Connected Places Catapult

Light vehicle motorway NO_x exhaust emissions

Review of Highways England motorway speed banding methodology

December 2019

CATAPULT Connected Places

Contents

Authorisation page

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1. Project Overview

Background and objectives

Since 2015, Highways England have utilised a speed banding methodology[1] to estimate the vehicle NO_x exhaust emissions associated with traffic model link speed and flow outputs. It has been recognised in recent years that the current approach, utilising 3 motorway speed categories or ranges, is relatively coarse and may not capture significant variability in vehicle emissions with respect to average link speed.

Since the publication of Interim Advice Note (IAN) 185/15 in 2015, more research has been undertaken on vehicle emissions, including Portable Emissions Monitoring System (PEMS) data collection by the Department for Transport (DfT) and others. Highways England therefore commissioned Transport Systems Catapult, in partnership with specialists within Highways England, to investigate potential methodological refinements.

The UK Emission Factor Toolkit is widely utilised for estimating vehicle exhaust emissions. However, its ability to adequately replicate the elevated congestion related NO_x emissions observed by researchers (termed the 'harmonica' effect by Dutch researchers at TNO[2]) is questionable. Further discussion of this effect is included in Annex C. The EFT emission curves arguably under-represent NO_x emissions in congested speed ranges in the context of a UK motorway operating with a 70mph national speed limit.

It should be noted that the requirements of Highways England in this context are quite specific; to estimate with an appropriate level of robustness the NO_x g/km values to be associated with traffic assignment model link speed and flow outputs. Highways England and its contractors develop and utilise (typically macroscopic) traffic assignment models for highway scheme assessment and forecasting. These models output a traffic flow value for a particular link and time period (AM peak, inter-peak, PM peak, off-peak), and an associated average speed value for the link and time period in question (derived from link speed / flow curve relationships). Traffic assignment model 'links' are simplified mathematical representations of real world sections of motorway, described by parameters such as link length, flow capacity (e.g. based on number of lanes), and a link specific speed / flow relationship. Therefore, the NO_x g/km values generated by any proposed emission estimation methodology need to be compatible with, and consistent with, these traffic assignment model outputs (taking into consideration the inherent assumptions, robustness and accuracy of the traffic models themselves).

It should also be noted that any proposed methodology will be constrained by the availability of relevant data. In this context, the two key data types of particular relevance are (a) vehicle exhaust NO_x emission data by vehicle type (fuel type, Euro standard, emissions control technology etc.) derived from, and applicable to, a UK motorway context and (b) information on UK motorway vehicle dynamics (e.g. variability in speed and acceleration by vehicle type). It is recognised that other factors, such as variability in driver behaviour, are also relevant. The constraints imposed by limitations in data availability have been investigated and are referred to in this report.

[1] Interim Advice Note 185/15. Updated traffic, air quality and noise advice on the assessment of link speeds and generation of vehicle data into 'speed-bands' for users of DMRB Volume 11, Section 3, Part 1 'Air Quality.
[2] TNO report R10827 "Definitie congestie op de snelweg voor emissiefactoren" (Translation: "Definition of congestion on the highway for emission factors"). V.A.M. Heijne & N.E. Ligterink, 2017.

2. Highways England surveys of motorway light vehicle dynamics

Highways England implemented a programme of instrumented (GPS) vehicle surveys in the period March 20th – 23rd 2017 inclusive. The surveys collected vehicle speed and position information at a frequency of 10Hz using a commercial GPS data logger installed in two passenger cars. The overall objective was to begin to quantify and characterise light vehicle dynamics, particularly on the Highways England motorway network.

One of the approaches adopted by Highways England to the categorisation and classification of the vehicle dynamics survey data was to organise the data according to road type, speed limit, and time period. Motorway data were classified depending on whether the road links were 'on-slips', 'off-slips, 'junctions', 'mainline', or 'roadworks'. This approach was considered most closely compatible with the network structure of traditional macroscopic traffic models, typically utilised for highway scheme assessment and forecasting. Such disaggregation facilitates the capture of systematic variation in vehicle dynamics within different road link types, and facilitates the exploration of variation in vehicle exhaust emissions as a consequence of such variation in vehicle dynamics, in particular acceleration and speed. In total, there were 486 'mainline' motorway links (1092 km in total), 141 motorway 'slip road' links (116 km in total), and 198 motorway 'roadworks' links generally subject to 50mph average speed cameras (285 km in total). An important constraint of the surveys was that vehicles were generally not driven in excess of the 70mph motorway speed limit. This is a significant issue which will be discussed later in the context of published DfT traffic speed census statistics.

3. Initial exploration of TNO aggregate emission rate approach

TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek - Netherlands Organisation for Applied Scientific Research) is an independent research organisation in the Netherlands that focuses on applied science. It is a leading European research organisation in the field of exhaust emissions and vehicle dynamics.

In previous years, TNO had proposed a methodological approach to estimate vehicle exhaust emissions on a link or route basis which utilised aggregated emission rate data and aggregated information on vehicle dynamics (using a combination of vehicle speed and acceleration data to estimate a proxy value for engine load)[3,4]. The method defines three speed ranges for light vehicles (0-50kph, 50-80kph, and greater than 80kph), and three thresholds of engine load within each speed range, resulting in nine combinations of speed and engine load. A single emissions rate is calculated for each of the nine combinations, and a tenth value allocated to idling conditions.

This aggregate TNO approach was explored extensively by Highways England as a possible methodology for application to the UK motorway system for scheme assessment, primarily because Highways England at that time did not have access to alternative UK sources of vehicle exhaust emission data, and TNO were willing to share relevant aggregate emission rate data with Highways England. However, it was found that in some circumstances the method could result in unrealistic step changes in emission rates at the boundaries between speed ranges and/or engine loads. This could lead to large and unrealistic differences in calculated emission rates for very small changes in speed

[3] Refined vehicle and driving-behaviour dependencies in the VERSIT+ emission model. Norbert E. Ligterink and Ronald de Lange. Environment & Transport 2009.

[4] TNO report R10188 "On-road determination of average Dutch driving behaviour for vehicle emissions". Norbert E. Ligterink, February 2016.

and/or acceleration at the boundaries. The method was therefore eventually rejected as a preferred option. Indeed, it is understood that TNO themselves no longer utilise this aggregate methodology, preferring to apply exhaust emission rates derived from PEMS (Portable Emissions Monitoring System) directly to vehicle dynamics data to estimate link or route emissions.

4. Highways England PEMS survey data

Highways England commissioned a programme of PEMS exhaust emissions surveys for a number of Euro 4, Euro 5, and Euro 6 diesel vans (N1) and passenger cars (M1) on a test track. The primary objective of the survey programme was to investigate the efficacy of diesel GTL (gas-to-liquid) fuel for reducing NO_x emissions. In total, the surveys included four Euro 4 diesel vans, five Euro 5 diesel vans, three Euro 6 diesel vans, eight Euro 5 diesel cars, and two Euro 6 diesel cars. The surveys were carried out on a test track at Bruntingthorpe Aerodrome and Proving Ground. Clearly, collecting PEMS data on a test track potentially has both advantages and disadvantages. Operating on a test track permits speeds above the legal road speed limit of 70mph (in principle). On the other hand, the specific drive cycle characteristics attainable may be constrained by the physical layout of the test track being used. In the case of Bruntingthorpe, the test track is essentially a 2.8 km runway, with a perimeter road running parallel.

The PEMS emissions data generated from the surveys facilitated the derivation of NO_x emissions relationships, particularly at lower speeds. However, the physical constraints of the test track did not permit sustained higher speed operation (i.e. above 60mph); operation at higher speeds was limited to short transient durations (after hard acceleration, and followed by hard deceleration). This meant that the data derived from these particular test track surveys would not be particularly representative of sustained higher speed vehicle operation on UK motorways.

5. Department for Transport PEMS surveys 2016, and DVSA 2017 Market Surveillance Surveys.

In late 2015 / early 2016, the UK Department for Transport designed and implemented a vehicle emissions measurement programme to help quantify the divergence of on-road emissions from those measured in laboratories during the type approval process, and to help understand the variation between the current emissions standard (Euro 6) and its predecessor (Euro 5).

The surveys included elements of laboratory measurements, test track measurements, and on-road measurements. The on-road element involved operating the vehicle for a period of approximately 1.5 hours over a test route that satisfied the general requirements of the new Real Driving Emission (RDE) test. “In general this process followed the proposed RDE procedures but, as these procedures were not finalised and not all vehicles had been subjected to a representative WLTP precursor, this test cannot be truly considered as a valid RDE assessment. Nevertheless energy input levels were monitored to maintain inputs within the prescribed limits.”[5]

Vehicle exhaust emissions data were collected in 2016 from a sample of diesel passenger cars (19 Euro 5 diesel cars, and 18 Euro 6 diesel cars), representative of the UK vehicle fleet composition. Figure 1 illustrates the on-road test route driven during the 2016 PEMS surveys. The test route includes the A5 between Nuneaton, Tamworth, and Lichfield, and includes sections of the M6 toll road to the west, for a total distance of just over 70 km. All vehicles drove essentially the same test route, so the main differences between drive cycles for each vehicle will be due to prevailing traffic conditions, weather conditions, and driver behaviour. These data were released into the public domain in April 2017.

[5] Vehicle Emissions Testing Programme. Department for Transport. Command 9259 dated April 2016.

Between January and June 2017, the DfT / DVSA Vehicle Market Surveillance Unit carried out a further programme of PEMS surveys, including laboratory testing, track testing, and on-road testing[6]. The data collected in these DfT / DVSA surveys were released into the public domain in July 2018. The tests included fifteen Euro 6 petrol cars, two Euro 5 diesel cars, two Euro 6 diesel cars, six diesel vans (five Euro 5, one Euro 6), five Euro 6 diesel trucks, and three Euro 6 diesel buses. It should be noted that the small sample of Euro 5 diesel vans comprised two N1 class II (1305-1760kg reference mass), and three N1 class III (1760-3500kg reference mass). Unfortunately, the Department for Transport has to date not been able to release the second by second GPS coordinate data from the 2017 on-road testing[7], so it is not possible to determine the test routes driven, or to reliably differentiate data by speed limit or road type. It is not known whether any or all of the DfT / DVSA 2017 PEMS surveys used the same on-road test route as the DfT 2016 PEMS surveys.

Figure 1: DfT / MIRA 'on road' PEMS route 2016

The primary aim of the 2017 DfT / DVSA surveys was to assess if the vehicles complied with the standards to which they were approved. For the cars and vans the testing was also designed to assess how the real world performance of these vehicles compared against the newly introduced Real Driving Emissions (RDE) standards. The on-road testing element involved driving the vehicle for approximately 1.5 hours over a test route on public roads. The published survey report states that the route included urban, rural and motorway driving and tests were carried out during the day in normal traffic conditions. The motorway driving element of the 2016 and 2017 PEMS surveys are of particular relevance to the current Highways England analysis.

[6] DVSA Vehicle Market Surveillance Unit. Results of the 2017 programme.
[7] Personal email exchange with DfT International Vehicle Standards, November 2018.

6. Processing of DfT 2016 and DfT / DVSA 2017 light vehicle PEMS data using EMROAD

The DfT 2016 and DfT / DVSA 2017 light vehicle PEMS data are the only such data sets, collected in recent years on UK motorways, which are in the UK public domain. Given the previously discussed limitations of the aggregate emissions data available from TNO, it was decided to utilise the DfT / DVSA published PEMS data to generate motorway NO_x emissions estimates for Euro 5 and Euro 6 light vehicles. When the 2016 and 2017 data sets were combined, this resulted in a sample size of 21 Euro 5 diesel cars, 20 Euro 6 diesel cars, 5 Euro 5 diesel vans, and 14 Euro 6 petrol cars. These data are generally collected at a frequency of 1Hz, although some published data sets are at 10Hz.

Generally speaking, the published DfT 2016 and DfT / DVSA 2017 PEMS survey data did not include instantaneous (second by second) NO_x mass emissions (g/sec), but rather NO_x concentrations measured in parts per million or percent. Therefore, instantaneous NO_x mass emissions had to be calculated based on gas concentrations, and exhaust gas flow rate. To ensure consistency across the data sets, all PEMS data sets were processed using EMROAD version 5.96[8].

EMROAD is a Microsoft Excel add-in for analysing vehicle emissions data recorded with Portable Emissions Measurement Systems (PEMS). EMROAD is developed and maintained by the European Commission Joint Research Centre (JRC). EMROAD has been updated in recent years by the JRC to meet:

- For light-duty vehicles, the applicable methods and requirements laid down in Regulations 2016/427 (except for the Power Binning Method in Appendix 6), 2016/646 and 2017/1154.
- For heavy-duty vehicles, the applicable methods and requirements laid down in Regulations 582/2011 and 2016/1718.

Second by second NO_x mass emission rates were generated using EMROAD for each PEMS data set, and these data sets were then utilised to estimate NO_x g/sec emission rates with respect to vehicle speed and acceleration. Emission rates were calculated at a speed resolution of 5mph, and an acceleration resolution of $0.1m/s^2$ (although obviously emission rates can also be calculated at other levels of speed and acceleration resolution as required). These calculated emission rates are presented in Annex A for Euro 5 diesel cars, Euro 6 diesel cars, Euro 5 diesel vans, and Euro 6 petrol cars (vehicle types and Euro standards constrained by data availability). One issue to note is the lack of data at speeds above 70mph. This is a significant constraint for the estimation of real world UK motorway emission rates, as will be discussed later.

7. DfT motorway speed statistics

The Department for Transport publishes a range of statistics relating to observed vehicle speeds on the UK motorway network. Of particular relevance in this context is DfT Table SPE0111 Free flow vehicle speeds by road type and vehicle type in Great Britain, 2017. Table SPE0111 (2017) highlights the fact that 48% of cars drivers and 49% of van drivers choose to exceed the 70mph speed limit when traffic conditions permit. Further, 12% of car drivers and 14% of van drivers exceed 80mph when traffic conditions permit. Utilising the same 2017 DfT traffic speed census data sets, Figures 2, 3, and 4 illustrate the extent to which passenger cars, vans (up to 3.5 tonnes), and rigid 2 axle HGV's (above 3.5 tonnes) exceed 70mph, 75mph, and 80mph, by hour of the day.

[8] European Commission DG JRC EMROAD version 5.96 Build 3.M4

The significance of these observations are twofold. Firstly, there is clearly a requirement to collect PEMS vehicle emissions data at real world motorway speeds, not just up to the 70mph speed limit for light vehicles as has generally been done in the DfT / DVSA PEMS surveys in 2016 and 2017. A significant proportion of motorway vehicle kilometres is being driven at speeds above 70mph. It is recognised that there are potential legal and health & safety constraints to implementing PEMS surveys systematically above 70mph on the UK motorway network. However, PEMS surveys of sustained higher speed (>70mph) vehicle operation could be carried out on suitable 'off road' test tracks where sustained high speed operation is practical, for example the Millbrook Proving Ground high speed circuit[9].

Secondly, surveys of motorway vehicle dynamics (speed and acceleration) should ideally be undertaken across a 'real world' range of vehicle operating speeds, reflecting the actual distribution of vehicle speed and acceleration behaviour on the UK motorway network. This should include higher speed operation, as reflected in the published Department for Transport motorway speed statistics (Table SPE0111).

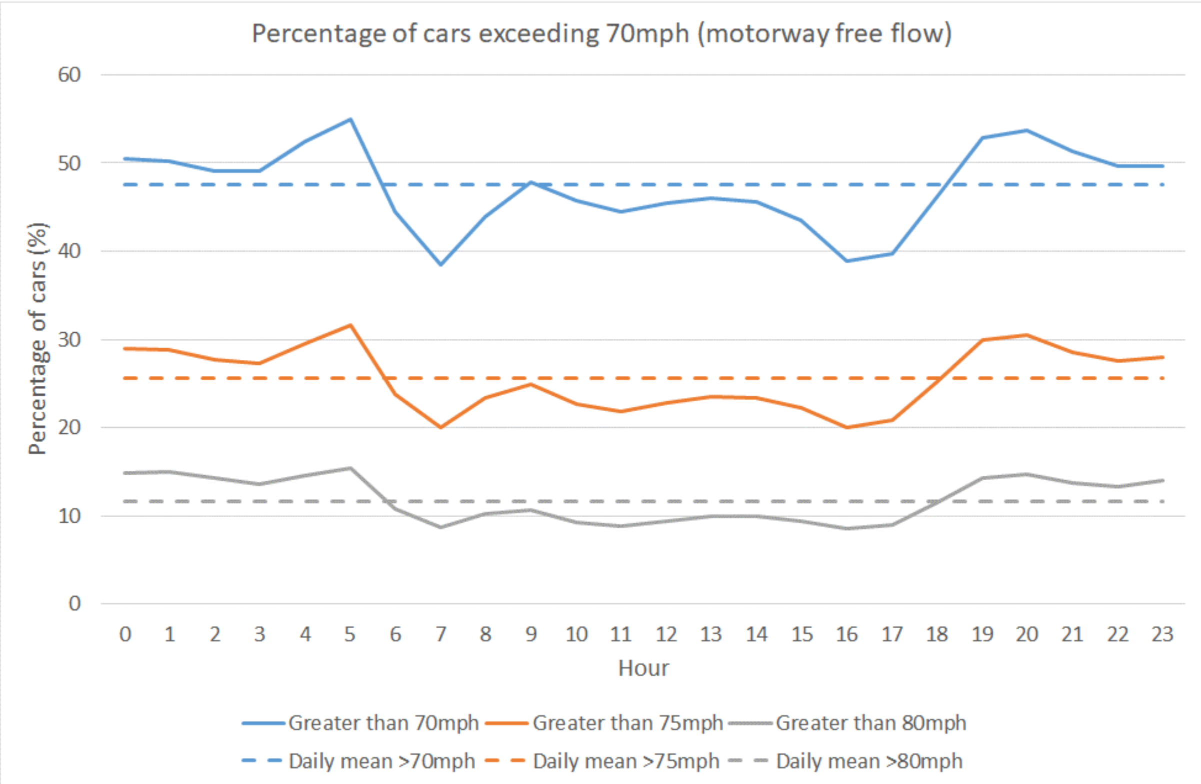

Figure 2: Percentage of passenger cars exceeding 70mph (motorway free flow)

[9] http://www.millbrook.co.uk/services/tracks-and-facilities/

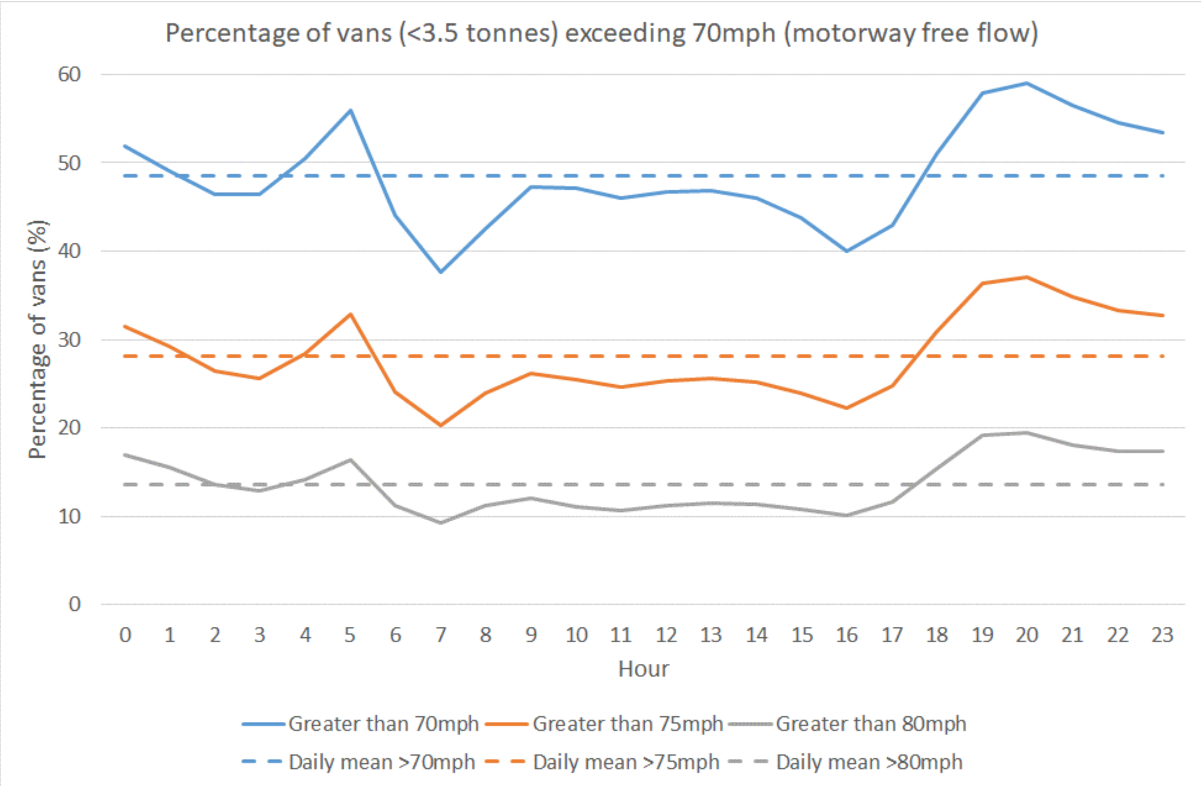

Figure 3: Percentage of vans (<3.5 tonnes) exceeding 70mph (motorway free flow)

