AN OVERVIEW OF REAL-WORLD VEHICLE EMISSION MEASUREMENTS IN AUSTRALIA

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Abstract

Several vehicle emission measurement campaigns have been conducted in Australia since 2015, using different techniques such as remote sensing, on-board testing (PEMS) and a tunnel study. These different techniques have their own strengths and weaknesses and highlight different aspects of real-world emissions performance of Australian vehicles. This paper will bring together the main results of these studies and highlight the need for a nationally coordinated program.

Keywords: motor vehicle emissions, greenhouse gas, air pollutant, real-world, on-road, monitoring, measurement, PEMS, RSD, tunnel, air quality.

1. Introduction

In the late 1990s and early 2000s, large-scale vehicle emission testing programs were conducted in Australia (e.g. Anyon *et al*., 2000; RTA, 2009). These programs tested hundreds of motor vehicles on a chassis dynamometer over real-world Australian drive cycles, generating large databases with raw measurements. For instance, the second National In-Service Emissions program (NISE2) provided almost 2 million seconds of modal vehicle emissions data for criteria pollutants and CO_2. These large and publicly available databases have enabled the development of dedicated Australian vehicle emission software such as COPERT Australia (CopAUS) and PΔP (Figure 1). These software tools reflect unique Australian conditions, and they are critical for technology impact assessment, policy development, trend analysis and development of emission inventories at national, state or regional levels.

Figure 1. The close connection between vehicle emission measurement and modelling.

Although there was some discussion of continuing with NISE3 in the early 2010s, large vehicle emission testing programs were not continued. Vehicle emission assessment in Australia therefore relies increasingly on overseas emissions data. The validity of using EU/US data is of concern, given large differences in terms of fuel quality standards, emission standards (lagging or not present), fleet mix (e.g. large proportion of SUVs), lack of inspection/maintenance programs and tampering with emission control systems, etc. Small-scale but targeted emission testing programs were conducted in Australia in the period 2015-2022 using different techniques. This paper presents a succinct overview of these recent studies, including the main outcomes, showing how essential information is created through real-world vehicle emission measurements. The paper will hopefully inspire a revival the NISE program in Australia. For more details, the reader is referred to the scientific papers and reports referenced in this paper. It is noted that other methods for vehicle emission measurement exists, for instance vehicle plume measurements, on-board sensors, mass-flux and tracer gas methods (more information can be found in Ropkins *et al*., 2009 and Smit *et al*., 2010; 2022b).

2. Laboratory emission testing

Emission testing traditionally involved laboratory emission testing with engine/vehicle dynamometers and predefined test or driving cycles.

This type of testing is an essential component of emission legislation and manufacturer technology development. An advantage is controlled conditions. This enables investigation of specific aspects such as driving patterns, hot-running/cold-start conditions, vehicle loading, use of air conditioning, ambient temperature and emission control technology. In addition, laboratory measurements are amenable to a broad range of instrumentation. A disadvantage of this method is the limitation on the number of vehicles or engines that can be tested due to time/budget constraints. Another consideration is how well on-road conditions are replicated regarding dynamometer settings and dilution conditions. Testing should be conducted with representative real-world drive cycles. In Australia, the last laboratory-based test program was NISE2 (RTA, 2009). A recent study specifically examined the correlation between dynamometer and remote sensing emission measurements (Smit and Kennedy, 2020). The correlation was found to be strong, providing further support for combination of emission data sources.

3. On-board emission testing

On-board measurement – commonly referred to as PEMS (Portable Emissions Monitoring System) – has become a popular method of providing detailed and reliable emissions data. On-road PEMS testing has reached maturity and overcomes limitations such as potentially poor replication of resistive loads in dynamometer testing. Due to these advantages, PEMS have been widely used to measure vehicle emissions in real-world conditions.

Compared with laboratory testing, this method provides reasonable control over influencing factors (cold-start, vehicle loading). However, testing a large vehicle sample is still restricted by labour time, effort and costs, particularly for older vehicles that require more set-up time. Lower-cost simplified PEMS are now developed to evaluate real-world emissions performance in a simple yet robust way.

