SPaTS Task 1-650 – Consideration of methodologies for introducing cold starting emissions into the NTM

Task in: Production of updated emission curves for NTM and WebTAG

Report for Department for Transport

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Table of contents

Glossary of abbreviations

ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems (A DG TREN Programme which concluded around 2007)
COPERT	Software tool for calculating pollutant emissions from road transport
DfT	UK Department for Transport
ECE	Urban drive cycle component of NEDC
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme (an ongoing co-operative programme within Europe)
ERMES	European Research on Mobile Emission Sources
EXEMPT	EXcess EMissions Planning Tool
HGV	Heavy Goods Vehicle
LAQM	Local Air Quality Management
LDV	Light duty vehicle
LGV	Light Goods Vehicle
NAEI	National Atmospheric Emissions Inventory
NE	Not Estimated
NEDC	New European Drive Cycle
NTEM	National Trip End Model (component within the NTM)
NTM	National Transport Model
PM	Particulate matter
TRL	Transport Research Laboratory
WebTAG	DfT Web-based Transport Analysis Guidance

1 Introduction

DfT require an update to the speed-emission factor and fuel consumption curves in a specified format for use in the NTM and WebTAG consistent with the exhaust emission factors in the European COPERT 5 model, now used in the compilation of the UK's National Atmospheric Emissions Inventory (NAEI) on behalf of Defra and BEIS (http://naei.beis.gov.uk/) and in national air quality modelling under the MAAQ contract for Defra. This includes modelling that underpinned the UK's Plans for reducing roadside nitrogen dioxide concentrations. The update to these speed-emission curves has been reported separately.

The updated emission curves provided for the NTM and WebTAG are restricted to vehicles running on conventional petrol and diesel engines in normal warm conditions. In this separate project we consider methodologies by which the excess emissions generated when a vehicle starts from cold (referred to as "cold start emissions") might be included within the NTM. These are not currently a component of the NTM emission calculations. Care has been taken to restrict suggestions to those that are compatible with the cold start emissions totals reported in the NAEI so that there is a consistency between the suggestions generated here, and those quantified in other government reporting.

The structure of this short report is:

1. A description of the methodology used in the NAEI and other potential cold start excess emissions methodologies (Chapter 2);

2. Some numerical evaluation of the COPERT methodology which underpins the NAEI methodology, and the cold start emissions reported by the NAEI (Chapter 3)

3. Some recommendations regarding how the excess cold start emissions might practically be accounted for within the NTM (Chapter 4).

2 Methodologies for estimating cold start emissions

Cold start emissions are the excess emissions that occur when a vehicle is started with its engine below its normal operating temperature. The excess emissions occur from petrol and diesel vehicles because of the lower efficiency of the engine and the additional fuel used when it is cold, but more significantly for petrol cars, because the three-way catalyst does not function properly and reduce emissions from the tailpipe until it has reached its normal operating temperature.

2.1 Methodology used in NAEI for estimating cold start emissions[1]

Cold start emissions are calculated following the recommendations made by TRL in a review of alternative methodologies carried out on behalf of DfT (Boulter and Latham, 2009). The main conclusion was that the inventory approach ought to take into account new data and modelling approaches developed in the ARTEMIS programme and COPERT 4 (EMEP, 2007). However, it was also acknowledged that such an update can only be undertaken once the ARTEMIS model and/or COPERT 4 have been finalised and that at the time of their study it was not possible to give definitive emission factors for all vehicle categories.

Boulter and Latham (2009) also stated that it is possible that the incorporation of emission factors from different sources would increase the overall complexity of the UK inventory model, as each set of emission factors relates to a specific methodology. It was, therefore, necessary to check on progress made on completing the ARTEMIS and COPERT 4 methodologies and assess their complexities and input data requirements for national scale modelling.

The conclusion from this assessment of alternative methodologies was that neither ARTEMIS nor a new COPERT 4 was sufficiently well-developed for national scale modelling and that COPERT 4 referred to in the EMEP/EEA Emissions Inventory Guidebooks still utilises the approach in COPERT III (EEA, 2000). COPERT III was developed in 2000 and is quite detailed in terms of vehicle classes and uses up-to-date information, including scaling factors for more recent Euro standards reflecting the faster warm-up times of catalysts on petrol cars. COPERT III is a trip-based methodology, which uses the proportion of distance travelled on each trip with the engine cold and a ratio of cold/hot emission factor. Both of these are dependent on ambient temperature. Different cold/hot emission factor ratios are used for different vehicle types, Euro standards, technologies and pollutants.