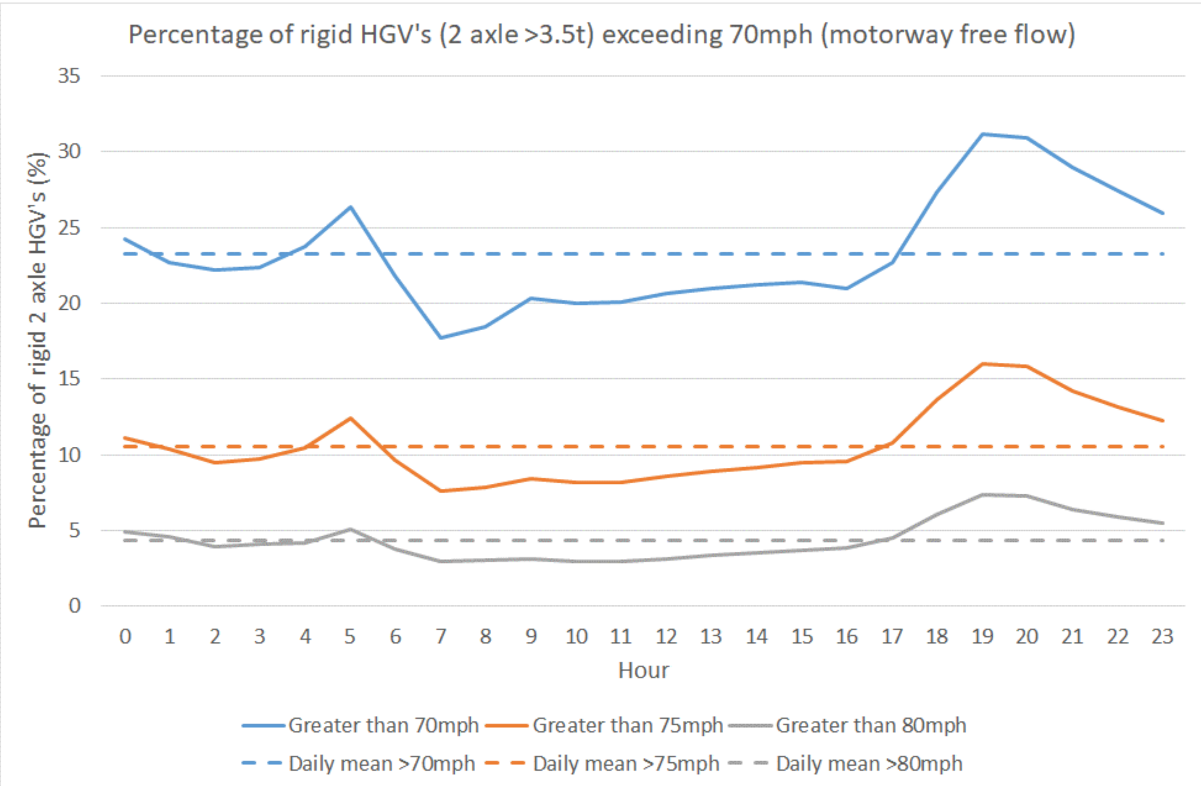

Figure 4: Percentage of rigid 2 axle HGV's (>3.5 tonnes) exceeding 70mph (motorway free flow)

8. DfT / DVSA PEMS NOx emissions raw data results

Prior to any consideration of UK motorway vehicle dynamics, or the application of any constraints relating to Highways England network link structures, Figures 5 to 10 present a comparison of the raw NO_x emission rates derived from the DfT / DVSA PEMS surveys, and the comparable EFT NO_x emission curves. It should be noted that the comparison in Figures 8, 9 and 10 for Euro 5 diesel vans should be treated with caution because of the very small sample of vehicles. The two N1 class II vehicles in the sample were a Citroen Berlingo (1560cc) and a Volkswagen Caddy (1598cc). Although these are both ‘car derived’ vans, the reference weight of the tested vehicles was between 1305kg and 1760kg, hence classifying them as N1 class II with an EU NO_x emission standard of 235mg/km, relative to the comparable Euro 5 passenger car emission standard of 180mg/km. The three N1 class III vehicles included two Ford Transits (2189cc) and a Volkswagen Transporter (1968cc).

It can be seen from Figures 5, 6, and 7 that the observed PEMS NO_x emissions rates are generally higher than the emission rates assumed in the Emissions Factor Toolkit (particularly for Euro 5 diesel cars). In addition, the elevated mid speed range NO_x emissions (termed the ‘harmonica’ effect by TNO) are visible for Euro 5 diesel cars between 65kph and 95kph, and for Euro 6 diesel cars between 65kph and 90kph.

Figures 8, 9, & 10 present the results for the Euro 5 diesel vans. Figure 8 compares the N1 class II data (2 vehicles) with the assumed NO_x emissions derived from EFT, whereas Figure 9 compares the N1 class III data (3 vehicles) with the assumed NO_x emissions derived from EFT. Figure 10 presents the combined N1 class II and class III, with the results weighted by the fleet proportions assumed in EFT at 2017 (6% N1 class I, 26% N1 class II, and 68% N1 class III), i.e. class III is given around 2.6 times the weight of class II.

It should be noted that the Emissions Factor Toolkit v8 assumes the same NO_x emissions rate for both N1 class II (1305kg to 1760kg) and N1 class III (1760kg to 3500kg). Even with the very small PEMS data sample size available from the DVSA surveys, this EFT assumption is questionable. The NO_x emission rates observed from the ‘car derived’ N1 class II diesel vans in the (very small) sample are significantly lower than the emissions rates observed from the N1 class III diesel vans. Indeed, the emission rates observed from the two N1 class II diesel vans are arguably more consistent with the EFT emission assumptions for N1 class I diesel vans, as illustrated in Figure 8.

For Euro 5 diesel vans, the ‘harmonica’ effect tends to occur at lower speeds, between 50kph and 80kph. It is also notable that NO_x emissions for the Euro 5 diesel vans tend to increase as speed increases above 80kph (50mph), particularly for the N1 class III diesel vans (reference mass 1760kg to 3500kg).

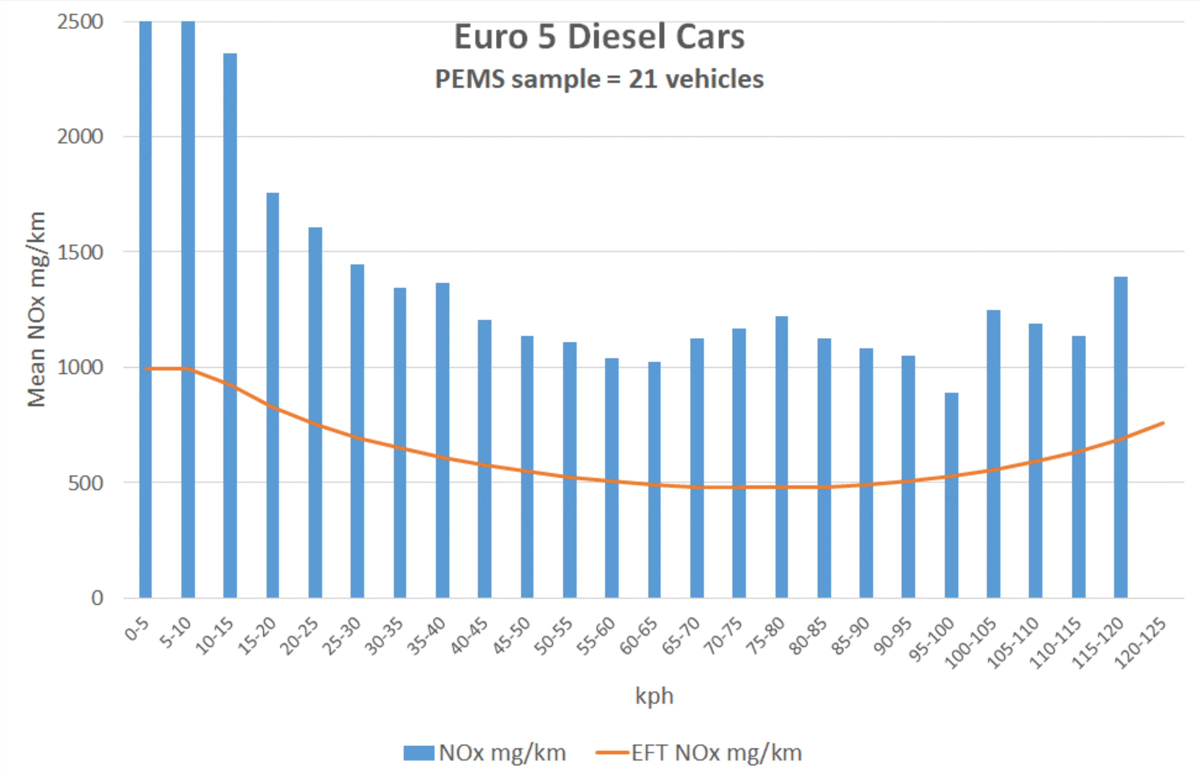

Figure 5: Comparison between DfT / DVSA PEMS data and EFT – Euro 5 diesel cars

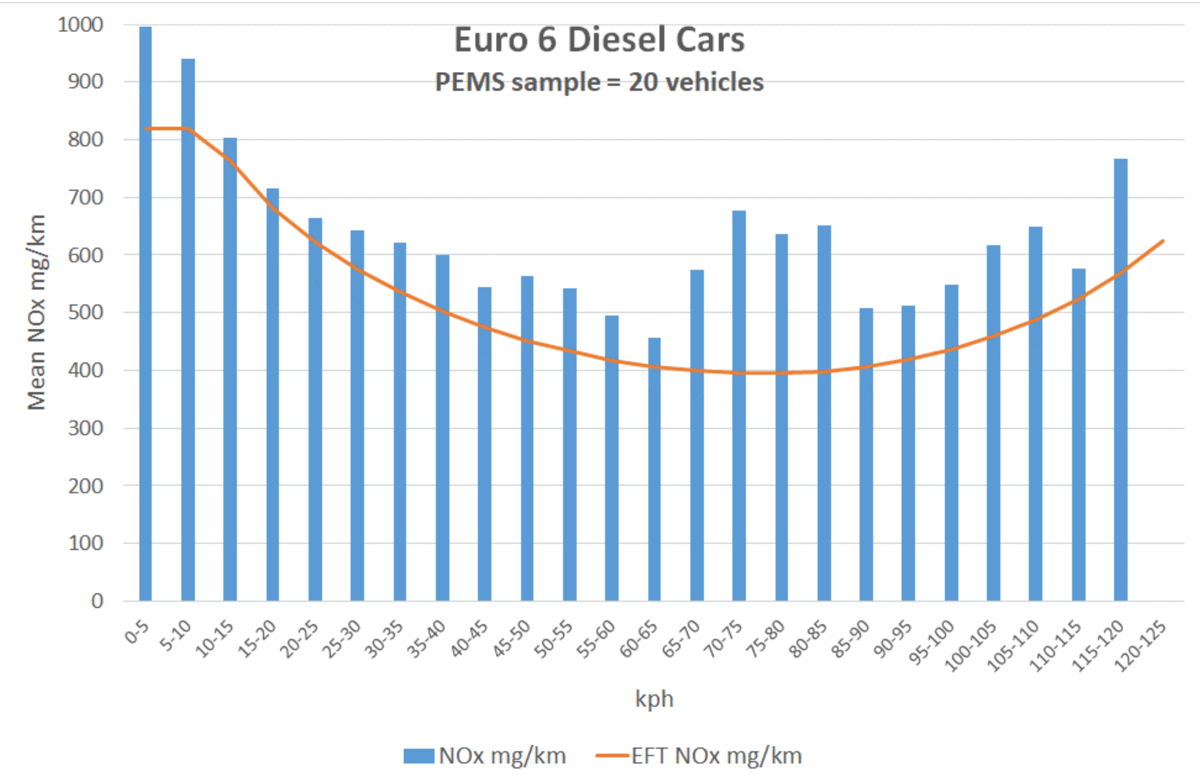

Figure 6: Comparison between DfT / DVSA PEMS data and EFT – Euro 6 diesel cars

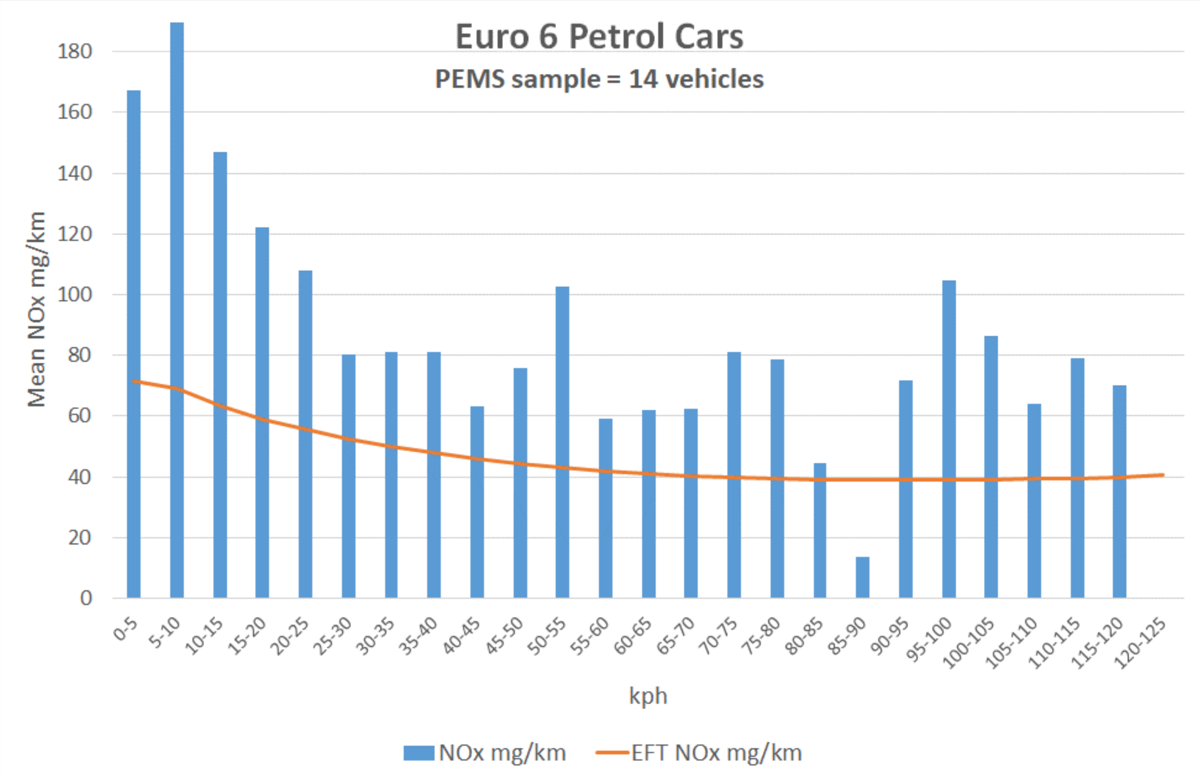

Figure 7: Comparison between DfT / DVSA PEMS data and EFT – Euro 6 petrol cars

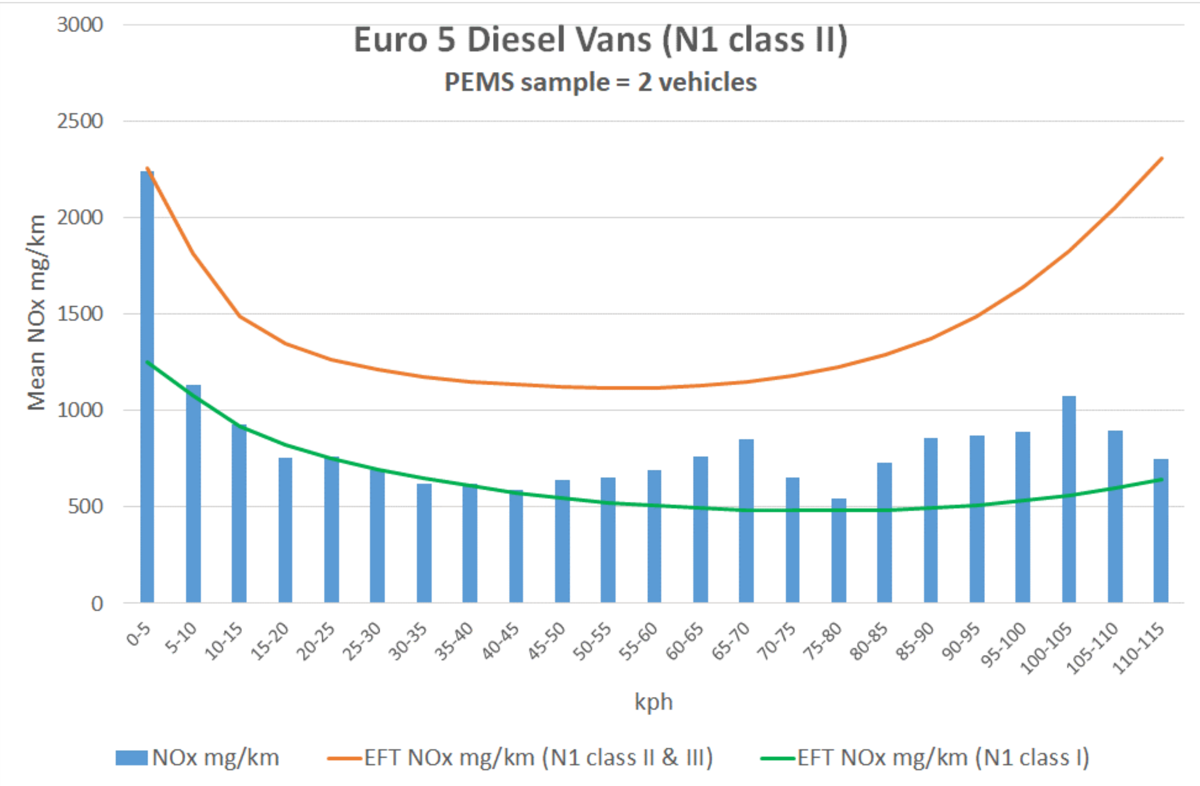

Figure 8: Comparison between DfT / DVSA PEMS data and EFT – Euro 5 diesel vans (N1 class II)

