SIMULATION OF VEHICLE EMISSION FACTORS FOR COLD START CONDITIONS: AN INITIAL EXAMINATION OF MODAL DATA AND A NEW METHOD

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Abstract

Cold start emissions are gaining increasing importance in vehicle emission inventories, where cold start emissions (i.e. CO, HC) from modern (petrol) passenger cars typically make up 50%-80% of total trip emissions. There is also a strong spatial and temporal component to cold start emissions. These factors make improved modelling of cold start emissions essential.

This paper provides a brief review of international methods for developing cold start emission factors and then examines in detail the cold start emissions behaviour of Australian light-duty petrol vehicles. A large empirical database of modal (second-by-second) emissions test data for Australian vehicles that was recently released (NISE2) is used to explore the performance (e.g. goodness-of-fit) of different methods and types of cold start emission algorithms, and a recommendation is made as to the best approach for Australian light-duty vehicles.

Keywords: Motor vehicles, Emissions Modelling, Cold start.

1. Introduction

Cold start emissions (i.e. CO, HC) from modern (petrol) passenger cars typically make up 50%-80% of total trip emissions (Smit, 2011). Cold start emissions have a strong temporal and spatial component. In terms of location, the bulk of cold start emissions are typically emitted within the first few minutes of driving (e.g. Kemmler et al., 2000), which effectively means that the majority of cold start emissions are emitted in locations where vehicles are started (e.g. residential areas, parking lots, underground parking garages). Cold-start emissions are not evenly distributed over the cold-start period. For instance, previous work (TRL, 1999; Joumard and Sérié, 1999) has shown that most (say about 80%) of the CO and HC excess emissions from petrol cars are emitted during the first 20% of the cold-start distance.

Cold start emissions are a complex function of fleet technology mix, local climate, fuel characteristics and driving behaviour:

1) Cold start emissions are a function of the level of emission control technology in vehicles. Cold engines use more fuel and generate more air pollution than engines that are fully warmed up. In cold conditions fuel does not fully evaporate, so it is necessary to enrich the air-fuel mixture in order to provide an ignitable mixture to the engine. The rich mixture and poor combustion conditions under cold-start emissions cause elevated emissions of greenhouse gases (CO_2) and in particular pollutants associated with incomplete combustion (CO, HC, PM). Furthermore, catalyst technology does not work adequately until their temperature reaches a suitable level of approximately 200-400 ^oC (so-called “light-off” conditions) and engines run stoichiometrically. This further impacts adversely on the emissions and also leads to elevated emissions of air pollutants such as NO_x.

2) The relevance of cold start conditions is also a function of local climate and weather conditions. Lower ambient temperatures increase the heating required for the engine and catalyst to reach effective operating temperatures and thus prolong the period of elevated exhaust emission rates. A decrease in ambient temperature generally results in an increase in cold-start emissions and fuel consumption (INRETS-LTE, 1999).

3) Driving behaviour is another significant factor and it influences the level of cold start conditions in different ways. Firstly, the time period between engine shutdown and restart is relevant. Catalysts cool significantly if an engine is shutdown for more than approximately 30 to 60 minutes before being started. Studies have shown that about 25-30% of engine starts are made in cold start mode (Watson, 2001; André, 2004). Secondly, the way a vehicle is being driven is relevant. As catalysts are heated by engine exhaust gases, catalyst and engine warm-

up occurs more rapidly when the engine operates under heavier loads. As a consequence, the driving cycles used in emissions testing will determine the cold start emission levels. For instance, DoTRS (2001) found different light-off times for the FTP75 and Euro test cycles, where the Euro test cycle required significantly more time (about 100 seconds) before the engine coolant reached typical operating temperature. Similarly, Watson (2001) found that the Austra lian Urban Cycle (AUC) required significantly longer warm-up times (± 600 sec) compared to the FTP city cycle (± 300 sec). It is believed that the high speed micro-trip that occurs at three minutes in the FTP city cycle rapidly warms up the engine and the transmission encouraging early light-off.

