Detecting cold start vehicles in the on-road fleet

Robin Smit and Phil Kingston

ABSTRACT

Cold start vehicle emissions can make a significant contribution to total emission levels and local air pollution, but this depends on the proportion of cold start vehicles in traffic. This paper has examined two ways to identify cold start vehicles in the on-road fleet 1) by tracking the journeys of individual vehicles using Bluetooth technology and 2) using thermal infrared imaging. The paper demonstrates that the two methods provide useful information that can be used to understand the relevance of cold start conditions in a small road network or to better understand emissions behaviour of individual vehicles in the on-road fleet.

Keywords: cold start, thermal image, emission, motor vehicle, infrared, Bluetooth.

INTRODUCTION

An on-road vehicle emissions measurement campaign was conducted in September 2018 at two locations in Brisbane: a freeway on-ramp and a heavily trafficked urban road. This work is a follow up project from an earlier tunnel study (Smit *et al.,* 2017) and part of a larger validation program for the Australian vehicle emissions software programs COPERT Australia (Smit and Ntziachristos, 2013a) and P∆P (Smit, 2014).

In cooperation with the Western Australian (WA) Department of Water and Environmental Regulation (DWER), the project has employed DWER's remote sensing device (RSD) to provide snapshot information on vehicle emission distributions, as well as instantaneous pollutant-to-CO_2 emission ratios for individual vehicles. However, the program was taken a step further than conventional RSD programs, with the specific aim of examining data accuracy, enhancing data capture rates and potentially addressing specific issues (bias) that relate to the use of the RSD (Smit and Bluett, 2011; NIWA, 2015).

The two monitoring sites were instrumented with a RSD and a range of additional measurement devices, namely loop detectors, a dedicated license plate camera, a thermal imaging infrared (IR) camera, a network of Bluetooth MAC address units, two integrated air quality monitoring stations and speciated VOC sampling equipment. The additional data gained from these pieces of equipment provides for independent verification of the robustness and accuracy of RSD monitoring data (emissions and driving behaviour), provision of additional data, and correlation with on-road air quality. The collective set of measurements provides a rich and unique database that can be analysed in various ways to enhance data capture rates and potentially addressing specific bias issues.

This paper focusses on one particular aspect of the study: identification of cold start vehicles in the on-road fleet. It is noted upfront that this paper does not present an analysis of emission and air quality monitoring results, but is does provide proof of concept for using different technology to identify cold start vehicles. It is noted that other publications will further report, elaborate and expand on the 2018-2019 Brisbane on-road vehicle measurement campaign (e.g. Smit *et al.*, 2019).

COLD START EMISSIONS

Vehicle emissions are significantly elevated in cold start conditions, and are particularly relevant in cold climates. At initial start-up the vehicle engine and emission control systems are cold (ambient temperature), which means more fuel is required and emission control efficiency is reduced and often very low. In contrast, stabilised and low emission hot running conditions occur when the vehicle engine, transmission and emission control technologies have reached their optimal operating temperatures (e.g. engine coolant 75-90 °C, catalysts > 200-250 °C). For instance, in hot running and real-world conditions, three-way catalysts are very effective in reducing engine-out emissions of CO, HC, (organic) PM and NO_x substantially (emission reduction efficiency > 90%). As a consequence, reduced catalyst efficiency due to cold starts has a large impact on vehicle emission levels.

There are different factors that contribute to cold start emissions and they differ in magnitude and duration of impact. Elevated fuel consumption and air pollutant emissions in cold start conditions are due to 1) reduced catalyst efficiency, 2) fuel enrichment in the engine combustion process, and 3) lower fuel efficiency due to increased frictional losses in the engine and transmission systems. The literature suggests that, at an ambient temperature of about 20°C, hot running conditions should generally be achieved for all relevant vehicle components (engine, transmission, catalyst) within 15 minutes of driving. However, "light-off" conditions[1] for the catalyst and tight control of the air-to-fuel ratio, which together largely determine the magnitude of cold start emissions, will be achieved much faster than this, i.e. typically within a minute of engine start for modern vehicles and a maximum of a few minutes for older technology vehicles (Smit and Ntziachristos, 2013b).

