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# Production of Updated Emission Curves for Use in the National Transport Model

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Contact:

Tim Murrells
Ricardo-AEA Ltd
Gemini Building, Harwell, Didcot, OX11 0QR
t: 01235 753633
e: tim.p.murrells@ricardo-aea.com

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**Author:**

Rebecca Rose and Tim Murrells

**Approved By:**

Tim Murrells

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# Executive summary

The National Transport Model (NTM) is the Department for Transport's main strategic policy testing and forecasting tool used to forecast traffic levels and the subsequent congestion and emissions impacts on the national road network of Great Britain (GB).

The model currently uses a series of speed emission factors that were developed by AEA Technology in 2009 to represent the change in emission factors as a function of vehicle speed for the average composition of vehicles in the fleet in years up to 2035. These curves are used, together with forecasts of traffic levels and vehicle speeds, to predict future fuel use and road traffic emissions.

The objective of this work was to provide up-dated speed-emission factor curves for $NO_x$, $PM_{10}$ and $CO_2$ that are:

(a) Consistent with new evidence that shows real world emission factors for $NO_x$ have not developed in the way expected across the series of Euro emission standards.

(b) Consistent with the latest fleet composition and projections and methods used in the National Atmospheric Emissions Inventory (NAEI).

An updated set of emission curves have been developed for GB covering each main vehicle class reflecting the composition of the national fleet in the years 2003, 2010, 2015, 2020, 2025, 2030 and 2035. An additional set of curves have been developed for vehicles in London reflecting the impact of the London Low Emission Zone (LEZ) and measures introduced by Transport for London (TfL) that affect emission performance of the London Bus fleet. All the emission curves were developed to a common polynomial expression of the form:

$$EF[g/km] = \left(a + bv + cv^2 + dv^3 + ev^4 + fv^5 + gv^6\right)/v$$

Fuel and $CO_2$ speed emission factor curves are also used within the Department for Transport's wider modelling scheme and appraisal guidance, WEBTAG, which requires curves to be constrained to just four coefficients. An updated set of fuel and $CO_2$ speed-emission factor curves were developed for GB in 2010 in the format required for WEBTAG.

The fleet composition data and assumptions that underpin the emission curves and methods used to develop them are described in this report. The use of the emission curves within the NTM is explained and uncertainties in the developed emission curves are discussed.

Total GB emissions of $NO_x$, $PM_{10}$ and $CO_2$ in 2003 and 2010 by main vehicle type are provided from the NAEI model to effectively calibrate the base line figures from the NTM using the emission curves.

The emission curves for $PM_{10}$ and $CO_2$ show little change from those developed in 2009, but more significant changes occur for $NO_x$, particularly for diesel cars and LGVs where the average emission factors from 2010 onwards are higher than previously estimated as a consequence of using the higher COPERT 4 emission factors for these vehicle types.

The fitting of emission curves to common mathematical formulae used by the NTM and WEBTAG had the potential for introducing significant errors, especially given the complexity and variety of the equations used for individual vehicle categories in the COPERT 4 source of $NO_x$ factors. However, these were shown to be negligible across a wide range of speeds, typically less than 0.5% and at most 4% for some vehicle types at the extreme end of the speed range. However, significant uncertainties could be introduced if the NTM curves are used outside the speed range defined by the COPERT 4 source of factors for $NO_x$, especially factors for petrol and diesel cars.

The report points out the other sources that add to the air quality impacts of traffic not currently covered by the NTM, in particular the non-exhaust sources of PM from tyre and

brake wear and road abrasion. These are becoming increasingly dominant sources as tailpipe emissions are reduced. The report provides average emission factors for these sources.

Finally, a wider qualitative assessment of the uncertainties considered the limitations of the average speed parameterisations themselves as a means of quantifying the effect of changes in traffic situations on emissions, especially at a local level.

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# 1 Introduction

The National Transport Model (NTM) is the Department for Transport's main strategic policy testing and forecasting tool used to forecast traffic levels and the subsequent congestion and emissions impacts on the national road network of Great Britain (GB).

The model uses a series of speed emissions curves that were developed by AEA Technology in 2009 for pollutants $NO_x$, $PM_{10}$, $CO_2$ and fuel consumption (FC). They were derived using the original speed-emission curves for detailed classes of vehicles published in 2009 by TRL and were weighted by the composition of the fleet using the (then) latest fleet composition projections developed by AEA Technology for the National Atmospheric Emissions Inventory (NAEI). These are used together with forecasts of traffic levels and vehicle speed to predict future quantities of fuel use and road traffic emissions.

Since these speed emission curves were developed, new evidence has emerged showing that real-world emission factors for $NO_x$ have not developed in the way expected across a series of Euro emission standards, with emissions for the recent Euro standards tending to be higher than previously thought, particularly for diesel vehicles. The NAEI now uses a new set of speed-emission equations published for national emission inventory reporting by the European Environment Agency through the COPERT4 model.[1]

In addition, the NAEI has updated the fleet composition projections using revised predictions of diesel car penetration rates provided by DfT in 2011 and new information arising from the analysis of Automatic Number Plate Recognition data also provided by DfT. These data show the age mix of vehicles on the road and how the petrol/diesel car mix varies on different road types. The new fleet information also makes use of new data from Transport for London (TfL) on the composition of the HGV and bus fleet in London.

The objective of this work was to provide updated speed emission curves which reflect the new evidence about $NO_x$ emissions and are consistent with the updated NAEI fleet projections. A series of updated curves were developed as polynomial functions relating emission factors for the air pollutants $NO_x$ and $PM_{10}$ in grammes per kilometre to average speed for each main vehicle class (petrol cars, diesel cars, petrol LGVs, diesel LGVs, rigid HGVs, articulated HGVs, buses and coaches) that are representative of the GB fleet in the years 2003, 2010, 2015, 2020, 2025, 2030 and 2035. Similar curves were also required for $CO_2$ based on speed-related equations for fuel consumption (in grammes fuel consumed per km) using the direct relationship between ultimate $CO_2$ emissions and fuel consumption. This relationship is according to the carbon content of petrol and diesel fuels and works on the premise that all carbon present in the fuel will ultimately produce $CO_2$ in the atmosphere even if a small proportion is initially emitted in other forms (e.g. carbon monoxide (CO) and volatile organic compounds (VOCs)).

The work also requires updates to the speed-emission factor curves for $CO_2$ and fuel consumption in the format required for use in WEBTAG for the year 2010. In addition the fleet composition data by area or road type used in the generation of the speed emissions factor curves for the future years were required. Historical emission figures for $NO_x$, $PM_{10}$ and $CO_2$ for each main vehicle and fuel type in GB in the years 2003 and 2010, consistent with the NAEI published in 2012 (the 2010 NAEI) were also required for calibrating the NTM.

The speed-emission factor curves for each main vehicle class and year, the speed emission factors for $CO_2$ and FC in 2010 in WEBTAG format, the fleet composition data and the GB

[1] COPERT is the "Computer Programme to Calculate Emissions from Road Transport". The COPERT model is available to download from http://www.emsia.com/copert

total road transport emissions for 2003 and 2010 from the NAEI have been provided to the Transport Appraisal and Strategic Modelling (TASM) Division of DfT in spreadsheet form. This report describes the derivation and use of the factors and discusses the uncertainties in the emission factors.

# 2 Updated Curves for Emissions of $PM_{10}$ and $CO_2$ for use in the NTM

The same general approach was adopted as was used in the derivation of the NTM emission curves in 2009.[2] Speed-emission factor curves for many detailed categories of vehicles are scaled according to year dependent and vehicle-specific scaling factors that take account of fuel quality and emission degradation effects. The scaled coefficients are weighted according to the composition of the national fleet by Euro standard and vehicle size. Coefficients which define the shape and magnitude of emission curves are derived for each main vehicle type and for each year by summing the contributing weighted coefficients. The differences in the emission curves between years reflect the turnover in the fleet with lower emitting vehicles gradually replacing older, higher emitting vehicles as the years progress.

The final result was a single curve represented as a fleet-weighted polynomial emission factor-speed function for each main vehicle category and year for each pollutant. The following section describes the key input data and assumption made when developing the emission curves.

## 2.1 Source of Raw Speed Emission Factor Curves

The basic speed-emission factor curves for PM and fuel consumption (from which $CO_2$ curves are derived, as described later) were taken from equations published by DfT in 2009 following the work undertaken by TRL. TRL hold a large database of emission factors measured over a range of drive cycles in vehicle emission test programmes in Europe and the UK, including the EU ARTEMIS Programme and a number of research programmes funded by DfT. The raw test data are grouped into a number of vehicle categories by TRL, plotted against average speed of the test cycle and fitted to a common polynomial expression of the form:

$$EF = k\left(a + bv + cv^2 + dv^3 + ev^4 + fv^5 + gv^6\right)/v \qquad (1)$$

where EF is the emission factor in units of g/km for $PM_{10}$ and litre/100km for fuel consumption; a, b, c, d, e, f, g and k are coefficients; and v is speed in kph. The factors are provided for a range of vehicle classes, sizes and fuel types and for each legislative Euro standard from pre-Euro 1 up to Euro 6/VI. The factors are normalised to 50,000 km accumulated mileage.

The TRL project report to DfT by Boulter *et al.* (2009)[3] details the raw test data, including their source, analysis methods and the development of the polynomial speed-emission factor curves. As vehicles meeting Euro 5/V and 6/VI standards had not entered into service in 2009, TRL made assumptions about the emission performance of these vehicles relative to Euro 4/IV on the basis of limit values given in relevant EU directives on emissions taking into account durability requirements.

[2] The approach used to develop emission curves in 2009 is described in: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4556/aeat-updated-vehicle-emission-curves.pdf
[3] http://www.dft.gov.uk/pgr/roads/environment/emissions/report3.pdf

## 2.2 Fleet Composition Data

Emission curves were calculated that reflect the speed-dependence of the average emissions or fuel consumption factor for each main vehicle category (weight or size class and Euro class) weighted by the composition of the vehicle fleet in each year. Thus, the speed emission curves described above must be weighted by a fleet composition reflecting the fraction of vehicles of different size or weight class and the proportion of vehicle kilometres travelled by each Euro standard.

The NAEI updated the fleet composition data and projections for each main vehicle category in July 2012. These have been used by the NAEI to update the UK emission projections of $NO_x$, PM and other air pollutants. The updated fleet composition projections are based on updated assumptions about vehicle survival rates, new vehicle sales, and the mix of petrol and diesel in new car sales. Collectively, these assumptions define the turnover in the vehicle fleet. In deriving the fleet composition, the following assumptions were made:

- Traffic growth assumptions according to the TfL's growth factors for London (April 2012) and DfT's Road Traffic Forecast 2011 for the rest of the UK.
- Future sales of diesel car vehicles follow advice from DfT (December 2011). These are summarised in Appendix A.
- Revised catalytic failure assumptions derived from advice provided by DfT and taking into account EU regulations Controlling Sale and Installation of Replacement Catalytic Converters and Particle Filters for Light Vehicles for Euro 3 (or above) after June 2009. For diesel cars account is taken of the fact that some new vehicles sold to Euro 3 and Euro 4 standards are fitted with particulate traps.
- Fleet turnover is based on assumed survival rates of vehicles in the fleet derived from historic licensing data and estimates of projected new vehicle sales. Projections are from a 2010 base year and take into account the current economic downturn.
- DfT's Automatic Number Plate Recognition (ANPR) data (2007-2010) provides information on the age mix of vehicles on roads across the country.
- Specific fleet data for London were updated with data provided by TfL in July 2012. Diesel LGVs, HGVs and buses are affected by the Low Emission Zone (LEZ) scheme in London which affects the current and projected fleet composition. TfL provided detailed data on the composition of the London bus fleet, including the proportions of different bus types and vehicles with retrofit Selective Catalytic Reduction (SCR) and Diesel Particulate Filter (DPF) systems and hybrid technologies.

The updated fleet data for the years 2008 to 2035 have been made available on the NAEI website (http://naei.defra.gov.uk/data/ef-transport) and the reader is referred to the spreadsheet accessed from the "New vehicle fleet composition projections (Base 2011)" link on this website for full documentation of the fleet composition figures used to generate the speed-emission factor curves. The 2003 numbers are not reported in this spreadsheet, but can be provided on request.

## 2.3 Scaling Factors for Emission Degradation and Fuel Quality Effects

Emission factors calculated from the TRL functions are normalised to an accumulated mileage of 50,000 km and a specific quality of fuel. For some categories of vehicles, TRL analysed how emission factors change with a vehicle's accumulated mileage and provided a set of scaling factors to apply to the basic factor calculated from the speed-emission curve assuming a linear relationship with mileage. In most cases, emissions deteriorate with increasing mileage. The change in accumulated mileage can be associated with vehicle age, and this enabled TRL to develop year-dependent scaling factors to take into account emission degradation with mileage and the change in mileage with age.

Fuel quality has been improving as a result of more stringent fuel quality directives since the TRL measurements were made, for example the sulphur content has gone down over the years, and this can affect emission factors of different pollutants. TRL provide scaling factors to take into account the impact of changes in fuel quality on emissions and using the uptake rates of improved fuels in the UK, it was possible to convert these into year-dependent scaling factors that take into account the effects of changing fuel quality and using the uptake rates of improved fuels in the UK.

The fuel quality factors for $NO_x$ and PM also take into account the small proportion of biofuels blended into fossil fuel petrol and diesel. Biofuels are mostly used in the UK as weak blends of up to around 5-10%. When blended at these strengths, the different chemical formulations of biofuels have a small effect on exhaust emissions of air pollutants.[4] Note that in the NAEI, following international inventory reporting guidelines, emissions of carbon from the biofuel component of the fuel are excluded from the national inventory. This reflects the fact that the emitted carbon comes from the fuel itself so the carbon emissions can be directly attributed to the fossil fuel and biofuel proportions of the fuel. Air pollutants such as $NO_x$ and PM are a by-product of the combustion process and cannot be identified with any particular component of the fuel. It is important to include the total emissions of these pollutants from combustion, regardless of the fossil and biofuel proportions of the fuel.

## 2.4 $CO_2$ Emission Curves

$CO_2$ emission curves are presented as 'ultimate' $CO_2$ emission curves, where ultimate $CO_2$ defines the situation when all of the carbon content of the fuel is converted to carbon dioxide emissions. Vehicle exhaust gas emissions are likely to contain a lower $CO_2$ content than implied by the ultimate $CO_2$ emission factors. However emissions of carbon in other forms such as CO from incomplete combustion or trace emissions of hydrocarbons are ultimately oxidised in the atmosphere to form $CO_2$, therefore it is valid to present $CO_2$ emissions in terms of ultimate values. Ultimate $CO_2$ curves are derived directly from fuel consumption curves by converting the units from litre/100km to g fuel/km and applying a simple conversion factor based on the carbon content of petrol and diesel fuel. The fuel carbon contents used in the UK's Greenhouse Gas Inventory are provided by personal communication with the UK Petroleum Industry Association and remain constant in all years at 85.5% for petrol and 86.3% for diesel (UKPIA, 2004). These figures refer to the percentage carbon content by mass, thus 100 g diesel comprises 86.3 g carbon.

The mass density of diesel is 1.203 litre per kg fuel in 2003 and 1.191 litre per kg fuel in 2010 according to figures published by DECC in the Digest of UK Energy Statistics (DUKES 2003 and 2010). For years past 2010 the mass density for 2010 is assumed. The mass density of petrol is 1.361 litre per kg fuel for petrol and this value is assumed for all years. From these values, it follows that the factors for converting fuel consumption in litres/100km to $CO_2$ emissions in $gCO_2$/km are:

Petrol: 23.03

Diesel: 26.30 (2003) and 26.57 (2010+)

## 2.5 Normalisation of Fuel Consumption Factors for HGVs and Buses

Additional information is available about fuel efficiency of HGVs and Buses which allows an additional normalisation step to be taken. DfTs Continuous Survey of Road Goods Transport

[4] T Murrells and Y Li, 2008, "Road Transport Emissions from Biofuel Consumption in the UK". Report to Defra. AEA Report AEAT/ENV/R/2662. July 2008. http://uk-air.defra.gov.uk/reports/cat15/0901151441_NAEI_Road_Transport_Biofuels_report_2008_v1.pdf

(CSRGT) provides fleet-averaged fuel efficiencies for different weight classes of HGVs.[5] The advantage of these data over the TRL speed functions as a source of fuel consumption factors for HGVs in the UK is that they are based on a larger sample of HGV operations obtained through surveys of haulage, whereas the fuel consumption factors derived from the TRL database are based on measurements from tests on just a few individual vehicles in controlled situations.

For buses additional information is available from the Bus Service Operators Grant system (BSOG) which provides grants to local bus services and community transport organisations to help them recover some of their fuel costs base in annual fuel consumption. From BSOG financial figures DfT were able to calculate the costs and hence total quantity of fuel used for local bus services. Using additional bus km data DfT were able to derive implied fuel consumption factors for local bus services and, like CSRGT data for HGVs, these have the advantage of sampling a larger sample of vehicle operations. However, BSOG data does not include rural bus routes or coaches.

In accordance with the methodology adopted for the NAEI, use was made of both sources of fuel consumption data for HGVs and buses: the CSRGT and BSOG data which give single, average fuel consumption factors covering a large and representative sample of UK operations, but no indication of how this varies with speed; and the TRL speed curves which are based on much smaller, less representative sample of UK operations, but give a wide indication of how fuel consumption varies with speed.

Initially speed-emission factor curves were derived for rigid HGVs, artic HGVs and buses using the TRL curves in the same way as described for other pollutant and vehicle types. Normalisation factors were developed to scale the emission factor curves to match the average fuel consumption factors provided by CSRGT and BSOG. First the curves were used to calculate the average fuel consumption factors at typical HGV and bus speeds on urban, rural and motorway. An overall average fuel consumption factor was then calculated for each vehicle type by weighting the road-type factors according to the proportion of vehicle kilometres (vkm) on urban, rural and motorway roads using data from DfT. The average fuel consumption factors derived from the two different methodologies (in units of g fuel per km) and resulting normalisation factors are presented in Table 1. Normalisation factors are calculated as the ratio of 'real world' CSRGT or BSOG fuel consumption to the average fuel consumption derived from the research based emission curves.

**Table 1: Average fuel consumption factors derived from speed-emission factor curves and CSRGT (HGVs) and BSOG (buses) data and resulting normalisation factors derived from the ratio of CSRGT or BSOG average fuel consumption to average fuel consumption derived from the emission curves.**

| Vehicle type | Year | Emission curve (g fuel/km) | CSRGT or BSOG (g fuel/km) | Normalisation factor |
|---|---|---|---|---|
| Rigid HGV | 2003 | 184.11 | 231.91 | 1.260 |
| | 2010 | 194.62 | 246.48 | 1.266 |
| Artic HGV | 2003 | 303.07 | 303.27 | 1.001 |
| | 2010 | 296.50 | 305.65 | 1.031 |
| Bus | 2003 | 283.60 | 303.94 | 1.072 |
| | 2010 | 279.06 | 337.99 | 1.211 |

[5] https://www.gov.uk/government/publications/road-freight-statistics-2010

The NAEI has found that the normalisation factor fluctuates year-on-year, as a reflection of the different usage patterns of HGVs and buses in the UK fleet, captured by the CSRGT and BSOG data in a manner that cannot be captured in the research-based factors. The increase in normalisation factor for buses reflects the BSOG figures given by DfT that have shown a deterioration in bus fuel efficiencies in recent years (increased fuel used per km), believed to be due to changes in configuration of new buses with the introduction of new safety and accessibility standards. These bus configuration features which may be unique to the UK cannot be represented in the research-based fuel consumption factors from TRL derived from a very small sample of buses tested. These factors are meant to represent changes in fuel efficiency of bus engines when used in the same configuration. They show an opposite trend implying a gradual improvement in fuel efficiency of bus engines. These opposite trends in fuel efficiencies implied by BSOG and research-based factors explain the increase in normalisation factors shown in Table 1 for buses.