Cold start emissions are calculated from the formula:

$$E_{cold} = \beta \cdot E_{hot} * (e^{cold}/e^{hot} - 1)$$

where:

E_{hot} = hot exhaust emissions from the vehicle type

β = fraction of kilometres driven with cold engines

e^{cold}/e^{hot} = ratio of cold to hot emissions for the particular pollutant and vehicle type.

[1] This description is extracted from NAEI report "*Methodology for the UK's Road Transport Emissions Inventory*", https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1804121004_Road_transport_emissions_methodology_report_2018_v1.1.pdf

The parameters β and e^{cold}/e^{hot} are both dependent on ambient temperature and β is also dependent on driving behaviour, in particular, the average trip length, as this determines the time available for the engine and catalyst to warm up. The equations relating e^{cold}/e^{hot} to ambient temperature for each pollutant and vehicle type were taken from COPERT III and were used with monthly average temperatures for central England based on historic trends in UK Met Office (Annual) data.

The factor β is related to ambient temperature and average trip length by the following equation taken from COPERT III:

$$\beta = 0.6474 - 0.02545 * l_{trip} - (0.00974 - 0.000385 * l_{trip}) * t_a$$

where:

l_{trip} = average trip length in km

t_a = average temperature in ^oC

The method is sensitive to the choice of average trip length in the calculation. A review of average trip lengths was made, including those from the National Travel Survey, which highlighted the variability in average trip lengths available (DfT, 2007b). A key issue seems to be what the definition of a trip is according to motorist surveys. The mid-point seems to be a value of 10 km given for the UK in the EMEP/EEA Emissions Inventory Guidebook (EMEP, 2016), so this figure was adopted.

The COPERT III method provides pollutant-specific reduction factors for β that is applied to petrol cars to take account of the effects of Euro 2 to Euro 4 technologies in reducing cold start emissions relative to Euro 1. No such reduction is observed for, or applied to, the factor β for diesel vehicles.

In the NAEI road transport model, this methodology was used to estimate annual UK cold start emissions of air pollutants NO_X, PM, CO and NMVOCs from petrol and diesel cars and LGVs. Emissions were calculated separately for each Euro standard of petrol cars. In addition to air pollutants, COPERT III also gives values for e^{cold}/e^{hot} for energy consumption, and hence carbon emission, with a single expression being used for all classes of petrol vehicles and another expression being used for all diesel passenger cars.

Cold start emissions data are not available for heavy-duty vehicles, but these are thought to be negligible (Boulter, 1996).

2.2 Alternative methodologies for estimating cold start emissions

The Excess Emissions Planning Tool (EXEMPT) model was researched and created around 2001 to predict the excess emissions in terms of actual mass of excess emission per trip. The experimental investigations controlled key parameters, including:

- Ambient temperature (within the range -7°C to 20°C);
- Engine oil starting temperature (-7°C, 0°C, 20°C, 40°C, 60°C and the engine's normal operating temperature);

The driving cycle used was the ECE (urban phase of the NEDC) repeatedly. Also engine cooling curves were generated so that the impact of different “parking times” could be quantified.

This model has been recommended in Defra technical guidance notes for LAQM support, e.g. TG09. Its principal advantage, particularly in the context of a model appropriate for the NTM, is that it is a trip based emissions calculation. However, its principal weaknesses include:

- It has become outdated as recent vehicle technologies have become available and whose cold start over-emissions have not been quantified and are therefore not correctly modelled;
- It is a distinctly different methodology to that described in the peer reviewed, and internationally accepted, EMEP/EEA Guidebook.

Therefore, although EXEMPT is, in principle, an alternative way of calculating excess emissions on a per trip basis, it is not recommended as a methodology for introduction into the NTM.

3 Quantification of cold start emissions in the UK inventory

3.1 Illustrative calculations

Evaluation of the equations described in the methodology of the previous chapter, and in the 2016 EMEP/EEA Guidebook gives the following values:

For the fraction of kilometres driven with cold engines (i.e. β)

These were calculated for an average trip length of 10 kilometres, at an ambient temperature of 10°C.

For Euro 1 petrol cars and LGVs $\beta = 0.344$

For Euro 2 petrol cars and LGVs $\beta = 0.248$[2]

For Euro 3 petrol cars and LGVs $\beta = 0.110$

For Euro 4 and later petrol cars and LGVs $\beta = 0.062$

For diesel cars and LGVs (all emissions standards) $\beta = 0.344$

From the above calculations the fraction of kilometres driven with cold engines (β) can be converted into kilometres by multiplying by 10 (because the average trip length is 10 km). Therefore, for diesel cars and vans the excess cold emissions are, from the COPERT model, emitted over the first 3.44 km of a trip.