Cold start emissions can make a substantial contribution to total emissions from motor vehicles. For instance, the 2010 national (Australian) motor vehicle emission inventory (UQ, 2014) predicted that hot running emissions generally dominate total emissions from road transport in Australia, but that cold start emissions vary from small to significant for a number of pollutants: e.g. 42% CO, 31% VOCs, 14% NH_3, 7% NO_x, and 5% $PM_{2.5}$.

However, at a local scale, excess emissions due to cold start conditions can have a substantially larger contribution. This is because excess cold start emissions exhibit strong non-linear behaviour. If excess cold start emissions are plotted against time since engine start, typically a log-shaped profile would occur (Smit and Ntziachristos, 2013b). As a consequence, the bulk (~80%) of the cold start excess emissions are emitted at locations between a few hundred metres to several kilometres from the journey start point. Depending on the vehicle (class) and pollutant considered this means that the majority of cold start emissions are concentrated in a localised area where vehicles start their engines, such as parking lots, residential areas and shopping centres.

IDENTIFYING COLD START VEHICLES

Despite the local significance of cold start emissions, there is little real-world data available regarding the proportion of cold start vehicles traveling in local on-road fleets. This is because it is challenging to accurately determine if a vehicle is in cold start mode in real-world driving conditions.

To estimate the proportion of cold start vehicles, assumptions therefore have to be made regarding average trip length and cold start distance for national or state level vehicle emission estimates. In local emission (remote sensing) testing programs it is generally (and often incorrectly) assumed that cold start emissions are not significant and can be ignored (NIWA, 2015). This is a particularly risky strategy for urban sites (e.g. Sjödin and Lenner, 1995). For local emission and air quality impact studies it is therefore important to examine the (expected) proportion of cold start vehicles in the remote sensing measurements for each location, and to determine if the measured emissions are likely to be mainly hot running emissions, or not.

Few researchers have attempted to determine which specific vehicles operate in cold start mode. Monateri *et al.*, (2004) reported on the (manual) use of an infrared (IR) camera to measure the heat signature of passing vehicles (exhausts, tyres, and underbody) and determine if a vehicle is in cold start mode.

Two independent methods were developed and employed in this study to identify vehicles operating in cold start mode:

1) Assessing the likelihood that a particular

measurement site is impacted by cold start vehicles by tracking the journeys of individual vehicles using a network of Bluetooth monitoring units at and around each location.

2) Analysing the thermal IR signatures of individual vehicles to identify those in cold start conditions.

BLUETOOTH UNITS

To track the journeys of individual vehicles six Bluetooth MAC (media access control) address units were installed at specific points in the road network, one at the measurement site (denoted as Site 1) and the other units at sufficient distances (up to about two kilometres) away from the measurement sites.

The units record time stamps and log the unique MAC address of any Bluetooth device inside a vehicle (e.g. audio system) that is scanned by the unit when the vehicle passes by. This also includes the unique MAC address of the audio system from the vehicle itself. With this unique identification of the vehicle individual vehicle movements in time and space can be tracked before the RSD measurement took place. The method is relatively new and primarily used to calculate travel times between 2 or more nodes.

The units typically capture about 15% of total vehicles passing a given point, and should therefore be regarded as an indicative sample of vehicle movements in the road network. For this study, vehicles coming out of nearby suburbs are of particular interest as they could potentially be in cold start mode. Vehicles passing units more than one kilometre away are not likely to have significant residual cold start emissions .

The location of the units and the analysis results are shown in Figure 1. Major road sections (node to node) are indicated with different colours showing different types of road (side street, major through road) and road lengths.

For the urban site, movements from/past sites 3 and 2 capture local traffic coming from nearby suburbs, just before the RSD test site. It can be seen that a significant number of vehicles (10 + 11% so about 20% in total) could potentially be driving in cold start conditions for the urban site. As a consequence, the RSD results are likely to be affected to some extent by cold start vehicles and analysis of thermal images is warranted.