A recent study (Smit *et al*., 2022a) tested five Euro 5 SUVs in Sydney (MY 2015-2020) in a wide range of real-world driving conditions (Figure 2). The program included testing of fuel quality, coast-down and emissions in cold/hot start, hot running and extended idling conditions. Geo-computation methods were used to add high-resolution (second-by-second) road gradient information to the emissions data.

Figure 2. PEMS testing in Sydney.

The PEMS study results were also used to validate CopAUS emission algorithms. SUV CO_2 predictions are well behaved. Measured CO, THC and NO_2 emission factors (g/km) for petrol SUVs are, however, significantly higher than currently predicted values. The largest difference was observed for diesel SUVs and measured NO_x and NO_2 emission factors (g/km). For instance, measured NO_x was a factor of 3 to 9 higher than predicted NO_x values. Measured Euro 5 diesel NO_x exceeded 2 g/km in urban conditions, which is about 30-90 times higher than the measured values for the petrol SUVs. It is also higher than 1.8 g/km reported overseas for older technology Euro 3 LCVs (Hadavi *et al*., 2012) and substantially higher than Euro 6 technology vehicles, where a range of 0.4 to 0.8 g/km has been reported (O'Driscoll *et al*., 2016; Triantafyllopoulos *et al*., 2019; Valverde *et al*., 2019). The Australian results for NO_x are however comparable to PEMS testing done in New Zealand (Kuschel *et al*., 2019; Smit *et al*., 2022b). The PEMS data suggest that modern diesel SUVs in Australia and New Zealand have a NO_x emission problem.

4. Tunnel emission measurements

The tunnel measurement method (Figure 3) is well established for validating vehicle emission models at fleet level.

Figure 3.CLEM7 tunnel measurements in Brisbane.

With this method, composite emission factors are determined using the differences in pollutant concentrations at the tunnel entrance and exit (corrected for background levels), combined with relevant tunnel parameters such as road length and cross-sectional area, traffic flow and traffic conditions, as well as either measured tunnel air flow or dilution factors based on a tracer gas such as SF_6. Regression analysis is often used to develop average emission factors (g/km) for basic vehicle classes (example in Figure 4, next page).

Tunnel studies measure emissions from a large sample of the on-road fleet, thereby capturing inter-vehicle variability in emissions and high emitters. Moreover, measurements are carried out under relatively controlled conditions with, for instance, pollutant dispersion constrained by tunnel geometry. However, the tunnel method relies on indirect estimation rather than direct exhaust measurement, and this can introduce errors. Moreover, it captures only a limited range of operating conditions (typically smooth, uncongested, high-speed driving) and may induce a bias due to uphill or downhill gradients and the 'piston effect' and forced ventilation, which can produce a tail wind that reduces aerodynamic drag on the vehicles in the tunnel and therefore reduce emissions.

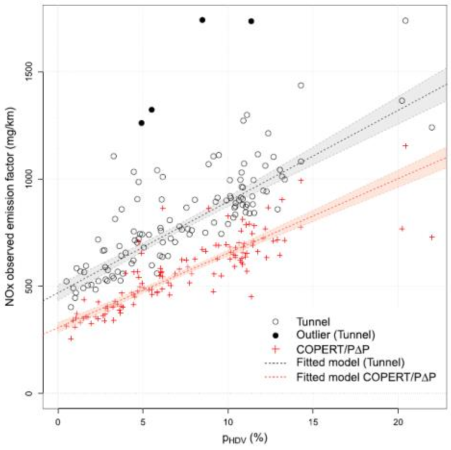

Figure 4. Measured and predicted NO_x emission factors (hourly values) by proportion HDVs.