For the ratio of cold to hot emissions for a particular pollutant and vehicle type (i.e. e^{cold}/e^{hot}) at an ambient temperature of 10°C)

For NOx emissions from petrol cars and LGVs (all emissions standards) $e^{cold}/e^{hot} = 1.75$

For NOx emissions from diesel cars and LGVs (all emissions standards) $e^{cold}/e^{hot} = 1.17$

For PM emissions from diesel cars and LGVs (all emissions standards) $e^{cold}/e^{hot} = 2.10$

For energy consumption from all petrol cars and LGVs (all emissions standards) $e^{cold}/e^{hot} = 1.38$

For energy consumption from all diesel cars and LGVs (all emissions standards) $e^{cold}/e^{hot} = 1.26$

Because the excess emissions are $e^{cold}/e^{hot} - 1$, for NOx emissions these are 75% for petrol cars and LGVs, and 17% for diesel cars and LGVs, and for energy consumption they are 38% for petrol cars and LGVs and 17% for diesel cars and LGVs

For the relative overall size of the excess cold start emissions relative to vehicles' hot emissions

[2] The EMEP EEA Guidebook gives scaling factors for β for Euro 2, 3 and 4 vehicles for NOx of 0.72, 0.32 and 0.18, respectively (see Table 3-40 of the Guidebook. These are applied to the 0.344 value of β that applies to Euro 1 vehicles. (Hence for Euro 4 and later 0.344 x 0.18 (scaling factor) gives the revised value for β of 0.062, as indicated above.

When the ratio of cold to hot emissions for a particular pollutant and vehicle type is combined with the fraction of kilometres driven with cold engines (i.e. β) then the above analysis generates the following percentages for the cold start excess fraction, relative to the hot emissions:

For NOx emissions from Euro 1 petrol cars and LGVs	25.8%
For NOx emissions from Euro 2 petrol cars and LGVs	18.6%
For NOx emissions from Euro 3 petrol cars and LGVs	8.3%
For NOx emissions from Euro 4 and later petrol cars and LGVs	4.6%
For NOx emissions from diesel cars and LGVs (all emissions standards)	5.8%
For PM emissions from diesel cars and LGVs (all emissions standards)	37.8%
For energy consumption from petrol cars and LGVs (all emissions standards)	13.1%
For energy consumption from diesel cars and LGVs (all emissions standards)	8.9%

3.2 Cold start emissions reported in the NAEI

However, it is recognised that the above is only an illustration using specific vehicle models and assumptions regarding ambient temperature. The data calculated from the NAEI road traffic model, and reported to DfT as a deliverable on this project, for 2015 are given in Table 1, together with their ratio.

Table 1 NOx and PM, hot and cold start emissions in Great Britain, from different vehicle categories reported in the NAEI for 2015

Vehicle type	Pollutant	Hot start emissions/ktonnes	Excess cold start emissions/ktonnes to be added to the hot exhaust emissions	Ratio
Petrol passenger cars	NOx	19.6	2.3	11.63%
Petrol passenger cars	PM	0.3	NE	
Diesel passenger cars	NOx	112	6.6	5.94%
Diesel passenger cars	PM	2.1	0.8	36.27%
Petrol light commercial vehicles	NOx	0.4	0.05	11.46%
Diesel light commercial vehicles	NOx	85.7	4.2	4.88%
Diesel light commercial vehicles	PM	1.6	0.3	21.62%
HGV articulated	NOx	20.6	NE	NE
HGV rigid	NOx	28.4	NE	NE
Buses and coaches	NOx	19.1	NE	NE
HGV articulated	PM	0.4	NE	NE
HGV rigid	PM	0.4	NE	NE
Buses and coaches	PM	0.2	NE	NE

These are the results from the authoritative, more detailed calculations that comprise the NAEI road traffic model. The key numbers from these that could be applied to the NTM are based on the ratio: excess cold start emissions to hot start emissions.

Note PM emission factors for petrol vehicles, and all cold start emissions for heavy duty vehicles are not estimated (NE) because there is no methodology available, and consequently no ratio is given for these. The hot start emissions are included because it provides a wider, road transport context, within which the cold start emissions can be assessed.

The NAEI does not take into consideration the impact of cold starting on energy (fuel) consumption. This is because the fuel consumption calculated by the NAEI road transport model is normalised to fuel consumption statistics in DUKES so in effect the normalisation factor accounts for the cold start excess fuel consumption. The fact that fuel consumption in the NAEI model derived from the emission curves is underestimated relative to DUKES is consistent with the cold start emissions being excluded in the calculation.