For the freeway site, vehicles passing site 3 are of particular interest as site 3 is a large shopping centre. Site 2 is also of interest as vehicles recording a S2-S1 trip are coming out of a nearby suburb. A significant fraction of traffic (36%) is coming from the shopping centre. However, the travel distance is slightly over 1 km so it is likely that the bulk of cold start emissions have already been emitted. Nevertheless, residual cold start emissions may remain. A significant fraction (15%) is also coming from the nearby suburb. As a consequence, the RSD results are likely to be affected to some extent by cold start vehicles and analysis of thermal images is warranted.

THERMAL IMAGING

A thermal imaging IR camera (Noptic Thermal Camera, Strategic Innovations, STH1000) was used at the two RSD sites to record and visualise the thermal profiles of individual vehicles.

A small separate test program was set up to investigate the impact of vehicle operation on thermal imagery.

As a first step, the impact of time since engine start on thermal imaging was examined for three cold and parked vehicles in idling mode. The test vehicles were:

- Ford Ranger, 2016, 2.1 litres, Diesel, Auto, GVM 3200 kg
- Toyota RAV4, 2018, 2.5 litres, Petrol, Auto, GVM 2150 kg
- Toyota Corolla, 2016, 1.8 litres, Petrol, Auto, GVM 1845 kg

The results are shown in Figure 2 for 0, 1, 2, 3, 4 and 10 minutes after engine start. Some variability can be observed regarding the visibility of the heat signature, which reflects differences in vehicle build, engine/fuel type and thermal management of the engines. Nevertheless, the engine exhaust shows as dark and cold for the first 1-2 minutes since engine start for all vehicles, which aligns well with the time period in which the bulk of cold start emissions are expected to occur. If travel time exceeds a few minutes, it can be assumed that the vehicle has negligible cold start emissions. After 2 minutes of idling, the exhaust system starts to light up, progressively becoming brighter with time. A distinct yellow/red heat signature becomes visible after approximately 2 minutes. The idle test demonstrates that the IR signature of exhaust systems in the early stages of cold start conditions are hardly distinguishable from the surrounding environment.

As a second step, the thermal imaging camera was set up on a quiet stretch of road with roundabouts at either end, to replicate urban driving conditions with short periods of constant speed driving close to the speed limit and regular stops and turns (Figure 3).

Cold vehicles were driven in loop mode past the thermal imaging camera and changes in thermal images were recorded. The same test vehicles were used as listed before. Figure 4 shows the results for 26 July 2018 with an ambient start temperature of ~14°C and Figures 5/6 show the results for 15 February 2019, with an ambient start temperature of ~24°C.

As seen for the idle test results, it is again clear that the entire vehicle shows as dark and cold for the first 1-2 minutes since engine start for all vehicles. After about 2 minutes of driving, the thermal signature of the vehicle becomes visible. The IR signature has various components that light up varying from the exhaust system, tyres/brakes and the thermal reflection that radiates from the underbody. The tyres/brakes and exhaust pipe (if visible) in particular appear to be good indicators for driving in cold start conditions.