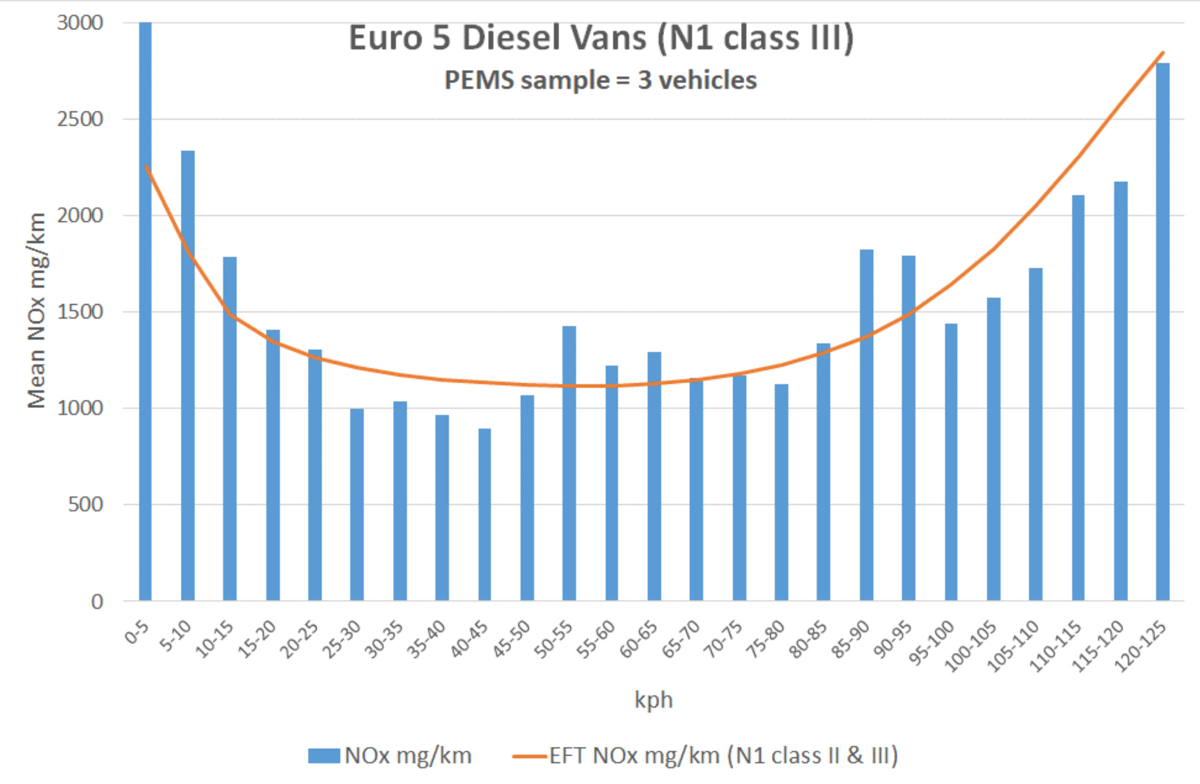

Figure 9: Comparison between DfT / DVSA PEMS data and EFT – Euro 5 diesel vans (N1 class III)

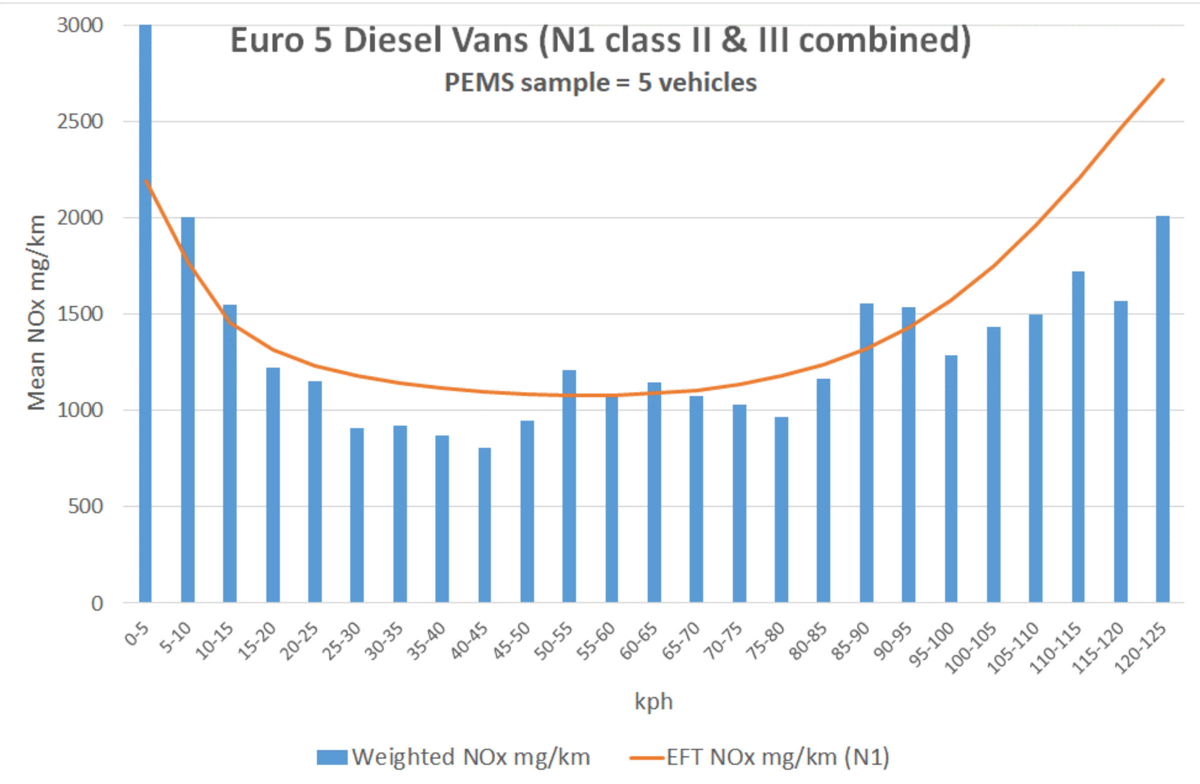

Figure 10: Comparison between DfT / DVSA PEMS data and EFT – Euro 5 diesel vans combined

9. Application of DfT / DVSA PEMS NO_x emissions data to Highways England motorway vehicle dynamics data at a link spatial resolution

The next step is to apply the observed PEMS NO_x g/sec emissions rates to the Highways England motorway vehicle dynamics data at a link spatial resolution. This entails calculating for each individual link in the Highways England data set the associated mean NO_x emissions in mg/km for each vehicle type and Euro standard. The mean surveyed link length for 'mainline' motorway links was 2.24km, for slip roads 0.83km, and for roadworks 1.44km. The calculation of mean NO_x emissions at a highway link resolution will therefore tend to 'average out' any particularly high emissions events (for example, hard acceleration), or low emission events (for example, coasting downhill), particularly for longer links. Very short links may retain and be dominated by more extreme emission events.

It should be noted that the Highways England passenger car motorway dynamics data collected in March 2017 contained only 22 motorway links (out of 486, or 4.5%) with mean speeds above 70mph. Only 4 of the 22 links had mean speeds higher than 75mph. It is therefore reasonable to conclude that the Highways England probe vehicle data set is not fully representative of 'real world' higher speed motorway driving, with reference to published DfT speed census data. The Highways England survey drivers were (understandably) generally complying with the prevailing speed limits.

Annex B presents the mean NO_x mg/km emissions calculated for the Highways England probe vehicle survey data, at highway link resolution. It is important to note that each data point in the graphs in Annex B represents a highway link, each with an associated link length, driving profile (variation in speed and acceleration), mean speed, and calculated mean NO_x mg/km emissions rate. It can be seen that the vertical distribution of the NO_x emission data points varies depending on vehicle type, fuel type and Euro standard.

These Annex B 'link' data points can be aggregated by speed bin, as presented in Figures 11 to 14. In this context, the emissions values are weighted by link length, so that short links with potentially more extreme emissions values do not dominate the calculation of the mean speed bin result. The key difference between Figures 11 to 14, and Figures 5 to 10, is that Figures 5 to 10 present raw PEMS emissions data (unconstrained by observed link characteristics), whereas Figures 11 to 14 apply the PEMS NO_x mg/second emissions data to the Highways England probe vehicle survey data (speed and acceleration profiles), aggregated at motorway link resolution. The act of calculating aggregate values at a link level resolution tends to reduce the variability in the NO_x emissions results, in comparison with the raw PEMS data. However, the 'harmonica' effect can still be seen in the results for Euro 6 diesel cars (Figure 12), and for Euro 5 diesel vans (Figure 13), although its magnitude is reduced.

For completeness, Annex E presents a summary of the calculated mean 'slip road' NO_x emissions, based on the observed Highways England probe vehicle survey dynamics aggregated at link resolution, and the available PEMS data by vehicle category.

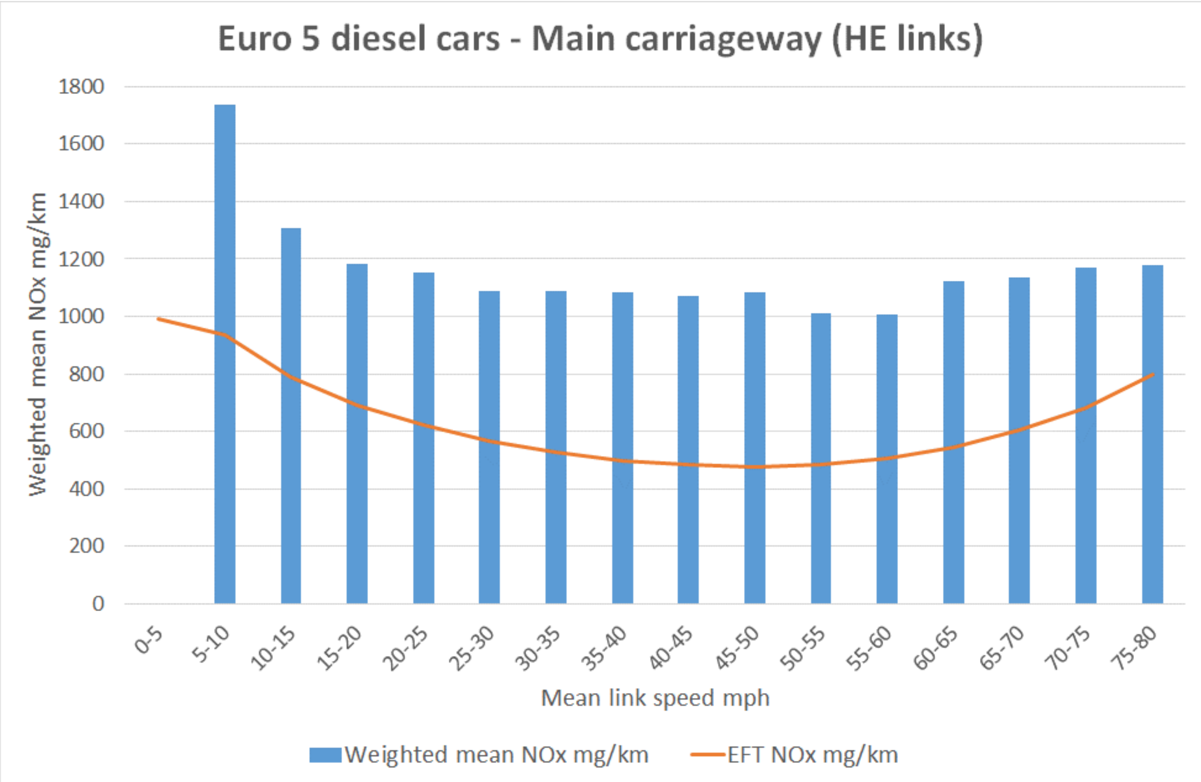

Figure 11: Highways England motorway link NO_x emissions data by speed bin – Euro 5 diesel cars

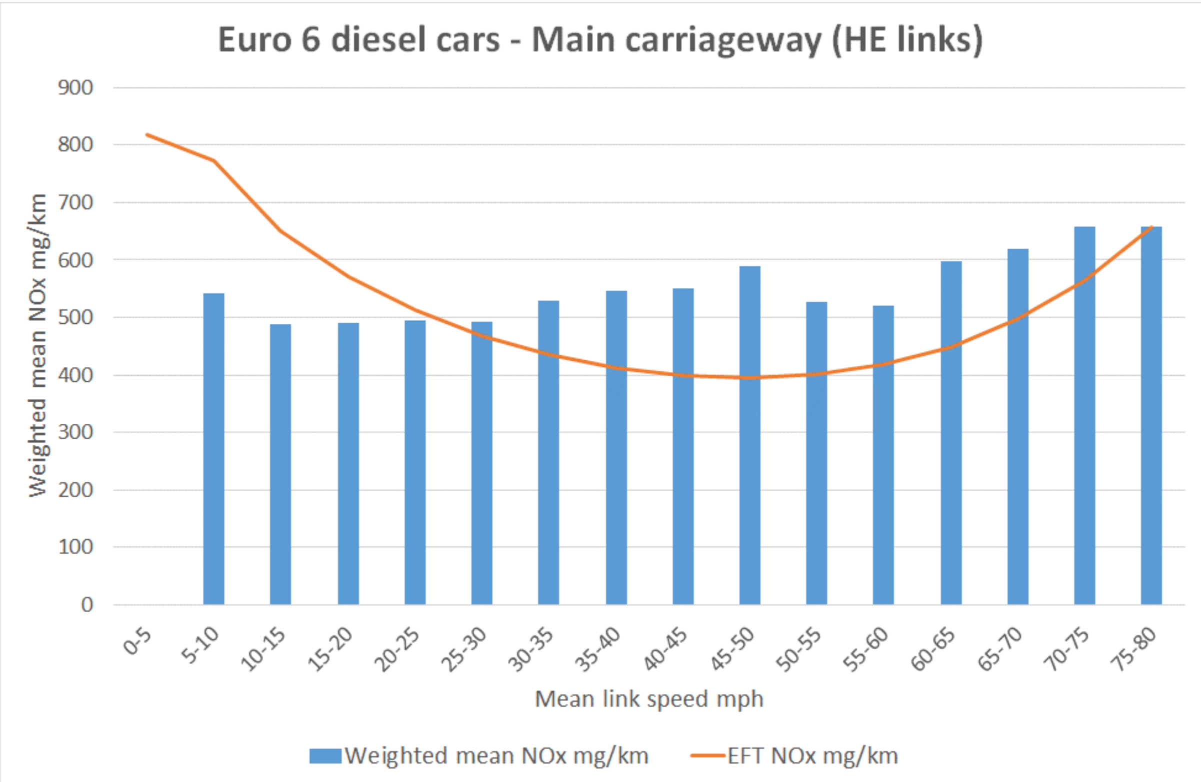

Figure 12: Highways England motorway link NO_x emissions data by speed bin – Euro 6 diesel cars

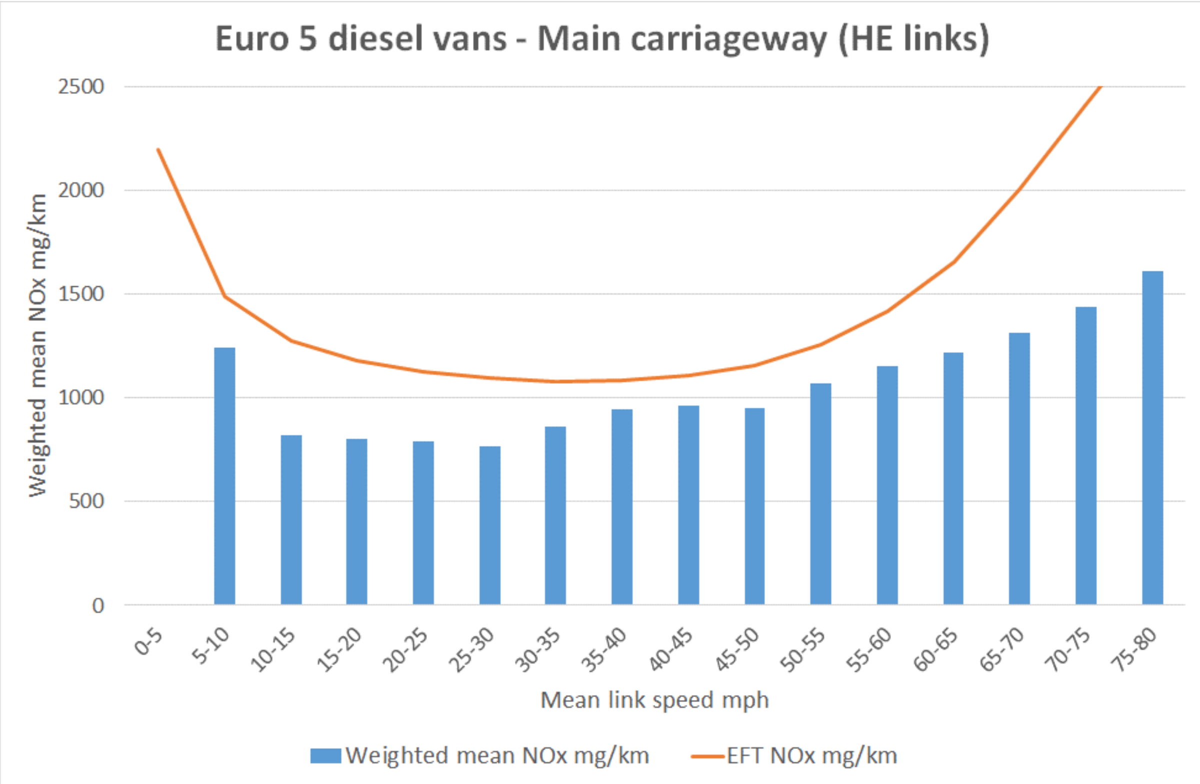

Figure 13: Highways England motorway link NO_x emissions data by speed bin – Euro 5 diesel vans

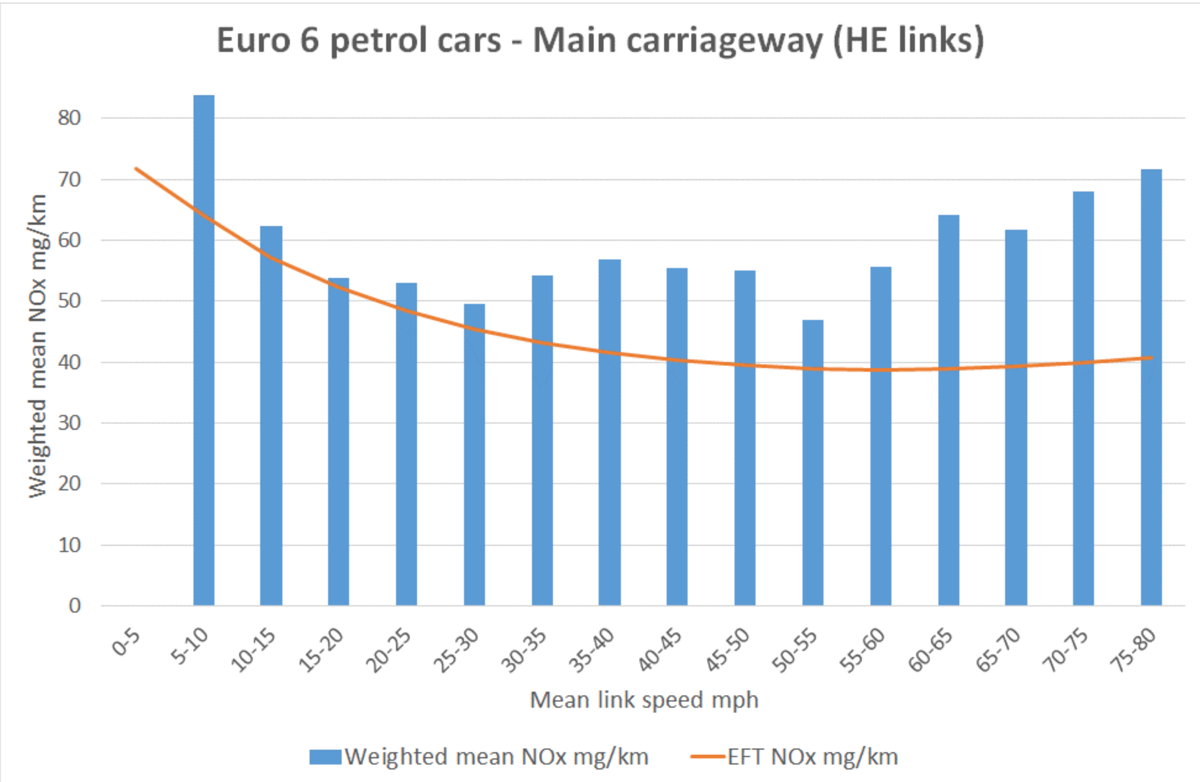

Figure 14: Highways England motorway link NO_x emissions data by speed bin – Euro 6 petrol cars

10. Derivation of revised Highways England light vehicle NO_x emission speed bands

A significant number of potential speed band permutations are possible in principle. The preferred option should address the following criteria:

- It should succeed in capturing significant differences in NO_x emissions performance with respect to speed, without unnecessary complexity;
- It should capture significant differences in NO_x emissions across different light vehicle classes, Euro standards, and fuel type;
- It should be compatible and consistent with traffic modelling assumptions and outputs;
- It should strike an appropriate balance between analytical robustness and usability;
- It should facilitate the assessment of possible future policy interventions, for example speed management.