For all years after 2010, the normalisation factor calculated for 2010 is assumed in the development of the curves.

## 2.6 Generation of Emission factor curves

Emission factors for all the detailed vehicle categories were provided in the same functional form, as 6-order polynomial equation. Thus, it was straightforward to develop a single curve in the same form representing the average emission factor for all vehicles in the main vehicle category in a given year by weighting all the common coefficients according to the composition of the vehicle fleet in that year.

The generation of emission curves for the main vehicle types is described in detail in the report which details the development of the 2009 emission curves.[6] In summary, the emission curves developed take the 6-order polynomial form. The seven coefficients A-G for the main vehicle types in each year are weightings of the individual coefficients for the different constituent Euro standards and vehicle or engine sizes which make up the fleet according to the fractions in the fleet in the year. In addition, the individual coefficients of the detailed vehicle categories are scaled to account for degradation and fuel quality effects for each Euro standard vehicle. This is expressed mathematically in equation 2 which shows how the coefficient A is calculated for a particular size of a vehicle type in year y.

$$A_y = R_{y0}D_{y0}S_{y0}k_0a_0 + R_{y1}D_{y1}S_{y1}k_1a_1 + R_{y2}D_{y2}S_{y2}k_2a_2 + R_{y3}D_{y3}S_{y3}k_3a_3 + R_{y4}D_{y4}S_{y4}k_4a_4 + R_{y5}D_{y5}S_{y5}k_5a_5 + R_{y6}D_{y6}S_{y6}k_6a_6 \quad (2)$$

$R_{ye}$ is the fraction of vkm by vehicles of Euro standard e in year y.

$D_{ye}$ is the scaling factor for degradation effects for Euro standard e in year y.

$S_{ye}$ is the scaling factor for fuel quality effects for Euro standard e in year y.

$k_e$ and $a_e$ are the speed emission factor coefficients for Euro standard e from the TRL emission factor equations.

Similar expressions can be derived for the other coefficients B-G by replacing the coefficient $a_e$ with the appropriate coefficient.

Coefficients $A_y$ are developed for each size or weight of vehicle that makes up the main vehicle category. A further weighting is required to derive a single expression for the vehicle type according to the engine size or weight mix of the vehicles in the fleet. Examples of the resulting coefficients derived for $PM_{10}$ emissions curves for petrol and diesel vehicles are presented in Table 2.

[6] The approach used to develop emission curves in 2009 is described in: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4556/aeat-updated-vehicle-emission-curves.pdf

Coefficients were calculated in this way for all main vehicle types and years for $PM_{10}$ and fuel consumption. $CO_2$ speed-emission factor curves are derived from fuel consumption curves, as described in Section 2.4. Additional normalisation of fuel consumption curves for HGVs and buses is carried out to bring the fuel consumption curves in line with fuel efficiency rates published by CSRGT and BSOG, respectively. This normalisation step is described in Section 2.5.

**Table 2: Speed-emission factor coefficients for $PM_{10}$ emissions from the fleet of petrol and diesel cars in years 2003-2035. These coefficients are to be used in an equation of the form $EF = (a + bv + cv^2 + dv^3 + ev^4 + fv^5 + gv^6)/v$ where v is the average speed in kph. Coefficients for other vehicle types and for $CO_2$ were provided in spreadsheet tables to DfT.**

| Region | Pollutant | Year | Vehicle type | Fuel type | Unit | Function | | Coefficients | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Type | Formula (y=EF in g/km; x=speed in km/h) | a | b | c | d | e | f | g |
| GB | PM | 2003 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.03280452 | 0.00099963 | 2.3222E-06 | 3.5111E-07 | -2.584E-09 | 2.0886E-11 | 0 |
| | | 2010 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.02577583 | 0.00074815 | 2.5727E-06 | 2.3599E-07 | -1.65E-09 | 1.3814E-11 | 0 |
| | | 2015 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.01839185 | 0.00052899 | 1.9337E-06 | 1.6319E-07 | -1.128E-09 | 9.518E-12 | 0 |
| | | 2020 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.01185628 | 0.00034047 | 1.2576E-06 | 1.0462E-07 | -7.216E-10 | 6.0976E-12 | 0 |
| | | 2025 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.01185506 | 0.00034041 | 1.2578E-06 | 1.0459E-07 | -7.213E-10 | 6.0958E-12 | 0 |
| | | 2030 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.01185532 | 0.00034042 | 1.2578E-06 | 1.0459E-07 | -7.214E-10 | 6.0962E-12 | 0 |
| | | 2035 | Car | Petrol | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.01185508 | 0.00034041 | 1.2578E-06 | 1.0459E-07 | -7.213E-10 | 6.0958E-12 | 0 |
| | | | | | | | | | | | | | | |
| GB | PM | 2003 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.69742325 | 0.01420626 | 0.00014702 | -6.705E-07 | 3.705E-08 | -3.338E-10 | 1.653E-12 |
| | | 2010 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.2670616 | 0.00863055 | 0.00016565 | -2.814E-06 | 4.9386E-08 | -3.619E-10 | 1.1479E-12 |
| | | 2015 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.10092273 | 0.0037671 | 7.859E-05 | -1.488E-06 | 2.4627E-08 | -1.785E-10 | 5.3704E-13 |
| | | 2020 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.02918783 | 0.0013909 | 2.8984E-05 | -6.175E-07 | 9.9971E-09 | -7.31E-11 | 2.1786E-13 |
| | | 2025 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.00580262 | 0.00063457 | 6.4831E-06 | -1.446E-07 | 2.3284E-09 | -1.71E-11 | 5.0932E-14 |
| | | 2030 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.00282026 | 0.00053984 | 3.2415E-06 | -7.299E-08 | 1.1746E-09 | -8.635E-12 | 2.5719E-14 |
| | | 2035 | Car | Diesel | g/km | Polynomial | y=(a+bx+cx2+dx3+ex4+fx5+gx6)/x | 0.00273713 | 0.00053722 | 3.1459E-06 | -7.084E-08 | 1.14E-09 | -8.38E-12 | 2.4961E-14 |

# 3 Updated Curves for $CO_2$ Emissions and Fuel Consumption for Use in WEBTAG

Additional updated emission curves were provided for fuel consumption and $CO_2$ in a form which is compatible with the specific format required for use in WEBTAG for the year 2010. WEBTAG requires curves in a 3-order polynomial emission factor equation:

$$EF = \left(a + bv + cv^2 + dv^3\right)/v \quad (3)$$

Where a-d are coefficients, v is speed and EF is the speed dependent emission factor in units of g/km. Emission curves are provided for petrol cars, diesel cars, petrol LGVs, diesel LGVs, HGVs in OGV1 and OGV2 categories and PSVs.

Emission factors were generated using the curves produced in the development of the $CO_2$ emission factors for the NTM in Section 2. The following sections describe the process of deriving the WEBTAG compatible curves from the curves developed for the NTM. First the methodology for deriving 3-order polynomial equation from the 6-order polynomial equation by curve fitting is discussed and then the methodology for each vehicle type is presented.

## 3.1 Curve fitting methodology

The speed-emission factor curves developed for the NTM are 6-order polynomial functions, whereas the WEBTAG format requires emission curves as 3-order polynomial functions. A procedure to convert to the lower order polynomial format was developed and the principles are summarised here:

- Calculate the emission factors at 5 kph intervals between the maximum and minimum speed over which the speed-emission factor curve is valid using the 6-order polynomial functions developed for the NTM for each vehicle type in 2010.
- Fit the resulting speed-emission factor curve to the 3-order polynomial function in equation (3), optimising the values of the coefficients a-d to provide the best fit.

The resulting optimised coefficients a-d describe the shape and magnitude of the speed-emission factor curve in WEBTAG format.

Fitting routines within two software packages were tested. First the nonlinear least squares regression function provided in the Solver package in Excel. The second method was a nonlinear least squares fitting function available in the R statistical software package, a free software programming language and environment for statistical programming and graphics.[7] Later sections provide further discussion of the capabilities of these fitting routines.

## 3.2 Petrol and diesel cars

The speed-emission factor curves for petrol and diesel cars provided by TRL are 3-order functions. Therefore the coefficients a-d are the same as those developed for NTM, as described in Section 2.

[7] http://www.r-project.org

## 3.3 Petrol and diesel LGVs

The coefficients of the 3-order polynomial were derived from the 6-order emission factor equations generated in Section 2 by refitting the fleet-weighted factors derived for 2010 at 5 kph intervals from 5-120 kph. Two software packages were tested for fitting: (1) the nonlinear regression function provided in the Solver package in Excel and (2) a nonlinear least squares fitting function available in the R statistical package. It was found that both fit methods arrived at the same solution for the 3-order coefficients for petrol and diesel cars.

## 3.4 HGVs

The categorisation of HGVs differs from the rigid and articulated HGV categories required for the development of emission curves for the NTM. The OGV1 category refers to rigid HGVs < 26 GVW and OGV2 refers to rigid and articulated HGVs > 26 GVW. Firstly, 6-order coefficients for the two categories were calculated from the TRL equations for each of the individual vehicle weights and Euro standard. The raw TRL coefficients were weighted by the fleet composition and normalised to be consistent with CSRGT data. The fleet composition of OGV1 and OGV2 HGVs is derived from the fleet compositions for rigid and artic HGVs and the relative distribution of rigid and artic HGVs on roads, and the resulting distribution is presented in Table 3.

The derived 6-order coefficients of OGV1 and OGV2 vehicles were then used to calculate fuel consumption (FC) at 5kph intervals between 5 and 90 kph for each HGV category. The resulting sets of speed dependent FC factors were then refitted to the 3-order polynomial equation, Eq. (2), using fitting routines available in Excel and R statistical package as described above. In both cases the coefficients that were derived from the two different fitting routines were the same.

**Table 3: Composition of rigid and artic HGV vehicles of different weights within the OGV1 and OGV2 classes of HGV vehicles.**

| OGV1 | Population | | OGV2 | Population |
|---|---|---|---|---|
| Rigid HGV 3.5-7.5 t | 48.2% | | Rigid HGV 26-28 t | 7.1% |
| Rigid HGV 7.5-12 t | 8.8% | | Rigid HGV 28-32 t | 14.2% |
| Rigid HGV 12-14 t | 3.5% | | Rigid HGV >32 t | 3.5% |
| Rigid HGV 14-20 t | 16.7% | | Artic HGV 28-34 t | 1.8% |
| Rigid HGV 20-26 t | 22.9% | | Artic HGV 34-40 t | 27.8% |
| | | | Artic HGV 40-50 t | 45.6% |

## 3.5 PSVs

PSVs are a combination of buses and coaches weighted by the split between two vehicle types on GB roads. The speed-emission factor curves for buses and coaches are 3-order functions and therefore are already compatible with the WEBTAG format. Thus, the 3-order coefficients for PSVs can be derived directly from the speed-emission factor curves for buses and coaches developed for the NTM in Section 2 by weighting the coefficients by the split between buses and coaches.

## 3.6 Errors associated with limiting WEBTAG fuel consumption curves to a four coefficient equation

For LGVs and HGVs the errors associated with limiting the WEBTAG curves to a four coefficient equation can be assessed by comparing the speed dependent emission factors calculated with 3-order WEBTAG equations with the emission factors calculated using the 6-order equations developed in the previous section. Table 4 presents an analysis of the percentage difference errors between emission factors calculated with the WEBTAG 3-order equations and 6-order equations developed for the NTM for 5 kph intervals in speed within the valid speed range. Percentage error is defined as:

$$\%\ \text{error} = (EF_3 - EF_6)/EF_6 \qquad (4)$$

where $EF_3$ and $EF_6$ are the emission factors calculated using the 3-order and 6-order speed-emission factor equations. Percentage errors for each vehicle type are plotted in Figure 1 which demonstrates that absolute values of percentage errors are small and are not more than 3.2%. The oscillating shape taken by the speed dependent percentage errors is a consequence of the reduction in the order of the polynomial curve from 6-order to 3-order in the fitting process. The oscillations are a feature of the fit and have no physical meaning, the magnitude of the percentage errors however provide guidance on the quality of the fit.

Table 4 also presents the average of the absolute values of percentage errors for each vehicle type. The percentage error in the WEBTAG emission factors calculated for petrol LGVs are on average 0.32% with a maximum error 0.75% at the maximum speed of 120 kph and for diesel LGVs the average error is higher at 0.91% with a maximum error of 1.8% at 120 kph. For HGVs, the average error is 0.73% for OGV1 vehicles with a maximum error of 1.8% at 90 kph and the average error is 1.55% for OGV2 vehicles with a maximum error of 3.2% at 10 kph.

**Figure 1: Plot of percentage errors between emission factors calculated using 3-order WEBTAG polynomial equations and 6-order polynomial equations calculated for the NTM.**

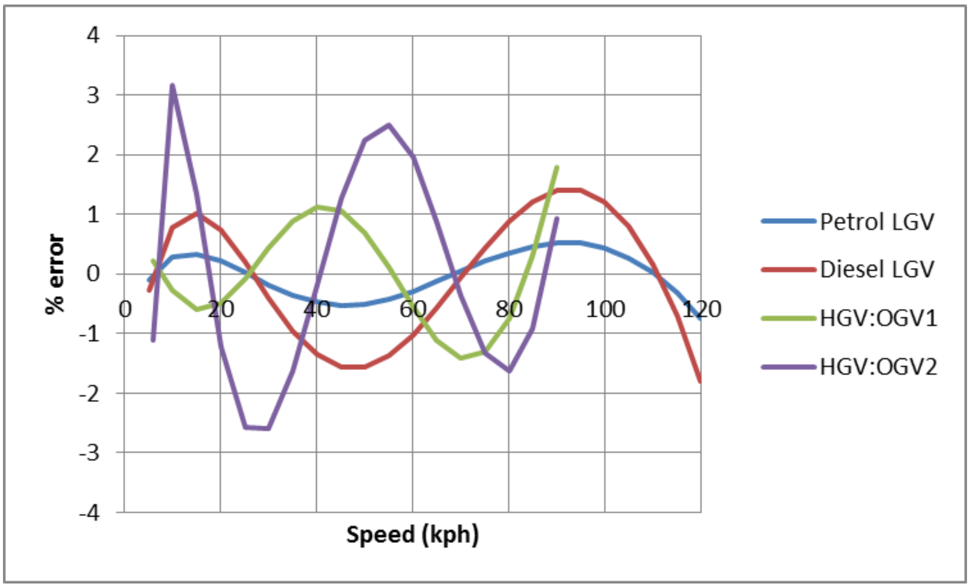


**Table 4: Percentage errors between emission factors calculated using the 3-order WEBTAG equations and the 6-order equations developed for the NTM. Positive errors imply that the emission factor calculated using the 3-order WEBTAG equation is greater than the emission factor calculated using the 6-order equation and negative errors imply the emission factor calculated using the 3-order WEBTAG equation is smaller. Average values of the absolute percentage errors are presented at bottom the table.**

| Speed | % error | | Speed | % error | |
|---|---|---|---|---|---|
| (kph) | Petrol LGV | Diesel LGV | (kph) | HGV: OGV1 | HGV: OGV2 |
| 5 | -0.09 | -0.28 | 6 | 0.21 | -1.10 |
| 10 | 0.28 | 0.79 | 10 | -0.28 | 3.16 |
| 15 | 0.33 | 1.03 | 15 | -0.59 | 1.34 |
| 20 | 0.22 | 0.75 | 20 | -0.48 | -1.22 |
| 25 | 0.02 | 0.21 | 25 | -0.08 | -2.57 |
| 30 | -0.19 | -0.40 | 30 | 0.44 | -2.59 |
| 35 | -0.36 | -0.95 | 35 | 0.89 | -1.64 |
| 40 | -0.48 | -1.35 | 40 | 1.12 | -0.18 |
| 45 | -0.52 | -1.56 | 45 | 1.05 | 1.27 |
| 50 | -0.50 | -1.56 | 50 | 0.69 | 2.25 |
| 55 | -0.42 | -1.37 | 55 | 0.10 | 2.49 |
| 60 | -0.29 | -1.02 | 60 | -0.55 | 1.97 |
| 65 | -0.13 | -0.57 | 65 | -1.11 | 0.89 |
| 70 | 0.05 | -0.07 | 70 | -1.41 | -0.35 |
| 75 | 0.21 | 0.43 | 75 | -1.31 | -1.32 |
| 80 | 0.36 | 0.89 | 80 | -0.74 | -1.62 |
| 85 | 0.47 | 1.21 | 85 | 0.31 | -0.93 |
| 90 | 0.52 | 1.40 | 90 | 1.80 | 0.93 |
| 95 | 0.51 | 1.41 | **Average** | **0.73** | **1.55** |
| 100 | 0.43 | 1.22 | | | |
| 105 | 0.27 | 0.80 | | | |
| 110 | 0.02 | 0.16 | | | |
| 115 | -0.32 | -0.71 | | | |
| 120 | -0.75 | -1.80 | | | |
| **Average** | **0.32** | **0.91** | | | |

# 4 Updated curves for emissions of $NO_x$ for use in NTM

## 4.1 Source of Raw Speed Emission Factor Curves

Since 2009 when the previous emission curves for use in the NTM were produced, new evidence has emerged showing that real-word emission factors for $NO_x$ have not developed in the way expected across the series of Euro emission standards. Emissions for the recent Euro standards tend to be higher than previously thought, particularly for diesel vehicles. A new set of speed-emission equations were developed by the European Joint Research Centre and the European Environment Agency through the COPERT 4 model which is designed for compiling national emission inventories. The factors are taken from version 9 of COPERT 4 published November 2011.[8] The factors used are available from http://naei.defra.gov.uk/data/ef-transport. Note that a further update to the $NO_x$ factors in COPERT 4 occurred as the work for this project was underway. These could not be incorporated into the NTM curves at the time, but a re-calculation of the curves for diesel cars and LGVs using the latest factors has been carried out since initial completion of the project and the changes to the curves are described in Appendix C.