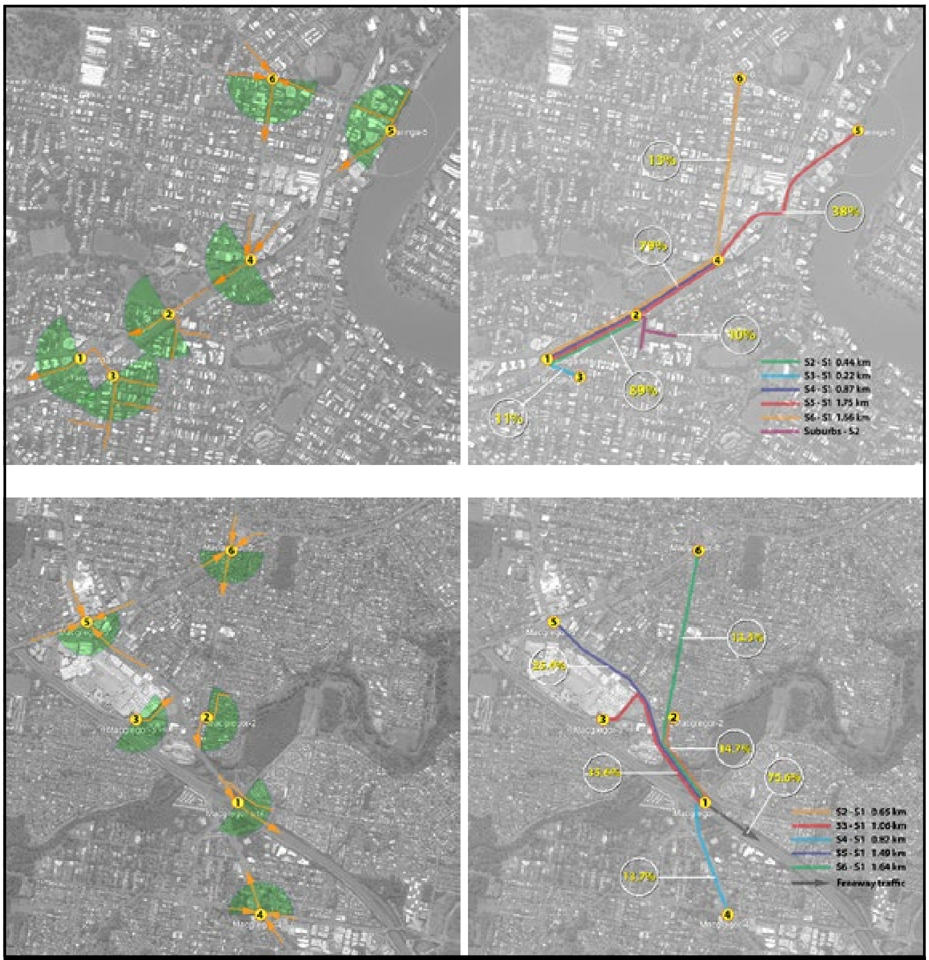

Figure 1: Example of Network of Bluetooth devices (left); results of vehicle movement analysis (right); Urban Site top; Freeway Site Bottom.

Hot vehicles will exhibit hot and clearly distinguishable wheels/brakes and exhaust systems, and regularly an intense and bright reflection off the road surface. In contrast, cold vehicles will generally appear to be dark and have the same or only slightly brighter IR reflection on the road.

The short test program confirms that vehicles in the early (and most relevant) stage of cold start conditions have a distinctive thermal image, which can be used to identify these vehicles in the on-road fleet. It is noted that hours of thermal image footage could in principle be analysed to identify a relatively small number of cold start vehicles, which is time consuming.

An alternative and more cost-effective approach is to focus the thermal image analysis on specific vehicles of interest. For instance, remote sensing has been used as a roadside real-time vehicle emissions information system to identify high-emitting vehicles (e.g. Sjödin *et al.,* 1997; Bishop and Stedman, 2008). High emitters are vehicles that have excessive emissions due to e.g. engine issues, malfunctioning or partly functioning emission control systems, incorrect repairs, poorly retrofitted fuel systems or even tampering. However, cold start conditions can also lead to (temporarily) elevated emission levels. After identification of a high emitting vehicle, subsequent analysis of the IR signature could confirm if the vehicle is in cold start conditions and therefore not a high emitter as defined previously. This has been done as part of the analysis of the 2018-2019 Brisbane on-road vehicle emission measurement campaign (Smit *et al.*, 2019)