Discussions were held with traffic modelling experts at Highways England to gain a better understanding of the context and meaning of average speed values output from macroscopic traffic assignment models, and in particular the operation of speed / flow relationships embedded within traffic model links.

Generally speaking, such traffic models have mathematical speed / flow relationships which do not exceed 70mph. WebTAG traffic modelling speed / flow curve guidance specifies a maximum speed of 118kph (73mph) for dual 3 lane motorways, and 111kph (69mph) for dual 2 lane motorways. The advice from traffic modelling experts at Highways England is that if the traffic model is predicting a mean speed for a particular time period above about 60mph, the assumed traffic conditions are essentially free flowing. However, if the traffic model is predicting a mean speed of between 50mph and 60mph, the traffic model is representing a degree of congestion where drivers are not able to attain their desired free flow speed.

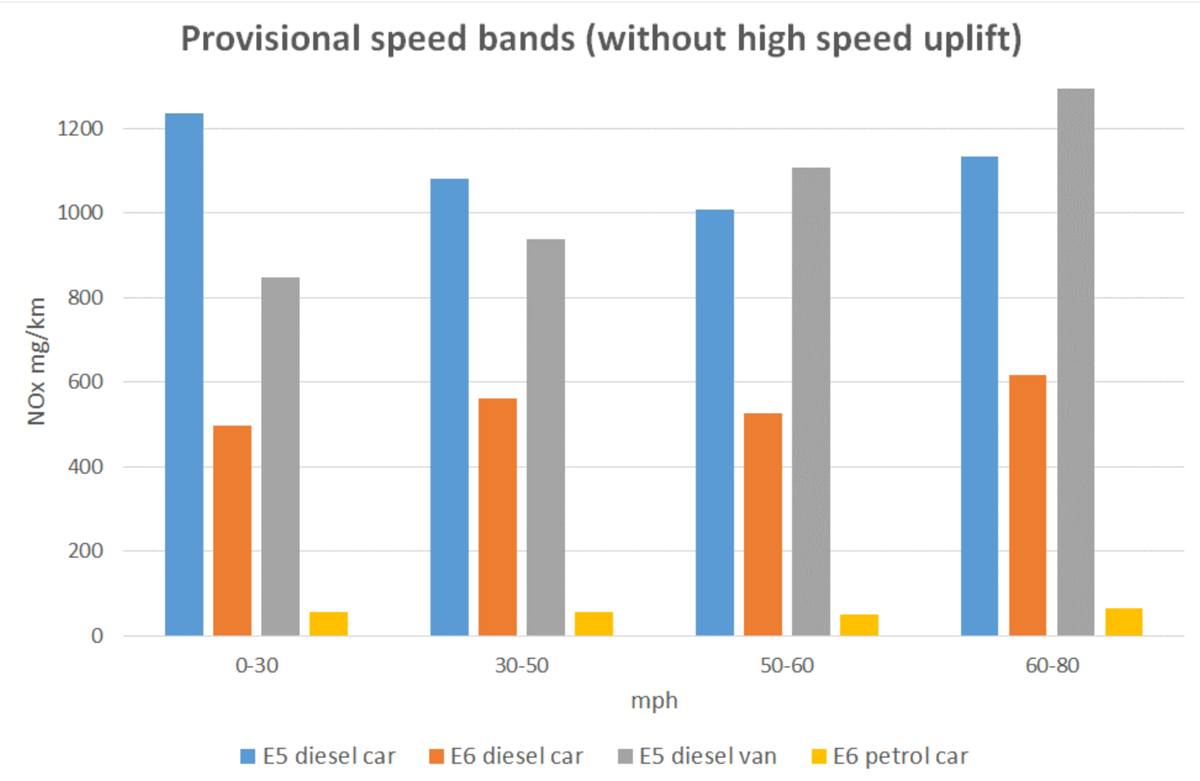

Figure 15: Provisional speed bands (without high speed uplift)

Figure 15 presents a provisional speed banding approach, based on the NO_x emissions rates calculated from the Highways England motorway link data (Figures 11 to 14). In comparison with the existing Interim Advice Note 185/15, the width of the most congested speed band is increased from 0-30kph (0-19mph) to 0-48kph (0-30mph). The lighter congestion speed band is amended from 30-80kph (19-50mph) to 48-80kph (30-50mph). A third speed band is introduced at 80-96kph (50-60mph), which generally coincides with lower levels of NO_x emissions for passenger cars, and finally a high speed band is proposed for speeds above 96kph (60mph), compared to a high speed threshold of 80kph (50mph) in Interim Advice Note 185/15.

Looking at the effect of the provisional speed bands on proposed emission rates across different Euro standards, Euro 5 diesel cars display reductions in NO_x emissions as speed increases from band 1 (heavy congestion) to band 3 (approaching free flow conditions). In band 4 (high speed operation), NO_x emissions are seen to increase as engine load increases. Euro 6 diesel cars generally have significantly lower absolute NO_x emissions rates compared to Euro 5, with a ‘flatter’ profile across the speed ranges. However, Euro 6 diesel cars still display a reduction in emissions at band 3 (between 50mph and 60mph) compared to band 2, and then an increase in emissions in band 4 (high speed operation). The small sample of Euro 5 diesel vans generally display a monotonic increase in NO_x emissions as speed increases above 80kph (50mph).

The choice of including provisional speed bands from 50-60mph (band 3), and above 60mph (band 4), is also consistent with the advice received from the traffic modelling experts regarding the practical operation of traffic assignment model speed flow curves. It should be remembered that the primary use of any revised NO_x speed band approach will be its application to traffic assignment model outputs, so this is a key issue.

It will be noted that Figure 15 is labelled ‘without high speed uplift’. It should be remembered that whilst DfT speed census statistics demonstrate the extent of higher speed (greater than 70mph) light vehicle operation (see Figures 2 and 3), neither the DfT / DVSA PEMS data collected in 2016 and 2017, nor the Highways England vehicle dynamics survey data, include higher speed operation to the extent actually observed on UK motorways. This means that we do not know (from UK PEMS data) what the NO_x emission rates are for higher speed operation, and we also do not have detailed profiles of such operation (speed and acceleration) on the motorway network in the Highways England data set.

TNO have reported NO_x emission results for surveys carried out on Dutch motorways with a 130kph speed limit in TNO report R10827[10]. Figure 16 presents an abstract from TNO R10827, illustrating the increase in NO_x emissions observed as speeds increase from 100kph (60mph) to 130kph (81mph). The TNO results suggest that NO_x emissions can be of the order of 40% higher at speeds between 70 and 80 mph, when compared to NO_x emissions at speeds between 60 and 70 mph. TNO have indicated that they would expect an increase in NO_x emissions of between 15% to 20%, based on their PEMS survey results, for every 10kph increase above 100kph[11]. This increase would need to be independently confirmed by future UK PEMS tests, but such an estimated uplift can be applied to the current Highways England speed band emission results, using the published DfT speed census data to quantify the proportion of light vehicles operating at higher speeds. A comparison between the TNO assumptions and EFT is presented in Annex D.

It is known from DfT statistics that approximately 26% of passenger cars exceed 75mph in free flow conditions, and 12% exceed 80mph. It is also known that approximately 28% of vans exceed 75mph in free flow conditions, and 14% exceed 80mph. Therefore, if we assume that a notional uplift of 30% in NO_x emissions (estimated from the TNO data)

[10] TNO report R10827 “Definitie congestie op de snelweg voor emissiefactoren” (Translation: “Definition of congestion on the highway for emission factors”). V.A.M. Heijne & N.E. Ligterink, 2017.
[11] Personal email exchange with TNO, January 2019.

is applied to those vehicles exceeding 75mph, the NO_x emissions associated with band 4 (high speed operation above 60mph) is increased, as illustrated in Figure 17.

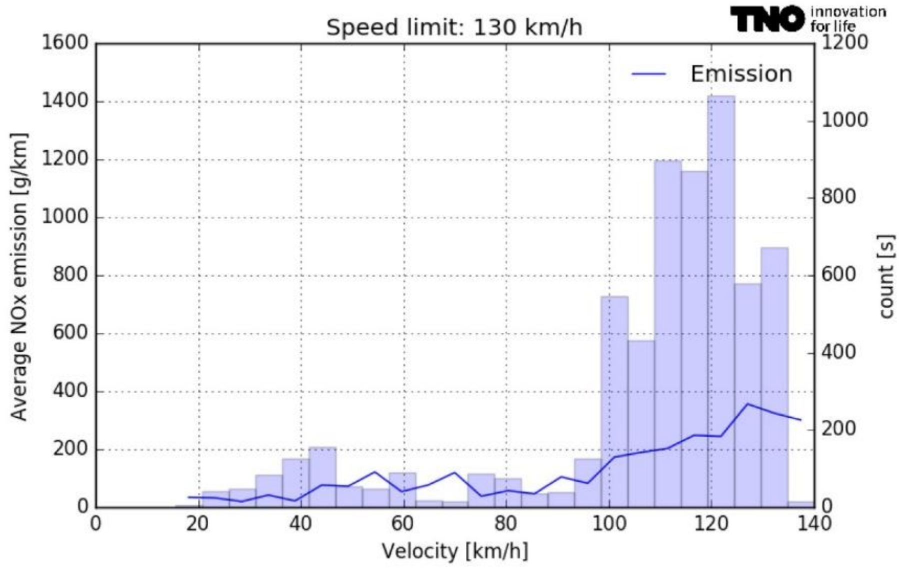

Figure 16: TNO NO_x emission results for 130kph speed limit

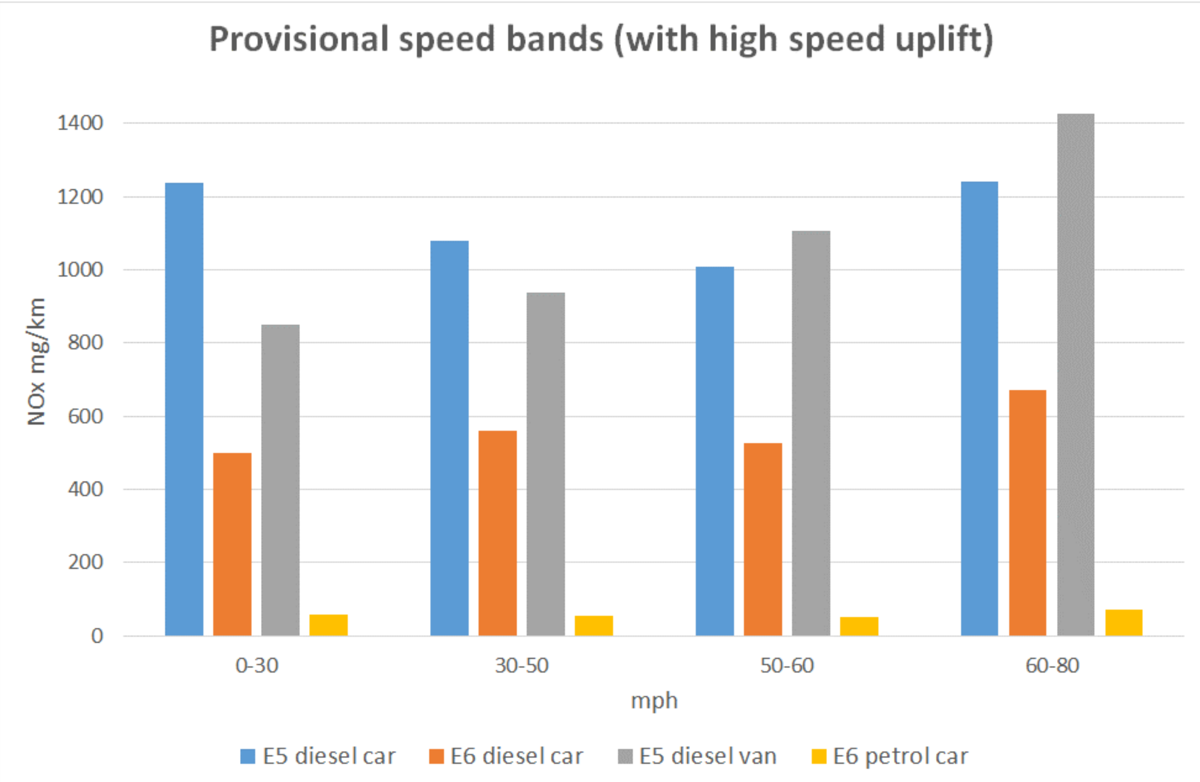

Figure 17: Provisional speed bands (with high speed uplift)

11. Impact of speed management interventions

One of the potential policy interventions to reduce NO_x exhaust emissions is to manage motorway speeds, for example using average speed cameras. In order to quantify the potential impact of such interventions, it is necessary to quantify emission rates at different speeds. Estimates have been made of the differences in emission rates by utilising the emission rate information presented in Annex A, combined with samples of vehicle velocity profile data obtained from instrumented vehicles. Figures 18, 19, and 20 present samples of vehicle velocity profile data which are broadly consistent with the application of average speed limits at 70mph, 60mph, and 50mph respectively. In the case of 60mph and 50mph, these profiles are derived from existing motorway speed management interventions. In the case of 70mph, the data is obtained mainly from the application of cruise control in non-congested traffic conditions. Tables 1, 2, and 3 present summary statistics for each of the data sets, together with the calculated NO_x mg/km emissions values associated with each velocity profile.

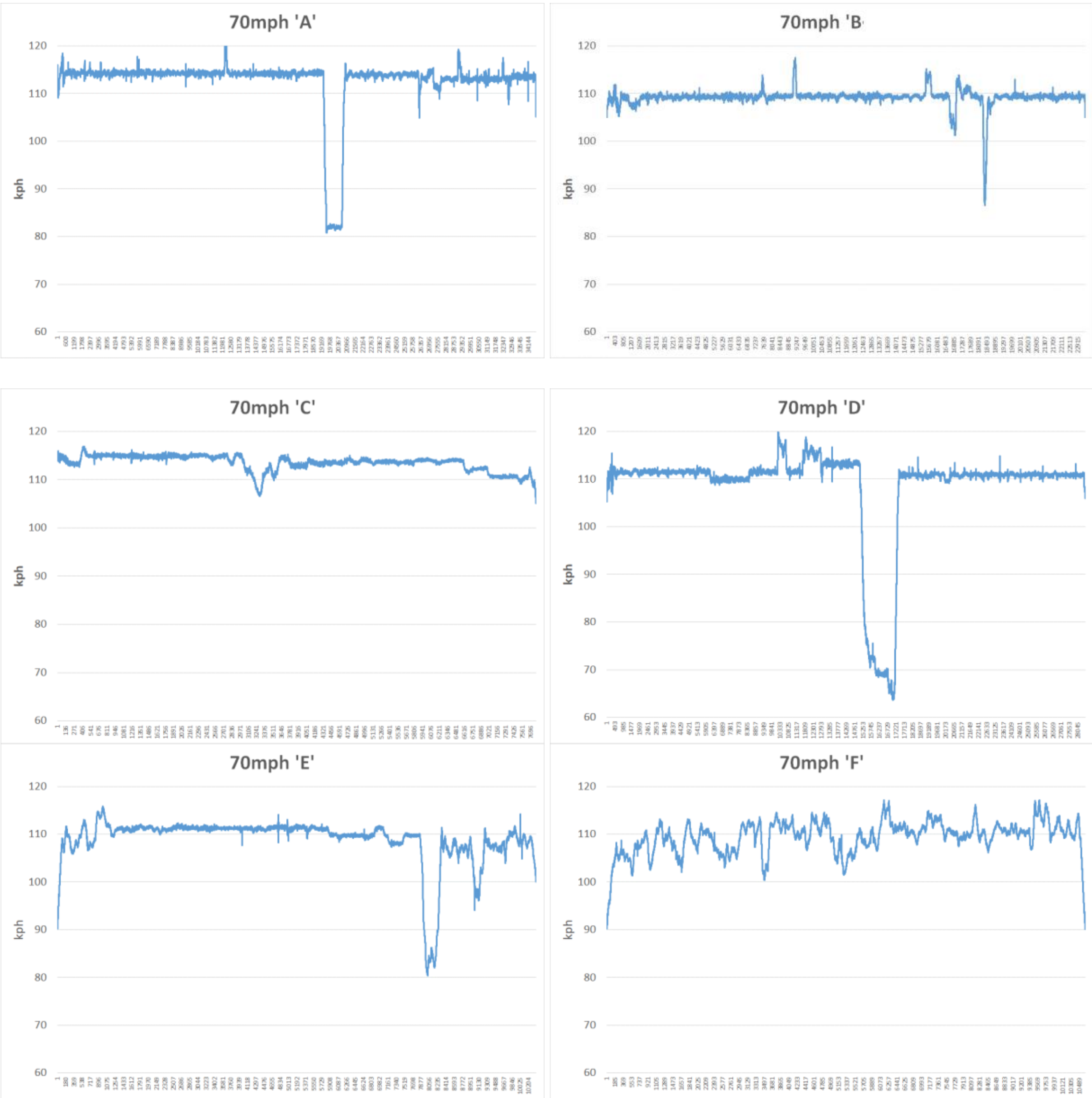

Figure 18: Sample 70mph 'speed management' velocity profiles

Table 1: 70mph 'speed management' NO_x emission rates

	Mean kph	Distance km	Max kph	Min kph	SD kph	NO_x mg/km			
						Euro 5 diesel cars	**Euro 6 diesel cars**	**Euro 5 diesel vans**	**Euro 6 petrol cars**
70mph 'A'	112.7	108.6	122.5	80.8	6.0	1247	690	1597	75
70mph 'B'	109.2	70.6	117.5	86.5	1.9	1198	671	1389	61
70mph 'C'	113.5	24.5	116.9	105.1	1.7	1275	699	1635	74
70mph 'D'	108.5	85.9	119.8	63.7	10.5	1180	654	1374	62
70mph 'E'	108.9	31.3	115.9	80.4	5.1	1189	666	1371	62
70mph 'F'	109.4	32.3	117.1	90.3	3.5	1183	659	1381	64
Mean						***1212***	***673***	***1458***	***66***

Figures 21, 22, 23 and 24 present the upper and lower ranges of NO_x mg/km emissions for each speed limit intervention (obtained from Tables 1, 2, and 3), for Euro 5 diesel cars, Euro 6 diesel cars, Euro 5 diesel vans, and Euro 6 petrol cars respectively. It can be seen from these examples that Euro 5 and Euro 6 diesel cars emit minimum emissions with a 60mph speed limit, with higher emission rates with both 70mph and 50mph average speed limits.

The Euro 5 diesel vans respond to speed limit interventions in a different way. NO_x mg/km emissions are lowest with a 50mph speed limit, and increase as speed increases to 60mph and 70mph. Emissions from Euro 5 diesel vans at 70mph are significantly higher than at 60mph or 50mph. Finally, Figure 24 presents the results for Euro 6 petrol cars. Whilst the absolute level of NO_x emissions from the Euro 6 petrol cars is substantially lower than from Euro 6 diesel cars, it is notable that whilst the highest emissions are observed with a 70mph speed limit, there is significant variability in NO_x emissions with a 50mph speed limit.

From these simple examples, the results indicate that an average motorway speed limit of 60mph would probably be the most effective intervention to reduce NO_x emissions from the overall light vehicle fleet.

