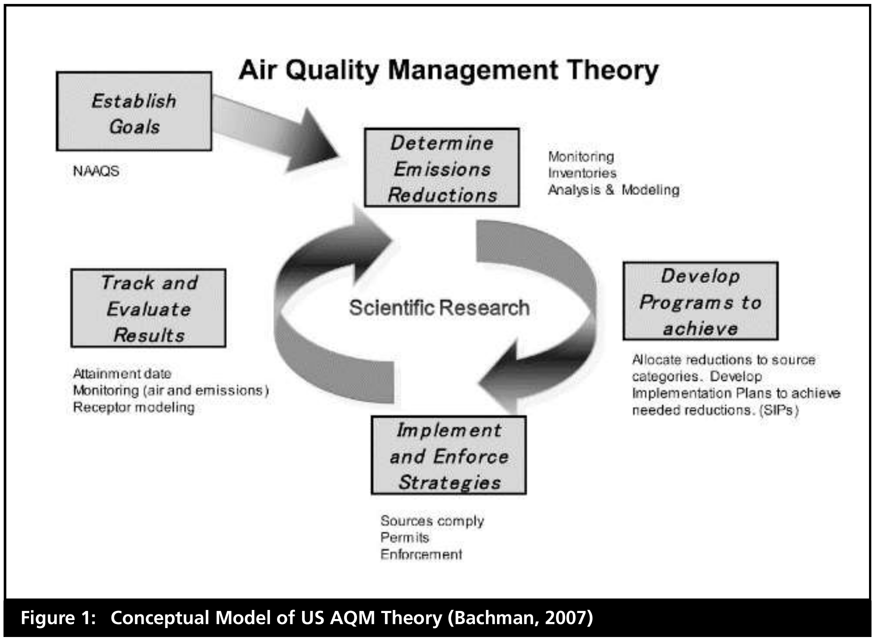


Figure 1: Conceptual Model of US AQM Theory (Bachman, 2007)

INTRODUCTION

National emission inventories facilitate meaningful comparisons of total emission loads between jurisdictions and with other sources. This information is required for the development of cost-effective environmental policies. It is used to prioritise source categories with respect to greenhouse gas emissions and air quality impacts. In Australia, a national aggregation of emissions is of particular relevance when changes to federal regulations (e.g. fuel standards) are under consideration.

A nationally consistent vehicle emission inventory is an important element of an integrated and effective air quality management system. An example of this system, from the USA, is shown in Figure 1. Air quality criteria (goals, objectives, standards, etc.) are used to provide a uniform basis for the protection of public health and ecosystems from the adverse effects of air pollution, and to eliminate (or reduce as much as is practical) exposure to those pollutants that are known or likely to be hazardous.

Ambient air quality criteria are needed for regulatory authorities to develop, plan and implement effective policies designed to reduce ambient concentrations of air pollutants. As shown in Figure 1, emission inventories and air quality modelling/monitoring are used to develop appropriate strategies and emission reduction policies, track progress and evaluate the effectiveness of emission reduction measures.

However, this can only be done in a cost-effective manner when accurate and precise information on emissions and ambient air quality is available. As a consequence, vehicle emissions need to be resolved at a high resolution in space and time. This is because vehicle emissions are especially heterogeneous through time and space, and continuously undergo dispersion and chemical processes after release into the atmosphere. This leads to highly varying local and regional concentration levels. It is these local concentrations that are of interest with regards to exposure assessment and human health impacts. It can be argued that highly time-space resolved GHG emissions are also of particular interest from an emission management perspective. For instance, it would be useful to identify GHG emission 'hot-spots' and situations with high emission levels to guide targeted emission mitigation measures.

Although the link between emission inventories and greenhouse gas emissions is direct, the link between emissions and air quality is not as clear as it may seem. In fact, the difference between emissions and air quality (ambient concentrations) is often overlooked, or the two terms may be used interchangeably. They are not the same thing.

To illustrate this point, the contribution of motor vehicle emissions to population exposure (and thus potential health effects) is substantially greater than one would expect on the basis of their emissions alone. International studies have found that motor vehicles are the largest single contributor to human health effects (PM, ozone), and that emission levels are leveraged by about a factor of three to four when population exposure is considered (e.g. Caiazzo *et al.,* 2013).