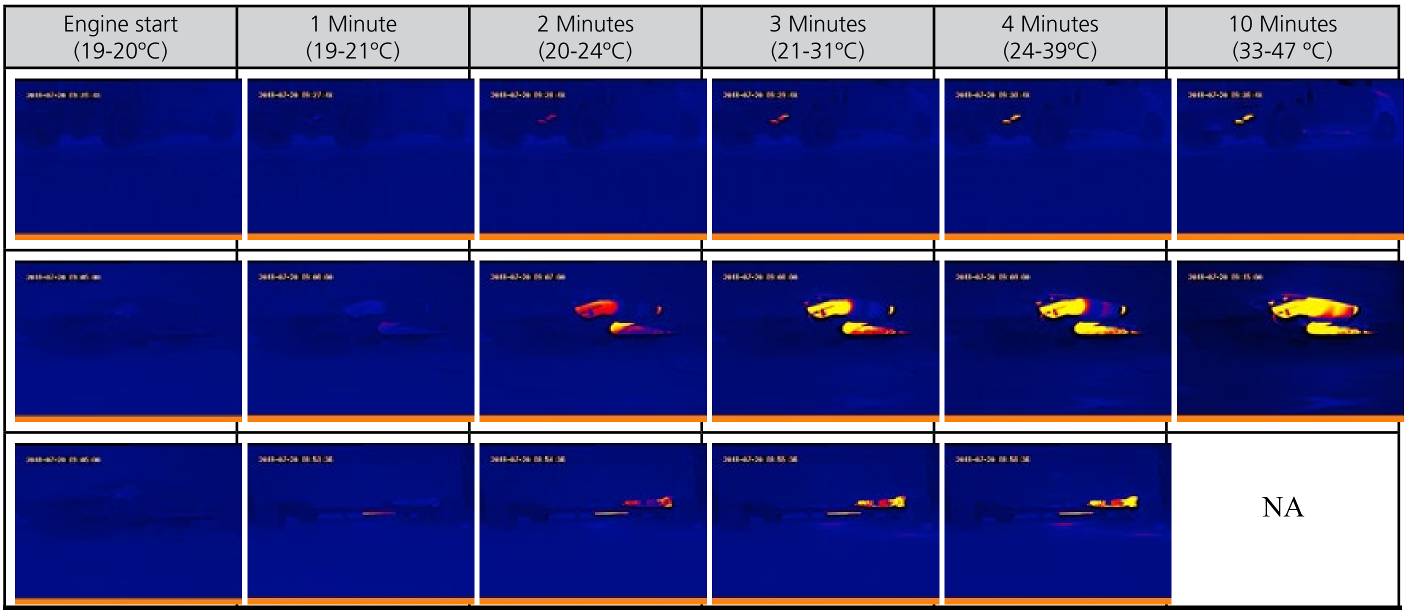

Figure 2: Time-series of thermal images since engine start for three vehicles in idling mode, from top to bottom: Ford Ranger, Toyota RAV4, Toyota Corolla.

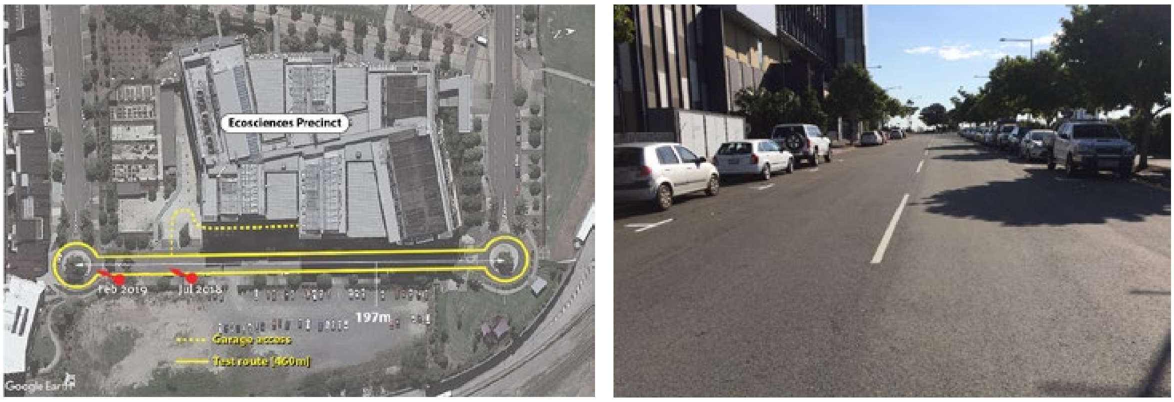

Figure 3: Test loop for real-world thermal imaging showing camera locations.