The emission factor curves from COPERT 4 are provided in several different, often complex, mathematical formats depending on the vehicle type, fuel type, vehicle size and emission standard. It is therefore not valid to weight the coefficients in these different equations for each vehicle class according to the fleet mix as described in Section 2 for the development of $PM_{10}$ and $CO_2$ emission curves. To overcome this, an alternative approach was developed and may be summarised as follows:

1. Emission factors were calculated for each Euro standard of each vehicle size and class in intervals of 5 kph between the maximum and minimum speed in the range over which the COPERT function is valid.
2. Individual emission factors were adjusted to account of emission degradation rate and changes in fuel properties using scaling factors used in the NAEI and derived from accumulated mileage adjustment factors provided by TRL
3. Individual emission factors for each speed and vehicle type were weighted according to the Euro standard fleet composition to produce the final $NO_x$ emission factors for petrol cars, diesel cars, petrol LGVs, diesel LGVs, rigid HGVs, articulated HGVs, buses and coaches.
4. Speed dependent $NO_x$ emission factors were refit to a common mathematical function which was selected to be the 6-order polynomial of the form in Eq. (1), with the coefficient k set equal to 1.

The final result was a set of seven coefficients a-g which define the shape of the emission curve.

[8] COPERT is the "Computer Programme to Calculate Emissions from Road Transport". The COPERT model is available to download from http://www.emisia.com/copert.

## 4.2 Fitting methodology

Fits were carried out using R statistical software a free software programming language and environment for statistical programming and graphics.[9] Fits were carried out using a built in non-linear least squares regression function provided in the R statistical software package. The fitting routine works by minimising the square of the differences between input data (speed-emission factors at 5 kph intervals calculated using the COPERT equations) and speed dependent emission factors calculated from the 6-order polynomial equation. The coefficients a-g which describe the shape and magnitude of the 6-order polynomial equation are initialised with values 10, 1, 0.1, 0.001, 0.0001, 0.0001 and 0.0001, respectively, and with each iteration in the optimisation procedure these values are updated to provide a better solution until convergence criteria are met.

The Excel fitting routine provided within the Solver function was also tested, but the large number of fit coefficients meant that the method was unable to converge, or converged to a local minimum which was a poor fit, unless the initial values of the coefficients were set to be close to the optimal values of the coefficients. Obtaining a set of initial values close to the optimised solution for each individual curve would be a time consuming process therefore the R-fitting method was selected in preference.

## 4.3 Extending the speed range of the emission curves

To maximise the usage of the speed-emission curves it is desirable to extend the speed range to the low speeds used in the NTM. The lowest speed at which the COPERT equations are valid is between 10 and 12 kph, depending on vehicle type, and outside of this range the equations may break down. However, the TRL equations are valid to lower speeds of 5 or 6 kph, depending on vehicle type a range required by the NTM.  It was proposed that the relative trends implied by the TRL equations at low speeds could be used to extend the range of the speed emission factors generated from the COPERT equations.

To test this proposal, coefficients for the 6-order speed-emission curves were calculated using the TRL emission factor equations scaled and adjusted using the same fleet composition data and emission degradation and fuel quality scaling factors that were used in the calculation of the speed emission factor curves from the COPERT emission factor equations described in the preceding section. As an example, Figure 2 presents the 6-order speed-emission factor curves for petrol vehicles derived (a) from fits to the weighted COPERT functions and (b) from TRL emission factor equations plotted between their respective valid speed ranges. Inspection of the curves developed using the two different sets of emission factor equations shows that the emission factors developed for equivalent years are similar in magnitude, but there are differences between the shapes of the curves. The TRL curves tend to have a steeper negative gradient at low speeds and a minimum in emission factor at a lower speed than the COPERT curves.

To extend the COPERT speed-emission factors to lower speeds the TRL emission factors between 5 and 10 kph were used as a scaling factor to extend the COPERT speed-emission factor curves to 5 kph according to Eq. 5:

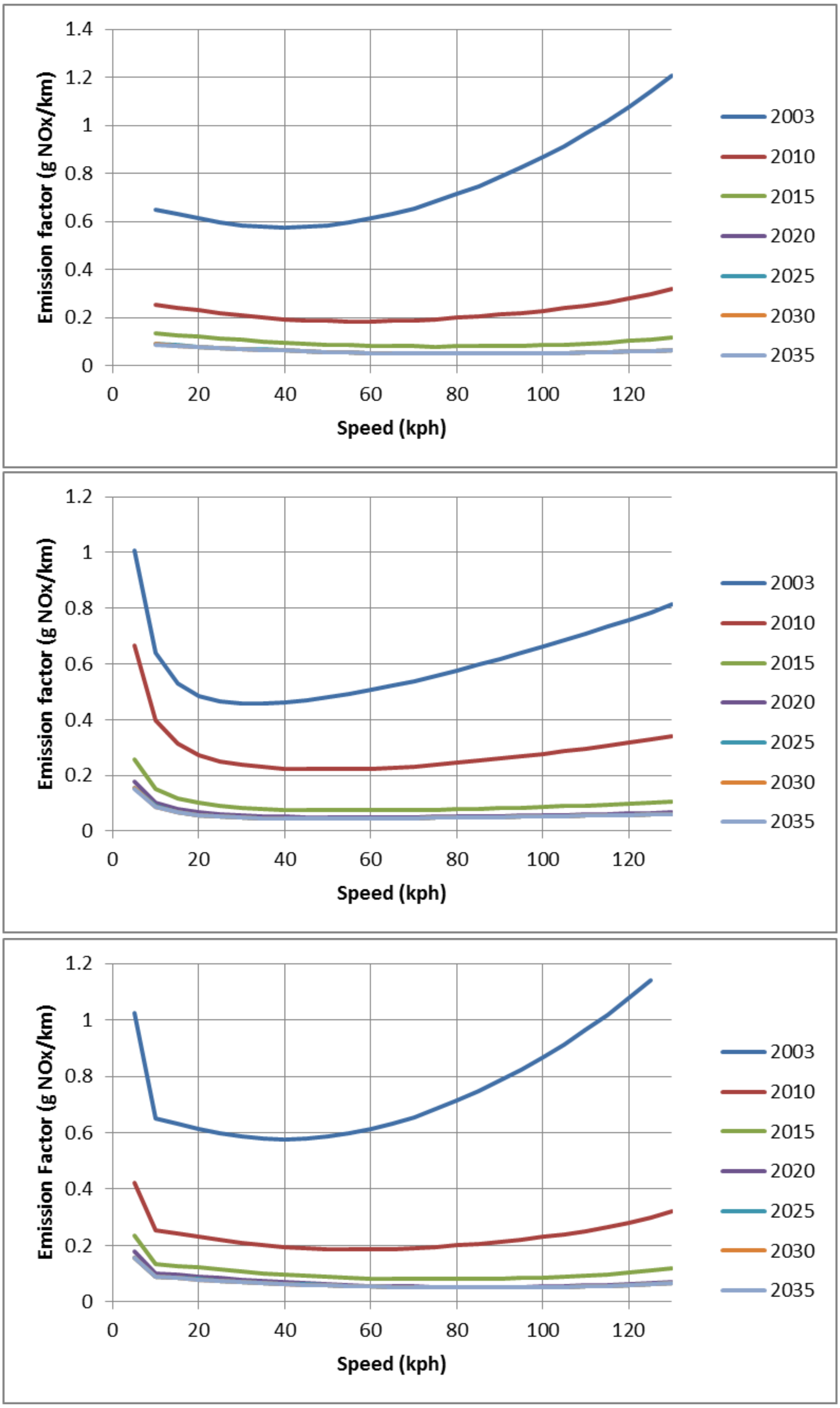
$$\mathrm{EF_{COPERT}}(5\mathrm{kph}) = \frac{\mathrm{EF_{TRL}}(5\mathrm{kph})}{\mathrm{EF_{TRL}}(10\mathrm{kph})} \times \mathrm{EF_{COPERT}}(10\mathrm{kph}) \qquad (5)$$

The resulting speed emission factor curves are presented in Figure 2(c). The emission factor shows a sharp increase from 10 to 5 kph which is not in fitting with the trends implied by the COPERT derived speed-emission factors. As a result of the differences between the COPERT and TRL speed-emission factor curves at low speeds the method of extending the COPERT speed emission factor curves using the trends implied by the TRL curves was

[9] Information about R Programming and a link to download the software is available at: http://www.r-project.org/

judged not to be reliable. We have therefore not extended the range of the COPERT curves using the TRL-based relationships at low speed, but have opted to retain them for the speed range they were designed for and tested their robustness when used at speeds outside this range. A discussion of the uncertainties in using the curves outside their intended speed range is discussed in Section 4.4.

A similar analysis was carried out for LGVs, HGVs, buses and coaches. The resulting 6-order speed-emission factor curves derived from COPERT and TRL equations are presented for buses in Figure 3. The minimum speed at which the COPERT functions for buses are valid is 12 kph, whereas for the TRL equations the minimum speed is 6 kph. The COPERT functions are therefore extended by calculating scaling factors implied by the TRL emission factors between 6 and 10 kph and 10 and 15 kph. The TRL speed emission factors appear to be consistent with the trends implied by the COPERT emission factor curves meaning the COPERT-derived curves could be extended using the TRL trends. Similar plots for LGVs, HGVs or coaches (not shown) also demonstrate that the TRL emission factor curves are consistent with trends implied by the COPERT emission factor curves at low speeds. However, to be consistent with the approach used for cars, the TRL curves were not used to extend the range of the COPERT-derived curves and again the uncertainties in using the emission curves outside their range is discussed in the next section.

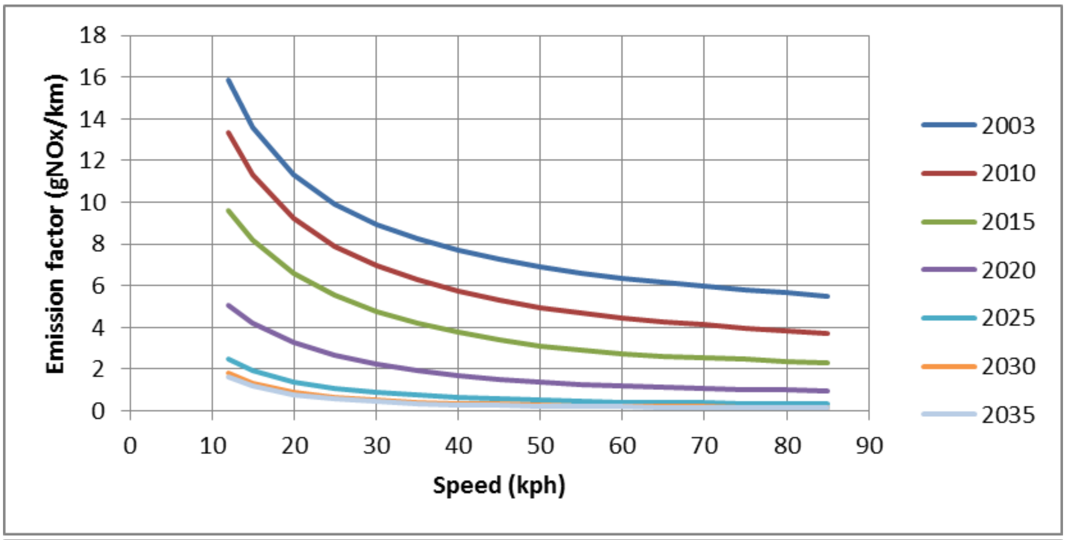



(a)

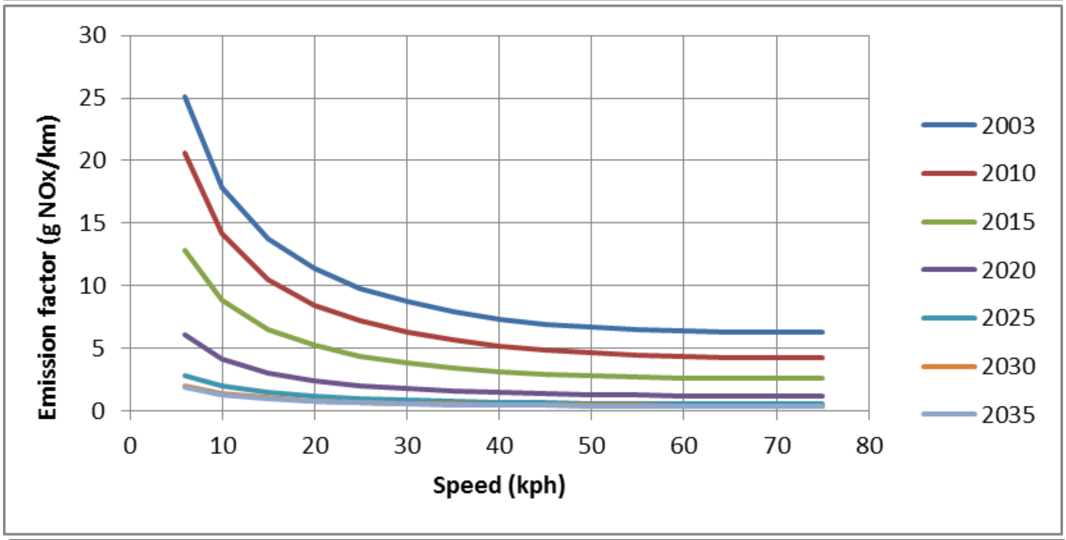
(b)

(c)

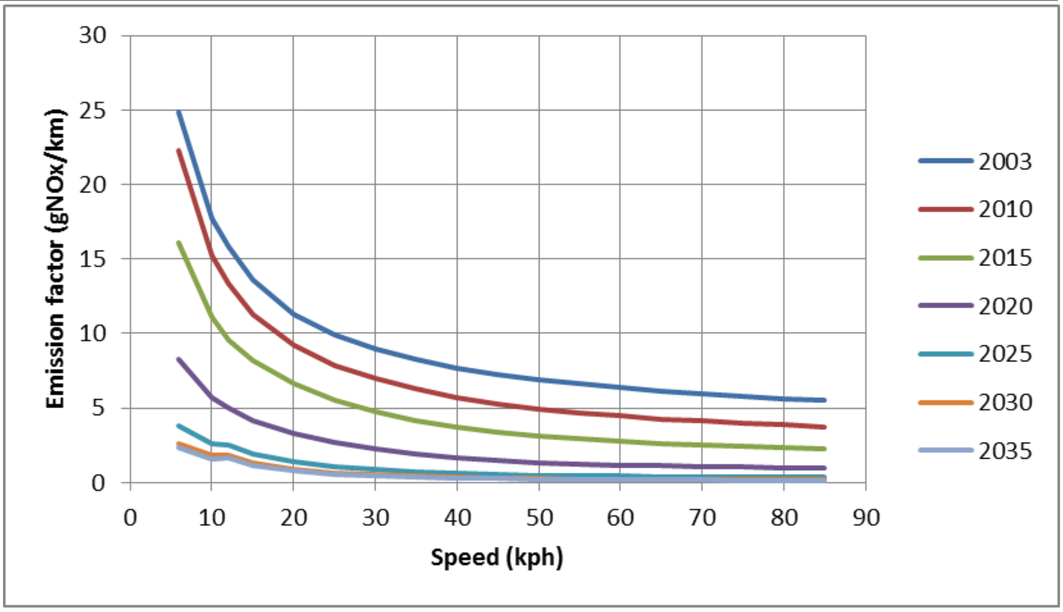
**Figure 2: Speed-emission factor curves for $NO_x$ emissions from petrol cars derived using (a) COPERT speed emission factor equations, (b) TRL emission factor equations and (c) COPERT emission functions extended using the trends implied by TRL emission curves.**




(a)




(b)




(c)

**Figure 3: Speed-emission factor curves for $NO_x$ emissions from buses derived using (a) COPERT speed emission factor equations, (b) TRL emission factor equations and (c) COPERT emission functions extended using the trends implied by TRL emission curves.**

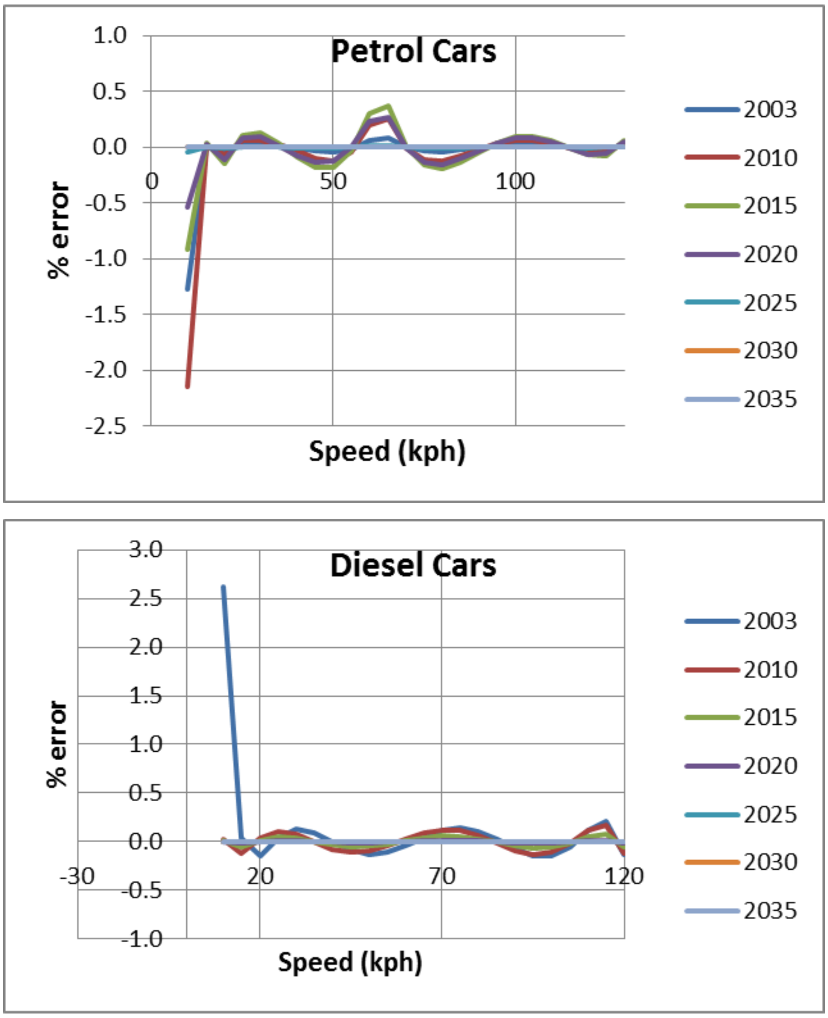
## 4.4 Discussion of Uncertainties in $NO_x$ Emission Factors

This section provides a discussion of the applicability of the $NO_x$ speed-emission factor curves outside of their speed range and an assessment of the errors associated with refitting the speed-emission factor curves generated from the COPERT equations with the 6-order polynomial equations.

### 4.4.1 Emission curve re-fitting

Assessment of the errors associated with refitting the speed emission curves generated from the COPERT equations with the 6-order polynomial equations is performed by calculating the percentage error between the emission factors calculated directly from the COPERT equations and the emission factors calculated from the 6-order polynomial fits developed by this method and provided to DfT. Detailed results showing the percentage difference between the factors calculated from the COPERT equations and 6-order polynomial equations at different speeds are shown in the tables in Appendix B for each vehicle type. They are also shown graphically for petrol cars and diesel cars in Figure 4. A positive value implies that the factor from the fit is greater than the factor calculated directly from the weighted COPERT equations.