This is because motor vehicle emissions are ubiquitous and are typically emitted in close proximity to where people live and work. In contrast, other sources may be more localised and have different dispersion characteristics. For instance, industry emissions are typically emitted through vents and stacks, and are generally located some distance from populated areas.

Understanding the variability of emissions and air quality in space and time is important to properly assess exposure to human health impacts. In fact, valid estimates of the spatial and temporal distribution of air pollution are required so that exposure-response associations can be investigated in epidemiological studies (Hanigan *et al.*, 2017).

1. Modelling process

It is cost-prohibitive to measure ambient concentrations at many locations. And, of course, it is also not possible to measure the future. As a consequence, statistical methods (e.g. land use regression models) and simulation tools (emission and dispersion/chemical transformation models) are commonly used to assess air quality in a local, regional and national context. This information can be used to identify hot spots, conduct scenario/what-if modelling, design and evaluate cost-effective environmental policies (source prioritisation, understanding main drivers).

Internationally, the estimation of motor vehicle emissions and assessment of their impacts usually follows distinct and sequential modelling steps, which are either calibrated or validated with monitoring data:

1. 'traffic data' – quantification of traffic activity and traffic performance
2. 'traffic emissions' – quantification of vehicle emissions
3. 'ambient concentrations' – simulation of dispersion and chemical transformation processes
4. 'impact assessment':
    a. 'human health' – quantification of population exposure and health impacts
    b. 'ecosystem' – quantification of environmental exposure and associated impacts
    c. 'structures' – quantification of impacts on e.g. buildings
    d. 'economic' – quantification of any of the previous impacts in monetary terms

The *scale* of modelling is a relevant consideration here. In general, the size of a study area, or rather size of the road network, affects the availability and practical use of input data for the modelling process. The level of detail is effectively reduced with increasing size of the road network. As a consequence, a 'modelling framework' exists, where fit-for-purpose software programs are designed to operate at specific scales (Table 1).

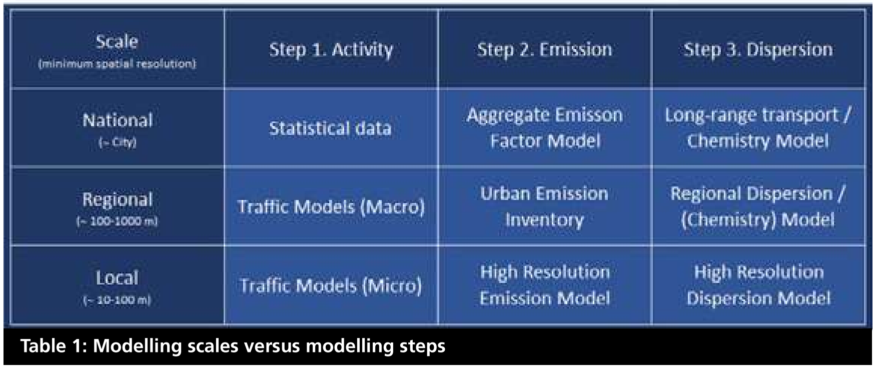
Indeed, transport and vehicle emission modelling systems around the world reflect this framework. In Europe, a hierarchy of models exist for different modelling scales varying from high resolution second-by-second vehicle emission simulation (e.g. PHEM) to national emission inventory level (e.g. COPERT or HBEFA). In the US, MOVES presents an integrated approach where the user has the option to model at different scales. In Australia, a high resolution second-by-second vehicle emission simulation (PΔP) and a street/regional/national emission software (COPERT Australia) are both available, which means that dedicated Australian software exists to simulate emissions at all relevant scales. Within this framework, the user has the flexibility to use a bottom-up or a top-down approach to develop emission inventories.

An alternative approach to combined emission/dispersion/chemistry modelling is land use regression modelling. A statistical model is created where ambient concentrations in a local area are directly estimated as a function of land use (e.g. total km of major roads within 500 m) and seasonal variables (e.g. month).

2. Comparison of different approaches

Most, but not all, Australian jurisdictions develop motor vehicle emission inventories (MVEIs), as is shown in Table 2.