Mitigation of cold start emissions can be achieved through technological measures such as modified engine enrichment strategies, a catalyst location closer to the engine (close coupled catalyst) and active catalyst warm-up to achieve faster light-off conditions and also through behavioural change such as reduction of the number of short trips. It has been shown that light-off times have improved substantially with the advent of improved engine and catalyst technology. For instance, Ntziachristos and Samaras (2001) reported a decrease in light-off times from about 220 seconds for Euro 1 cars to about 40 seconds for Euro 4 cars.

The proportion of vehicles that are in cold start driving mode is dependent on time of day and location and can vary from practically 0% on freeways that are far removed from residential areas to almost 100% in residential areas in the early morning hours. But in any case, a high proportion of mileage is driven under cold start conditions, due to typically small average trip lengths of a few kilometres in urban areas (INRETS-LTE, 1999). For instance, Van den Brink (2000) reported the following proportions of total travel (i.e. vehicle kilometres travelled or VKT) that is driven in cold start mode: 50% in urban areas and 5-10% for non-urban areas and freeways. It is noted, however, that it is difficult to accurately determine the proportion of travel in cold start conditions because it is affected by local variations in trip length distributions, climate and on-road vehicle technology. It is clear though that the contribution of cold start emission to total emission loads is substantial. For instance, Kirchstetter et al. (1996) reported that more than 50% of total regional CO and HC emissions in wintertime in the San Francisco Air Basin are cold start emissions.

2. Simulation of Cold Start Emissions: A Brief Review of Commonly used Models

This section will briefly discuss how cold start emission factors are developed and applied in two commonly used emission models.

The MOVES2010 model (US EPA, 2009a; 2009b) defines a cold start as "a start emission following a soak period of 12 hours or longer". Cold start emission factors for both light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) were computed as the difference in measured aggregate emissions of FTP75 (Federal Test Procedure) 'Bag 1' minus 'Bag 3'. 'Bag' refers to the tedlar bags used in laboratory testing in which exhaust is stored for analysis. Figure 1 depicts the FTP75 driving cycle used in this process.

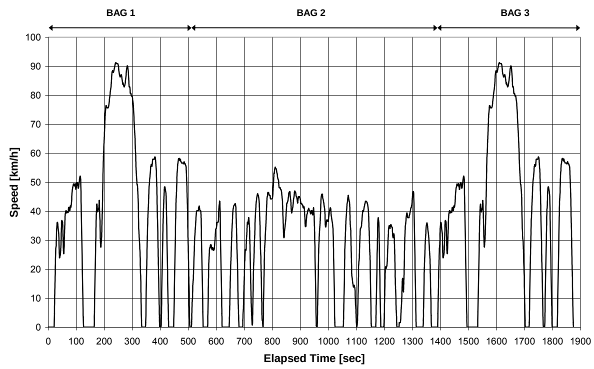

Figure 1. FTP75 (Urban) Test Procedure (Source: Smit, 2006).

The model incorporates correction factors for soak periods less than 12 hours, and these correction factors were taken from the previously used MOBILE 6 model. Algorithms to simulate the effects of ageing were also included but are assumed to be the same as those developed for hot running emissions due to a lack of data.

Interestingly, the MOVES2010 model appears to use a more simplified approach as compared to its predecessor MOBILE 6. For MOBILE 6 US EPA developed the so called Hot Running 505 cycle (HR505) and a special test program was conducted to allow for better separation of vehicle start emissions from hot running emissions (US EPA, 1999). The HR505 basically was an additional exhaust emission bag ('Bag 4') that was performed immediately following 'Bag 3' of the standard FTP and it was a duplicate in terms of the speed-time trace to 'Bag 1' and 'Bag 3', with the only difference that it did not contain an engine start. This implies that the start emission factors in MOVES2010 do not fully reflect start emissions as it reflects the difference between a soak of 12 or more hours and a 10 minute soak.