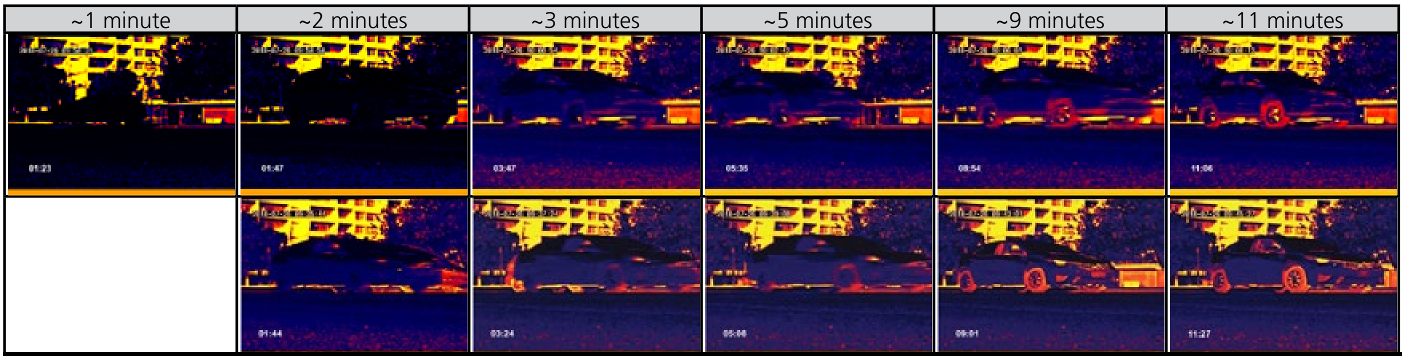

Figure 4: Front of vehicle time-series of thermal images (26 July 2018) since engine start for 2 vehicles in real-world operation, Toyota RAV4 (top), Toyota Corolla (Bottom).

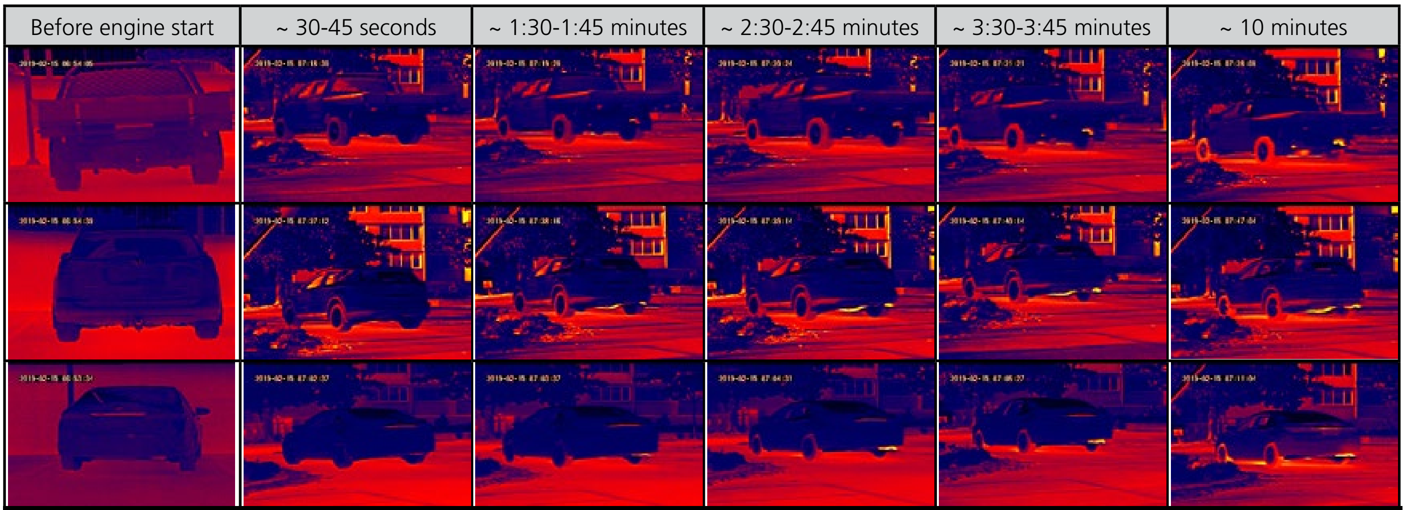

Figure 5: Back of vehicle time-series of thermal images (15 February 2019) since engine start for three vehicles in real-world operation, from top to bottom: Ford Ranger, Toyota RAV4, and Toyota Corolla.