These MVEIs are published at uncoordinated points in time, leading to different base years. They are also generally developed for metropolitan areas only, and not the entire state, although Victoria is currently preparing a state-wide MVEI. Finally, MVEIs use different methods, but emission factors from COPERT Australia are most often used.



Scale (minimum spatial resolution)	Step 1. Activity	Step 2. Emission	Step 3. Dispersion
National (~ City)	Statistical data	Aggregate Emisson Factor Model	Long-range transport / Chemistry Model
Regional (~ 100-1000 m)	Traffic Models (Macro)	Urban Emission Inventory	Regional Dispersion / (Chemistry) Model
Local (~ 10-100 m)	Traffic Models (Micro)	High Resolution Emission Model	High Resolution Dispersion Model

Table 1: Modelling scales versus modelling steps

State	Vehicle emission modelling/factors	Base year	Spatial scale	Temporal and spatial resolution	Reference
NSW	In-house developed NSW EPA	2008, 2013 **)	Greater metropolitan region NSW	1 x 1 km grid, hourly	NSW EPA, 2012
VIC	COPERT Australia	2016	Victoria	1 x 1 km grid, hourly	Report in preparation
WA	COPERT Australia	2013	Greater Perth metropolitan area	1 x 1 km grid, hourly	DWER, 2018
QLD	COPERT Australia	2015	SEQ metropolitan area	46,000 road links, hourly	Report in preparation
SA	COPERT Australia *)	NA	NA	NA	NA
TAS	NA	NA	NA	NA	NA
ACT	COPERT Australia *)	NA	NA	NA	NA
NT	NA	NA	NA	NA	NA

Table 2: MVEI by Australian jurisdiction

*) Jurisdiction is using the NMVEI results (UQ, 2014) for this state/territory.
**) 2013 base year report in preparation.

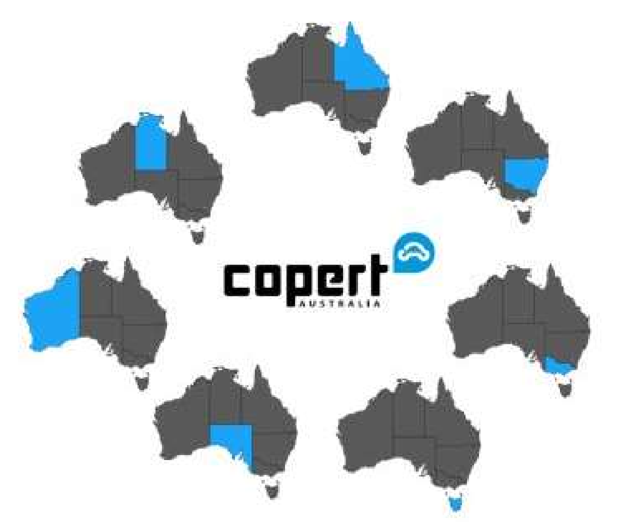


Figure 2: Total emission loads for each jurisdiction for base year 2010 (UQ, 2014)

At Federal level, the Bureau of Infrastructure, Transport and Regional Economics (previously the Bureau of Transport and Regional Economics) published national vehicle emission estimates for a limited number of pollutants for each state in the past (e.g. BTRE, 2003).

The most recent comprehensive and up-to-date national MVEI was developed for a single base year (2010) using a consistent method: COPERT Australia (UQ, 2014). The 2010 NMVEI provides total emission loads (tonne/annum) for each State and Territory for 116 substances (air pollutants, greenhouse gases, fuel consumption) and different types of emissions (hot running, cold start, evaporative, non-exhaust). COPERT Australia predicts emissions for 226 vehicle classes as a function of total travel, meteorological parameters (temperature and humidity), fuel quality and driving conditions. The emission predictions are expected to be robust and reasonably accurate, as the

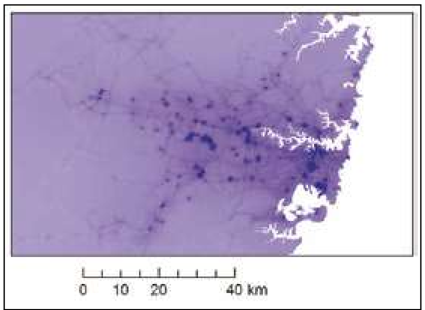


Figure 3: Average NO$_2$ concentration in 2008 predicted for the greater Sydney area at 100m resolution (Knibbs *et al.*, 2014)

Figure 4: Predicted total NO$_x$ emissions for different road segments in part of the Adelaide CBD network for two morning peak hours (Smit, 2013)

modelling includes an iterative calibration process using available fuel consumption data.