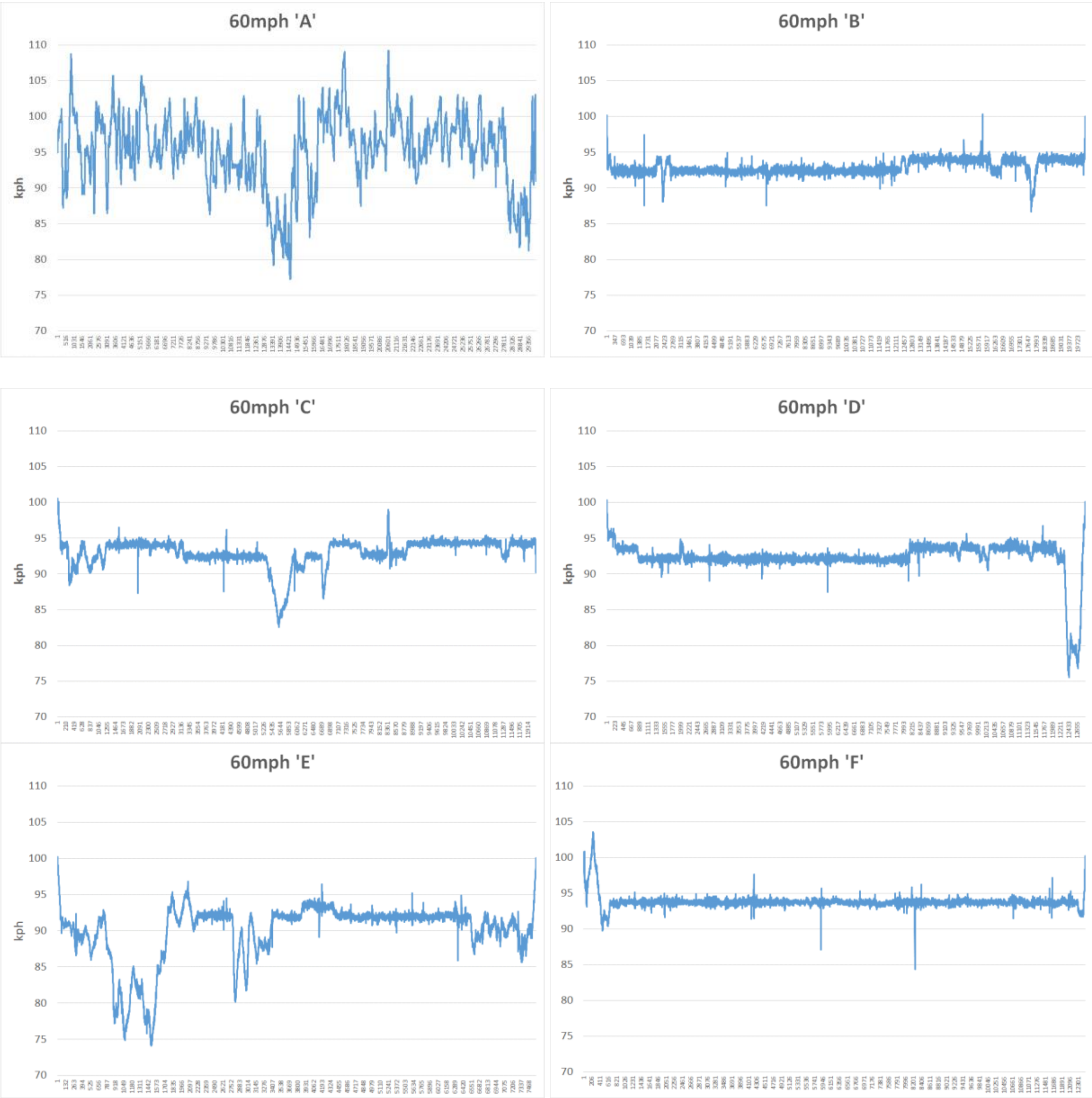

Figure 19: Sample 60mph 'speed management' velocity profiles

Table 2: 60mph 'speed management' NO_x emission rates

	Mean kph	Distance km	Max kph	Min kph	SD kph	NO_x mg/km			
						Euro 5 diesel cars	Euro 6 diesel cars	Euro 5 diesel vans	Euro 6 petrol cars
60mph 'A'	95.3	78.9	109.2	77.3	5.1	945	468	1100	53
60mph 'B'	92.9	51.7	100.3	86.6	1.0	946	481	1361	65
60mph 'C'	93.0	31.3	100.6	82.5	2.0	879	439	1289	59
60mph 'D'	92.3	33.0	100.4	75.6	2.5	980	506	1375	67
60mph 'E'	90.0	18.9	100.2	74.1	4.1	1056	568	1386	66
60mph 'F'	93.8	32.5	103.6	84.4	1.0	879	439	1300	60
Mean						***948***	***484***	***1302***	***62***

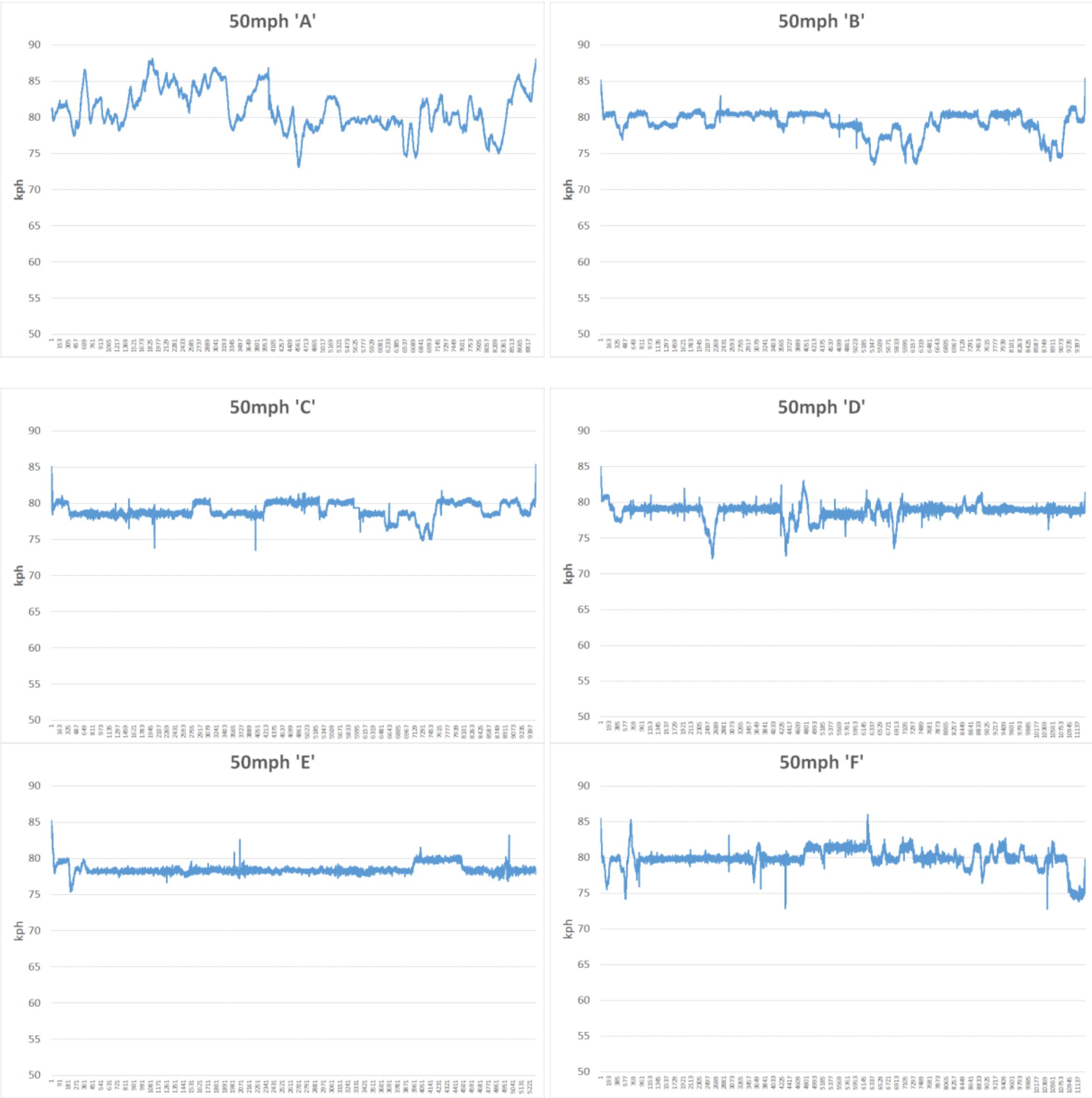

Figure 20: Sample 50mph 'speed management' velocity profiles

Table 3: 50mph 'speed management' NO_x emission rates

	Mean kph	Distance km	Max kph	Min kph	SD kph	NO_x mg/km			
						Euro 5 diesel cars	Euro 6 diesel cars	Euro 5 diesel vans	Euro 6 petrol cars
50mph 'A'	81.1	20.2	88.1	73.1	2.9	1084	584	920	43
50mph 'B'	79.2	21.0	85.3	73.4	1.7	1130	635	940	60
50mph 'C'	79.0	20.9	85.3	73.5	1.1	1133	648	916	68
50mph 'D'	78.8	24.8	85.0	72.1	1.1	1179	683	1002	73
50mph 'E'	78.5	11.5	85.2	75.3	0.7	1169	677	981	73
50mph 'F'	79.9	25.1	86.0	72.8	1.4	1202	701	1081	65
Mean						***1150***	***655***	***973***	***64***

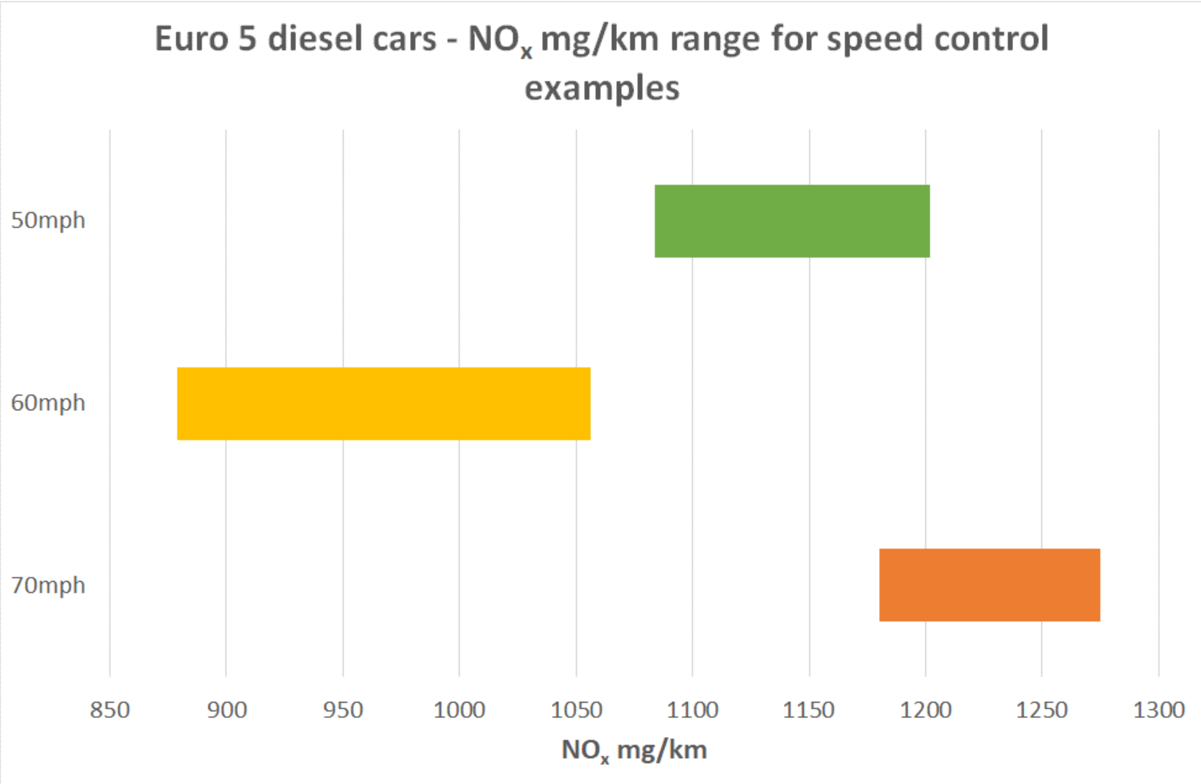

Figure 21: NO$_x$ mg/km ranges for speed control examples – Euro 5 diesel cars

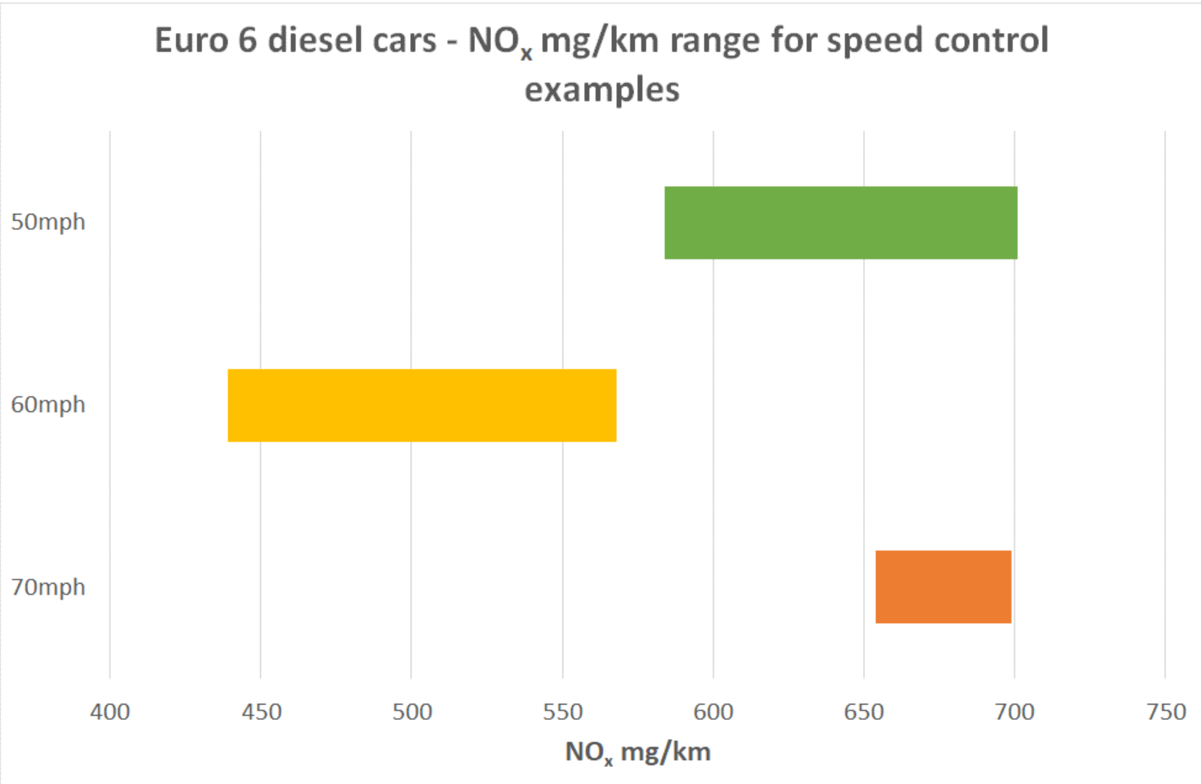

Figure 22: NO$_x$ mg/km ranges for speed control examples – Euro 6 diesel cars

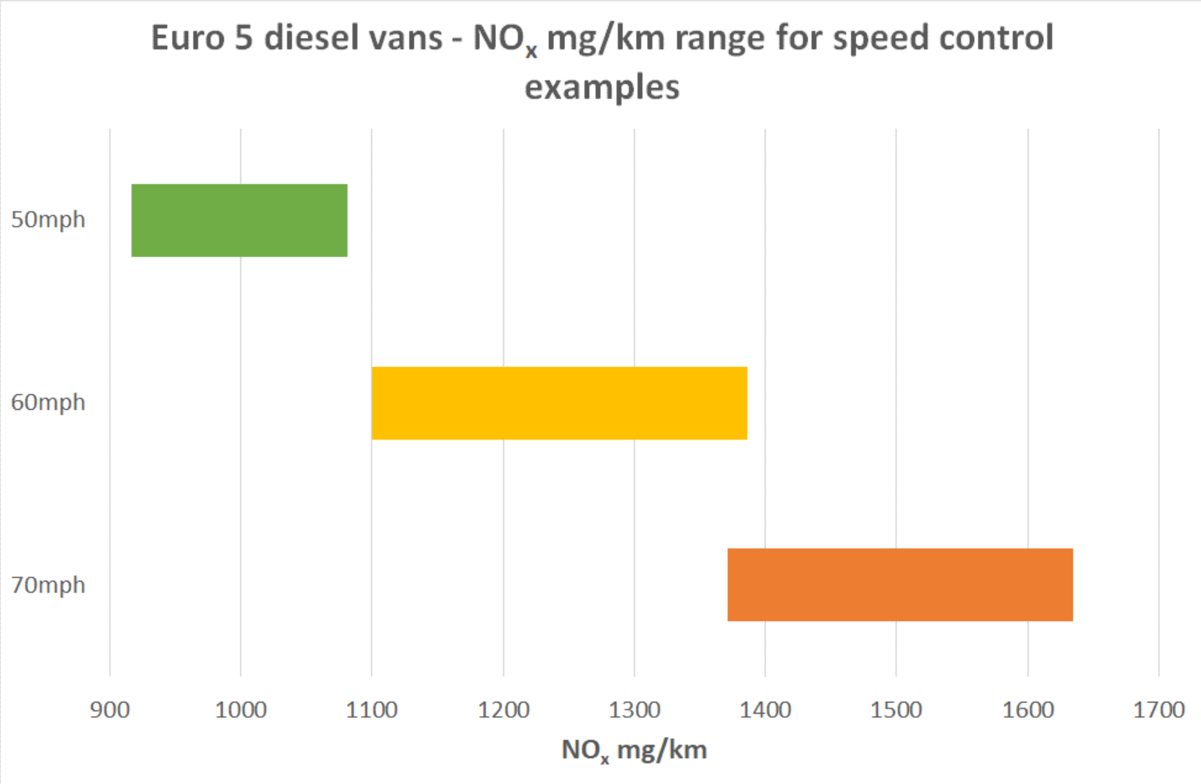

Figure 23: NO_x mg/km ranges for speed control examples – Euro 5 diesel vans

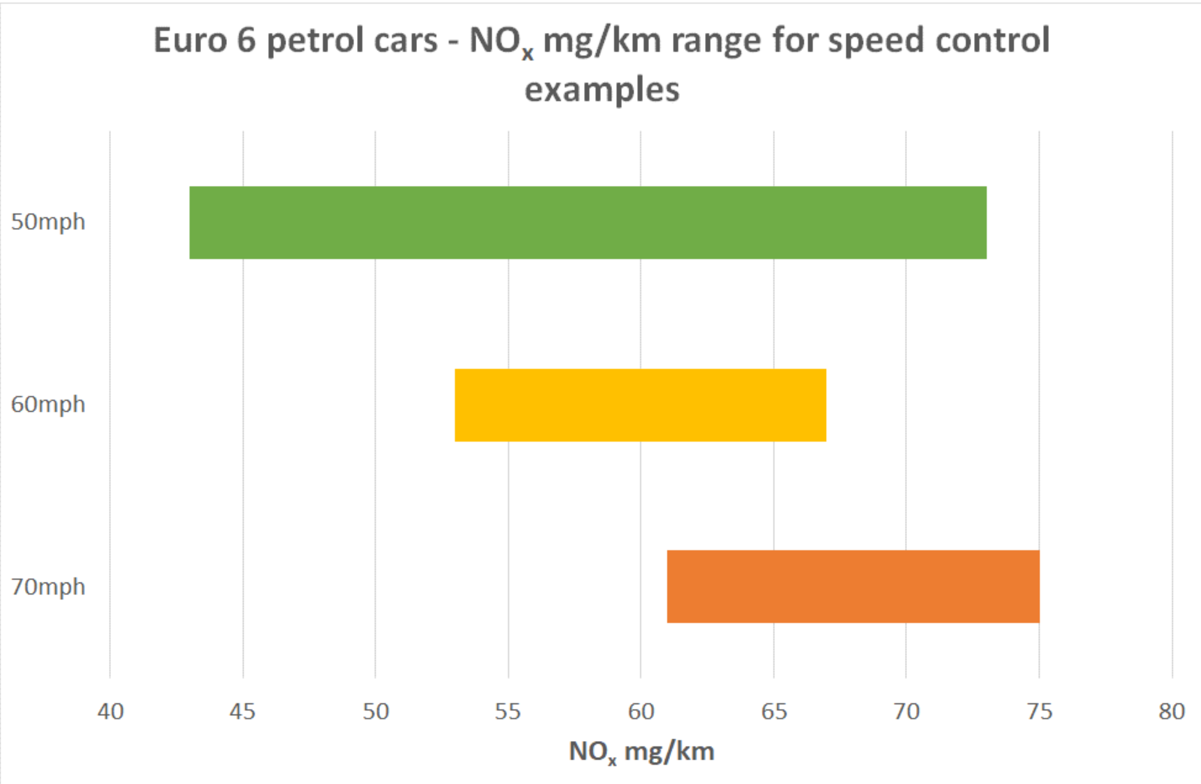

Figure 24: NO_x mg/km ranges for speed control examples – Euro 6 petrol cars

12. Light vehicle NO_x reduction benefits of motorway speed management

Section 11 estimated the NO_x mg/km emission rates for speed management interventions at 50mph, 60mph, and 70mph. Figures 21 to 24 illustrated the calculated upper and lower emission rate ranges of with each intervention for a sample of velocity profiles.