In 2015, a tunnel study was conducted in Brisbane (Smit and Kingston, 2015a; 2015b; Smit *et al*., 2017) to (partially) validate CopAUS and PIARC emission factors. The impact of road gradient and in-tunnel air flow was accounted for through simulation with the PΔP emissions software. The measured NO_2-to-NO_x ratio of 0.15 agreed with the value of 0.13 predicted with CopAUS. It was found that PIARC emission factors are conservative and that they exhibit the largest prediction errors, except for good agreement for LDV NO_x. CopAUS is generally accurate at fleet level for CO, NO_x, $PM_{2.5}$ and PM_{10}, when compared with other international studies but consistently underestimates emissions by 7%-37%, depending on the pollutant. Possible contributing factors are under-representation of high/excessive emitting vehicles, inaccurate mileage correction factors, and lack of empirical emissions data for Australian diesel cars.

The situation for NO_x is interesting. A significant bias (underprediction) is clear in Figure 4. The CopAUS NO_x emission factor for LDVs is 41% lower than the (humidity-corrected) value measured in the tunnel. The CopAUS NO_x emission factor for HDVs is 19% lower than the measured tunnel value. It was suggested at the time that this may reflect a higher-than-expected proportion of (diesel) vehicles with maintenance issues and elevated NO_x emissions that are not yet fully reflected in the software. The result is also of interest as there has been a lack of empirical vehicle emissions test data for Australian light-duty diesel vehicles. In contrast, extensive emission test programs have been carried out in Australia for light-duty petrol vehicles (NISE1+2).

Finally, the tunnel study also identified issues with predicted emission factors for volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). It was found that: 1) CopAUS substantially underestimates emission factors for individual VOCs, typically with a factor of five (VOCs will be discussed further in the next section). 2) Regarding PAHs, it was found that CopAUS substantially overestimates emission factors for almost all PAHs, typically with a factor of 3 to 13, except for naphthalene, which is underestimated with a factor of 7. In addition, 12 PAHs for which CopAUS provides emission factors, were not measured above the limit of detection in the tunnel.

5. On-road air quality measurements

Air quality was measured on the road (1 m from road markings and the kerb) using two integrated AQM65 air quality monitoring stations, a meteorological station and two VOC Summa canisters at either side of the road (Figure 5) (Smit *et al*., 2019a).

Figure 5. On-road air quality measurements in Brisbane.

Although air quality measurements do not measure vehicle emissions, they provide useful information. One example is measured NO_2 to NO_x ratios, which were about a factor of two higher than the tunnel study, which indicates that about half of measured NO_2 concentrations are due to urban background levels and rapid reaction with ozone. Statistical analysis suggests that on-road NO_2 and ozone concentrations are largely driven by atmospheric chemistry processes, and not significantly affected by variation in local traffic volume and fleet mix.

VOC measurements show large discrepancies when compared with CopAUS. The VOC composition is markedly different from predicted values. For instance, the CopAUS VOC profile is dominated by alkanes and alkenes (about 50%), whereas this is 17% for the tunnel and 7% on the road. In contrast, the aromatics content is similar for the tunnel and CopAUS (almost 30%) but 17% for the on-road measurements. The observed proportion of ketones in the tunnel and on the road (~10–15%) is substantially higher than the predicted value of 0.4%. Alkynes are predicted with CopAUS but have not been measured in the tunnel and on the road above the level of detection. Aldehyde predictions with CopAUS are significantly higher than the levels measured in the tunnel, and aldehydes have not been measured on the road above the level of detection. The on-road air quality study confirms the substantial proportion (~25–30%) of alcohols (mainly ethanol) that were found in the tunnel study and are absent in the CopAUS predictions. The high-observed values are likely related to the use of petrol-ethanol fuels (E10) in Queensland. A plausible reason for the discrepancies is that the (EU) COPERT exhaust VOC speciation factors, which are adopted in CopAUS, are still based on emissions data that were collected in the 1990s and have not kept up with changes in technology and fuel quality.

6. Remote sensing

Remote sensing – referred to here as RSD (remote sensing device) – is well established (Figure 6).

Figure 6. Remote sensing in Brisbane.