The COPERT4 model (EMEP/CORINAIR, 2007) simulates start emissions as additional emissions for the pollutants CO, NOx, VOCs and fuel consumption for LDVs only (petrol, LPG, diesel). The method is based on computation of a so-called “over-emission” ratio, which predicted as a function mean monthly temperature and average speed. This ratio is then used to predict cold start emission factors though multiplication with the corresponding hot running emission factor. This computation also takes into account the fraction of travel in cold-start mode, which is estimated as a function of mean monthly temp and mean trip length.

3. Cold Start Emissions: An Examination of Modal Empirical Data

A u seful concept that is commonly used by emission modellers is the cold start distance or cold start time (e.g. Joumard et al., 2000), which is either the distance or the time period for emission levels to stabilise around its hot running value. These values depend on the pollutant that is considered. It can be determined through comparison of modal (second-by-second) hot running and cold start emission profiles under same test conditions (vehicle, cycle, laboratory) and assessment of the point in time where both profiles converge. As will be discussed later in this section, this ‘theoretical’ convergenc e point is not always obvious in practise due to random fluctuations from one test to another.

Examination of modal (second-by-second) emissions data can provide important insights for the development of accurate cold start emission factors. Modal emissions data from the NISE 2 studies has been used to illustrate this process in this paper.

The NISE 2 studies (Orbital, 2005; RTA, 2009) provide test data for about 400 petrol vehicles (i.e. passenger cars, SUVs (sport utility vehicles), light-commercial vehicles; model years 1986-2008). The vehicles tested represent a cross section of typical vehicles on Australian metropolitan roads. Tests were conducted on a second-by-second (‘modal’) and aggregate (‘bag’) basis. The exhaust emission data were collected in a vehicle emissions testing laboratory (Orbital, Perth) over a 30-minute real-world driving cycle (speed-time profile) called the ‘CUEDC-P’ (composite ur ban emission drive cycle for petrol vehicles). This cycle was developed from Australian driving pattern data collected in the field.

Figure 2 shows an example of two emission profiles, one in cold start conditions and one in hot start conditions. It can be seen that cold start conditions produce a typical hump of excess emissions at the start of t he test in the time period of about 0-50 seconds. After this period, the profiles are roughly similar. It is noted that the hot running emission profile does not exceed 1.4 mg/s, which makes it appear as a flat (red) line in Figure 2.

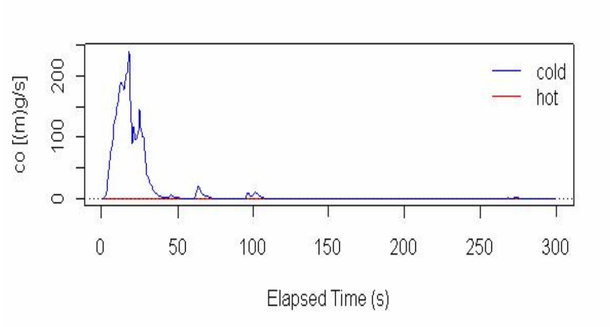

Figure 2. Example of Modal CO Emission Profiles of Cold and Hot Running Conditions.

When cumulative distributions are developed from the cold and hot start emission time-series data, as is shown in Figure 3, the cumulative difference in cold and hot start emissi ons represents the excess cold start emissions (grams). This approach seems relatively straight forwar d and theoretically the cold start emission factor should be time-independent after the point where cold start and hot start emission profiles become equivalent.

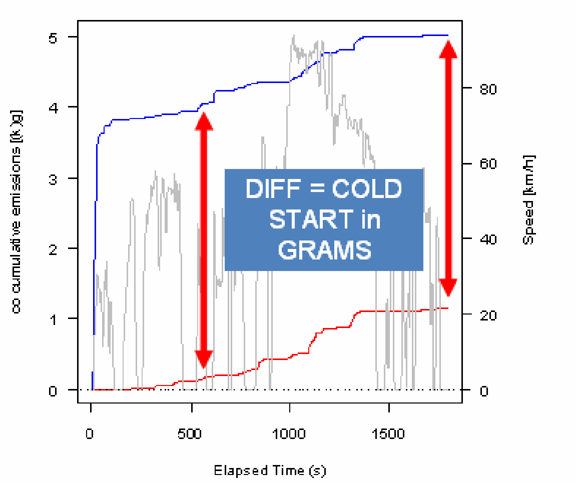

Figure 3. Cumulative Modal CO Emission Profiles (Grey Line represents Driving Cycle).