**Figure 4: Plots of the speed dependence of the percentage errors in the 6-order fits to the weighted COPERT equations for petrol (top) and diesel (bottom) cars.**




The percentage errors are typically less than 0.5% for all vehicle types when used within the COPERT speed range, indicating that the 6-order polynomial equations capture the shape of the speed-emission factor curves very well and are a valid representation of the true speed emission factor curves. In many cases, the error is significantly less than 0.5%.

The largest errors are at the lowest end of the speed range and even here, at around 10 kph, the errors were no higher than 4% for all vehicle types and years. There is no tendency for errors to become larger at the top end of the speed range.

The percentage error at each speed is a measure of the fit quality when fitting the 6-order polynomial equation (1) to curves derived from the weighted COPERT equations. As such, the errors presented depend on the functional form of contributing COPERT equations which are variable in their complexity. Figure 4 demonstrates that percentage errors in the fits for cars tend to decline in later years. This is because the COPERT functions reduce to 3-order polynomial functions for Euro 1 and higher Euro standard vehicles much better than those for pre-Euro 1 vehicles. The COPERT equation for pre-Euro vehicles involves a complex log function.

For other vehicle types, the COPERT speed-emission factor equations are often more complex, yet the magnitude of the errors continues to reflect how well the weighted COPERT equations may be reproduced by the 6-order polynomial fit equation. This depends on the nature of the nature of the contributing COPERT speed–emission factor equations which vary with vehicle type, size and Euro standard and therefore the magnitude of the error shows a dependence on year.

### 4.4.2 Errors in extending emission curves outside their speed range

To assess the applicability of the $NO_x$ speed-emission factor curves outside of their speed range two methods of extending the emission factor equations to lower speeds were considered. First the 6-order polynomial equations generated by fitting to the COPERT speed-emission factor curves between the allowed speed range of the COPERT functions were simply extended to lower speeds. In the second method the COPERT equations were extended to lower speed using the trends implied by the TRL equations, as described in the previous section. The results are summarised in Appendix B and the key points are:

- Petrol cars
    - For years between 2003 and 2015 emission factors calculated by extension of the 6-order equations are smaller at 5 kph than 10 kph. This is in direct contradiction to trends implied by the TRL emission curves.
    - Extension of the EF equations using trends implied by the TRL equations gives an EF at 5 kph approximately 65-93% greater than the EF derived by direct extension of the EF equations.
- Diesel cars
    - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds.
    - Extension of the EF equations using trends implied by the TRL equations gives an EF at 5 kph approximately 19-68% greater than the EF derived by direct extension of the EF equations.
- Petrol LGVs
    - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds.
    - Extension of the EF equations using trends implied by the TRL equations gives an EF at 5 kph less than 2.7% different in value to the EF derived by direct extension of the EF equations. Therefore the two methods of extending the range of the emission factors are consistent.

- Diesel LGVs
  - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds.
  - Extension of the EF equations using trends implied by the TRL equations gives an EF at 5 kph less than 1.3% different in value to the EF derived by direct extension of the EF equations.
- Rigid HGVs
  - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds.
  - Extension of the EF equations using trends implied by the TRL equations gives EFs at 6 and 10 kph which are up to 41% less than the EF derived by direct extension of the EF equations. The differences are greatest for later years.
- Articulated HGVs
  - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds
  - Extension of the EF equations using trends implied by the TRL equations gives EFs at 6 and 10 kph no more than 60% smaller than the EF derived by direct extension of the EF equations. The differences are greatest for later years.
- Buses
  - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds.
  - Extension of the EF equations using trends implied by the TRL equations gives EFs at 6 and 10 kph no more than than 46% greater than the EF derived by direct extension of the EF equations. The differences are greatest for later years.
- Coaches
  - EFs calculated by direct extension of the 6-order equations appear to be a realistic extension, continuing the trends implied at higher speeds.
  - Extension of the EF equations using trends implied by the TRL equations gives EFs at 6 and 10 kph with no more than 2% difference compared to the EF derived by direct extension of the EF equations.  Therefore the two methods of extending the range of the emission factors are consistent.

In summary, $NO_x$ speed-emission factor curves should be extended outside of their speed range with caution and it is worth understanding the potential ranges in values that might result. Extension of the curves for petrol and diesel cars in particular is not recommended.

# 5 Use of Emission Curves in NTM

The spreadsheets provided to DfT have the coefficients a-g for calculating emission factors in g/km from average speed for each main vehicle type in the fleet in years from 2003 to 2035. The spreadsheets demonstrate the calculation of emission factors from a speed using the polynomial equation (1).

All the emission curves defined by the coefficients in Equation (1) have a valid speed range outside of which the curves should not be used. This is particularly the case at the low end of the speed range and the above analysis gives an indication of the potential uncertainties in the $NO_x$ emission factors derived from the equations outside the low end of the speed range. The spreadsheets provided gave the valid speed ranges for each vehicle type and pollutant and these are summarised in Table 5.

**Table 5: Valid speed range for speed-emission curves.**

| Vehicle type | Valid speed range (kph) | | |
|---|---|---|---|
| | $PM_{10}$ curves | $CO_2$ curves | $NO_x$ curves |
| Petrol cars | 5 - 120 | 5 - 140 | 10 - 130 |
| Diesel cars | 5 - 120 | 5 - 140 | 10 - 120 |
| Petrol LGV | 5 - 100 | 5 - 100 | 10 - 110 |
| Diesel LGV | 5 - 120 | 5 - 120 | 10 - 110 |
| Rigid HGVs | 6 - 90 | 6 - 90 | 12 - 86 |
| Artic HGVs | 6 - 90 | 6 - 90 | 12 - 86 |
| Buses | 5 - 75 | 6 - 75 | 11 - 86 |
| Coaches | 6 - 105 | 6 - 105 | 12 - 105 |

## 5.1 Using the curves to derive emission factors

At GB level, emission curves are provided for the following vehicle types:

- Petrol cars
- Diesel cars
- Petrol LGVs
- Diesel LGVs
- Rigid HGVs
- Artic HGVs
- Buses
- Coaches

To use these emission curves with its vehicle km data the NTM requires the petrol/diesel split for cars and LGVs and the bus/coach split for the NTM's PSV class of vehicle.

The NAEI uses current DfT licensing statistics on the petrol/diesel mix of cars and LGVs and forecasts the fuel split in future years on the basis of the turnover in the fleet and the percentage sale of new diesel car/LGV sales as described in Section 2.2. It also takes account of the fact that diesel cars tend to do more mileage than petrol cars using evidence from ANPR data and accounts for newer vehicles doing greater mileage than older ones. The ANPR data were also used to define how the diesel/petrol car share varies by road type. Table 6 summarises the proportions of vkm done by petrol and diesel cars on urban, rural and motorways roads that result from these assumptions.

**Table 6: Proportion of car km by fuel type on urban, rural and motorway roads.**

| | | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|---|---|
| Urban | Petrol cars | 0.79 | 0.65 | 0.51 | 0.44 | 0.45 | 0.47 | 0.48 |
| | Diesel cars | 0.21 | 0.35 | 0.49 | 0.56 | 0.55 | 0.53 | 0.52 |
| | | | | | | | | |
| Rural | Petrol cars | 0.78 | 0.63 | 0.48 | 0.41 | 0.42 | 0.44 | 0.45 |
| | Diesel cars | 0.22 | 0.37 | 0.52 | 0.59 | 0.58 | 0.56 | 0.55 |
| | | | | | | | | |
| Motorway | Petrol cars | 0.72 | 0.56 | 0.37 | 0.29 | 0.30 | 0.33 | 0.34 |
| | Diesel cars | 0.28 | 0.44 | 0.63 | 0.71 | 0.70 | 0.67 | 0.66 |

For LGVs the mix of diesel and petrol cars is assumed to be as indicated by the mix in LGV population, and is provided in Table 7. It is assumed that no additional mileage is done by diesel compared to petrol vehicles and that the split is the same on all road types.

**Table 7: Proportion of LGV km by fuel type. The same values should be assumed for all road types.**

| | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|---|
| Petrol LGVs | 0.12 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 |
| Diesel LGVs | 0.88 | 0.96 | 0.97 | 0.98 | 0.98 | 0.98 | 0.98 |

Separate emission factors are provided for buses and coaches, however these must be combined into a single category, 'PSV' in the NTM to represent all types of buses. The NAEI assumes a constant bus/coach split shown in Table 8 which should be applied to the NTM's PSV vehicle category. The split between buses and coaches on urban/rural roads was estimated from data showing the overall split in vkm by local bus services and other services.

**Table 8: Proportion of buses or coaches on urban, rural and motorway roads. The same split is assumed for all years but the split in GB (excluding London) and in London differ.**

| | | GB (exc. London) | London |
|---|---|---|---|
| Urban/rural | Bus | 0.72 | 0.80 |
| | Coach | 0.28 | 0.20 |
| | | | |
| Motorway | Bus | 0.00 | 0.00 |
| | Coach | 1.00 | 1.00 |

For roads in London a different set of emission curves is provided for petrol and diesel LGVs, rigid and artic HGVs, coaches and buses to take into account of the London Low Emission

Zone and the specific known features of the bus fleet managed by TfL. Emission curves for cars in London are assumed to be the same as for the GB fleet. For LGVs the fuel split is assumed to be the same as for the rest of GB and the split indicated in Table 7 should be applied to these vehicles in London. For buses and coaches the London specific bus/coach mix in Table 8 should be used to split the PSV vkm in London.

The GB average petrol/diesel vehicle split for cars and LGVs and the bus/coach vkm split presented in Tables 6 to 8, were provided to DfT in spreadsheet form. Where available, regional data for England, Scotland, Wales and Northern Ireland fleet split data were also provided to DfT. This information is also available at http://naei.defra.gov.uk/data/ef-transport .

The fuel and vehicle type mix data on different road types provided in Tables 6 to 8 are used in conjunction with the developed emission curves to derive overall emission factors for use in the NTM. The methodology required is described in detail in the previous report (Li *et al.*, 2009).[10] In summary:

- Emission factors at the required speed are calculated for each vehicle type within a vehicle category (cars, LGVs, HGVs or PSVs) using the relevant 6-order coefficients developed in Section 2 or 4.
- The emission factors are weighted by the fuel and vehicle type mix data on the required road type.

The result is an overall emission factor for a vehicle category for a particular speed and road type which is a weighted average of the constituent vehicle emission factors. The reader is referred to the 2009 report for a set of examples describing the derivation of emission factors for use in the NTM.[10]

[10] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4556/aeat-updated-vehicle-emission-curves.pdf

# 6 National Emission Totals for Calibration

DfT required figures on total emissions of NOx, $PM_{10}$ and $CO_2$ in 2003 and 2010 at GB level grouped by vehicle category from the NAEI model to effectively “calibrate” the baseline figures from the NTM using these emission curves. The vehicle categories required are petrol cars, diesel cars, petrol LGV, diesel LGV, and HGVs and PSVs grouped within a single category.

Some differences in bottom-up estimates of emissions from the NTM and NAEI can be expected for several reasons even though they are from the same source of emission factors and are based on the same input assumptions. One reason is the assumptions made about average vehicle speed in the NTM and NAEI models and the number of vkm travelled at different speeds. The NAEI uses speeds from a variety of sources, including figures reported in DfT statistics Bulletins and from the LAEI in the case of roads in London. Various sources, including outputs from the NTM model itself and also the 2007 Annual Avarage Daily Flow data from the DfTs national traffic census, are used by the NAEI to estimate the relative vehicle km travelled on different road and area types at different speeds. These speeds may not be the same as those used in the baseline NTM.

Another main reason for the differences is the NAEI figures include the contribution of cold start emissions, the excess emission that occurs when a vehicle is started with its engine below normal operating conditions. The emission curves all refer to hot exhaust emissions.

Further details on the methodology and assumptions used to develop the current UK inventory for $NO_x$, PM and $CO_2$ emissions from road transport are given in the methodology annex of the UK’s Greenhouse Gas Inventory, 1990 to 2010 (Brown *et al.*).[11]

The NAEI model was used to provide figures on $NO_x$ and $PM_{10}$ exhaust emissions by main vehicle type in 2003 and 2010 at GB level. The NAEI normally provides emissions at UK level, by including emissions from traffic in Northern Ireland, but Northern Ireland vkm was left out of the calculations to generate GB emissions. The NAEI also normally includes emissions from motorcycles, but these were left out of the calculations as this vehicle type is not covered in the NTM. The modelling methodology used is consistent with the emission factors and assumptions that underpin the emission curves and are those used for the 2010 version of the NAEI (published in 2012) and the latest road transport emission projections for Defra (Base 2011). These were the most recent versions of the inventory at the time the work was carried out.

Tables 9 and 10 show the GB emissions of $NO_x$ and PM, respectively in 2003 and 2010. These data were provided in spreadsheets to DfT and exclude emissions from motorcycles. Cold start and hot exhaust emissions for each vehicle type are listed separately for each vehicle type, as well as the total emissions which is the sum of the cold start and hot exhaust emissions. As the NTM does not include cold start emissions, the NAEI figures for hot exhaust emissions are more directly comparable, but the total emission figures give DfT the opportunity to provide a cold start ‘uplift’ to its output should it wish.

Table 11 shows the corresponding GB figures for $CO_2$ emissions expressed in million tonnes of $CO_2$. These numbers were derived from GB figures for fuel consumption using the direct relationship between FC and ultimate $CO_2$ emissions. This conversion uses the carbon factors of petrol and diesel of 855 and 863 g carbon per kg fuel and the mass ratio of carbon

[11] http://naei.defra.gov.uk/reports/reports?report_id=693

dioxide relative to carbon to provide multiplication factors of 3135 and 3164 to convert from Mtonne fuel consumption to ktonne $CO_2$ emissions for petrol and diesel vehicles, respectively.

However, there is an important note about the NAEI figures for $CO_2$. The “official” figures on UK $CO_2$ emissions from road transport are constrained to be consistent with the total fuel sales figures given in the Digest of UK Energy Statistics (DUKES). This is in accordance with rules for reporting national $CO_2$ emissions to the UN Framework Convention on Climate Change (UNFCCC). The NAEI calculates fuel consumption from a bottom-up method, based on emission curves and vehicle km data, and typically finds a gap between the total calculated fuel consumption of petrol and diesel with those figures reported in DUKES (after correcting the latter for small amounts of these fuels used for off-road transport and machinery). The bottom-up NAEI figures by vehicle type are then normalised to match the DUKES figures and $CO_2$ emissions reported from the normalised figures. The gap between DUKES and the bottom-up estimates by vehicle type fluctuates from year-to-year and reflects both the uncertainty in the fuel consumption factors, modelling methodology and activity data (e.g. the vehicle km figures) but also may reflect a real “fuel tourism” effect, whereby fuel is purchased abroad (and therefore not reported in DUKES) and consumed on UK roads, and vice versa. The year-to-year fluctuations in the gap does lead to anomalies in the trends in the official fuel consumption and $CO_2$ emissions reported for individual vehicle types.

The figures provided in Table 11 are “unconstrained”, that is they are the bottom-up estimates based on the speed-emission curves and activity data consistent with the data provided for the NTM, without any normalisation to match the fuel consumption in DUKES, so provide a better set of data for “calibrating” the outputs from the NTM.

For consistency with greenhouse gas inventory reporting to UNFCCC, the fuel sales figures taken from DUKES used in the normalisation process in the NAEI exclude the consumption of biofuels; the fuel sales figures for petrol and diesel in DUKES cover only fossil fuels. The unconstrained $CO_2$ figures in Table 11 include the emissions derived from the biofuel component and have not been corrected by removing the biofuel contribution.

**Table 9: GB emissions of $NO_x$ from road vehicles based on the NAEI model.**

| $NO_x$ ktonnes | | | 2003 | 2010 |
|---|---|---|---|---|
| | | | | |
| Car | Petrol | Hot exhaust | 213.40 | 51.39 |
| | | Cold start | 32.50 | 9.38 |
| | | Total | 245.90 | 60.77 |
| | | | | |
| | Diesel | Hot exhaust | 62.59 | 91.44 |
| | | Cold start | 3.50 | 6.00 |
| | | Total | 66.09 | 97.44 |
| | | | | |
| LGV | Petrol | Hot exhaust | 11.82 | 1.93 |
| | | Cold start | 0.79 | 0.19 |
| | | Total | 12.61 | 2.12 |
| | | | | |
| | Diesel | Hot exhaust | 58.45 | 57.92 |
| | | Cold start | 3.00 | 2.49 |
| | | Total | 61.45 | 60.41 |
| | | | | |
| HGV+PSV | Diesel | Hot exhaust | 227.54 | 146.27 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 227.54 | 146.27 |
| | | | | |
| Total | Petrol | Hot exhaust | 225.22 | 53.32 |
| | | Cold start | 33.29 | 9.57 |
| | | Total | 258.51 | 62.89 |
| | | | | |
| | Diesel | Hot exhaust | 348.57 | 295.62 |
| | | Cold start | 6.51 | 8.49 |
| | | Total | 355.08 | 304.11 |

**Table 10: GB emissions of $PM_{10}$ from road vehicles based on the NAEI model.**

| $PM_{10}$ ktonnes | | | 2003 | 2010 |
|---|---|---|---|---|
| | | | | |
| Car | Petrol | Hot exhaust | 1.05 | 0.65 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 1.05 | 0.65 |
| | | | | |
| | Diesel | Hot exhaust | 3.94 | 3.28 |
| | | Cold start | 1.43 | 1.43 |
| | | Total | 5.37 | 4.71 |
| | | | | |
| LGV | Petrol | Hot exhaust | 0.03 | 0.01 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 0.03 | 0.01 |
| | | | | |
| | Diesel | Hot exhaust | 4.03 | 2.59 |
| | | Cold start | 1.36 | 0.71 |
| | | Total | 5.39 | 3.30 |
| | | | | |
| HGV+PSV | Diesel | Hot exhaust | 5.90 | 2.36 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 5.90 | 2.36 |
| | | | | |
| Total | Petrol | Hot exhaust | 1.08 | 0.66 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 1.08 | 0.66 |
| | | | | |
| | Diesel | Hot exhaust | 13.88 | 8.24 |
| | | Cold start | 2.78 | 2.13 |
| | | Total | 16.66 | 10.37 |

**Table 11: GB emissions of $CO_2$ from the road vehicles based on the NAEI model.**

| $CO_2$ Mtonnes | | | 2003 | 2010 |
|---|---|---|---|---|
| | | | | |
| Car | Petrol | Hot exhaust | 56.12 | 42.01 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 56.12 | 42.01 |
| | | | | |
| | Diesel | Hot exhaust | 14.43 | 22.25 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 14.43 | 22.25 |
| | | | | |
| LGV | Petrol | Hot exhaust | 1.58 | 0.60 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 1.58 | 0.60 |
| | | | | |
| | Diesel | Hot exhaust | 12.09 | 14.75 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 12.09 | 14.75 |
| | | | | |
| HGV+PSV | Diesel | Hot exhaust | 25.99 | 24.69 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 25.99 | 24.69 |
| | | | | |
| Total | Petrol | Hot exhaust | 57.69 | 42.61 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 57.69 | 42.61 |
| | | | | |
| | Diesel | Hot exhaust | 52.50 | 61.68 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 52.50 | 61.68 |

# 7 Comparison with the 2009 NTM Emission Curves

The new emission curves developed in this work differ from those developed in 2009 for two main reasons:

- ***Changes in the fleet composition projections***. This has been mainly a consequence of:
  a) re-forecasts in the percentage of new diesel car sales based on figures provided by DfT, affecting the penetration of diesel cars in the fleet, and

  b) use of ANPR data provided by DfT that reveals how vehicle usage on the road differs with vehicle age and fuel type

- ***Changes in the source of raw emission factors for*** $NO_x$**.** This has involved the adoption of the speed-emission curves for detailed vehicle categories in COPERT 4v8.1

To show the impact of the changes and how the emission curves developed in 2009 differ from those developed in this work, the 2009 curves and new (2013) emission curves were used to calculate emission factors at speeds typical of urban and motorway conditions. Emission factors were calculated for each vehicle type and pollutant for 2010 and 2025 at speeds of 40 and 105 kph for cars and LGVs and 40 and 75 kph for HGVs and buses.