The main issues are that: (1) national emissions data for other base years, including future years, are not published and would be of great value, and (2) although the spatial (jurisdiction) and temporal (annual) resolution are appropriate for greenhouse gas emissions, they are too coarse to allow for accurate health impact assessment. Point 1 can be readily addressed by running a fleet mix model for different base years and point 2 requires further research, as will be discussed in this paper.

The NMVEI is an essential input to subsequent dispersion/chemical transformation modelling. For example, gridded chemical transformation models (CSIRO's Chemical Transport Model CTM; CMAQ; WRF-chem; TAPM) uses emissions data, meteorology and chemical transformation modelling to predict ambient concentrations of multiple gas- and aerosol phase species for grid cells up to a nominal resolution of a few kilometres.

The LUR model developed by Knibbs *et al*. (2014) also covers the whole of Australia, and it predicts ambient concentrations (based on regulatory monitoring), rather than emissions. This is considered a strength as it enables fast assessment of annual average ambient concentration levels in local areas. However, in this case, the LUR method is limited to a single air pollutant (NO$_2$), and does not predict concentrations with short term averaging times (hour, day), which are typically the most critical criteria in air quality assessments. The LUR model development process reflects the environmental predictors of the pollutant measured at each ambient air monitoring site. Caution is required to apply it to different situations such as local hot spots (e.g. intersections) that the algorithms are not intended to capture. Independent validation suggests that the LUR models estimate annual NO$_2$ surface concentrations generally with reasonable accuracy (urban background, urban near traffic), but with reduced performance near roadside sites, e.g. an coefficient of determination (R^2) of 36% meaning that 36% of the observed variation in concentrations is explained with the model (Knibbs *et al*., 2016). Nevertheless, the spatial resolution of the LUR model is much higher as compared with the NMVEI.

The highest resolution can be achieved with the PΔP model. This software simulates emissions at a second-by-second resolution using engine power and the change in engine power as the predictor variables for 73 Australian vehicle classes (cars, trucks, etc.). An example is shown in Figure 4. In this study, the traffic simulation software AIMSUN was used to simulate car, bus and truck movements in part of the Adelaide CBD generating almost 10,000 driving patterns (~ 60 hours of high resolution speed time data). The driving patterns were combined with the PDP emission algorithms to estimate more than 400,000 vehicle emission estimates allocated to a particular point and time in the network. These high resolution emissions data are then aggregated to specific time periods (e.g. 1 hour) and road segment. Similar to the LUR model, the current version of PDP is restricted to a few substances (i.e. NO$_x$, CO$_2$ and fuel consumption). In addition, obtaining data for the whole Australian road network for a full year may be impossible due to limitations on available input data. Nevertheless, the tool provides spatially detailed emission information that is suitable for a) comparison to near-road and on-road validation data, b) providing an alternative data set which could contribute to LUR development, and c) provide detailed sub-grid scale information above the available resolution of the NMVEI.

It may be more challenging to validate high resolution emission predictions, as compared with the LUR models. There are various methods to do this, including tunnel studies, remote sensing studies, kerb-side air quality monitoring and emission mass-flux studies (Smit *et al*., 2010). A recent tunnel study (Smit *et al*., 2017) suggests that emission predictions using PΔP/COPERT Australia combined is generally accurate at fleet level for CO, NO$_x$, PM$_{2.5}$ and PM$_{10}$, when compared with similar international studies. However, predictions were found to be biased with a consistent underestimation of emissions by 7% to 37%, depending on the pollutant. Possible contributing factors are under-representation of high/excessive emitting vehicles, inaccurate mileage correction factors, and a current lack of empirical emissions data for Australian diesel cars. The study results also demonstrate a large uncertainty in speciated VOC and PAH emission factors. One particular issue with tunnel studies is the limited range of driving conditions considered, i.e. relatively smooth driving close to the 80 km/h speed limit in this case. It is clear that further validation is required and this is currently being actioned using remote sensing and on-road air quality measurement in Perth and Brisbane (e.g. Smit *et al*., 2019).