It uses open-path instruments at a fixed location where the absorption of IR/UV light by ambient air pollution across the road is used to measure pollutant-to-CO_2 ratios with wavelength specific detectors for different air pollutants. Compared with other monitoring methods, RSD is typically restricted to a limited number of air pollutants (or rather, ratios). RSD provides a location-specific 'transect' snapshot of emissions under certain speed and acceleration conditions (Smit and Bluett, 2011). Pollutant-to-CO_2 concentration ratios are typically converted to fuel-based emission factors (g/kg fuel) or can be converted to emission factors expressed as g/km or g/s by using estimates for g CO_2/km or g CO_2/s (fuel consumption) for each vehicle class (Smit *et al*., 2022b).

RSD measurements in Western Australia (20 locations) and Queensland (3 locations) in the period 2009–2019 generated more than 100,000 valid emission samples over more than a decade. A detailed analysis (Smit *et al*., 2019a; 2021) provided several relevant insights.

1) The percentage of excessive emitters in the light-duty vehicle (LDV) fleet is about 2%.

2) Diesel LDVs have stabilising or increasing NO_x-to-CO_2 ratios with progressive Euro classes. For petrol vehicles, a consistent reduction in NO_x-to-CO_2 ratios was observed for successive emission standards. The Australian RSD data confirm that the NO_x emission issues reported for diesel vehicles in Europe (Carslaw *et al*., 2011) are similarly observed in vehicles sampled in Australia.

3) A consistent reduction in real-world PM ('soot') emissions with progressive emission standards is not visible for diesel LDVs. Euro 5 diesel light-commercial vehicles (LCV) and SUVs have soot emissions that are 141% and 64% higher than diesel passenger cars.

4) On average, across 1–5 years of vehicle age, 4%, 7% and 12% of the measured Euro 5 diesel cars SUVs and LCVs have smoke factor values that suggest diesel particulate filters (DPFs) are malfunctioning, potentially modified or are not present. Pooled data for the two most recent years of manufacture (2017–2018) suggest that 1% of one-two year old diesel SUVs and 2% of one-two year old diesel LCVs have DPF issues (malfunctioning or potentially modified DPFs). These percentages are high when compared with a similar study conducted in the UK (Carslaw, 2017). The RSD data suggest that higher PM emissions for diesel SUVs and LCVs may be caused, at least to some extent, by a higher portion of on-road vehicles with potentially malfunctioning or tampered diesel particulate filters (DPFs).

The RSD measurements were augmented at one location by co-locating RSD with other measurement devices (Figure 7, next page), including pneumatic loop detectors (vehicle counts and speed), a second license plate number (LPN) camera (vehicle identification), a thermal imaging infrared camera (cold start detection) and Bluetooth MAC address units (vehicle tracking) (Smit and Kingston, 2019b).

This RSD+ set-up reduced data loss, improved the capture rate with 10% and provided additional information that is useful in the analysis of emissions data such as speed/count data.

The impact of cold start conditions on thermal imagery was investigated by collecting images for parked (idling) as well as moving test vehicles on a test loop from cold engine start to 10 min after engine start (Smit and Kingston, 2019). It was found that hot vehicles exhibit bright yellow and clearly distinguishable wheels/brakes and exhaust systems and an intense and bright reflection off the road surface (Figure 8). In contrast, cold vehicles generally appear to be dark and have the same or only slightly brighter IR reflection on the road.

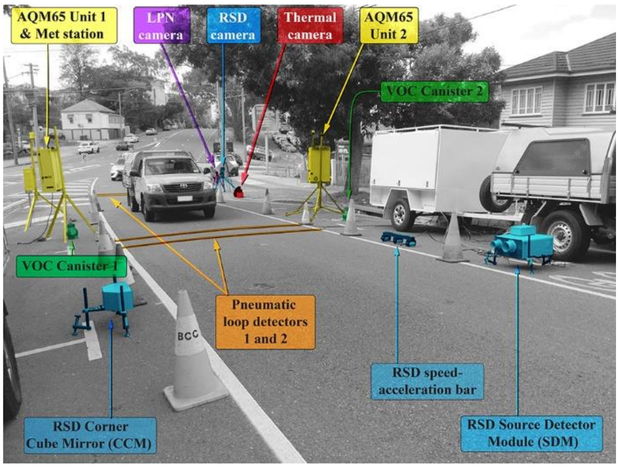

Figure 7. RSD+ setup.