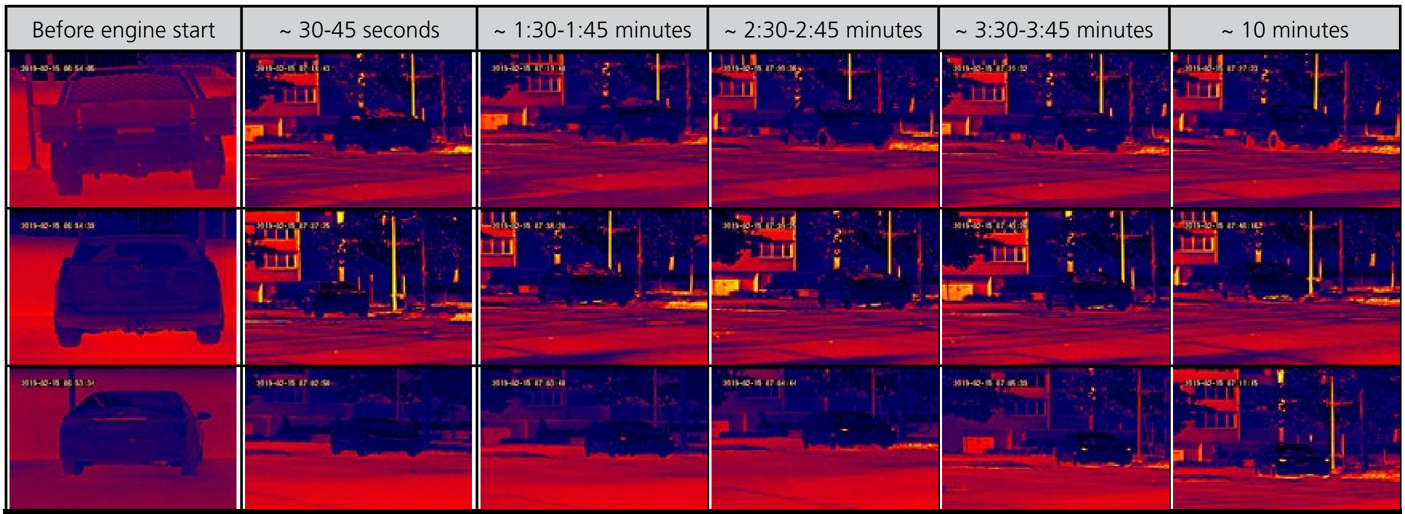

Figure 6: Front of vehicle time-series of thermal images (15 February 2019) since engine start for three vehicles in real-world operation, from top to bottom: Ford Ranger, Toyota RAV4, and Toyota Corolla.

Finally it is noted that this study was conducted in a subtropical climate (Brisbane) with relatively high ambient temperatures. It is expected that thermal imaging will work better in colder climates, as the temperature differences between hot vehicle components (tyres, exhaust system) and the ambient background will be larger and more easily distinguished in thermal images. This effect is clear by comparing Figure 4 (Brisbane winter) with Figure 5-6 (Brisbane summer), where the background temperature is significantly higher in summer leading to a reduction in temperature difference between the vehicles and background.

CONCLUSIONS

Cold start emissions can make a significant contribution to total emission levels and local air pollution, but this depends on the proportion of cold start vehicles in traffic. This paper has examined different ways to assess the local relevance and identify cold start vehicles in the on-road fleet, i.e. by tracking the journeys of individual vehicles using Bluetooth technology and using thermal infrared imaging. The two methods provide useful new information that can be used to identify and understand the relevance of cold start conditions in a small road network or to better understand emissions behaviour of individual vehicles in the on-road fleet.

ACKNOWLEDGEMENTS

The authors are grateful for the help provided by Mr Ray Wilson of the Department of Transport and Main Roads (DTMR), and for loaning the thermal imaging camera to the Department of Environment and Science (DES).