However, examination of the NISE 2 modal empirical data shows that this expected behaviour does not hold in several instances. An example is provided in Figure 4 and 5. It shows the time-series data in Figure 4. The red oval indicates a large emissions spike in the hot start test, which is not observed for the cold-start profile, despite the fact that both tests involve exactly the same test vehicle and the same driving cycle. The spike could be due to a number of reasons but most likely is caused by a temporary deviation from the optimum air-to-fuel ratio. The occurrence of spikes in emission profiles is quite commonly observed for modern petrol vehicles (Smit et al., 2010).

Figure 5 shows the effect of this emission spike on the cumulative emission profiles.

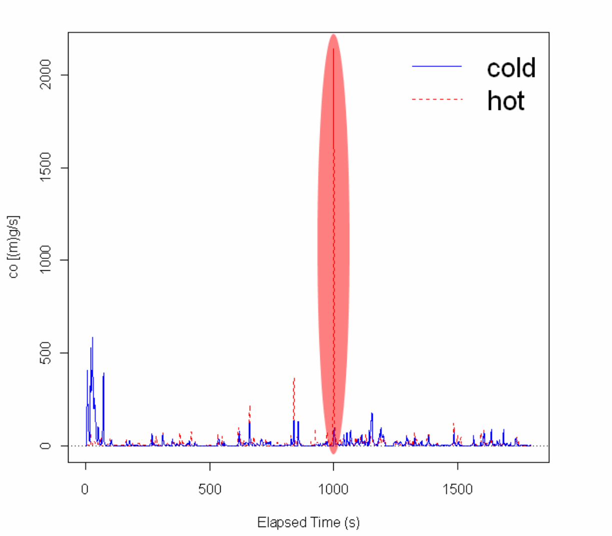

Figure 4. Modal Cold/Hot CO Emission Profiles.

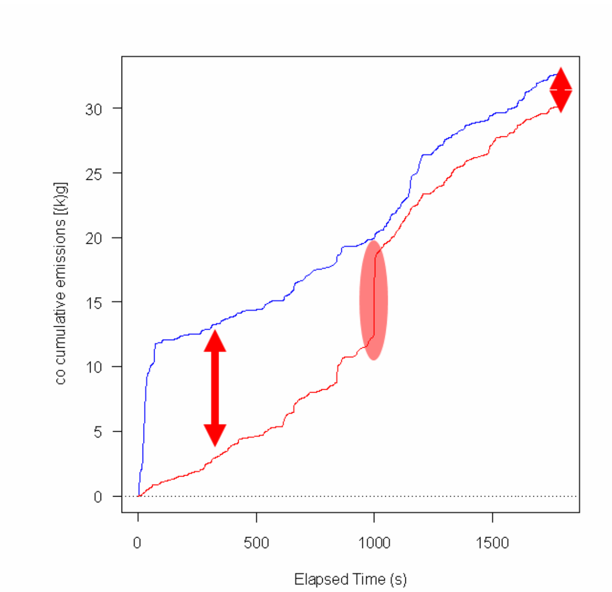

Figure 5. Cumulative CO Profiles.

Clearly, determination of cold start emissions is no longer time-independent. If the cold start emissions were computed as the difference between cumulative cold and hot start emissions before the emission spike, then the value would be approximately 10.5 grams per start in this specific case, whereas the value would be approximately 2.5 grams per start if computed after the emission spike. This is a relevant finding as aggregated (bag) data are often used directly to compute cold start emission factors, as was shown to be the case for e.g. MOVES2010. In this case, this would be equivalent to computing a value of 2.5 grams per start, which is more than a factor of three lower than the value if the emission spike were excluded.