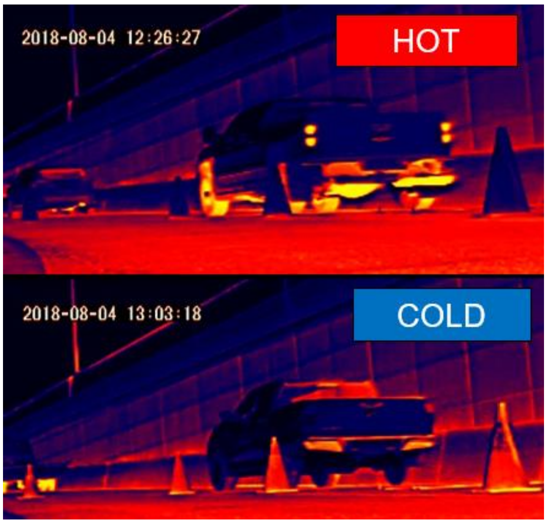

Figure 8. Using thermal imaging for cold start detection.

Vehicles may have excessive emissions due to technical issues with the engine or emission control system. However, cold starts also lead to short periods with high emissions. Thermal vehicle IR signatures were therefore investigated to determine if high emitting vehicles were in cold start mode. Approximately 65% of identified high emitters were assessed to be in hot running mode based on their thermal signatures (Smit and Kingston, 2019b).

7. Conclusions

Australia conducted extensive vehicle emission testing programs until 2008. The wealth of data from these in-service measurement programs has been instrumental in the development of dedicated emission estimation and forecasting models for the Australian on-road fleet (for instance CopAUS, P∆P). In the absence of ongoing and coordinated emissions testing in Australia, vehicle emission assessment necessarily relies on overseas empirical emissions data. However, overseas data does not reflect or account for the significant differences between the Australian on-road fleet with those in the EU or USA (fuel quality and emission standards, etc.).

Small-scale but targeted real-world emission testing programs were conducted in Australia in the period 2015-2022 using different techniques to 1) partially validate current emission factors, and 2) identify any emerging issues specific to Australia. They have provided valuable new data and insights.

The results from on-board emission testing, tunnel measurements and remote sensing consistently show that modern diesel SUVs and LCVs (and possibly trucks and buses) have very high NO_x emissions. They are currently underestimated by the real-world PEMS-based EU emissions data used in Australian emission prediction software. Continued dieselisation of LDVs in Australia under the current Euro 5 emission standards and more stringent NO_2 air quality criteria could potentially result in local air quality issues near busy roads, similar to Europe. Another issue identified with remote sensing is the poor performance of modern diesel regarding PM (soot) emissions and the RSD data suggest that issues with diesel particulate filters are noticeably higher in Australia when compared with the UK. In addition to the observed air pollution emission issues with diesel vehicles, the climate-friendly image of Australian diesel cars is incorrect: they have, on average, 10% higher CO_2 emission rates (g/km) than Australian petrol cars (TER, 2019).

The weight of evidence (tunnel study, on-road air quality measurements) also suggests that the current (EU based) VOC and PAH emission factors and speciation in CopAUS are not accurate for the Australian on-road fleet.

Reliable emission prediction software used for policy impact assessment critically relies on regular updates and re-calibration using empirical data from ongoing real-world emissions testing programs, as is common practice in the EU, USA and Asia.

The main limitations of the recent Australian test programs are that they are small-scale and ad hoc. It is recommended that more emission measurement studies are carried out to assess the real-world emissions performance of the Australian on-road fleet. The methods and improvements developed and reported in the small-scale studies (PEMS, tunnel, remote sensing) will hopefully assist with the development of a national coordinated emission testing program. This paper has demonstrated the value and importance of continued and coordinated emission testing and hopefully inspires the revival of the NISE program in Australia.

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