To estimate the potential benefits of such speed management interventions in terms of absolute reductions in NO_x emissions, these 'higher impact' and 'lower impact' emission rate constraints were applied to the calculated emission rates for the Highways England 'link' data for Euro 5 diesel cars, Euro 6 diesel cars, Euro 5 diesel vans, and Euro 6 petrol cars (as previously presented in Figures 11 to 14). For the purpose of calculation, it was assumed that 10,000 diesel and petrol light vehicles (M1 and N1) travelled 1km. The four groups of light vehicles identified above comprise 6050 vehicles out of 10,000, the remainder (for which no PEMS data are available) being Euro 5 and older petrol cars (3218), petrol vans of all Euro standards (68), and Euro 6 diesel vans (664). Proportions of light vehicle groups are based on DfT table SPE0111 (for relative proportions of cars and vans on the motorway), and EFTv8 for proportions of light vehicles by Euro class. Potential benefits relating to NO_x reductions from these other light vehicle groups, in particular Euro 6 vans, are ignored. It should also be remembered that the available PEMS data for Euro 5 vans is limited to only 5 vehicles (two class II, and three class III). As described in section 10, it is assumed that real world high speed (>70mph) NO_x emission rates exceed the rates observed in the UK PEMS surveys (where PEMS survey speeds rarely exceeded 75mph). For the proportions of light vehicles which do exceed the 70mph speed limit (derived from DfT statistics table SPE0111), it is assumed that emission rates are uplifted 15% higher for speeds between 75 and 80mph, and uplifted 30% higher for speeds in excess of 80mph.

The upper and lower NO_x emission rates presented in Figures 21 to 24 for different speed management interventions are applied to the Highways England 'link' data, together with the high speed uplift values previously discussed. Table 4 presents the calculated changes in emission levels for the four groups of vehicles, based on the above assumptions, relative to a 2017 base case (100%). So, with 50mph speed control, Euro 5 diesel cars emissions are reduced by 10.2% with the highest level of impact, 4.8% with the lowest level of impact, with a mean reduction of 6.3%, relative to the calculated Highways England 'link' emission rates, including high speed uplift.

Table 4: Percentage NO_x emissions reduction relative to 2017 base case with speed management interventions

	Euro 5 diesel cars	Euro 6 diesel cars	Euro 5 diesel vans	Euro 6 petrol cars	Total
50mph speed control					
Higher impact	-10.2%	-12.4%	-34.9%	-35.4%	-20.0%
Lower impact	-4.8%	-3.9%	-23.7%	-3.7%	-11.5%
Mean impact	*-6.3%*	*-5.8%*	*-31.0%*	*-8.4%*	*-15.2%*
60mph speed control					
Higher impact	-24.4%	-30.9%	-22.1%	-21.3%	-24.4%
Lower impact	-12.1%	-14.4%	-8.1%	-6.3%	-10.9%
Mean impact	*-19.6%*	*-25.1%*	*-11.2%*	*-10.1%*	*-17.1%*
70mph speed control					
Higher impact	-5.2%	-5.9%	-8.6%	-10.5%	-6.7%
Lower impact	-3.2%	-4.0%	-2.4%	-2.9%	-3.0%
Mean impact	*-4.6%*	*-5.0%*	*-5.9%*	*-7.0%*	*-5.2%*

Figures 25, 26, and 27 present the absolute changes on NO_x emissions (in grams) for the 6050 total vehicles over the four groups of vehicles over a distance of 1km. It can be seen that different levels of speed management intervention impact the four groups of vehicles in different ways. The 50mph speed control intervention has a particularly significant impact on emissions from Euro 5 diesel vans (reduced by between 23.7% and 34.9%). In contrast, the 60mph speed control intervention has the most significant impact on emissions from diesel cars, where Euro 5 diesel car emissions are reduced by between 12.1% and 24.4%, and Euro 6 diesel car emissions are reduced by between 14.4% and 30.9%.

Considering aggregate NO_x emissions across all four vehicle groups combined, the 60mph speed control intervention has the most significant impact, reducing emissions by between 10.9% and 24.4%, with an estimated mean reduction of 17.1% for these particular light vehicles. The 50mph speed control intervention is second best, reducing emissions by between 11.5% and 20.0%, with an estimated mean reduction of 15.2% (with the largest reduction being associated with Euro 5 van emissions). Finally, the 70mph speed control intervention reduces emissions by between 3.0% and 6.7%, with an estimated mean reduction of 5.2%, with most of the reduction being associated with the removal of 'high speed' (>70mph) operation generally, and reduction in Euro 5 diesel van emissions.

Again, it should be noted that potential emission reductions from 3950 out of 10,000 light diesel and petrol vehicles (39.5%) are excluded because no PEMS emission data is available for Euro 5 and older petrol cars, petrol vans of all Euro standards, and Euro 6 diesel vans. In addition, PEMS data is lacking for N1 vans of all weight classes.

Nevertheless, if the objective is to reduce motorway NO_x emissions from light vehicles using speed management, the available evidence at the present time indicates that speed control at 60mph (enforced with average speed cameras) is the most effective emissions reduction option.

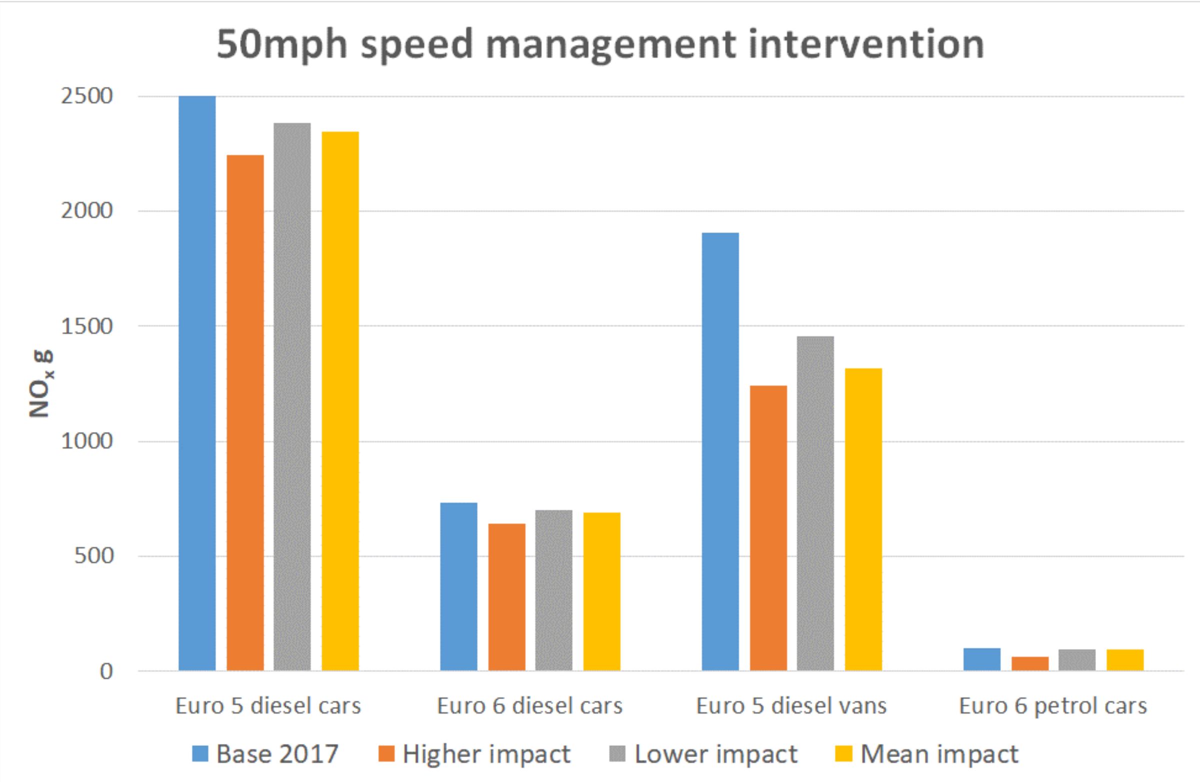

Figure 25: Reduction in NO_x emissions – 50mph speed control

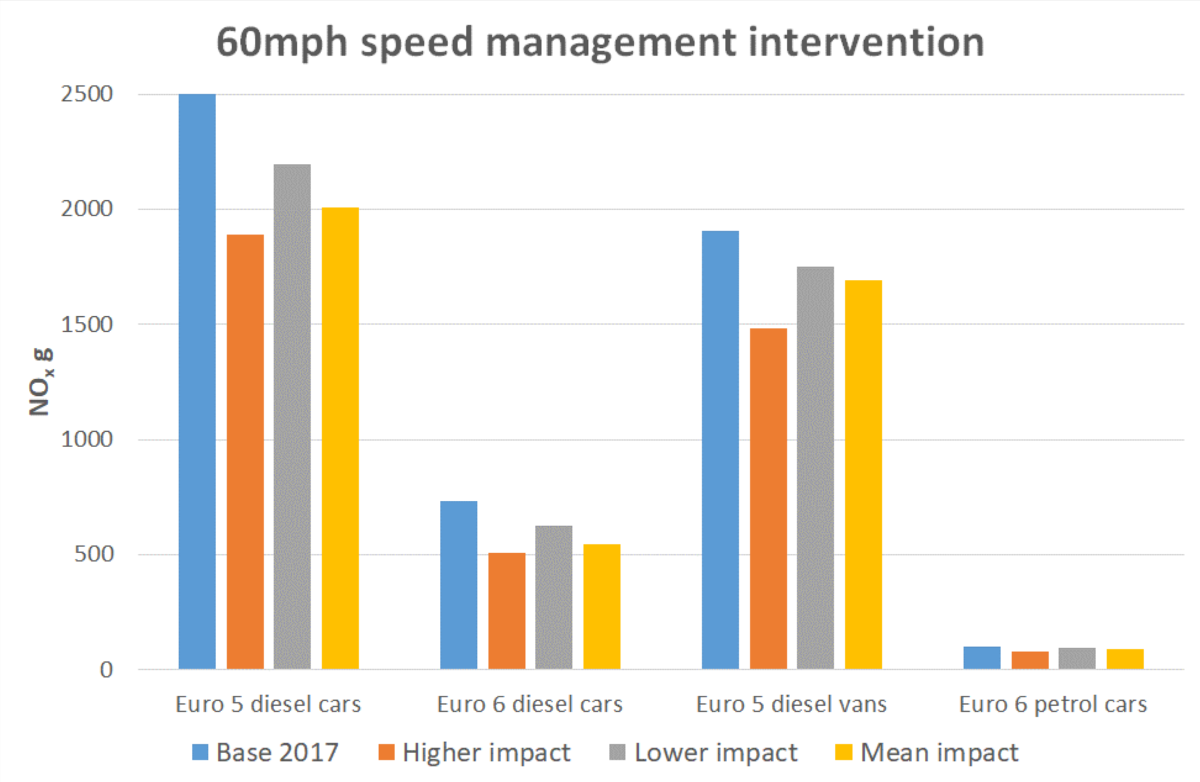

Figure 26: Reduction in NO_x emissions – 60mph speed control

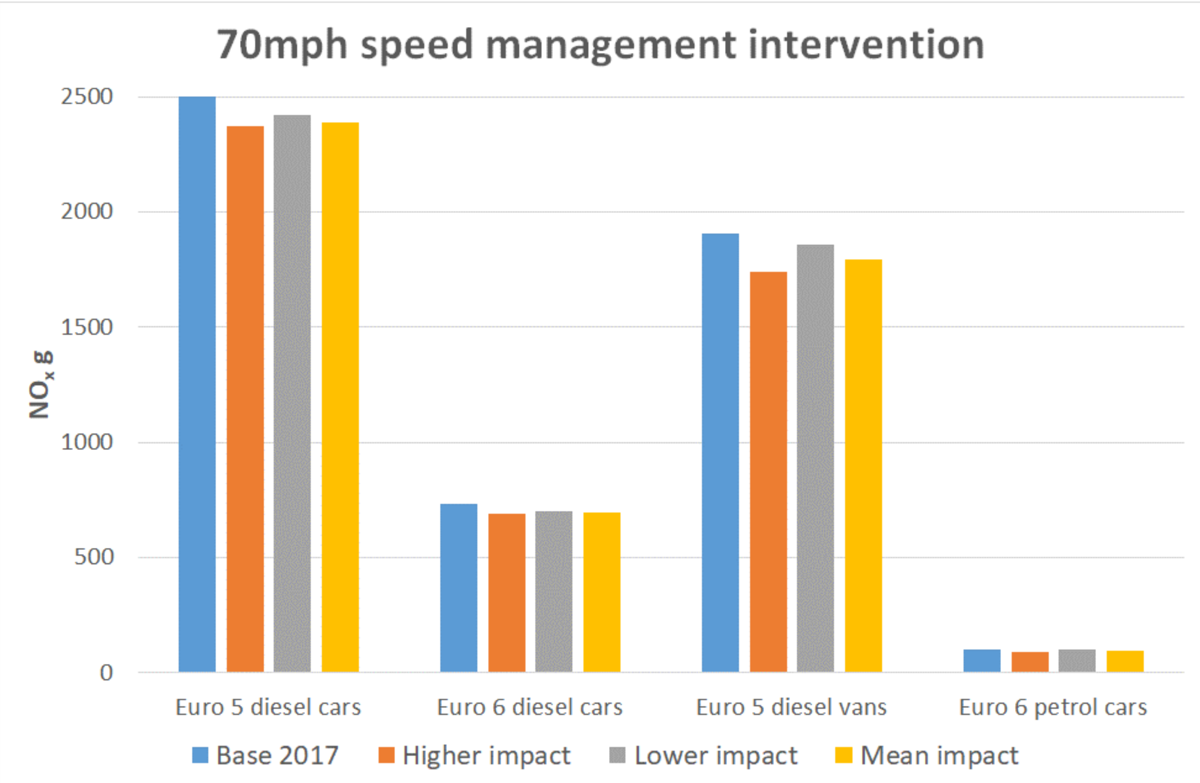

Figure 27: Reduction in NO_x emissions – 70mph speed control

13. Recommended Approach to Speed bands

Light duty vehicle speed bands

Informed by the information presented in this note, speed bands have been generated which will replace the current speed bands utilised in Interim Advice Note (IAN) 185/15. Based on the available evidence it is recommended that four speed bands are utilised for motorways as well as urban roads, which will capture the higher emissions at higher speeds.

The speed bands have been generated from the latest available version of the emission factor toolkit, EFTv9.0 dated May 2019. Whilst the analysis of available UK PEMS data has informed decision making, consistency with the Emission Factor Toolkit is ultimately considered important in the context of wider air quality policy. It should also be noted that the existing UK PEMS data sets in the public domain are incomplete, and do not adequately represent the whole UK vehicle fleet.

The urban speed bands will remain unchanged from the approach generated in IAN 185/15, which is the production of an average emission rate directly from EFT for the speeds that reside within the various speed bands as presented in Table 5.

Table 5: Speed Bands for Urban Roads.

Start (Speed kph)	End (Speed kph)	Speed Band
5	20	Urban Heavy Congestion
20	45	Urban Light Congestion
45	80	Urban Free Flow
80	112	Urban High Speed

The motorway speed bands have been adapted from the current IAN 185/15 approach due to the following;

1. The evidence collected does not support an emission reduction at high speeds;
2. The 'harmonica' effect during light congestion needs to be incorporated into the speed bands.

To generate the motorway speed bands the emission factor toolkit was run for each speed from 5 to 140 kph for Light Duty Vehicles (LDV) which includes cars and vans. To generate the speed bands the average emissions were calculated between the speeds presented in Table 6. The speeds chosen were based on the evidence obtained as part of this research.

Table 6: Speed Bands for Motorways.

Start (Speed kph)	End (Speed kph)	Speed Band
5	48	Motorway Heavy Congestion
48	80	Motorway Light Congestion
80	96	Motorway Free Flow
96	140	Motorway High Speed

For the calculation of the appropriate emission rate for the 'Motorway High Speed' band (greater than 96kph, or 60mph), it was necessary to make some assumptions regarding the distribution of speeds for cars and vans travelling on the UK motorway network with a 70mph speed limit in uncongested conditions without speed enforcement. Reference was made to the published DfT statistics Table SPE0111: 'Free flow vehicle speeds by road type and vehicle type in Great Britain, 2018'. These light vehicle speed distribution assumptions for motorways are summarised in Table 7. The NO_x emission rates obtained from EFT for the 'Motorway High Speed' band were weighted by the proportions presented in Table 8 in order to obtain a representative NO_x emission rate for the 'Motorway High Speed' band for light duty vehicles.

Table 7: Assumed distribution of motorway light vehicle speeds for 'Motorway High Speed' band. Based on DfT statistics Table SPE0111, 2018.

Speed	Cars	Vans
Under 50 mph	0.045	0.046
50-54 mph	0.046	0.054
55-59 mph	0.085	0.086
60-64 mph	0.144	0.138
65-69 mph	0.222	0.205
70-74 mph	0.217	0.205
75-79 mph	0.135	0.142
80-89 mph	0.093	0.107
90 mph and over	0.013	0.018
Total	**1.000**	**1.000**

The previous investigations into the relationship between vehicle dynamics effects and rates of NO_x emissions (termed by TNO as the 'harmonica' effect) indicated that NO_x emission rates within the 'Motorway Light Congestion' speed band (48-80 kph) would probably be underestimated if NO_x emissions were based simply upon EFT emission rates within this speed range. The analysis of available PEMS data and vehicle dynamics data indicated that NO_x emissions during 'Motorway Light Congestion' (48-80 kph) were approximately 7% higher than during 'Motorway Free Flow' conditions (80-96 kph) for Euro 5 and Euro 6 diesel cars (9% higher for Euro 6 petrol cars). Results for diesel vans have greater uncertainty because of the relatively small sample of PEMS data currently available.

Therefore, for the estimation of the 'Motorway Light Congestion' speed band NO_x emission rate for light duty vehicles, a pragmatic simplified approach has been adopted, where the 'Motorway Light Congestion' emission rate for light duty vehicles is defined as the calculated 'Motorway Free Flow' (80-96 kph) emission values derived from EFTv9.0, multiplied by 1.07. This approach has the benefit of simplicity, whilst capturing the vehicle dynamics and technology related component of the NO_x emissions within the 'Motorway Light Congestion' speed band.

Figures 28 and 29 illustrate the resultant Motorway LDV NO_x emission rates by speed band and by year from 2015 to 2030, based on EFT v9.0. Tables 8 and 9 present the same information in tabular format.