Figure 5 compares the factors for $NO_x$, Figure 6 for $PM_{10}$ and Figure 7 for $CO_2$.

The main impact of the changes to the curves is seen for $NO_x$ particularly for diesel cars, diesel LGVs and to a lesser extent petrol cars. These changes are mainly due to adoption of the COPERT 4 emission factors being generally higher, especially for the recent Euro standards for diesel cars and LGVs than used before. This feature is a reflection of the worse than expected real-world emission performance of the recent Euro 4 and 5 vehicles. COPERT makes relatively small changes in the emission factors for HGVs and buses compared with the TRL factors that were previously used. The decrease in the factors for artic HGVs is mainly due to changes in the fleet composition informed by ANPR data. These suggest the fleet of vehicles on the road is newer than estimated before indicating a stronger bias in the use of new vehicles compared with older vehicles than assumed before.

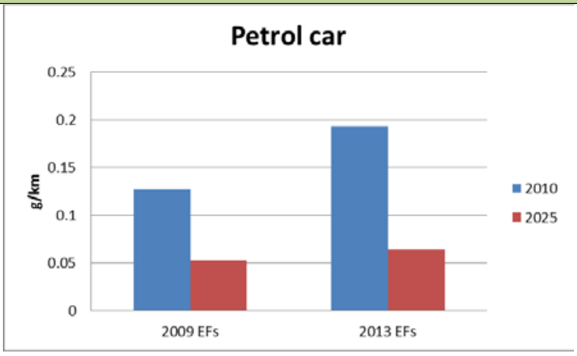
Note that the same $NO_x$ factors are used in the Defra Emission Factor Toolkit, a tool designed for estimating traffic emissions for local air quality management (LAQM). An advice note describing the impacts of the changes to the $NO_x$ emission factors is available on Defra's LAQM website at http://laqm.defra.gov.uk/documents/Advice-note-on-Emissions-Factors-Toolkit-5.pdf .

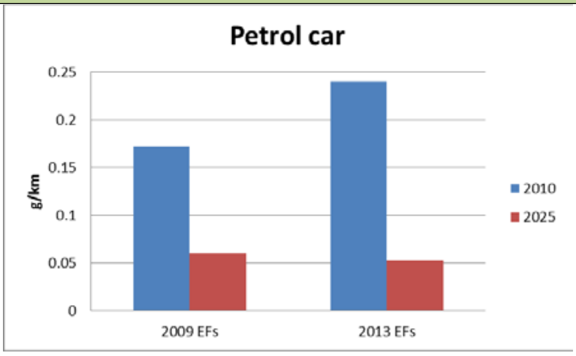
Rather smaller changes are evident in the factors for $PM_{10}$ (Figure 6). The changes here reflect the changes in fleet composition. Note that for diesel vehicles, the decrease in PM emissions from 2010 to 2025, occurring as a result of the introduction of Euro 5/V and 6/VI standards, is expected to be so significant that the bar representing the fleet-weighted factors for 2025 have been magnified by a factor of 10 so that the change in factors for the different versions of emission curves can be seen.

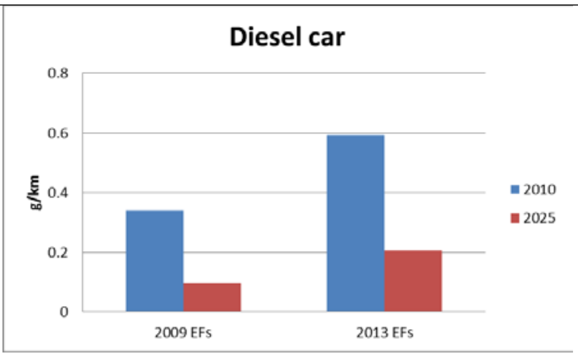
For $CO_2$, the change in factors is very small and reflects changes in fleet composition assumptions which have a much smaller effect on this pollutant.

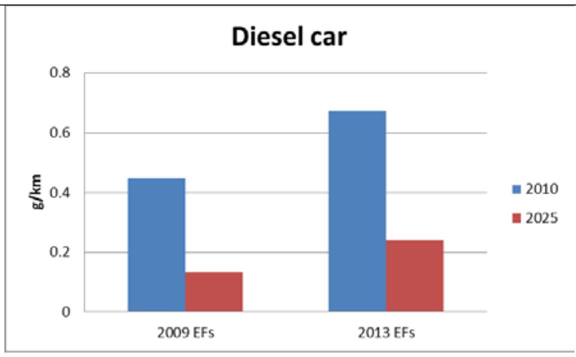
**Figure 5: Comparison of the $NO_x$ emission factors at different speeds for each vehicle category calculated for 2010 and 2025 using the previous and new speed-emission curves. 2009 EFs refer to the previous curves developed for DfT in 2009; 2013 EFs refer to the new emission curves.**

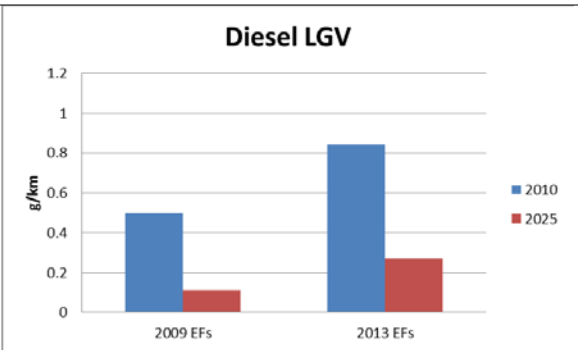
| 40 kph | 105 kph |
|---|---|

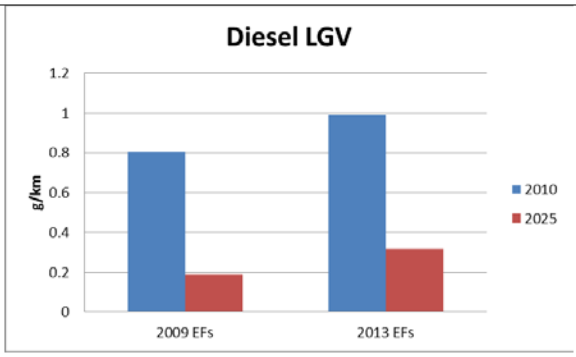


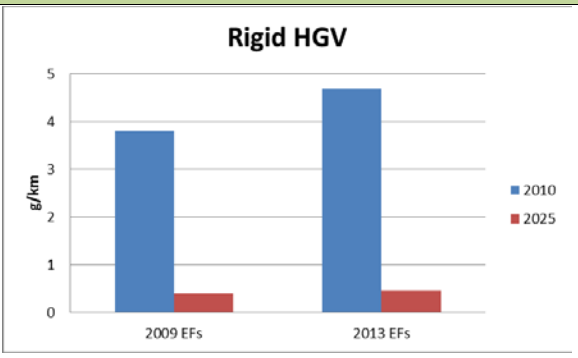



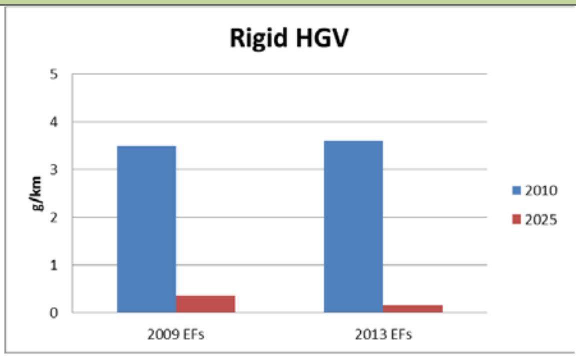




| 40 kph | 75 kph |
|---|---|



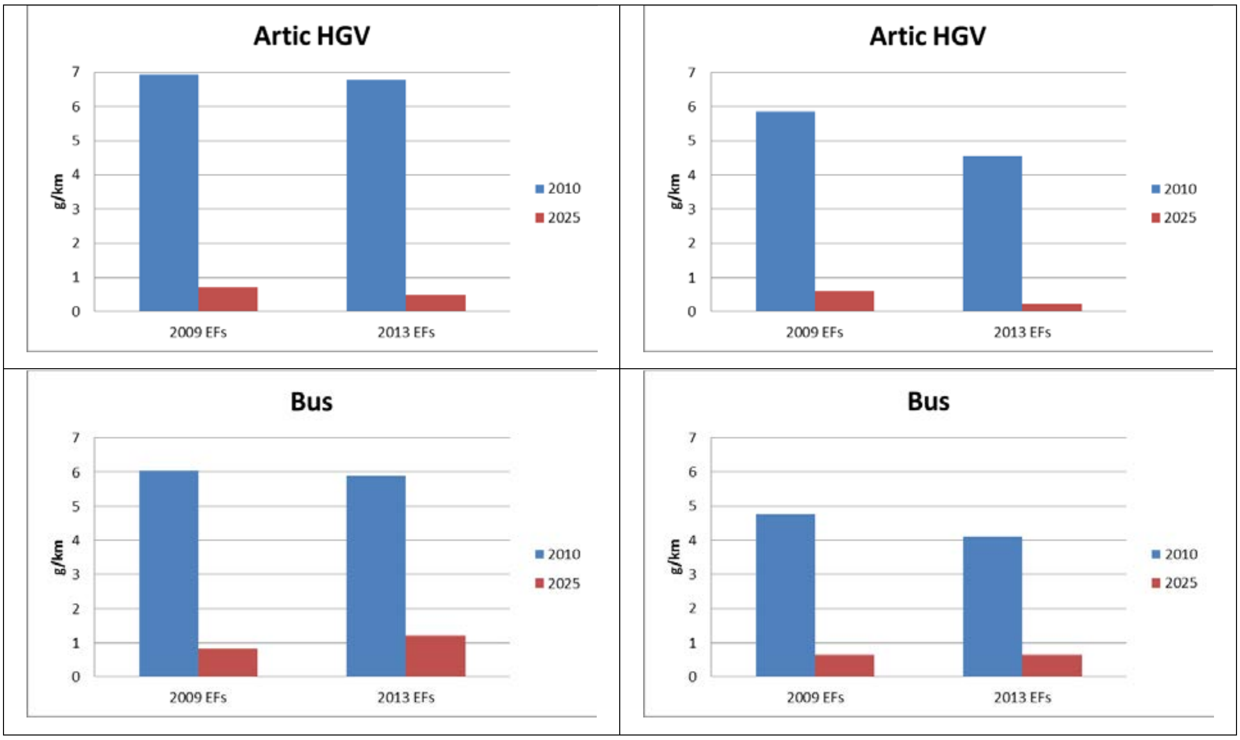
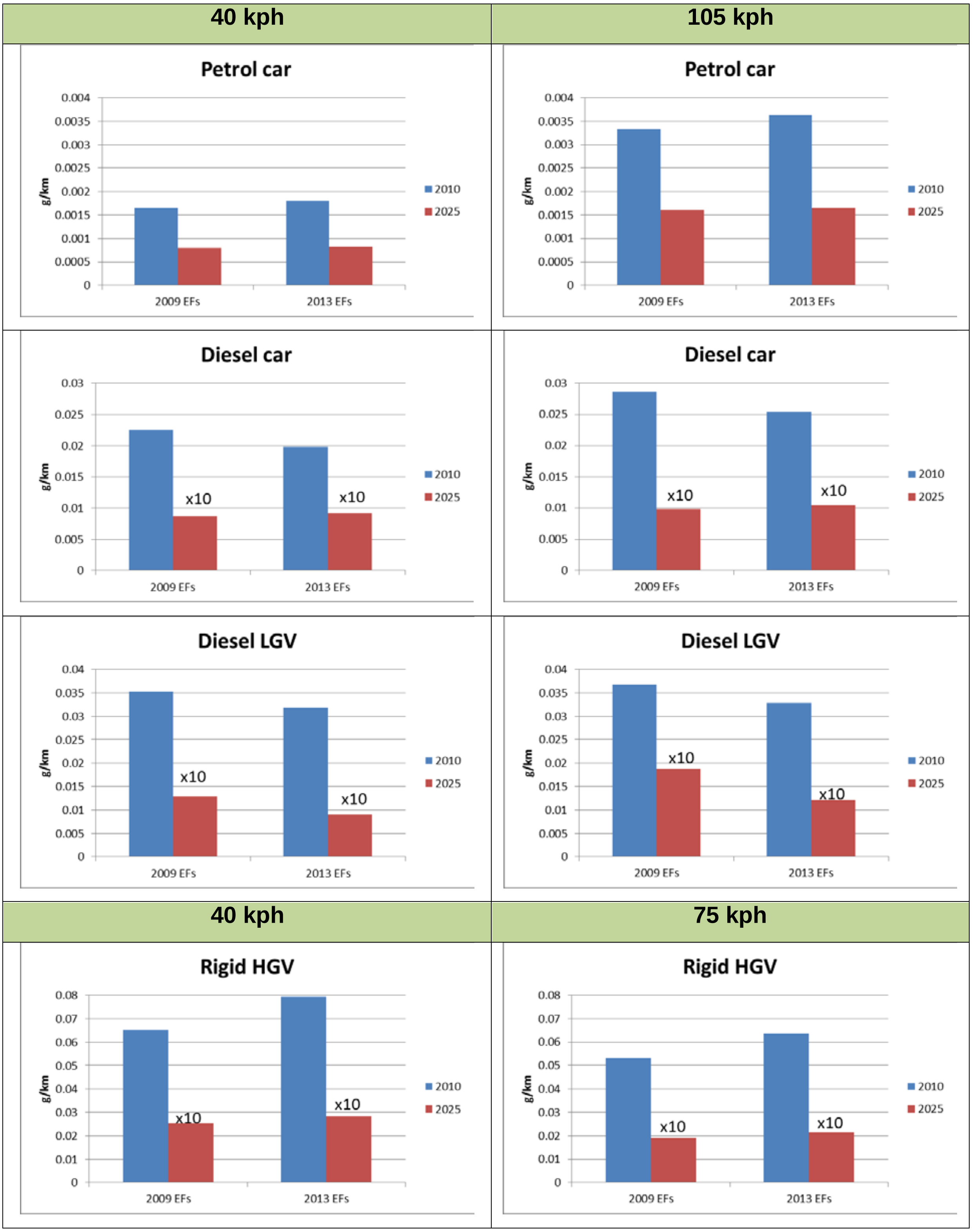

Artic HGV
g/km
0
1
2
3
4
5
6
7
2009 EFs
2013 EFs
2010
2025
Artic HGV
g/km
0
1
2
3
4
5
6
7
2009 EFs
2013 EFs
2010
2025
Bus
g/km
0
1
2
3
4
5
6
7
2009 EFs
2013 EFs
2010
2025
Bus
g/km
0
1
2
3
4
5
6
7
2009 EFs
2013 EFs
2010
2025

**Figure 6: Comparison of the $PM_{10}$ emission factors at different speeds for each vehicle category calculated for 2010 and 2025 using the previous and new speed-emission curves. 2009 EFs refer to the previous curves developed for DfT in 2009; 2013 EFs refer to the new emission curves. The factors for 2025 have been multiplied by a factor of 10 to make the comparisons visible.**



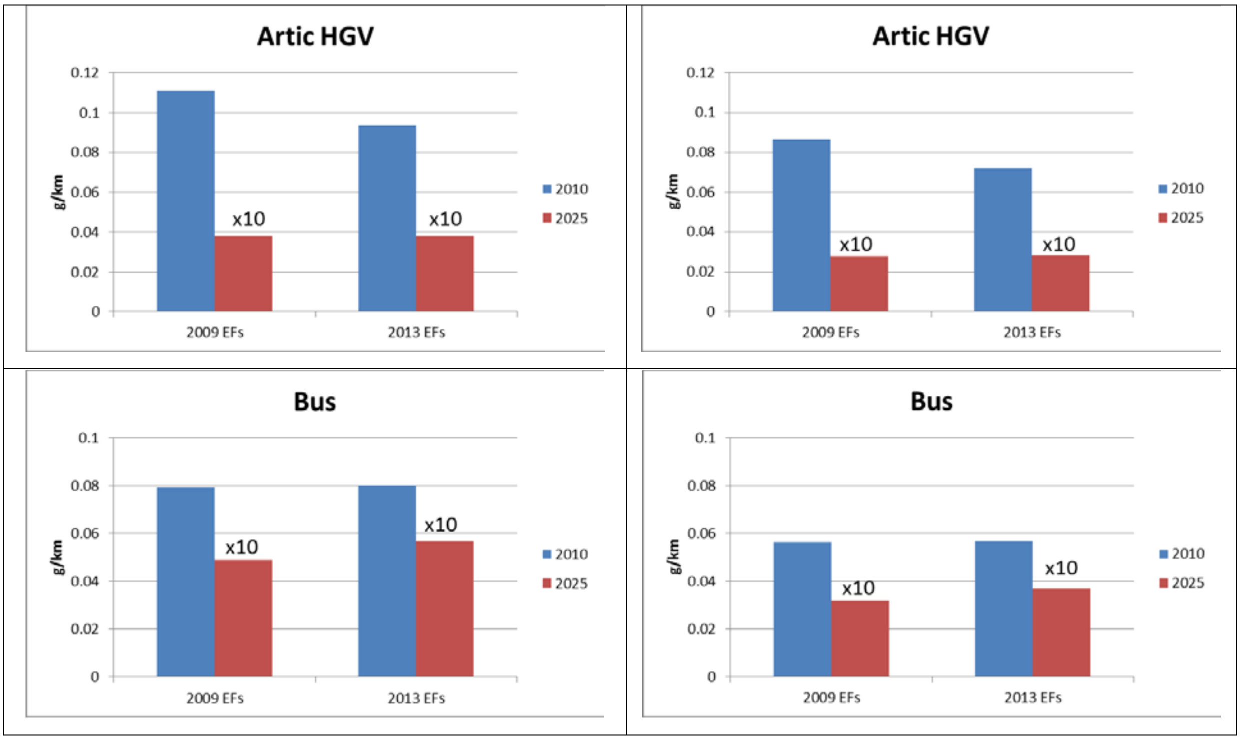
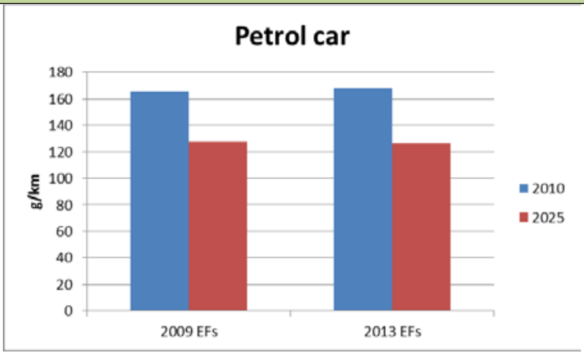
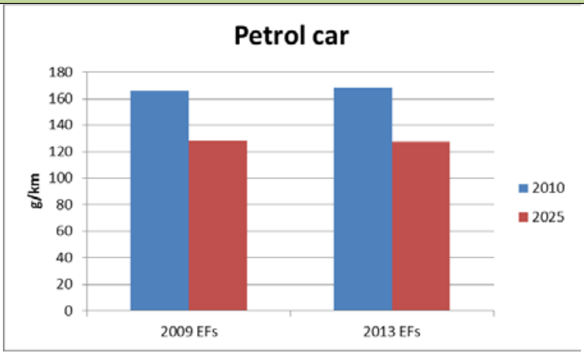
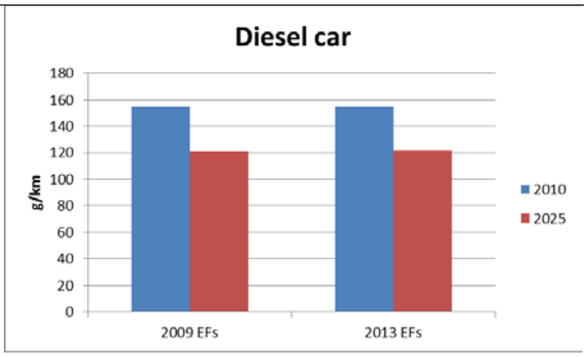