4. Proposed Method for Development of Cold Start Emission Factors from Modal Data

It is clear that analysis of modal data is essential to develop accurate cold start emission factors. One challenge is to accurately determine the point where hot and cold emission profiles converge ("cold-start time"). It was shown before that this is not as straightforward as it may seem at first instance.

A new method has therefore been developed to adequately estimate cold start emission factors. The method first computes an array with modal differences in emission rates (mg/s) between hot running and cold start conditions (denoted as D). It then performs a linear least-squares regression on the data of the form:

$$D = \alpha + \beta t \tag{1}$$

where t represents elapsed time (s) and α and β represent the regression coefficients. Once the coefficients are estimated, the cold start time (t_{cold}) is computed as follows:

$$t_{cold} = -\alpha / \beta \tag{2}$$

The process is graphically shown in Figure 6. Cold start time for this emission test is estimated to be 399 seconds.

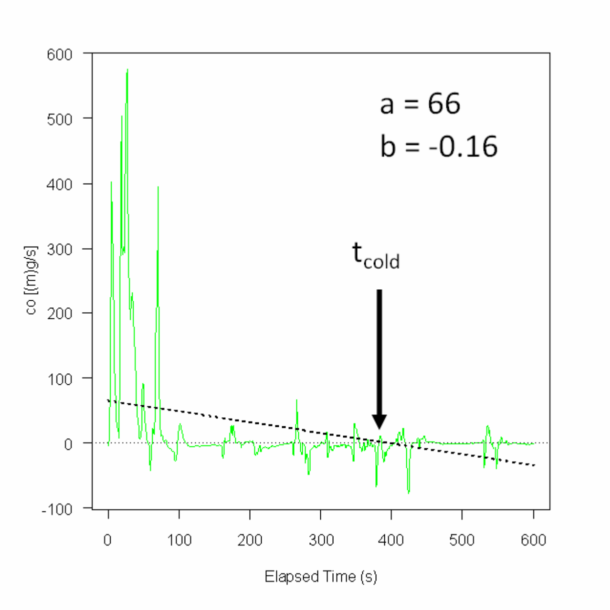

Figure 6. Cumulative CO Profiles.

Once t_{cold} is determined, the cold start emission factor can be estimated by subtracting the cumulative hot running emission value at t_{cold} from the cumulative cold start emission value at t_{cold}, which equates to 9.9 g/start.

The method was applied to modal data for Australian Design Rule 79/01 (ADR79/01) passenger cars (MY 2006 | 2007), and the results are presented in Table 1 for three car types. It can be seen that, on average, emission factors for small and large cars are substantially higher after using modal analysis, when compared to aggregate or "bag" analysis. Interestingly, the difference for medium cars, however, is small, which shows that the magnitude of errors will depend on the vehicle class that is considered and the empirical data that underlies it.

It is noted that "Bag" is put within quotation marks as it is not actually reflecting bag measurements but represents values from aggregated modal data.

Table 1 – CO Cold-Start Emission Factors (g/start) for ADR79/01 Cars (Data Source: RTA, 2009)

Vehicle Class	"Bag"	Modal	Error
PC Small	4.1	5.3	-24%
PC Medium	4.9	4.7	3%
PC Large	4.0	7.0	-44%

5. Discussion and Conclusions

This paper has discussed the increasing importance of (cold) start emissions with respect to emission inventories. It has shown that examination of modal test data is essential to increase our understanding and also demonstrated that modal data should be used in the development of cold-start emission factors in order to prevent substantial errors.

A new approach was presented that can be used to determine the cold-start time for each emission test and subsequently be used to estimate the cold-start emission factor for the test.

A simple linear least-squares regression was used in this paper to achieve a first-order examination of the results, but it is acknowledged that generalized least squares (autoregressive) regression models (e.g. Smit and McBroom, 2009) will be more appropriate for this purpose as they will account for likely autocorrelation effects in the data. The appropriate statistical method requires further examination.

The initial results presented in this paper warrant further analysis for all vehicle classes and other pollutants. This will be the subject of further work, with the final aim to develop accurate cold start emission factors for Australian vehicles.

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