It can be argued that the use of available UK PEMS data directly to generate the speed band emission values is a better representation of 'real world' motorway emission rates, but such an approach would diverge to some extent from EFT. It has been noted above that the existing UK PEMS data sets in the public domain are incomplete, and do not adequately represent the whole UK vehicle fleet, or the full extent of high speed operation. The use of PEMS data directly may perhaps be more justified in the future as more PEMS data becomes available (especially for light goods vehicles / vans). Therefore, the availability of real world UK PEMS data, and their consistency (or otherwise) with EFT should be kept under review.

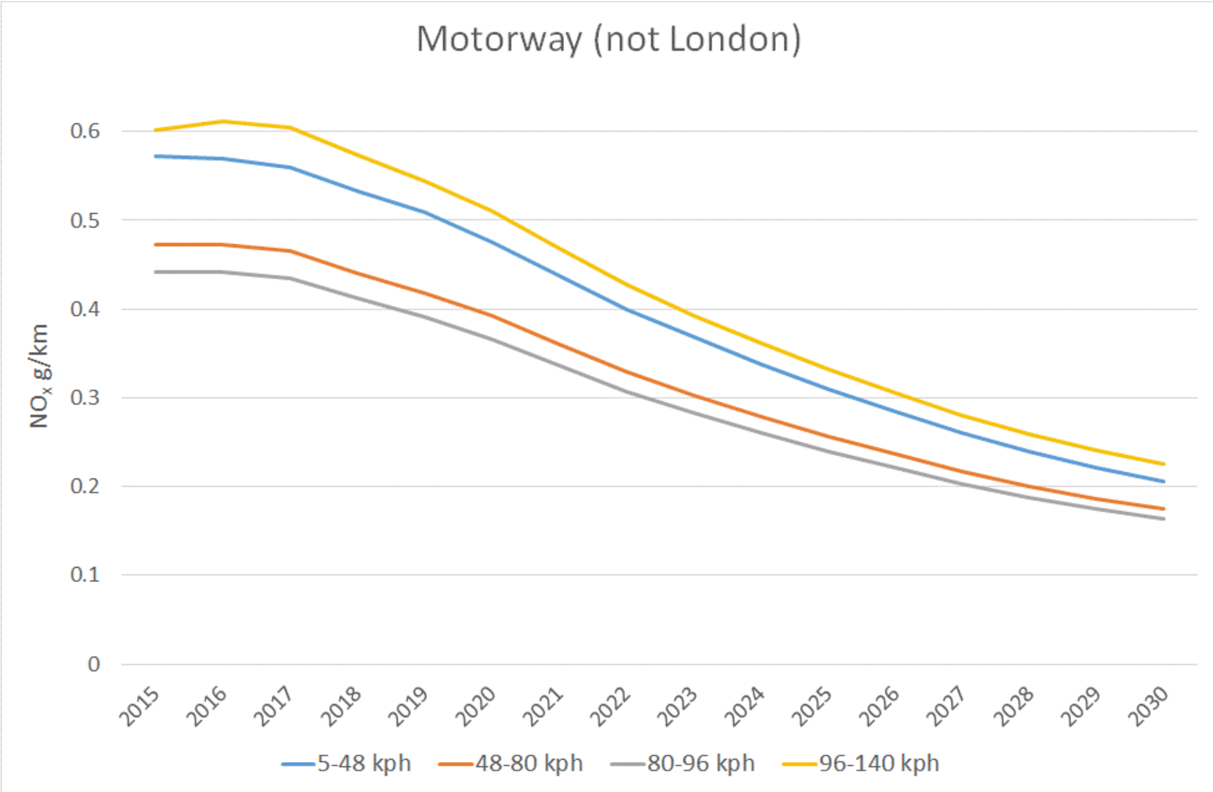

Figure 28: Motorway (not London). LDV NO_x emissions based on EFT v9.0. 'Motorway Light Congestion' emission rates for LDV's defined as 'Motorway Free Flow' emission values multiplied by 1.07.

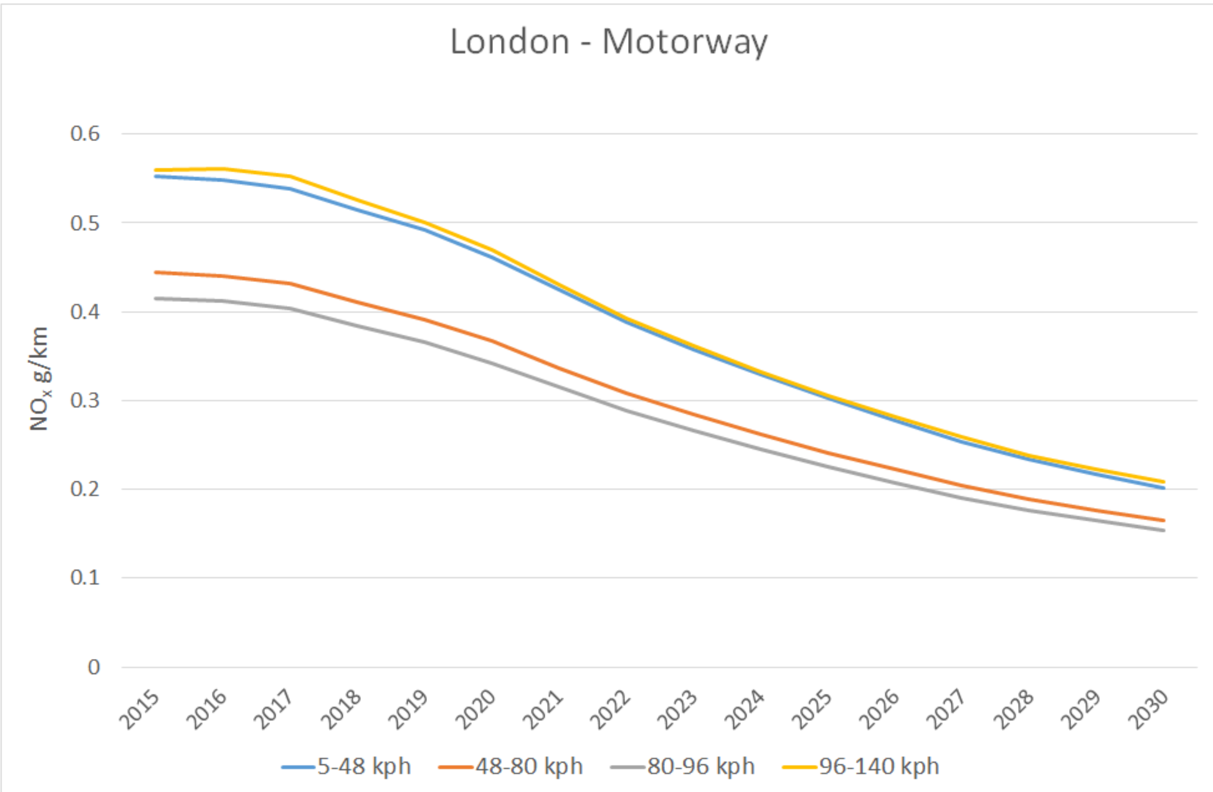

Figure 29: London - Motorway. LDV NO_x emissions based on EFT v9.0. 'Motorway Light Congestion' emission rates for LDV's defined as 'Motorway Free Flow' emission values multiplied by 1.07.

Table 8: Motorway (not London). LDV NO_x emissions based on EFT v9.0. 'Motorway Light Congestion' emission rates for LDV's defined as 'Motorway Free Flow' emission values multiplied by 1.07. (NO_x g/km)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
5-48 kph	0.572	0.570	0.560	0.533	0.509	0.475	0.437	0.400	0.368	0.338	0.310	0.284	0.260	0.239	0.221	0.206
48-80 kph	0.472	0.473	0.465	0.441	0.418	0.392	0.360	0.329	0.303	0.279	0.256	0.236	0.217	0.201	0.187	0.175
80-96 kph	0.442	0.442	0.434	0.412	0.391	0.367	0.336	0.307	0.283	0.260	0.240	0.221	0.203	0.188	0.175	0.164
96-140 kph	0.602	0.612	0.605	0.574	0.544	0.511	0.468	0.427	0.393	0.361	0.332	0.305	0.281	0.259	0.241	0.226

Table 9: London - Motorway. LDV NO_x emissions based on EFT v9.0. 'Motorway Light Congestion' emission rates for LDV's defined as 'Motorway Free Flow' emission values multiplied by 1.07. (NO_x g/km)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
5-48 kph	0.553	0.548	0.538	0.515	0.492	0.461	0.424	0.389	0.358	0.329	0.302	0.278	0.254	0.234	0.216	0.202
48-80 kph	0.444	0.440	0.432	0.411	0.391	0.367	0.337	0.308	0.284	0.262	0.241	0.222	0.204	0.189	0.176	0.165
80-96 kph	0.415	0.412	0.403	0.384	0.366	0.343	0.315	0.288	0.266	0.245	0.225	0.208	0.191	0.177	0.164	0.154
96-140 kph	0.560	0.562	0.553	0.526	0.500	0.469	0.430	0.393	0.362	0.333	0.306	0.281	0.259	0.239	0.222	0.208

Speed management intervention emission rates

In addition to the speed bands for the description of the average driving conditions on motorways, the impact of speed management interventions has also been investigated, as described in section 11. The desirability to retain consistency with EFT has been highlighted above.

In order to estimate the light duty NO_x emissions with particular speed management interventions using EFT, it is necessary to estimate the frequency distribution of light vehicle speeds for a particular speed management intervention, and for a particular mode of enforcement.

Data has recently become available from the M1 Smart Motorway (J28-J35a), where a weekday peak period speed limit of 60mph has been in operation between 0700 and 0900 hours, and between 1500 and 1800 hours. 60mph speed limit roundels were displayed during these periods of operation, with enforcement via fixed speed cameras.

A sample of MIDAS data at 1 minute time resolution was obtained for the period from January 2018 to October 2018 inclusive for a sample of MIDAS sites between M1 junctions 32 and 35a (both directions). The data included lane by lane speed data. The frequency distribution of speeds by lane was derived from this data set during the time periods when the 60mph speed limit was in operation, and is presented in Table 10 below.

Table 10: Observed distribution of motorway speeds with 60mph speed limit (M1 Smart Motorway)

MPH	<50	50-54	55-59	60-64	65-69	70-74	75-79	80+	Total (%)
Lane 1	8.1	42.9	45.6	2.8	0.4	0.1	0.0	0.0	100.0
Lane 2	5.7	16.9	71.0	5.5	0.6	0.1	0.0	0.0	100.0
Lane 3	4.1	2.9	37.4	50.7	3.9	0.7	0.2	0.1	100.0
Lane 4	3.1	1.7	7.7	42.7	34.3	8.5	1.6	0.5	100.0
Lanes 2, 3 & 4	4.3	7.2	38.8	32.9	12.8	3.1	0.6	0.2	100.0

An estimate of the light vehicle speed distribution is required to determine light vehicle NO_x emissions using EFT. Lane 1 is dominated by heavy good vehicles, so the light vehicle speed distribution with a 60mph speed limit was estimated by combining the speed data from lanes 2, 3, and 4, as presented in Table 10.

A similar data set is not available with an enforced 70mph speed limit in operation. Therefore, the frequency distribution of light vehicle speeds with an enforced 70mph speed limit was estimated by taking the midpoint between the 60mph enforced speed limit scenario (derived from the above analysis of MIDAS data), and the uncontrolled 70mph operation scenario (obtained from DfT Table SPE0111, 2018). This is presented in Table 11 below.

Table 11: Estimated distribution of motorway speeds assuming 70mph enforced speed limit

MPH	<50	50-54	55-59	60-64	65-69	70-74	75-79	80+	Total (%)
60mph SL	4.3	7.2	38.8	32.9	12.8	3.1	0.6	0.2	100.0
70mph SL	***4.6***	***6.1***	***23.4***	***23.5***	***17.4***	***12.5***	***7.5***	***5.0***	***100.0***
70mph no enforcement	5.0	5.0	8.0	14.0	22.0	22.0	14.0	10.0	100.0

It should be noted that the method of enforcement may have a significant influence on the observed frequency distribution of speeds. This analysis uses data from a 60mph speed limit on the M1 Smart Motorway enforced only by fixed point speed cameras, i.e. drivers can choose to travel at higher speeds between speed cameras, and reduce speed when in the vicinity of a speed camera. This type of behaviour is clear when one looks at the observed speed frequency distribution by lane in Table 10. If average speed camera enforcement is used, a higher degree of compliance with speed limits would be expected.

Applying these frequency distributions of light vehicle speeds, Figures 30 and 31 illustrate the resultant Motorway LDV NO_x emission rates by enforced speed limit (60mph and 70mph) and by year from 2015 to 2030, based on EFT v9.0. A comparison is provided with unenforced 70mph operation (based on DfT SPE0111, 2018). Tables 12 and 13 present the same information in tabular format.

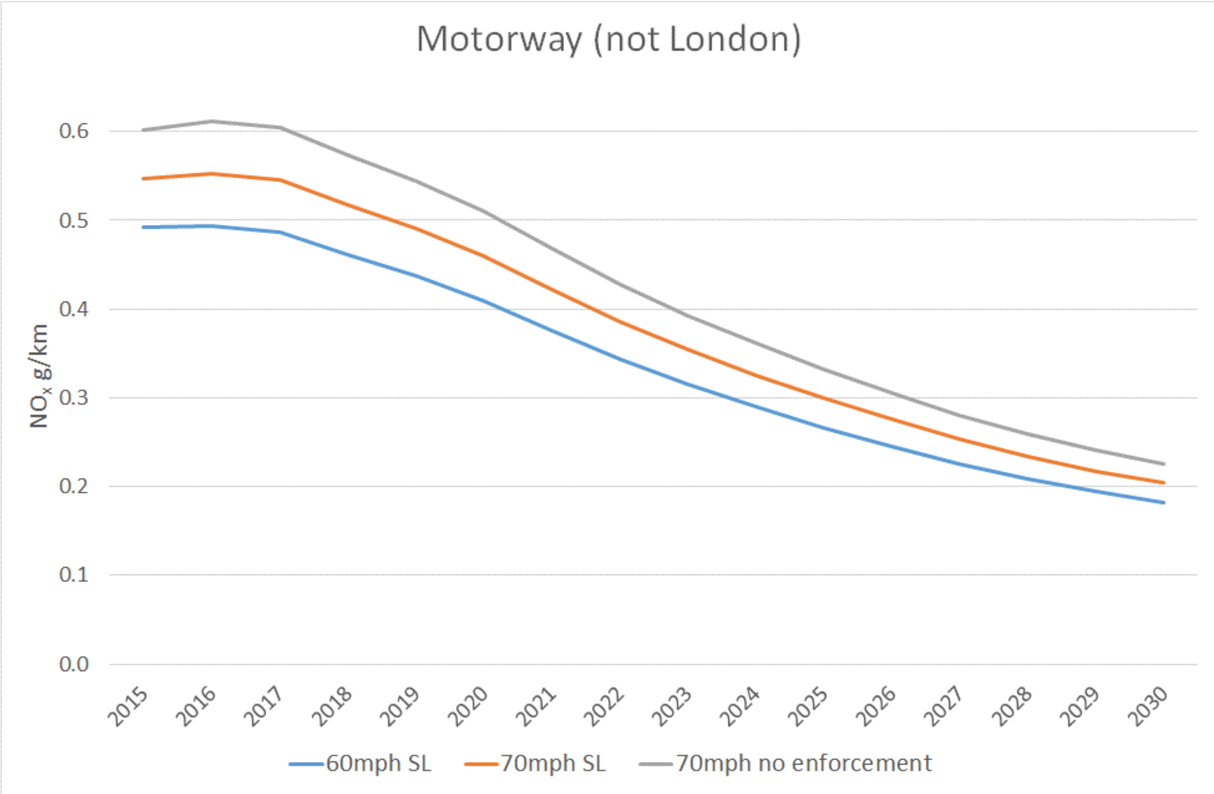

Figure 30: Motorway (not London). LDV NO_x emissions based on EFT v9.0. Comparison of 60mph and 70mph speed enforcement, with 70mph unenforced

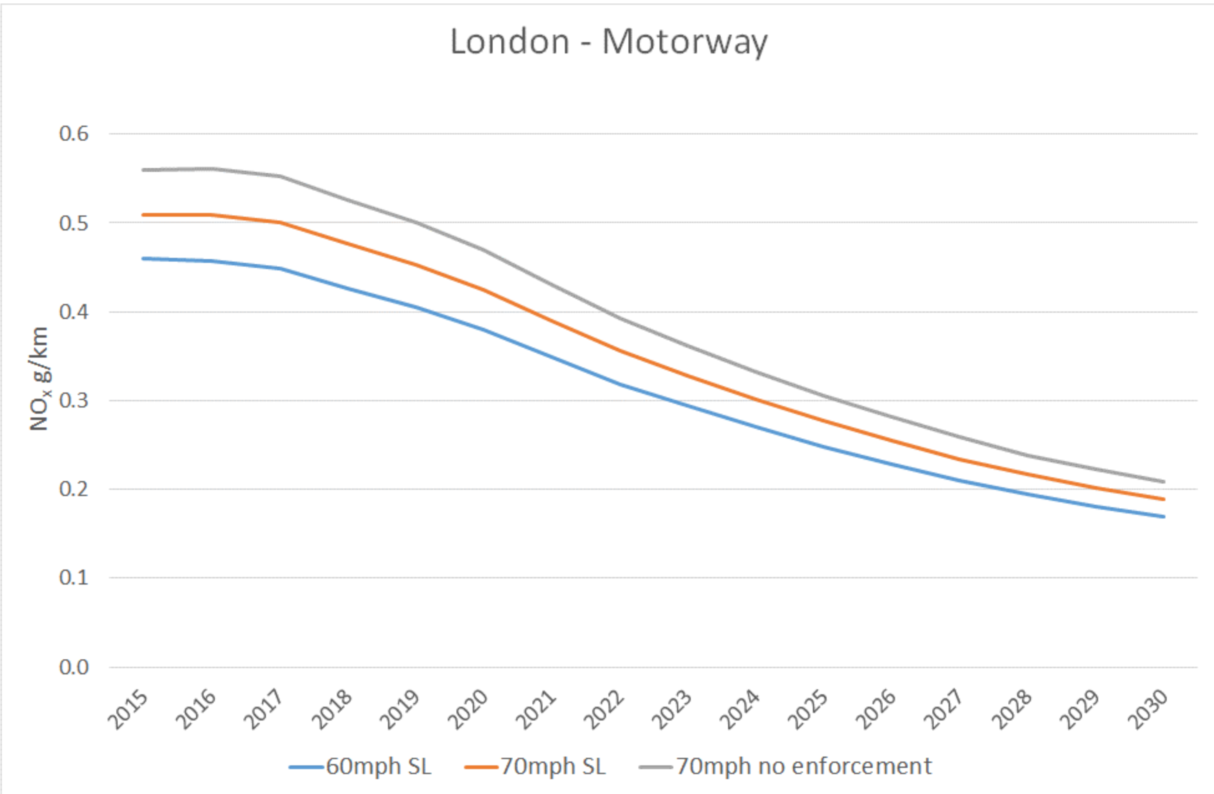

Figure 31: London - Motorway. LDV NO_x emissions based on EFT v9.0. Comparison of 60mph and 70mph speed enforcement, with 70mph unenforced

Table 12: Motorway (not London). LDV NO_x emissions based on EFT v9.0. NO_x g/km emission rates with 60mph and 70mph speed enforcement (fixed speed cameras)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
60mph	0.492	0.494	0.486	0.461	0.437	0.410	0.376	0.343	0.316	0.290	0.267	0.245	0.226	0.208	0.194	0.182
70mph	0.547	0.553	0.546	0.517	0.491	0.460	0.422	0.385	0.354	0.326	0.299	0.275	0.253	0.234	0.218	0.204
70mph no enforcement	0.602	0.612	0.605	0.574	0.544	0.511	0.468	0.427	0.393	0.361	0.332	0.305	0.281	0.259	0.241	0.226

Table 13: London - Motorway. LDV NO_x emissions based on EFT v9.0. NO_x g/km emission rates with 60mph and 70mph speed enforcement (fixed speed cameras)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
60mph	0.459	0.457	0.448	0.426	0.405	0.380	0.349	0.319	0.294	0.270	0.248	0.229	0.210	0.194	0.181	0.170
70mph	0.509	0.509	0.501	0.476	0.453	0.425	0.390	0.356	0.328	0.301	0.277	0.255	0.235	0.217	0.202	0.189
70mph no enforcement	0.560	0.562	0.553	0.526	0.500	0.469	0.430	0.393	0.362	0.333	0.306	0.281	0.259	0.239	0.222	0.208