Table 3 shows an overview of the three methods considered.

3. A hybrid approach – 'model blending'

It is clear that the methods discussed so far all have specific strengths and weaknesses, and that a general issue is a lack of sufficient validation with independent observations.

The NMVEI is comprehensive regarding the number of substances considered and has national spatial coverage, but lacks high resolution in time and space. Simple allocation methods (e.g. population based) can be applied, but have unknown uncertainty and have not been properly validated. The LUR model also has national spatial coverage and has a reasonable spatial resolution, but is limited to a single pollutant (NO$_2$) and low time resolution (annual). The PΔP software has high spatial and temporal resolution, but may only feasibly be applied to small road networks (input data availability, runtime, costs), and therefore cannot provide national coverage.

In contrast to LUR models, vehicle emission models require additional dispersion/chemical modelling to estimate local ambient concentration and exposure levels, which complicates the process and increases resource requirements. On the other hand, vehicle emission models can 'explain' the main factors driving local emissions and can also predict future situations (what-if scenario modelling), which are both essential for cost-effective policy development, something LUR models cannot do.

A logical conclusion therefore is that a hybrid approach that intelligently combines the methods and uses the strengths of each method is the best way forward. Indeed, 'spatial interpolation' or model blending of CSIRO's CTM, the LUR model and fixed

Method	Spatial coverage and resolution	Temporal resolution	Substances included	Reference
NMVEI (COPERT Australia)	Australia (state/territory)	Annual	116 (criteria, VOCs, metals)	Smit and Ntziachristos, 2013; UQ, 2014
CTM	Australia- 12 x 12 km^2; urban scale 1 x 1 km^2	Hourly	6 (NO_x, VOCs, CO, SO_2, PM, O_3)	
LUR models	Australia, 13x24 km^2 (satellite NO_2 predictor only), ABS census mesh blocks (median size: 0.04 km^2)	Annual, Monthly	1 (NO_2 Note: method has recently been extended to $PM_{2.5}$)	Knibbs *et al.*, 2014; 2016; 2018
PΔP	~ 1-30m (speed dependent)	Second-by-second	3 (CO_2, NO_x, FC)	Smit, 2013; 2014