Artic HGV
g/km
0.12
0.1
0.08
0.06
0.04
0.02
0
x10
x10
2009 EFs
2013 EFs
2010
2025
Artic HGV
g/km
x10
x10
2009 EFs
2013 EFs
2010
2025
Bus
g/km
x10
x10
2009 EFs
2013 EFs
2010
2025
Bus
g/km
x10
x10
2009 EFs
2013 EFs
2010
2025

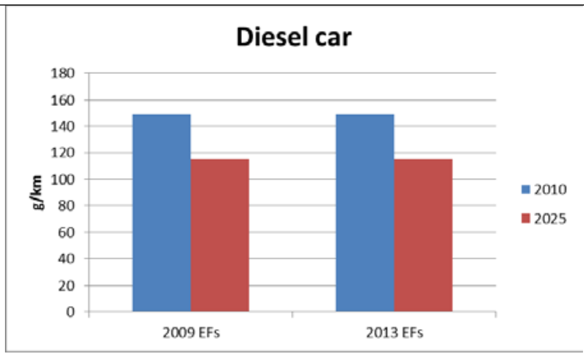
**Figure 7: Comparison of the $CO_2$ emission factors at different speeds for each vehicle category calculated for 2010 and 2025 using the previous and new speed-emission curves. 2009 EFs refer to the previous curves developed for DfT in 2009; 2013 EFs refer to the new emission curves.**

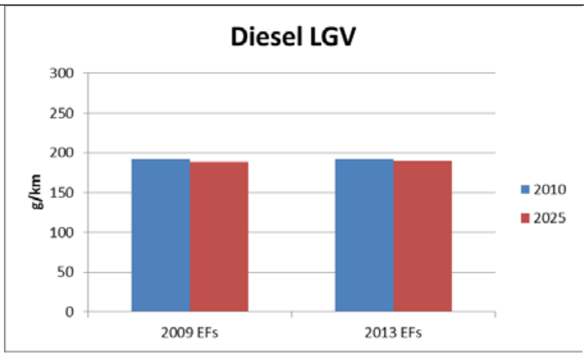
**40 kph** | **105 kph**

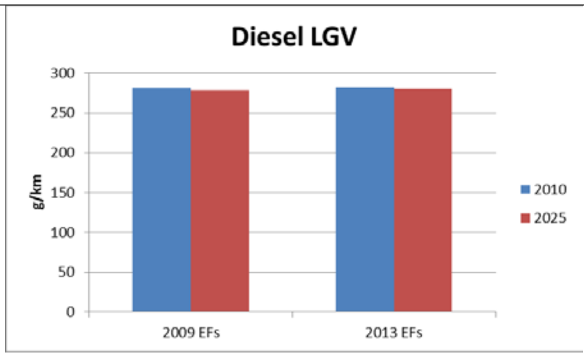


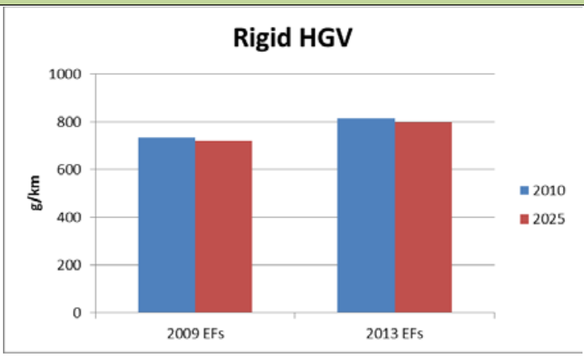



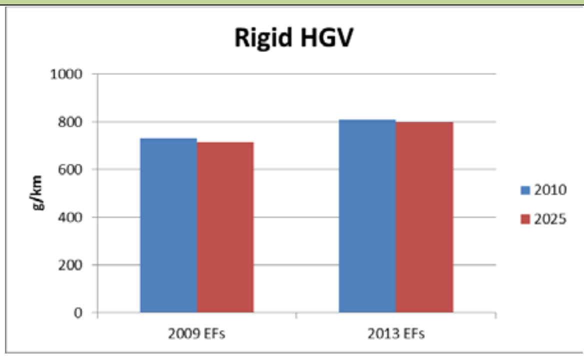



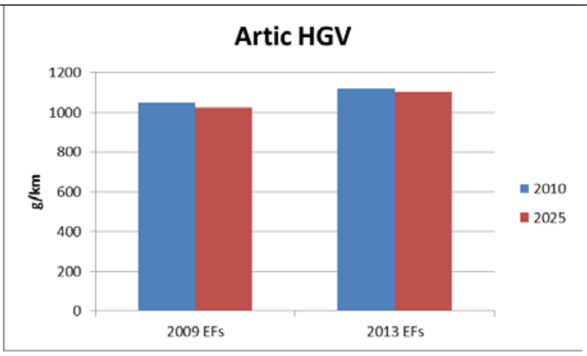



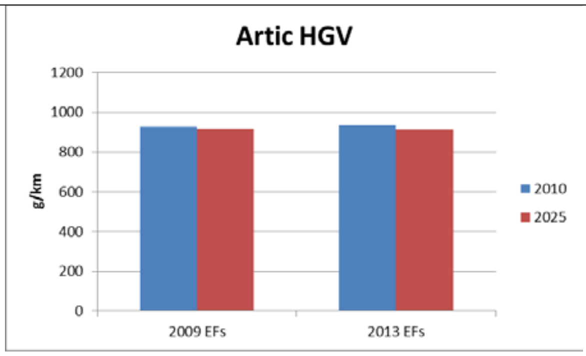



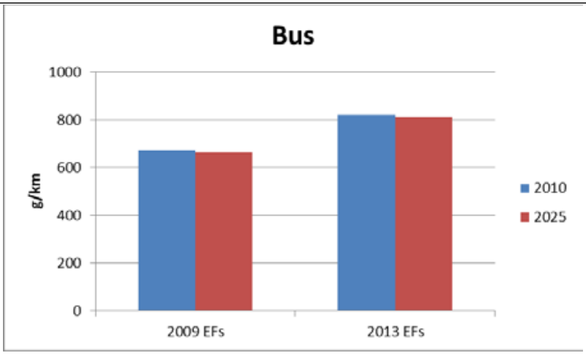

**40 kph** | **75 kph**

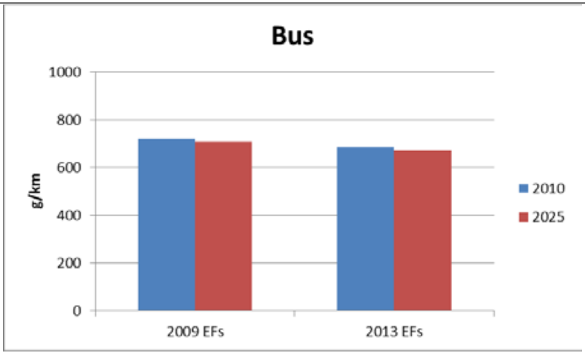



Artic HGV
g/km
0
200
400
600
800
1000
1200
2009 EFs
2013 EFs
2010
2025


Artic HGV
g/km
0
200
400
600
800
1000
1200
2009 EFs
2013 EFs
2010
2025


Bus
g/km
0
200
400
600
800
1000
2009 EFs
2013 EFs
2010
2025


Bus
g/km
0
200
400
600
800
1000
2009 EFs
2013 EFs
2010
2025

# 8 Quality Assurance

A number of quality assurance checking procedures were carried out to ensure the new emission curves and supporting information provided for the NTM are robust.

Previous chapters of this report showed the method used to check the integrity of the curve fitting procedure used to translate the $NO_x$ curves from the formats used in COPERT to the 6-order polynomial equations required of the NTM and also the conversion of the 6-order NTM curves for fuel consumption and $CO_2$ into the 3-order curves required for WEBTAG.

The errors introduced by changing the equation formats for $NO_x$ were shown to be less than 4% at all speeds and for all years and vehicle types and in the vast majority of cases were less than 0.5%.

The errors introduced by changing the equation formats for WEBTAG were less than 4% for all vehicle classes and on average was less than 1% for LGVs and 2% for OGVs.

Several additional checks were made to ensure the data were consistent with the NAEI and showed the expected trends. These were all shown in the spreadsheets provided to DfT with the emission curves. The spreadsheets showed how the curves were derived from the source data.

For the curves for $NO_x$ and PM the following checks were carried out:

- ✓ The fleet composition data used in the model was checked against data used in the NAEI road transport emissions model
- ✓ The fuel scaling factors used were checked against data used in the NAEI road transport emissions model
- ✓ The emission degradation factors used were checked against data used in the NAEI road transport emissions model
- ✓ Emission factors calculated from the curves at four different speeds corresponding to average speeds on urban, rural major, rural minor and motorway roads were compared with those derived directly from the NAEI road transport emissions model at equivalent speeds
- ✓ The factors were comparable to those calculated in the 2009 version of the NTM emission curves
- ✓ The trend in values of the factors over time shows expected decline

For the curves for $CO_2$ the following additional checks were carried out:

- ✓ The CSRGT (HGV fuel efficiency) and BSOG (bus fuel efficiency) factors for normalisation were checked against those used in the NAEI model
- ✓ The fuel density factors were checked against those in DUKES and carbon factors checked against those used in the NAEI
- ✓ Emission factors from the current curves were compared against those calculated with the curves for the NTM in 2009 at the same speed
- ✓ The trend in values of the factors over time were checked they showed the expected change over time

For the WEBTAG curves for $CO_2$, the following additional checks were made:

- ✓ An independent check was made of the coefficients for OGV1 and OGV2 that they were consistent with coefficients for rigid and articulated HGV categories
- ✓ An independent check was made that the coefficients for PSVs were consistent with the bus and coach coefficients and fleet split data used in the NAEI

# 9 Uncertainties in the Emission Curves

The quantification of traffic emissions by the NTM using these speed-emission curves will have inherent uncertainties associated with them. Whilst very difficult to quantify, an understanding of the main uncertainties in the factors themselves and their limitations will help DfT understand the main factors contributing to these uncertainties in the NTM outputs.

Previous sections of the report have focused on some aspects of these uncertainties by considering the effects of re-fitting the speed emission factor relationships to different mathematical formulae and on using them outside their intended speed range. The errors introduced by re-fitting the curves are generally very small, but using them outside the low end of their intended speed range does introduce greater uncertainty.

However, there are other additional factors which influence the overall uncertainties in the speed-emission curves used in the NTM. These are related to

- the provenance and uncertainties in the key input data
- the completeness of the factors as representative of all traffic-related emissions, and
- the limitations of the emission factor parameterisations themselves

## 9.1 Uncertainties in key input data

### 9.1.1 Raw emission factors

The emission curves developed for the NTM are only as accurate as the original (raw) emission factor-speed curves developed by TRL and (for $NO_x$) COPERT.

The provenance of these sources is good, especially those from COPERT in the sense that the factors have been peer-reviewed and are both derived from a common data source, albeit that the COPERT one is more up-to-date than the one used by TRL in 2009. The scientific development of the COPERT 4 model is overseen by the European Commission's Joint Research Centre (JRC) through the European Research Group on Mobile Emissions (ERMES) activity. ERMES aims to coordinate research (and measurement programmes) for the improvement of transport emission inventories in Europe and provides a clearinghouse for data and modelling tools. Its aim is to provide harmonised data for all EU transport emission models including COPERT. COPERT is the source of emission factors recommended in the EMEP/EEA Emissions Inventory Guidebook, aimed at providing a common source of emission factors for national emission inventories across Europe[12].

These sources analysed raw emission test data measured by various institutes around Europe, but from a fairly limited sample of vehicles and over prescribed test cycles. The sample of vehicles tested would have been quite limited for some vehicle classes, especially heavy duty vehicles and whilst the coverage of older Euro standards (e.g. Euro 1, 2) light duty vehicles was good, it was far more limited for the most recent Euro classes, especially Euro 4 and 5.

It is mainly because of this that changes to the factors for $NO_x$, in particular for diesel cars and vans, has been changing quite rapidly as new evidence is emerging on the real-world performance of the latest Euro 4 and 5 vehicles. The evidence base on Euro 5 and 6 performance is still developing and hence the need to recalculate emission curves for diesel car and LGV $NO_x$ emissions after this project had been completed, following a new release

[12] See for example http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

of factors in COPERT 4. The recalculations are described in Appendix 3. The emission factor situation for these vehicles is still quite fluid and further updates in the near future may be made in COPERT and similar databases of emission factors.

The relevance of the test cycles used for emission testing and their relevance to real-world traffic situations in the UK provide an additional area of uncertainty.

### 9.1.2 Fleet composition

The DfT has a robust source of fleet composition data for historic years via the comprehensive vehicle licensing statistics. However, representing future years is more challenging and requires a range of assumptions on fleet turnover and new vehicle sales. There are no centralised sources of data on fleet projections.

The NAEI uses its own fleet turnover model based on historic trends in vehicle survival rates and estimates of future trends in new vehicle sales. DfT contribute key information to the NAEI on the split between petrol and diesel among future car sales. Vehicle sales projections and the turnover in the future HGV fleet is particularly limited and the NAEI is totally dependent on its own assumptions. As far as is practicable, the fleet turnover assumptions made by the NAEI are shared with DfT officials for comment.

Detailed data on the future fleet projections for vehicles in London are provided directly by TfL. Although not published, this information is regularly updated and considers all the latest policies and measures to be introduced in London to improve air quality, e.g. the Mayor's Air Quality Strategy, introduction of the Low Emission Zone and various transport schemes including the renewal of the London bus fleet.

A recent improvement to the fleet composition data used in these latest speed-emission curves is the application of information from ANPR data provided by DfT from a network of around 250 sites in Great Britain. This has helped to improve the understanding of vehicle usage patterns, e.g. the greater use of diesel cars relative to petrol cars, especially on motorways, the tendency for new HGVs to be used more than older vehicles. This has provided important information on the relative mileage by age and fuel type across the national fleet which is used by the NAEI and for the latest emission curves to define the mix of Euro standards and fuel types on the road as distinct from the mix in the vehicle population.

Further details on the use of ANPR data and how they are applied to the NAEI have been reported in the UK's national inventory report[13].

Whilst the emission curves developed for the NTM make optimum use of available fleet data, predicting the future fleet is inherently uncertain. Future trends in new vehicle sales and fleet turnover will depend on future economic conditions, fuel prices and consumer behaviour in response to transport and other policies and measures brought in to influence purchasing choice, travel demand and modal shift.

## 9.2 Other traffic-related emissions not covered by the NTM emission curves

The speed-emission curves provided for the NTM represent hot exhaust emissions from vehicles. For the pollutants covered, particularly $NO_x$ and $PM_{10}$, there are other significant sources of traffic-related emissions: cold start emissions and non-exhaust emissions of $PM_{10}$.

[13] Passant, N et al, "UK Informative Inventory Report (1980 to 2011)", March 2013. http://uk-air.defra.gov.uk/reports/cat07/1303261254_UK_IIR_2013_Final.pdf

### 9.2.1 Cold start emissions

These are the excess emissions released by a vehicle during the time it takes the engine and exhaust to warm up to its normal operating temperature. This can take several minutes or kilometres travelled from the start of a trip if the engine is cold. The excess emissions occur because the engine is operating less efficiently when cold and therefore requires more fuel to move a given distance. Furthermore, and more significantly, excess emissions also occur because catalyst-based exhaust aftertreatment systems do not function until the catalyst has reached a certain temperature by the flow of hot exhaust gas. These include three-way catalysts fitted on petrol cars, diesel oxidation catalysts on diesel vehicles and selective catalytic reduction systems used for $NO_x$ control on Euro V and VI diesel vehicles.

The NAEI uses a trip-based approach to estimate cold start emissions recommended by the EMEP/EEA Emissions Inventory Guidebook. The approach calculates cold start emissions as a fraction of hot exhaust emissions and is dependent on ambient temperature and trip length, as well as pollutant type, technology and Euro standard. Cold start factors are only available for $NO_x$ emissions from petrol and diesel cars and LGVs and $PM_{10}$ emissions from diesel cars and LGVs; no factors are available for heavy duty vehicles.

The NAEI has used this approach to develop implied fleet-weighted grammes per trip emission factors that vary by year. In relation to hot exhaust emissions, they are more important for $PM_{10}$ than $NO_x$. Tables 9 and 10 illustrate this. These implied emission factors are available for the latest inventory year (2011) on the NAEI website and can be developed for other years[14].

It should be noted that the method and factors used by the NAEI to estimate cold start emissions has not been modified for some time and their importance as a fraction of hot exhaust emissions remains unchanged. However, parameterising cold start emissions in a model like the NTM is not likely to be straightforward. For use in the NTM, it would be necessary to know the origin and quantity of trip starts for cars and LGVs. As part of the emission mapping activities for Defra, the NAEI spatially resolves UK estimates of total cold start emissions on the road network using the spatial distribution of various proxy statistics such as employment and household data[15].

### 9.2.2 Non-exhaust sources of $PM_{10}$ from traffic

There are several types of non-exhaust sources of $PM_{10}$ emissions to air that arise from mechanical processes such as tyre wear, brake wear and road surface abrasion. The NAEI includes these sources of $PM_{10}$ in the UK inventory following methods and emission factors provided in the EMEP/EEA Emissions Inventory Guidebook. The factors are in grammes per km and are available for cars, LGVs and heavy duty vehicles (HGVs and buses).

Quantifying these emissions is limited by lack of available data and the emission factors are highly uncertain. Although there is a rough speed-dependence, with factors decreasing with increasing speed, lack of data has meant that a continuous speed-emission relationship has not been developed. Factors for tyre and brake wear emissions used by the NAEI for typical traffic situations on urban, rural and motorway road conditions are shown in Table 12 and are taken directly from the NAEI report[13]. Factors for road abrasion are not available for different speeds or road types, but average values for all road types are shown in Table 13.