REFERENCE LIST

1. Bishop, G.A., Stedman, D.H., 2008. A decade of on-road emissions measurements, *Environ. Sci. Technol.*, 42, 1651-1656.
2. Monateri, A. M., Stedman, D. H., Bishop, G. A. (2004). Infrared thermal imaging of automobiles, *Poster presented at the 14th CRC On-Road Vehicle Emissions Workshop*, San Diego, March 2004, http://www.feat.biochem.du.edu/reports.html.
3. NIWA, 2015. *The Use of Remote Sensing to Enhance Motor Vehicle Emission Modelling in New Zealand*, prepared by Robin Smit and Elizabeth Somervell, Report No. AKL2015-012, National Institute of Water & Atmospheric Research, New Zealand.
4. Sjödin, Å, Lenner, M., 1995. On-road measurements of single vehicle pollutant emissions, speed and acceleration for large fleets of vehicles in different traffic environments, *The Science of the Total Environment*, 169, 157-165.
5. Sjödin, Å, Andréasson, K., Wallin, M., Lenner, M., Wilhelmsson, H., 1997. Identification of high-emitting catalyst cars on the road by means of remote sensing, *Int. J. of Vehicle Design*, 18 (3/4), 326-339.
6. Smit, R., Bluett, J., 2011. A new method to compare vehicle emissions measured by remote sensing and laboratory testing: High-emitters and potential implications for emission inventories, *Science of the Total Environment*, 409, 2626–2634.
7. Smit, R., Ntziachristos, L., 2013a. COPERT Australia: a new software to estimate vehicle emissions in Australia, Australasian Transport Research Forum 2013 Proceedings, 2 - 4 October 2013, Brisbane, Australia.
8. Smit, R., Ntziachristos, L., 2013b. Cold start emission modelling for the Australian petrol fleet, *Air Quality and Climate Change*, 47 (3).
9. Smit, R., 2014. PΔP: A simulation tool for vehicle emissions and fuel consumption software with a high resolution in time and space, Vehicle Technology Engineer, SAE Australasia, July 2014, 17-21.
10. Smit, R., Kingston, P., Wainwright, D., Tooker, R., 2017. A tunnel study to validate motor vehicle emission prediction software in Australia, *Atmospheric Environment*, 151, 188-199.
11. Smit, R., Bainbridge, S., Kingston, P, Brown, M.K., Shaw, G., 2019. Augmented remote sensing:

measuring on-road vehicle emissions and on-road air quality, *23rd Transport and Air Pollution Conference*, Thessaloniki, Greece, 15-17 May 2019 (*submitted for publication*).

12. UQ, 2014. *Australian Motor Vehicle Emission Inventory for the National Pollutant Inventory (NPI)*, prepared by Robin Smit, University of Queensland, Project C01772, 2 August 2014, http://www.npi.gov.au/resource/australian-motorvehicle-emission-inventory-national-pollutant-inventory-npi.

FOOTNOTES

1 After an engine start, a cold catalyst goes through two main stages. In stage 1 the converter gradually heats up by hot exhaust gases, but the reaction rate in the converter is generally low. After a short period of time, the temperature in the converter becomes sufficiently high for the reactions rate to increase and this generates additional heat (exothermic). The temperature and reactions rate then increase dramatically at this point and the converter "lights-off". Light off is typically defined as the point in time where the catalyst achieves a 50% conversion efficiency. In stage 2, catalyst efficiency progressively improves after light-off conditions are reached as the so-called "light-off front" moves towards the converter outlet. Typically as the catalyst approaches optimal operating temperature, NO_x is the first to reach a high conversion efficiency, followed by CO and then HC. Light-off times have improved substantially with the advent of improved engine and catalyst technology. In comparison with older vehicles, which could take several minutes to achieve light-off conditions, modern vehicles achieve light-off conditions quickly within one to a few minutes.

AUTHORS

Robin Smit
Department of Environment and Science, Brisbane.
School of Civil Engineering, The University of Queensland.
Faculty of Engineering and Information Technology, University of Technology Sydney.

Phil Kingston
Department of Environment and Science, Brisbane.