4 Possible methods for introduction cold start excess emissions into the NTM

This chapter considers how the EMEP/EEA Guidebook methodology (i.e. the methodology on which cold start emissions within the UK National Atmospheric Emissions Inventory are calculated) might be introduced into the NTM.

Only light duty vehicles, (LDVs, i.e. cars and LGVs), would have a cold start over-emissions contribution because the guidebook makes no allowance for cold start emissions from heavy goods vehicles, buses or coaches.

4.1 Magnitude of the cold start over-emissions for LDVs

The hot and cold NOx and PM emissions from different vehicle categories data calculated from the NAEI road traffic model, and reported to DfT as a deliverable on this project, for 2015 are given in Table 1.

These are total emissions, a key parameter for the NAEI, but not too helpful for the NTM which is a vehicle trip based model. The emission factors which form the basis for the calculation of emissions within the NTM are expressed in units of grams of pollutant emitted per km travelled.

Therefore, an appropriate metric is the excess cold emissions **per trip**. This has been done, using the vehicle km data within the NAEI Road Transport model, and the average trip length of 10 km, to determine the number of trips. The excess (cold) emissions given in the fourth column of Table 1 are then divided by the number of trips to give an implied emissions factor for cold starting, in g/trip. Table 2 shows trip-based cold start emission factors calculated by the NAEI for the fleet in 2016. These trip-based cold start emission factors are calculated annually by the NAEI and presented for the latest inventory year (currently 2016) on the NAEI website at http://naei.beis.gov.uk/data/ef-transport in the spreadsheet titled "Fleet Weighted Road Transport Emission Factors 2016".

Table 2 NAEI NOx and PM cold excess emissions, (in addition to hot running emissions) from different vehicle categories

Vehicle type	NOx g/trip	PM_{10} g/trip	$PM_{2.5}$ g/trip
Petrol cars	0.081	NE	NE
Diesel cars	0.366	0.034	0.034
Petrol LGVs	0.124	NE	NE
Diesel LGVs	0.654	0.037	0.037

Note PM_{10} and $PM_{2.5}$ emission factors for petrol vehicles are not estimated (NE) because there is no methodology available.

4.2 Location and sub-division of the cold start over-emissions among NTM journeys

The preceding discussion has focussed on the overall magnitude of the cold starting over-emissions for current vehicles, in the context of the magnitude of hot start emissions. It has not considered the spatial distribution of these cold start emissions.

The NTM uses the National Trip End Model (NTEM) to determine trip destinations. These destinations become the starting point for the next trip. Consequently, for a return trip, home to destination, and then the return from destination to home, has as its two trip ends the two trip starts (although not in the correct time sequence). Therefore, it is probably a reasonable approach to use **the trip ends as proxies for trip starts**.

As described earlier, the method in the guidebook indicates that the location of the cold start over-emissions is within 3.4 km of this starting point for diesel light duty vehicles.

Two possible approaches to modelling cold starts in the NTM are:

1. Using the current NAEI reported cold emissions totals, divided by the number of 10 km trips implicit within the NAEI, to **generate NOx and PM cold start emissions on a per trip basis**, as given in Table 2;

2. Using the guidebook approach to calculate the **ratio of cold start emissions relative to hot start emissions**, and use this ratio with the hot NOx and PM emissions currently calculated by the NTM.

Whether Approach 1. would give the same total as that reported in the NAEI, would depend on whether the number of trips calculated by dividing the total number of vehicle km (for LDVs) by 10 (the assumed average distance) is the same as the number of trips calculated from the NTM.

Both approaches allocate an "average cold start emissions burden" to each trip, with a similar burden being ascribed to a short 3 km trip and a long 150 km trip, rather than uplifting the emissions for each and every kilometre travelled.

Further refinements would be possible by reducing the weighting of the cold start emissions for some return trips, i.e. for NTM purposes 3 and 4 (education/'school run' trips and shopping) where it could be assumed that on average parked time is insufficiently long to allow the car to cool down fully, and so the cold start over-emissions for these return journeys, i.e. starting from the education establishment or shops, are only reduced (e.g. to 33%) of the cold start emissions from the other trips, e.g. starting from home or the commute back home after the vehicle has been parked all day.

In summary, we would recommend using Approach 1 based on nationally-averaged g/trip factors from the NAEI, such as shown in Table 2 for cars and LGVs, are used for cold start emission calculations in the NTM.

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