Table 3: Comparison of methods

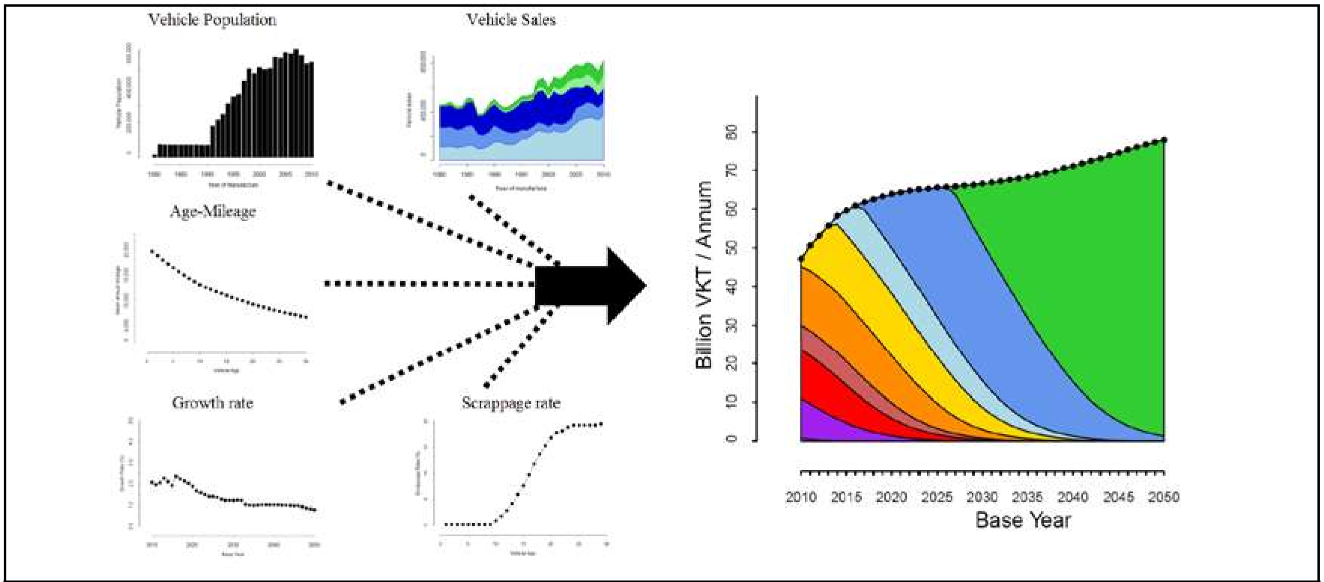


Figure 5: Components of AFM (Australian Fleet Model), left, and estimation of total travel (VKT) for the period 2010-2050 and a particular (example) vehicle class, right (TER, 2014)

monitoring site observations has recently been explored using statistical techniques. The creation of 'trend (concentration) surfaces' in the model blending process has been shown to improve prediction performance (accuracy) as measured with (independent) passive samplers (Hanigan *et al.*, 2017). However, it is acknowledged that a key weakness of the model blending approach is that it cannot overcome the limitations that are common across all input methods. For instance, it cannot completely reproduce the spatial and temporal variability in ambient concentrations, as none of the used methods can yet achieve this.

4. How can we achieve a national Australian MVEI at a high resolution?

An Australian National Motor Vehicle Emission Inventory (NMVEI) already exists for base year 2010 (UQ, 2014), and this may be a good *starting point* for the development of a high (space/time) resolution national vehicle emission inventory because:

- The fuel-calibrated total emission estimates in the NMVEI 2010 are the most accurate estimates of total emission loads at jurisdictional level.
- It covers a large range of air pollutants, as well as greenhouse gases.
- It allows for disaggregation to a high temporal resolution (hourly).
- Retaining the 'explanatory component' of emission inventories is important to enable detailed analysis of the main drivers of vehicle emissions (e.g. which vehicle classes, which traffic conditions, etc.).

A staged approach is proposed to achieve this. The approach moves from relatively simple/coarse to more advanced/refined and validated vehicle emission estimates.

Stage 1 – Disaggregation method

A key factor in improving emission estimates, as well as LUR models, at a high resolution is the *availability* of high resolution traffic activity (counts, density, fleet mix), traffic performance data (speed, acceleration, air conditioner use) and locational data (road gradient, meteorology) with a national coverage. A thorough examination of the availability of these types of data should therefore be a first step in developing improved emission inventories.

So Stage 1 would first examine and obtain available input data sets that can be used to develop a combined top-down and bottom-up disaggregation model (e.g. land use data, transport models, land-use regression models, traffic activity and performance data, fleet data, etc.). The input data can then be used to develop a robust disaggregation method and apply it to NMVEI 2010.

It would need to somehow combine different methods to achieve a hybrid approach. It is noted that NO_x/NO_2 is predicted by both the LUR and PΔP models, and it is the logical link to the 2010 NMVEI. This pollutant can be used in the initial development of a high resolution NMVEI. It is noted that PΔP models also predicts CO_2 emissions, which could be used to provide the GHG link to the high resolution NMVEI.

Stage 2 – Validation

The performance of the disaggregation method will be verified using a range of validation data/methods (e.g. tunnel, RSD, AQ, mass flux).

Stage 3 – Multi-year assessment

There is a need for an update, e.g. base year 2015, which will also align with the COPERT Australia software version (v1.3) with updated Euro 5/6 emission factors. This stage would focus on estimating the fleet mix for more recent base years e.g. 2015 by running a detailed fleet model (Figure 5).

This would then produce NMVEI 2015.

It could also back-calculate prior years e.g. 2005, 2000 and perform future year fleet modelling and create e.g. NMVEI 2020, 2025, 2030, 2035. The disaggregation model is then run to create higher resolution NMVEIs for these base years.

Stage 4 – Further refinement

This stage can include examination of new/other statistical approaches and addition of new functionalities such as prediction intervals.

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