These sources of $PM_{10}$ are not regulated and the relationship between emissions and tyre, brake and road surface material is not known. The factors therefore remain constant over time. However, with $PM_{10}$ factors from vehicle exhausts decreasing due to better engine and exhaust treatment technologies necessary to achieve compliance with more stringent exhaust emission standards, the relative contribution of these non-exhaust sources of $PM_{10}$ from traffic is becoming greater with time. The current predictions from the NAEI are that

[14] Fleet Weighted Road Transport Emission Factor 2011. Available at http://naei.defra.gov.uk/data/ef-transport

[15] The most recent published report on UK emission mapping methodology can be found at http://uk-air.defra.gov.uk/reports/cat07/1207021214_UK_Emission_Mapping_Methodology_2008.pdf

**Table 12: Emission factors for $PM_{10}$ from tyre and brake wear (in mg/km)**

| mg $PM_{10}$ /km | | Tyre | Brake |
|---|---|---|---|
| Cars | Urban | 8.74 | 11.68 |
| | Rural | 6.80 | 5.53 |
| | Motorway | 5.79 | 1.36 |
| LGVs | Urban | 13.80 | 18.22 |
| | Rural | 10.74 | 8.62 |
| | Motorway | 9.15 | 2.12 |
| Rigid HGVs | Urban | 20.74 | 51.00 |
| | Rural | 17.39 | 27.14 |
| | Motorway | 13.98 | 8.44 |
| Artic HGVs | Urban | 47.07 | 51.00 |
| | Rural | 38.24 | 27.14 |
| | Motorway | 31.49 | 8.44 |
| Buses | Urban | 21.18 | 53.60 |
| | Rural | 17.39 | 27.14 |
| | Motorway | 13.98 | 8.44 |
| Motorcycles | Urban | 3.76 | 5.84 |
| | Rural | 2.92 | 2.76 |
| | Motorway | 2.49 | 0.68 |

**Table 13: Emission factors for $PM_{10}$ from road abrasion (in mg/km)**

| mg $PM_{10}$/km | Road abrasion |
|---|---|
| Cars | 7.5 |
| LGVs | 7.5 |
| HGVs | 38 |
| Buses | 38 |
| Motorcycles | 3.0 |

non-exhaust sources of $PM_{10}$ will make up 88% of total UK emissions of $PM_{10}$ from road transport by 2020.

An additional source of $PM_{10}$ from traffic occurs from traffic-induced resuspension of road dust. This source is very difficult to quantify using conventional emission inventory approaches based on emission factors and is not required to be included in national inventories. Emissions are expected to be dependent on road surface conditions, traffic flow and weather conditions. Further details on this source of PM are given in the report of the Defra *Air Quality Expert Group* on $PM_{2.5}$.[16]

[16] "Fine Particulate Matter ($PM_{2.5}$) in the UK". Report of the Air Quality Expert Group, 2012. http://uk-air.defra.gov.uk/reports/cat11/1212141150_AQEG_Fine_Particulate_Matter_in_the_UK.pdf

### 9.2.3 Other pollutants

Traffic is a source of many other pollutants emitted to air. These include hydrocarbons, of which there are many individual components some of which are toxic such as benzene, carbon monoxide, ammonia, polyaromatic hydrocarbons (PAHs) and other air toxics, as well as other greenhouse gases such as nitrous oxide ($N_2O$) and methane ($CH_4$). However, from a human health exposure point of view, the focus of attention remains on the significant contribution that traffic makes to emissions of $NO_x$ and $PM_{10}$.

## 9.3 Limitations of the emission factor parameterisations

It is recognised that the speed-emission curves provided for the NTM are currently the only practical way of defining the variability in emission factors for the different roads and traffic situations represented by the NTM on a national scale.

The method of parameterising emissions as simple average speed related emission factor functions is a convenient way of expressing how emissions vary with traffic conditions. However, whilst acceptable for national inventory reporting, the method is quite simplistic and prone to high uncertainty for more local scale assessments and potentially as a means of expressing how emissions change in response to changes in traffic conditions.

The original emission factor-speed equations themselves are developed by fitting a measured emission factor averaged over a drive cycle that may be several tens of kilometres long to the average speed of the cycle. Factors are measured for a number of different cycles with different averaged speeds and a curve fitted to the data. Each drive cycle itself has many periods of acceleration, deceleration, cruise and idling included within it.

In reality, a vehicle's emissions is very transient in behaviour and varies second-by-second according to the load on the engine and various factors that influence it such as driving style (aggressive or mild), level of congestion and number of stop-starts, vehicle weight (the current factors assume a 50% load carried by HGVs) and road gradient. More complex, engineering-based vehicle emission simulation models are required to deal with these factors. These types of models are better suited for simulating emissions for specific traffic situations such as congested traffic, idling, and at road junctions, for example. Such models have not yet been used by the NAEI for national scale modelling.

Using the average speed-related emission curves to calculate the emission effects of incremental changes in speed is pushing them to their boundaries of acceptability. The variability in emission factor at any given average speed cannot be easily quantified but is expected to be high, especially at the low end of the speed range, and dependent of vehicle type and technology. Whilst the speed-emission curves allow the effect of a small change in speed to be estimated, the magnitude of change in emission factor shown by the calculations will not be very meaningful and should be regarded with a high degree of uncertainty. The shape of the curve gives a better sense of the directional change in emissions and how, for example, a generally slow urban emission factor compares with a less congested one, a rural and a free-flowing motorway emission factor. The evaluation of a change in speed limit of a particular road should ideally consider not just the change in average speed, but the dynamics of the traffic flow, e.g. how it changes the whole traffic situation and extent of stop-starts and free-flowing traffic.

# 10 Conclusions

A set of updated speed emission curves has been developed for the NTM for $NO_x$, $PM_{10}$ and $CO_2$ covering each of the main vehicle classes. The emission curves for $NO_x$ reflect the new vehicle, fuel and Euro standard specific speed emission factor curves from the European Environment Agency through the COPERT 4 model to account for new evidence that the real-world $NO_x$ emission factors have not developed as expected across the Euro emission standards. The emission curves for $NO_x$, $PM_{10}$ and $CO_2$ also reflect updates to the composition of the fleet in terms of the latest information on proportion of vehicle km travelled by different Euro standards in the years 2003, 2010, 2015, 2020, 2025, 2030 and 2035. An additional set of curves has been developed for vehicles in London affected by the introduction of the Low Emission Zone and taking account of the effect of the specific TfL bus fleet operating in London.

Speed-emission factor curves for $PM_{10}$ and $CO_2$ were developed using the same TRL speed-emission curves for detailed classes of vehicles as used before and the final fleet weighted, vehicle specific speed-emission factor curves are presented in the same 6-order polynomial format as used by TRL and previously used in the NTM. The new curves are only influenced by changes to the fleet composition data and show little change from those previously developed for the NTM in 2009.

The COPERT equations for $NO_x$ emissions express speed-emission factor in a variety of complex mathematical forms and a fitting procedure was used to simplify the format and produce $NO_x$ speed-emission factor curves in the same 6-order polynomial format as provided for $PM_{10}$ and $CO_2$ emissions. The changes to the $NO_x$ emission curves are more significant, especially for diesel cars and LGVs and to a lesser extent petrol cars. The errors introduced by the fitting procedure are very small, at most 4% at the low end of the speed range, but more typically less than 0.5%.

Speed-emission curves for fuel consumption and $CO_2$ emissions in the 3-order polynomial WEBTAG format were also developed and refer to the GB average fleet in 2010. Curves were generated for petrol and diesel cars, petrol and diesel LGVs, OGV1 and OGV2 class HGVs and PSV’s. The curves were developed from the 6-order curves produced for the NTM, and where necessary refitting was carried out to reduce the order of the polynomial equation.

The fleet composition data and assumptions that underpin the emission curves and the methods used to develop them are described in this report. The emission curves are designed to be used in conjunction with additional information relating to the fuel mix of vehicles (petrol and diesel cars and LGVs) and the bus/coach split of the PSV class of vehicles on different road types. The use of these additional data with the factors derived from the emission curves are illustrated by means of an example. Total emissions of $NO_x$, $PM_{10}$ and $CO_2$ in 2003 and 2010 at GB level by main vehicle type are provided from the latest NAEI model to effectively calibrate the baseline figures from the NTM using the emission curves.

The uncertainties in the emission curves and the applicability of the curves outside of their intended speed range have been assessed. The re-fitting of emission curves to the specific polynomial equations required by the NTM and WEBTAG introduced very small errors across the speed range, although larger errors occur at the low end of the speed range. Analysis showed that it is not advisable to use the $NO_x$ curves outside the speed range given by the COPERT 4 source, especially at the low end of the range in the case of petrol and diesel cars.

A wider qualitative assessment of the uncertainties considered the limitations of the average speed parameterisations themselves as a means of quantifying the effect of changes in traffic situations on emissions, especially at a local level. The wider air quality effects of traffic emissions need to consider other pollutants and non-exhaust sources from traffic, especially those for $PM_{10}$.

While the work was being undertaken, a further update to the $NO_x$ factors in COPERT 4 occurred. These could not be incorporated into the NTM curves at the time, but a re-calculation of the curves for diesel cars and LGVs using the latest factors has been carried out since initial completion of the project and the changes to the curves are described in Appendix C.

# Appendix A: Diesel Car Sales Assumptions

The following table shows the assumptions on the percentage of diesel cars sold in the new car fleet up to 2035. The figures were provided directly by Environment Analysis Division of DfT in December 2011.

| | % diesel car sales |
|---|---|
| **2010** | 45.7 |
| **2011** | 50.4 |
| **2012** | 50.5 |
| **2013** | 50.6 |
| **2014** | 50.6 |
| **2015** | 50.6 |
| **2016** | 50.6 |
| **2017** | 48.7 |
| **2018** | 46.8 |
| **2019** | 44.9 |
| **2020** | 43 |
| **2021** | 43 |
| **2022** | 43 |
| **2023** | 43 |
| **2024** | 43 |
| **2025** | 43 |
| **2026** | 43 |
| **2027** | 43 |
| **2028** | 43 |
| **2029** | 43 |
| **2030** | 43 |
| **2031** | 43 |
| **2032** | 43 |
| **2033** | 43 |
| **2034** | 43 |
| **2035** | 43 |

# Appendix B: Percentage difference in $NO_x$ emission factors before and after re-fitting emission curves

The following tables show the percentage difference, by vehicle type, in $NO_x$ emission factors developed before and after refitting of the emission curves derived by weighting of the COPERT functions. A positive value implies that the factor from the fit is greater than the factor calculated directly from the weighted COPERT equations.

Differences in factors calculated at speeds outside the range of the COPERT functions are highlighted in blue. For these speeds the percentage error calculation has a different meaning. It is instead a measure of the difference between the emission factors calculated by extending the range of the COPERT functions directly using the 6-order coefficients derived from the refitting procedure or using the trends implied by the TRL equations. In this case a positive value implies that the coefficient derived using trends implied by the TRL equations is greater than the coefficient derived by direct extension of the equation derived from refitting of the data.

| **Petrol Cars** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed (kph) | **Percentage error (%)** | | | | | | |
| | **2003** | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** |
| 5 | 69.37 | 92.88 | 79.71 | 72.20 | 65.36 | 64.75 | 64.74 |
| 10 | -1.28 | -2.15 | -0.92 | -0.54 | -0.04 | <0.01 | <0.01 |
| 15 | <0.01 | 0.02 | 0.04 | 0.03 | <0.01 | <0.01 | <0.01 |
| 20 | -0.02 | -0.07 | -0.15 | -0.12 | -0.01 | <0.01 | <0.01 |
| 25 | 0.02 | 0.05 | 0.11 | 0.09 | 0.01 | <0.01 | <0.01 |
| 30 | 0.01 | 0.05 | 0.13 | 0.10 | 0.01 | <0.01 | <0.01 |
| 35 | 0.01 | 0.03 | 0.04 | 0.02 | <0.01 | <0.01 | <0.01 |
| 40 | <0.01 | -0.03 | -0.08 | -0.08 | -0.01 | <0.01 | <0.01 |
| 45 | -0.03 | -0.10 | -0.18 | -0.14 | -0.01 | <0.01 | <0.01 |
| 50 | -0.04 | -0.13 | -0.18 | -0.12 | -0.01 | <0.01 | <0.01 |
| 55 | -0.02 | -0.04 | -0.03 | <0.01 | <0.01 | <0.01 | <0.01 |
| 60 | 0.06 | 0.20 | 0.30 | 0.23 | 0.01 | <0.01 | <0.01 |
| 65 | 0.09 | 0.25 | 0.37 | 0.27 | 0.02 | <0.01 | <0.01 |
| 70 | <0.01 | -0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 75 | -0.04 | -0.12 | -0.16 | -0.13 | -0.01 | <0.01 | <0.01 |
| 80 | -0.04 | -0.13 | -0.19 | -0.15 | -0.01 | <0.01 | <0.01 |
| 85 | -0.02 | -0.08 | -0.13 | -0.11 | -0.01 | <0.01 | <0.01 |
| 90 | -0.01 | -0.02 | -0.04 | -0.03 | <0.01 | <0.01 | <0.01 |
| 95 | 0.01 | 0.03 | 0.04 | 0.04 | <0.01 | <0.01 | <0.01 |
| 100 | 0.02 | 0.06 | 0.09 | 0.08 | <0.01 | <0.01 | <0.01 |
| 105 | 0.02 | 0.06 | 0.10 | 0.08 | <0.01 | <0.01 | <0.01 |
| 110 | 0.01 | 0.03 | 0.06 | 0.04 | <0.01 | <0.01 | <0.01 |
| 115 | <0.01 | -0.01 | -0.01 | -0.01 | <0.01 | <0.01 | <0.01 |
| 120 | -0.01 | -0.05 | -0.07 | -0.06 | <0.01 | <0.01 | <0.01 |
| 125 | -0.01 | -0.05 | -0.08 | -0.06 | <0.01 | <0.01 | <0.01 |
| 130 | 0.01 | 0.04 | 0.06 | 0.05 | <0.01 | <0.01 | <0.01 |

| Diesel Cars | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed (kph) | Percentage difference (%) | | | | | | |
| | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
| 5 | 18.78 | 48.11 | 58.65 | 65.99 | 67.96 | 68.08 | 68.10 |
| 10 | 2.62 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 15 | 0.04 | -0.12 | -0.05 | -0.01 | <0.01 | <0.01 | <0.01 |
| 20 | -0.14 | 0.04 | 0.02 | <0.01 | <0.01 | <0.01 | <0.01 |
| 25 | 0.03 | 0.11 | 0.05 | 0.01 | <0.01 | <0.01 | <0.01 |
| 30 | 0.13 | 0.07 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 |
| 35 | 0.10 | -0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 40 | <0.01 | -0.08 | -0.03 | -0.01 | <0.01 | <0.01 | <0.01 |
| 45 | -0.09 | -0.11 | -0.05 | -0.01 | <0.01 | <0.01 | <0.01 |
| 50 | -0.13 | -0.10 | -0.05 | -0.01 | <0.01 | <0.01 | <0.01 |
| 55 | -0.11 | -0.04 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 |
| 60 | -0.04 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 65 | 0.04 | 0.09 | 0.04 | 0.01 | <0.01 | <0.01 | <0.01 |
| 70 | 0.11 | 0.12 | 0.06 | 0.01 | <0.01 | <0.01 | <0.01 |
| 75 | 0.14 | 0.11 | 0.05 | 0.01 | <0.01 | <0.01 | <0.01 |
| 80 | 0.11 | 0.06 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 |
| 85 | 0.03 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 90 | -0.07 | -0.09 | -0.04 | -0.01 | <0.01 | <0.01 | <0.01 |
| 95 | -0.15 | -0.13 | -0.06 | -0.01 | <0.01 | <0.01 | <0.01 |
| 100 | -0.15 | -0.11 | -0.05 | -0.01 | <0.01 | <0.01 | <0.01 |
| 105 | -0.05 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 110 | 0.12 | 0.11 | 0.05 | 0.01 | <0.01 | <0.01 | <0.01 |
| 115 | 0.22 | 0.16 | 0.07 | 0.02 | <0.01 | <0.01 | <0.01 |
| 120 | -0.14 | -0.11 | -0.05 | -0.01 | <0.01 | <0.01 | <0.01 |

| Petrol LGVs | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed (kph) | Percentage difference (%) | | | | | | |
| | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
| 5 | 1.12 | 2.19 | 2.62 | 0.74 | 0.05 | -0.02 | -0.02 |
| 10 | -0.20 | -0.58 | -0.50 | -0.15 | -0.01 | <0.01 | <0.01 |
| 15 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 20 | 0.01 | 0.02 | 0.02 | 0.01 | <0.01 | <0.01 | <0.01 |
| 25 | -0.03 | -0.09 | -0.08 | -0.02 | <0.01 | <0.01 | <0.01 |
| 30 | 0.01 | 0.04 | 0.04 | 0.01 | <0.01 | <0.01 | <0.01 |
| 35 | 0.02 | 0.06 | 0.06 | 0.02 | <0.01 | <0.01 | <0.01 |
| 40 | 0.01 | 0.03 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 |
| 45 | -0.01 | -0.02 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 |
| 50 | -0.02 | -0.06 | -0.06 | -0.02 | <0.01 | <0.01 | <0.01 |
| 55 | -0.02 | -0.07 | -0.06 | -0.02 | <0.01 | <0.01 | <0.01 |
| 60 | -0.01 | -0.03 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 |
| 65 | 0.02 | 0.08 | 0.07 | 0.02 | <0.01 | <0.01 | <0.01 |
| 70 | 0.03 | 0.11 | 0.10 | 0.03 | <0.01 | <0.01 | <0.01 |
| 75 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 80 | -0.01 | -0.05 | -0.04 | -0.01 | <0.01 | <0.01 | <0.01 |
| 85 | -0.02 | -0.05 | -0.04 | -0.01 | <0.01 | <0.01 | <0.01 |
| 90 | -0.01 | -0.03 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 |
| 95 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 100 | 0.01 | 0.03 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 |
| 105 | 0.01 | 0.03 | 0.02 | 0.01 | <0.01 | <0.01 | <0.01 |
| 110 | -0.01 | -0.02 | -0.02 | -0.01 | <0.01 | <0.01 | <0.01 |

| Diesel LGVs | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed | Percentage difference (%) | | | | | | |
| (kph) | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
| 5 | -1.24 | -0.69 | -0.26 | -0.12 | -0.09 | -0.08 | -0.08 |
| 10 | 0.07 | 0.03 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 15 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 20 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 25 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 30 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 35 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 40 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 45 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 50 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 55 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 60 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 65 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 70 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 75 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 80 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 85 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 90 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 95 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 100 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 105 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 110 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |

| Rigid HGVs | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Speed (kph)** | **Percentage difference (%)** | | | | | | |
| | **2003** | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** |
| 6 | -14.14 | -4.22 | -6.66 | -26.85 | -39.16 | -41.30 | -41.30 |
| 10 | -6.27 | -3.33 | -5.65 | -16.11 | -23.65 | -25.06 | -25.06 |
| 15 | 0.15 | 0.19 | 0.15 | -0.03 | -0.18 | -0.21 | -0.21 |
| 20 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 25 | -0.01 | -0.01 | -0.01 | <0.01 | 0.01 | 0.01 | 0.01 |
| 30 | 0.01 | 0.01 | 0.01 | <0.01 | -0.01 | -0.02 | -0.02 |
| 35 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.01 |
| 40 | -0.01 | -0.01 | -0.01 | <0.01 | 0.01 | 0.02 | 0.02 |
| 45 | -0.01 | -0.01 | -0.01 | <0.01 | 0.02 | 0.02 | 0.02 |
| 50 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 55 | 0.01 | 0.01 | 0.01 | <0.01 | -0.02 | -0.02 | -0.02 |
| 60 | 0.01 | 0.01 | 0.01 | <0.01 | -0.02 | -0.03 | -0.03 |
| 65 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.01 | -0.01 |
| 70 | <0.01 | -0.01 | -0.01 | <0.01 | 0.02 | 0.03 | 0.03 |
| 75 | -0.01 | -0.01 | -0.01 | <0.01 | 0.03 | 0.04 | 0.04 |
| 80 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 | 0.01 |
| 85 | 0.01 | 0.01 | 0.02 | <0.01 | -0.05 | -0.07 | -0.07 |
| 86 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.02 | -0.02 |

| Artic HGVs | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed (kph) | Percentage difference (%) | | | | | | |
| | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
| 6 | -12.38 | -5.31 | -21.95 | -54.21 | -57.29 | -57.29 | -57.29 |
| 10 | -5.82 | -5.81 | -14.88 | -34.15 | -36.71 | -36.71 | -36.71 |
| 15 | <0.01 | <0.01 | <0.01 | -0.01 | -0.01 | -0.01 | -0.01 |
| 20 | -0.01 | -0.01 | <0.01 | 0.09 | 0.11 | 0.11 | 0.11 |
| 25 | 0.01 | 0.01 | <0.01 | -0.16 | -0.19 | -0.19 | -0.19 |
| 30 | <0.01 | <0.01 | <0.01 | -0.05 | -0.06 | -0.06 | -0.06 |
| 35 | <0.01 | -0.01 | <0.01 | 0.14 | 0.18 | 0.18 | 0.18 |
| 40 | -0.01 | -0.01 | <0.01 | 0.16 | 0.20 | 0.20 | 0.20 |
| 45 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 50 | <0.01 | 0.01 | <0.01 | -0.17 | -0.22 | -0.22 | -0.22 |
| 55 | 0.01 | 0.01 | <0.01 | -0.20 | -0.26 | -0.26 | -0.26 |
| 60 | <0.01 | <0.01 | <0.01 | -0.04 | -0.06 | -0.06 | -0.06 |
| 65 | <0.01 | -0.01 | <0.01 | 0.18 | 0.24 | 0.24 | 0.24 |
| 70 | -0.01 | -0.01 | <0.01 | 0.26 | 0.35 | 0.35 | 0.35 |
| 75 | <0.01 | <0.01 | <0.01 | 0.03 | 0.04 | 0.04 | 0.04 |
| 80 | 0.01 | 0.01 | <0.01 | -0.36 | -0.51 | -0.51 | -0.51 |
| 85 | <0.01 | <0.01 | <0.01 | -0.08 | -0.11 | -0.11 | -0.11 |

| Buses | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed (kph) | Percentage difference (%) | | | | | | |
| | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
| 6 | -7.28 | -2.97 | 2.90 | -5.67 | -28.51 | -41.40 | -45.60 |
| 10 | -2.04 | -0.27 | 1.78 | -1.86 | -13.05 | -21.25 | -24.26 |
| 15 | -0.07 | -0.19 | -0.16 | -0.28 | -0.61 | -0.87 | -0.97 |
| 20 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.01 |
| 25 | <0.01 | 0.01 | <0.01 | 0.01 | 0.02 | 0.04 | 0.05 |
| 30 | <0.01 | -0.01 | -0.01 | -0.01 | -0.04 | -0.07 | -0.08 |
| 35 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.02 | -0.03 |
| 40 | <0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.06 | 0.08 |
| 45 | <0.01 | 0.01 | <0.01 | 0.01 | 0.04 | 0.07 | 0.09 |
| 50 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 55 | <0.01 | -0.01 | -0.01 | -0.01 | -0.04 | -0.08 | -0.10 |
| 60 | <0.01 | -0.01 | -0.01 | -0.01 | -0.04 | -0.09 | -0.11 |
| 65 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.01 | -0.02 |
| 70 | <0.01 | 0.01 | 0.01 | 0.01 | 0.04 | 0.09 | 0.11 |
| 75 | <0.01 | 0.01 | 0.01 | 0.02 | 0.05 | 0.11 | 0.14 |
| 80 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | -0.01 | -0.01 |
| 85 | <0.01 | -0.01 | -0.01 | -0.02 | -0.08 | -0.16 | -0.20 |

| Coaches | | | | | | | |
|---|---|---|---|---|---|---|---|
| Speed (kph) | Percentage difference (%) | | | | | | |
| | 2003 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
| 6 | 0.09 | 0.06 | 0.07 | 0.10 | 0.17 | 0.22 | 0.23 |
| 10 | -0.62 | -0.44 | -0.49 | -0.77 | -1.31 | -1.66 | -1.78 |
| 15 | -1.18 | -0.80 | -0.84 | -1.43 | -2.67 | -3.48 | -3.76 |
| 20 | 0.19 | 0.02 | -0.09 | 0.04 | 0.47 | 0.78 | 0.91 |
| 25 | 0.52 | 0.35 | 0.36 | 0.68 | 1.46 | 2.06 | 2.29 |
| 30 | 0.38 | 0.34 | 0.45 | 0.69 | 1.16 | 1.54 | 1.67 |
| 35 | 0.09 | 0.17 | 0.29 | 0.34 | 0.31 | 0.26 | 0.23 |
| 40 | -0.15 | -0.04 | 0.01 | -0.11 | -0.56 | -0.97 | -1.15 |
| 45 | -0.27 | -0.21 | -0.24 | -0.48 | -1.09 | -1.68 | -1.91 |
| 50 | -0.27 | -0.27 | -0.39 | -0.63 | -1.16 | -1.68 | -1.86 |
| 55 | -0.17 | -0.23 | -0.38 | -0.55 | -0.79 | -1.03 | -1.08 |
| 60 | -0.03 | -0.11 | -0.23 | -0.26 | -0.15 | 0.01 | 0.10 |
| 65 | 0.10 | 0.04 | 0.02 | 0.13 | 0.56 | 1.07 | 1.28 |
| 70 | 0.18 | 0.18 | 0.26 | 0.48 | 1.07 | 1.78 | 2.03 |
| 75 | 0.20 | 0.24 | 0.41 | 0.67 | 1.21 | 1.85 | 2.04 |
| 80 | 0.13 | 0.21 | 0.39 | 0.59 | 0.86 | 1.17 | 1.22 |
| 85 | 0.01 | 0.08 | 0.18 | 0.22 | 0.09 | -0.12 | -0.25 |
| 90 | -0.11 | -0.11 | -0.17 | -0.34 | -0.85 | -1.57 | -1.82 |
| 95 | -0.19 | -0.26 | -0.48 | -0.81 | -1.46 | -2.40 | -2.63 |
| 100 | -0.12 | -0.22 | -0.43 | -0.69 | -1.02 | -1.48 | -1.52 |
| 105 | 0.17 | 0.25 | 0.47 | 0.82 | 1.50 | 2.57 | 2.83 |

# Appendix C: Updates to $NO_x$ Emission Curves for Diesel Cars and LGVs

Shortly before the time the emission curves were being developed in this project, a new version of COPERT 4 was released by the European Environment Agency: COPERT 4v10. This provided updated $NO_x$ emission factors for Euro 5 and Euro 6 diesel cars based on more recent emission testing of these vehicles which entered into service in 2010. These were significantly higher than values given in COPERT 4v9, indicating the relatively poor real-world performance of these vehicles.

After consulting with Defra and DfT during July 2013, the new COPERT 4v10 factors were adopted by the NAEI for both diesel cars and diesel LGVs and were included in the 2012 NAEI compilation of the official UK emissions inventory in late 2013. DfT requested a re-calculation of the speed-emission curves developed for diesel cars and applied to LGVs using the assumptions from COPERT 4v10. The re-calculations were done following exactly the same fitting procedures as explained earlier in this report.

This appendix provides a short summary of the main differences in the $NO_x$ factors for these vehicles and their impact on speed emission curves developed for the NTM. It also provides new emission totals for Great Britain using the new factors that DfT can use for calibration purposes.

COPERT 4v10 has only led to changes in the factors for $NO_x$.

## The COPERT 4v10 Factors for Euro 5 Diesel Cars

As Euro 5 cars and LGVs were only slowly entering service at the time COPERT 4 v9 was released, the $NO_x$ emission factors were still only estimates derived by applying scaling factors to Euro 4 on the basis of trends in Type-Approval limit values. There was an implicit assumption that the Euro 5 standards would deliver the intended improvements over real world cycles.

However, during 2012, there was becoming increasing evidence from around Europe that this was not the case and that real-world $NO_x$ emission factors for Euro 5 diesel cars were at least as high as Euro 4, if not higher.

Emission testing of Euro 5 vehicles has been coordinated in the framework of the European Research Group on Mobile Emissions (ERMES) activity. The results were made available to the COPERT group and led to the new release of COPERT 4v10 in November 2012[17]:

The available data on $NO_x$ emission levels of diesel passenger cars tested in ERMES (based on a real-world driving cycle mix i.e. average of Artemis Urban, Rural and Motorway) showed that Euro 5 vehicles have the highest $NO_x$ emissions of all the Euro standards (within the high uncertainty provided), even slightly exceeding the Euro 2 and Euro 3 emission levels. Some tests on a very small sample of early generation Euro 6 cars with advanced emission controls showed these were performing much better, but it was too soon to know if the vehicles would be representative of the Euro 6 fleet in the future. COPERT revised their assumptions on the reductions in Euro 6 factors.

To illustrate the difference between Euro 5 and 6 assumptions for diesel cars in the two versions of COPERT, Table A1 shows the change in $NO_x$ emission factors implied by COPERT 4v9 and COPERT 4v10 relative to factors for Euro 4.

[17] http://www.emisia.com/copert/Copert4.html

**Table A1: $NO_x$ emission factors for Euro 5/6 diesel cars relative to Euro 4 (expressed as indices with Euro 4 = 100).**

| Index: Euro 4 = 100 | COPERT 4 v9 | COPERT 4 v10 |
|---|---|---|
| Euro 4 | 100 | 100 |
| Euro 5 | 72 | 123 |
| Euro 6 | 32 | 43 |

This table indicates that $NO_x$ factors for Euro 5 are actually 23% higher than Euro 4, rather than being 28% lower. Factors for Euro 6 are also not as low as previously assumed.

The NAEI team at Ricardo-AEA were in discussions with Defra and DfT in the spring/summer of 2013, shortly after the curves were developed for the NTM, to decide whether to adopt these factors for the NAEI inventory submission for 2013. At the time, COPERT were unclear whether the changes made to COPERT 4v10 would be revised again later in 2013 as further test data were analysed. However, this has not been the case and COPERT 4v10 remains the most up-to-date version.

At the time of publication, the group responsible for the development of COPERT were unsure whether such changes to Euro 5 and 6 diesel cars should also apply to diesel LGVs, even though these vehicles are engined in a similar way to diesel cars. The COPERT group informed the NAEI that there was insufficient evidence to know whether any changes to factor for diesel LGVs was required. However, further emission remote sensing work carried out in the UK suggested diesel LGVs may be showing similar trends as diesel cars and that Euro 5 vehicles were also not performing well. Although not adopted for diesel LGVs in COPERT 4v10, the NAEI agreed with Defra to make a conservative assumption that Euro 5 factors for these vehicles are also 23% higher than their Euro 4 equivalent factors.

## Re-fitting of Speed-Emission Curves for Diesel Cars and LGVs

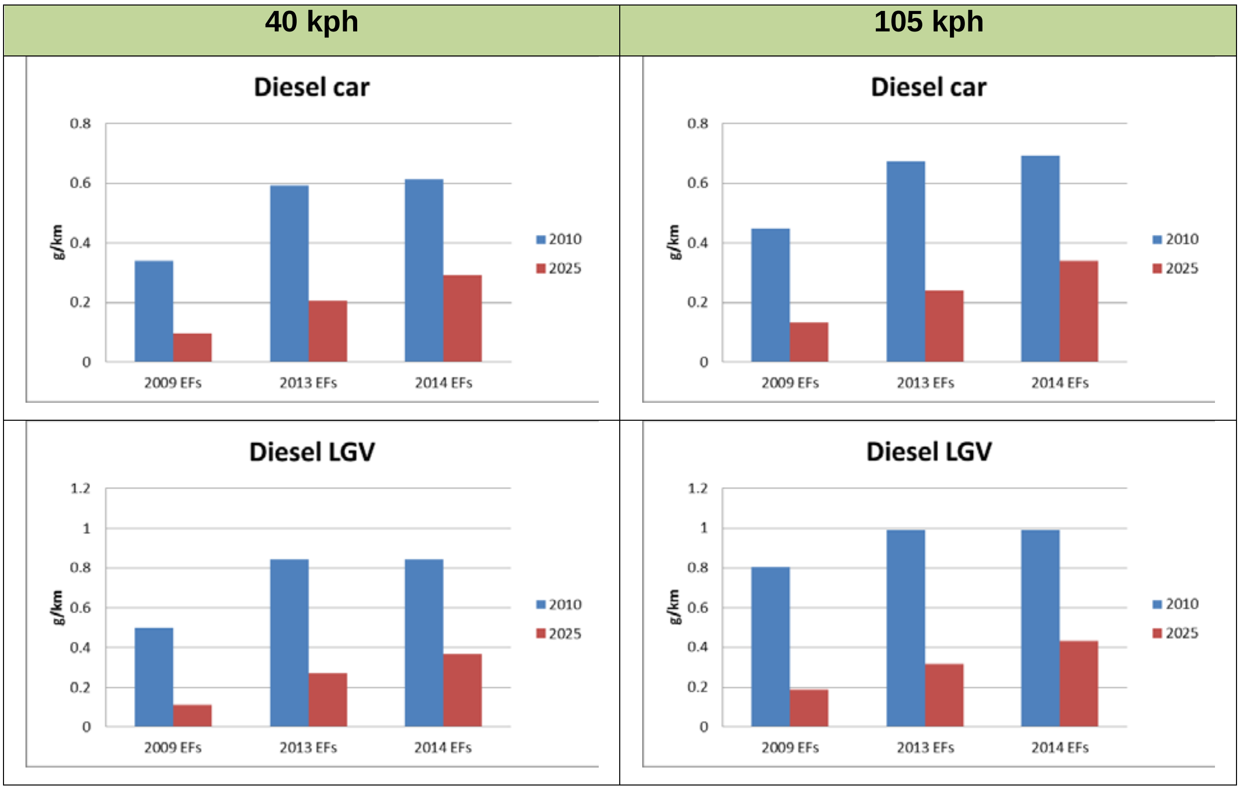
Using the COPERT 4v10 $NO_x$ emission factors for Euro 5 and 6 diesel cars, the speed-emission curves for these vehicles were re-fit using the same fleet information and procedures as explained in Section 4. The quality of the fits was equally as good as obtained using the original factors. Assuming the same proportionate changes in the Euro 5 and 6 factors for diesel LGVs, a new set of emission curves for these vehicles was also developed.

Spreadsheets have been provided to DfT containing a complete set of new coefficients for calculating emissions factors for $NO_x$ from average speed for each main vehicle type in the fleet in years from 2003 to 2035. The spreadsheets demonstrate the calculation of emission factors from a speed using the polynomial equation (1). Only the factors for diesel cars and LGVs are different to the previous versions provided. The changes apply to all years except 2003 which pre-dates the introduction of Euro 5 and 6 standards.

## Impacts of the Changes to Emission Curves for Diesel Cars and LGVs

Figure A1 shows the impact of the changes to the emission curves when used to calculate $NO_x$ emission factors for diesel cars and LGVs at speeds typical of urban and motorway conditions for 2010 and 2025. These graphs are the same in format as shown in Figure 5 (Section 7) and show for comparison the factors calculated by the 2009 curves and those calculated earlier in this work and described in Sections 4 and 7.

**Figure A1: Comparison of the $NO_x$ emission factors at different speeds for diesel cars and LGVs calculated for 2010 and 2025 using the previous and new speed-emission curves. 2009 EFs refer to the previous curves developed for DfT in 2009; 2013 EFs refer to the new emission curves described in Section 4; 2014 EFs refer to the curves calculated using the latest COPERT 4v10 emission factors.**




Relative to the curves initially developed in this project from COPERT 4v9, the new factors have only a modest impact on emission factors calculated for the 2010 fleet. This is because few Euro 5 and no Euro 6 vehicles have entered the fleet in this year. The impact is greater by 2025 where the new curves lead to higher emission factors.

## Re-calculation of National Emission Totals for Calibration

To make full use of the updated speed-emission curves, DfT requires updated figures on total emissions of $NO_x$ in 2003 and 2010 at GB level grouped by vehicle category from the NAEI model to effectively "calibrate" the baseline figures from the NTM. An updated version of Table 9 provided in Section 6 is therefore shown in Table A2.

**Table A2: GB emissions of $NO_x$ from road vehicles based on the NAEI model updated using the COPERT 4v10 emission factors for diesel cars and applied to diesel LGVs.**

| $NO_x$ ktonnes | | | 2003 | 2010 |
|---|---|---|---|---|
| | | | | |
| Car | Petrol | Hot exhaust | 213.40 | 51.39 |
| | | Cold start | 32.50 | 9.38 |
| | | Total | 245.90 | 60.77 |
| | | | | |
| | Diesel | Hot exhaust | 62.59 | 94.21 |
| | | Cold start | 3.50 | 6.18 |
| | | Total | 66.09 | 100.38 |
| | | | | |
| LGV | Petrol | Hot exhaust | 11.82 | 1.93 |
| | | Cold start | 0.79 | 0.19 |
| | | Total | 12.61 | 2.12 |
| | | | | |
| | Diesel | Hot exhaust | 58.45 | 58.03 |
| | | Cold start | 3.00 | 2.50 |
| | | Total | 61.45 | 60.53 |
| | | | | |
| HGV+PSV | Diesel | Hot exhaust | 227.54 | 146.27 |
| | | Cold start | 0.00 | 0.00 |
| | | Total | 227.54 | 146.27 |
| | | | | |
| Total | Petrol | Hot exhaust | 225.22 | 53.32 |
| | | Cold start | 33.29 | 9.57 |
| | | Total | 258.51 | 62.89 |
| | | | | |
| | Diesel | Hot exhaust | 348.57 | 298.51 |
| | | Cold start | 6.51 | 8.67 |
| | | Total | 355.08 | 307.18 |

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RICARDO-AEA

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR

Tel: 01235 753633

www.ricardo-aea.com