Annex A: Estimated light vehicle NO_x mg/sec emission rates derived from DfT 2016 PEMS surveys and DfT / DVSA 2017 PEMS surveys

DfT PEMS data - Euro 5 diesel cars

NOx mg/sec

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	NA	NA	4.0	3.7	1.9	2.0	2.9	3.3	2.4	2.4	2.6	2.4	2.5	2.5	2.8	2.3	2.4	2.5	2.7	3.0	3.1	3.0	3.4	3.2	3.8	2.7	4.3	5.0	4.1	5.1	4.9	5.6	6.7	7.0	7.4	6.8	8.3	9.6	10.0	13.9	13.4	14.0	16.8	17.0	20.2	16.1	17.7	15.2	NA	NA	19.2
5-10	6.0	2.9	2.9	2.0	2.2	2.3	2.1	2.5	2.4	2.7	2.7	2.7	2.2	2.0	2.8	3.3	3.2	3.2	3.0	3.5	3.1	3.1	3.5	4.5	5.0	5.2	5.9	6.0	7.0	7.5	8.7	10.4	10.2	11.9	13.0	13.5	15.2	16.5	17.7	17.1	18.7	16.0	18.5	20.0	16.9	21.7	23.8	18.4	24.6	31.3	11.7
10-15	1.5	4.2	3.6	4.5	2.0	1.4	2.5	2.7	3.4	2.2	3.9	3.4	2.9	3.0	2.8	2.8	3.1	3.6	3.6	3.5	3.6	4.2	3.9	4.7	5.5	5.8	7.1	7.9	9.2	10.1	11.4	12.8	13.9	15.4	15.8	17.7	19.6	19.4	19.7	24.8	24.2	28.6	25.3	32.0	28.2	36.2	28.4	18.7	33.3	48.0	NA
15-20	2.1	3.2	2.7	4.2	2.6	5.4	2.3	4.6	3.3	2.9	4.1	3.7	4.3	4.2	3.2	3.8	4.9	4.2	5.2	4.9	6.6	5.4	6.4	7.0	7.7	8.4	10.1	11.1	13.0	14.5	15.4	16.5	18.6	21.3	23.2	24.5	25.5	30.2	28.4	33.3	37.8	32.5	34.6	37.7	48.6	44.2	46.8	NA	26.5	119.6	41.6
20-25	1.9	2.8	2.5	3.9	2.1	1.9	1.3	1.9	4.7	2.2	2.9	3.8	4.4	4.9	3.7	4.3	4.8	6.2	5.8	7.4	7.2	8.2	7.7	9.1	10.4	12.1	13.8	15.5	17.2	19.1	19.4	21.3	24.8	26.3	27.7	31.4	34.6	35.7	46.7	41.4	37.0	56.1	65.4	75.7	97.4	83.0	87.4	69.5	114.6	110.0	NA
25-30	0.8	1.7	5.9	0.9	1.4	1.7	4.5	3.3	1.7	1.2	1.2	2.7	2.2	1.2	2.5	3.3	4.4	4.3	4.5	7.3	7.2	6.6	8.3	9.3	10.7	12.4	14.2	16.9	20.2	21.3	24.8	26.9	29.6	35.0	39.6	36.8	44.9	51.3	55.2	63.0	60.0	67.8	74.1	70.0	64.6	86.8	NA	NA	127.4	NA	NA
30-35	2.2	0.7	3.8	0.6	4.2	0.8	3.7	1.0	3.9	0.9	1.9	1.6	1.2	3.3	3.7	3.1	1.4	1.7	4.3	2.8	6.3	6.9	8.3	8.1	10.0	13.1	15.7	17.3	21.6	27.0	29.4	31.1	36.4	51.1	50.2	54.1	54.0	67.2	75.5	91.8	100.2	89.6	70.5	99.8	5.8	NA	NA	238.8	NA	NA	NA
35-40	2.6	NA	1.7	0.6	1.1	1.1	4.4	0.8	1.8	1.6	2.1	2.2	2.4	6.0	1.0	3.6	3.1	4.2	5.3	5.3	6.0	10.3	8.1	9.0	11.0	13.1	16.2	20.9	25.9	36.2	46.9	46.8	52.2	57.6	64.4	64.2	73.0	90.7	91.4	80.1	111.2	141.5	160.6	70.7	129.5	NA	NA	NA	NA	NA	NA
40-45	NA	NA	NA	4.4	1.2	NA	2.5	1.0	1.3	3.9	15.3	2.0	2.5	1.2	1.4	1.9	5.8	3.5	5.1	5.8	5.5	7.1	8.2	10.6	14.6	18.4	21.7	29.9	35.1	40.5	47.1	55.7	65.0	66.9	76.9	94.6	78.2	92.2	148.1	151.1	142.0	NA	211.0	NA	NA	NA	NA	NA	NA	NA	NA
45-50	NA	NA	NA	NA	NA	NA	NA	NA	0.3	16.5	5.9	2.3	7.0	13.5	2.7	2.9	2.5	2.6	6.1	6.9	6.7	8.0	10.8	14.3	17.7	22.8	29.5	37.3	39.8	47.9	55.2	72.1	79.4	71.5	83.1	104.6	148.3	96.6	115.5	NA	NA	174.5	NA	212.9	NA	NA	NA	NA	NA	NA	NA
50-55	2.3	NA	NA	NA	NA	NA	NA	1.5	NA	6.4	NA	2.1	0.8	2.3	0.8	9.3	2.1	7.0	7.1	10.2	7.9	11.8	14.1	16.5	19.2	22.8	28.7	39.4	44.7	57.0	62.8	75.6	84.2	117.9	142.3	142.4	147.1	107.3	89.7	181.9	NA	NA	NA	NA	165.5	NA	NA	NA	NA	NA	NA
55-60	NA	NA	NA	NA	NA	2.5	2.6	NA	NA	NA	NA	0.8	NA	15.3	3.3	0.9	0.6	5.5	12.3	5.0	5.9	5.3	9.8	9.1	12.8	17.3	20.2	26.1	50.4	80.2	66.4	95.2	122.1	125.0	140.4	151.3	138.5	166.9	NA	NA	NA	179.7	8.0	NA	NA	NA	NA	NA	NA	NA	NA
60-65	NA	NA	NA	NA	NA	NA	NA	NA	NA	20.3	NA	3.4	4.6	7.5	NA	3.2	2.3	4.3	5.7	4.8	5.6	7.8	9.1	15.8	23.4	31.7	37.4	47.9	58.2	83.4	85.1	99.6	127.1	129.2	129.1	130.6	167.8	108.6	312.8	231.5	243.8	NA	NA	NA	269.4	NA	NA	NA	NA	NA	NA
65-70	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	15.8	NA	NA	3.6	34.8	9.9	17.0	9.7	12.9	12.9	20.6	27.4	32.6	41.7	49.3	55.9	84.7	110.1	104.4	108.5	183.2	201.6	83.9	152.7	266.0	NA	254.1	21.9	NA	185.1	NA	NA	NA	NA	NA	NA	NA	NA
70-75	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	10.2	12.7	14.5	28.8	15.4	21.6	30.7	33.1	44.6	51.9	76.1	100.4	152.3	132.0	148.3	216.5	124.7	232.4	164.8	NA	NA	216.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
75-80	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.6	7.1	NA	32.1	31.2	33.5	NA	54.5	NA	104.7	NA	128.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Number of observations (sample size in seconds)

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	0	0	5	9	17	26	24	46	51	75	100	82	112	110	109	128	127	147	160	149	193	205	207	263	307	10809	399	293	202	215	164	169	145	168	166	135	125	122	132	105	89	68	42	30	15	15	2	3	0	0	1
5-10	11	25	31	33	54	70	78	87	104	87	100	99	102	94	101	96	78	99	96	98	115	127	150	133	185	184	170	166	197	202	174	186	164	180	164	117	160	123	131	138	119	81	71	59	47	32	17	12	5	5	5
10-15	8	20	22	32	32	70	79	93	114	96	125	141	152	175	178	188	190	210	214	229	233	251	256	304	317	317	327	387	369	436	414	459	474	476	396	316	298	188	137	96	64	38	24	15	12	8	5	2	2	1	0
15-20	3	8	16	11	19	25	54	60	77	74	110	141	157	197	212	239	241	295	366	395	417	573	658	846	987	1155	1175	1145	1019	870	759	640	535	404	310	258	172	130	107	93	42	24	19	8	11	8	3	0	1	2	1
20-25	4	3	11	8	11	9	17	26	27	47	47	76	78	103	98	143	181	212	250	360	443	619	883	1093	1417	1919	1771	1457	1123	822	647	461	369	225	176	113	105	64	43	25	20	12	8	6	1	3	3	3	2	1	0
25-30	6	6	5	3	5	12	9	17	24	20	18	21	36	46	42	49	58	67	84	132	182	280	474	790	1478	1787	1518	920	510	363	212	157	101	85	72	59	49	47	28	25	19	17	10	4	6	1	0	0	2	0	0
30-35	3	2	4	5	7	6	12	11	11	10	21	19	24	27	24	36	36	29	39	45	70	151	243	444	802	1193	891	459	260	154	129	72	70	60	49	46	32	25	16	20	19	9	6	1	1	0	0	1	0	0	0
35-40	2	0	2	1	3	5	6	7	6	10	13	11	20	14	22	24	31	35	37	47	68	94	241	514	1006	1480	1011	447	184	116	87	83	68	68	38	37	27	24	10	8	8	4	1	2	2	0	0	0	0	0	0
40-45	0	0	0	1	3	0	3	3	2	7	6	8	15	10	16	13	30	23	45	56	93	126	226	386	695	1008	864	431	230	153	110	75	59	38	20	16	10	7	1	6	2	0	1	0	0	0	0	0	0	0	0
45-50	0	0	0	0	0	0	0	0	2	1	2	2	5	8	11	12	17	26	35	38	67	139	259	491	1079	1567	1088	531	251	122	82	58	49	27	20	8	7	2	1	0	0	2	0	1	0	0	0	0	0	0	0
50-55	1	0	0	0	0	0	0	1	0	3	0	1	3	4	4	8	12	19	21	26	44	104	226	556	1537	2640	1718	526	174	61	41	39	44	27	15	7	7	2	2	2	0	0	0	0	1	0	0	0	0	0	0
55-60	0	0	0	0	0	1	1	0	0	0	0	1	0	2	3	9	3	7	12	16	50	84	108	163	339	561	266	90	57	50	32	40	36	24	16	9	5	3	0	0	0	2	1	0	0	0	0	0	0	0	0
60-65	0	0	0	0	0	0	0	0	0	2	0	1	1	2	0	6	7	8	5	15	72	207	314	618	1425	2139	1197	487	244	137	97	50	50	23	16	7	3	1	1	1	1	0	0	0	1	0	0	0	0	0	0
65-70	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	2	6	18	76	174	245	499	1134	2479	1282	501	225	100	60	30	21	11	4	1	2	1	0	1	1	0	1	0	0	0	0	0	0	0	0
70-75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	18	38	56	80	105	155	136	93	37	26	11	11	2	2	4	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
75-80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	5	10	2	0	3	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

DfT PEMS data - Euro 6 diesel cars

NOx mg/sec

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	NA	0.1	0.7	0.9	0.7	0.1	0.5	0.8	1.0	0.8	0.7	0.8	0.8	0.9	0.7	0.9	0.9	0.9	0.9	1.0	0.8	1.0	1.1	1.1	0.9	0.5	1.1	1.0	1.3	1.5	1.6	1.4	2.1	1.9	2.2	2.8	2.9	3.0	3.1	2.6	3.5	5.1	5.3	3.5	4.1	4.6	6.4	3.1	4.0	NA	NA
5-10	0.6	0.6	1.0	0.9	0.9	0.8	0.7	0.6	0.9	0.8	0.7	1.1	0.9	0.8	0.9	0.9	1.1	0.9	0.9	1.2	1.0	1.4	1.2	1.5	1.2	1.7	1.5	1.7	2.0	2.2	2.9	4.1	3.9	3.9	4.4	5.7	5.0	4.9	5.6	6.9	6.7	7.4	6.2	9.2	6.8	7.2	11.4	6.7	10.5	11.4	0.3
10-15	1.2	0.7	1.1	1.0	1.3	0.8	0.9	0.8	1.0	0.9	1.4	1.1	1.2	1.3	1.7	1.2	1.2	1.5	1.4	1.3	1.5	1.6	1.5	2.1	1.9	2.1	2.3	2.9	3.4	4.0	4.2	5.1	6.0	6.9	7.0	8.4	9.6	9.1	9.1	11.3	15.7	11.7	14.5	8.9	12.1	38.8	4.9	19.6	6.1	15.3	NA
15-20	1.9	0.5	1.1	1.2	1.8	0.7	1.2	1.3	0.9	2.0	1.1	1.6	1.4	2.4	1.8	2.1	1.8	2.0	2.2	2.2	2.5	2.3	2.7	2.8	3.2	3.4	4.0	4.6	5.3	6.2	6.9	8.5	9.3	11.4	10.9	13.9	12.6	16.2	16.3	18.2	14.7	23.6	22.9	13.0	18.9	4.9	31.5	34.8	32.1	NA	23.2
20-25	0.9	0.9	0.9	1.6	1.0	1.1	1.1	1.2	1.9	1.7	1.3	1.8	2.1	3.0	2.0	2.6	3.5	3.1	2.7	3.2	3.0	3.3	3.0	3.4	4.0	4.3	5.4	6.5	7.2	8.9	9.5	13.3	13.4	13.6	16.6	16.6	22.7	21.2	21.0	27.9	34.6	21.9	16.6	37.1	26.3	26.2	44.1	1.5	74.0	NA	73.9
25-30	0.5	0.5	-1.0	0.3	0.3	1.5	0.8	1.1	1.7	0.8	1.3	2.7	1.4	1.8	1.6	2.4	2.8	2.4	3.4	4.4	3.3	4.1	3.8	3.8	4.2	5.1	5.6	6.8	9.0	11.5	12.4	13.2	17.3	20.2	22.4	24.5	27.1	30.2	27.0	47.3	50.0	38.5	36.5	51.0	74.3	64.7	44.7	NA	NA	NA	NA
30-35	NA	2.1	2.0	0.1	0.3	0.2	0.3	0.1	2.2	2.1	0.9	0.4	0.7	1.1	1.5	1.5	1.3	1.4	1.5	2.0	2.4	2.6	2.9	3.6	3.9	4.7	6.8	8.1	11.6	16.0	18.5	19.8	26.7	27.9	35.5	38.3	36.0	37.9	57.4	45.6	77.5	62.6	68.7	76.1	53.5	70.0	1.8	74.8	10.9	NA	NA
35-40	1.7	0.5	0.1	NA	0.3	0.5	0.9	9.4	3.4	2.7	1.2	5.0	0.3	2.1	1.6	1.1	2.2	0.9	1.9	1.0	2.8	3.0	3.4	3.0	3.6	4.9	6.3	8.7	14.6	13.9	24.2	27.7	36.8	40.8	53.5	54.5	41.3	66.2	49.5	43.9	64.6	95.2	NA	76.6	0.2	65.1	NA	###	NA	NA	NA
40-45	NA	NA	-0.4	NA	0.2	NA	1.6	0.3	0.2	0.2	0.6	0.4	5.1	0.3	4.5	1.9	0.8	1.1	0.7	1.6	2.5	3.9	5.2	5.7	8.4	9.6	11.3	13.4	18.1	19.8	24.9	32.0	41.6	47.2	55.2	52.4	60.5	40.1	70.5	70.2	8.7	NA	65.6	NA	NA	133.2	NA	NA	NA	NA	NA
45-50	NA	NA	4.1	NA	NA	NA	NA	NA	0.9	NA	0.0	1.4	0.7	0.9	0.3	2.3	0.6	2.7	1.9	1.5	4.6	3.6	7.4	8.5	10.6	13.0	14.2	20.5	25.4	36.1	29.3	35.0	52.5	51.3	46.9	64.1	56.3	81.9	60.2	116.2	136.7	NA	92.8	113.1	NA	7.0	NA	NA	NA	NA	NA
50-55	NA	NA	NA	6.0	NA	NA	NA	0.3	NA	0.0	0.8	2.1	0.4	0.9	0.4	0.8	0.8	1.0	5.8	4.8	2.8	6.1	7.1	7.2	8.5	10.7	15.4	26.6	31.3	32.4	38.3	60.4	73.5	72.9	81.2	89.2	90.9	70.6	63.8	22.2	89.2	155.5	99.7	NA	NA	NA	NA	NA	NA	NA	NA
55-60	NA	NA	NA	NA	NA	NA	NA	0.0	NA	NA	NA	2.3	3.5	0.0	0.4	3.0	1.6	0.8	1.0	3.7	3.7	1.8	2.2	3.7	4.3	5.6	11.6	17.9	21.3	39.0	43.7	68.2	79.0	81.5	82.9	106.5	145.6	49.2	91.4	NA	120.5	NA	131.6	NA	NA	NA	NA	NA	NA	NA	NA
60-65	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	22.7	0.0	NA	NA	NA	4.6	1.6	2.7	3.5	3.1	3.5	4.3	4.0	8.5	10.6	15.0	19.2	29.3	38.4	46.2	56.9	61.0	77.3	79.3	50.8	45.7	113.8	23.1	123.6	0.3	124.7	NA	NA	NA	NA	1.2	NA	NA	NA	NA	NA
65-70	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	13.8	0.0	1.1	2.9	5.1	7.4	6.9	8.9	9.2	13.9	14.8	21.5	35.2	41.7	45.6	52.2	70.2	55.3	49.1	65.6	68.5	21.5	NA	32.7	2.0	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA
70-75	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.0	9.3	NA	NA	44.0	15.2	16.4	9.9	11.9	14.9	20.9	27.1	28.6	30.2	45.9	51.3	67.6	58.2	36.4	33.9	0.6	NA	56.0	74.0	NA	NA	NA	0.3	NA	NA	NA	NA	NA	NA	NA	NA
75-80	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	23.9	38.8	32.4	16.0	5.0	13.0	3.5	11.3	23.0	NA	21.6	98.6	NA	20.4	128.4	12.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
80-85	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	6.5	NA	NA	3.2	NA	3.7	NA	NA	NA	7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Number of observations (sample size in seconds)

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	0	3	5	8	11	13	31	30	50	71	63	83	92	115	123	146	163	151	180	174	216	220	278	300	427	11021	486	299	238	215	184	177	165	169	137	131	144	127	98	99	81	49	46	40	15	10	10	3	3	0	0
5-10	9	19	18	41	50	69	76	85	86	78	104	95	121	110	120	108	105	116	102	103	117	118	123	184	169	202	192	186	197	193	188	180	201	155	181	182	145	155	139	121	106	84	68	63	47	25	23	10	11	5	1
10-15	18	16	11	30	48	53	66	86	97	115	105	144	149	153	184	179	191	194	232	217	279	269	329	313	373	397	393	414	421	512	502	517	499	417	428	300	242	158	129	76	47	32	18	14	11	3	7	3	4	2	0
15-20	4	11	15	16	22	20	40	40	73	75	107	137	139	146	177	239	260	271	340	375	426	581	700	909	1185	1281	1178	1123	940	863	726	632	506	425	316	223	173	114	81	57	46	27	23	9	8	3	6	3	3	0	1
20-25	7	11	2	7	7	8	18	22	36	34	45	58	77	94	102	103	148	171	229	316	420	571	846	###	1423	1574	1574	1249	982	804	606	446	305	221	145	129	76	59	43	24	16	10	2	7	3	2	4	1	1	0	2
25-30	3	7	3	7	8	7	20	10	15	26	28	22	32	33	39	55	57	64	78	92	164	308	491	828	1381	1749	1427	895	460	315	204	155	129	94	64	60	51	42	33	20	18	8	11	8	2	3	1	0	0	0	0
30-35	0	5	5	4	6	7	4	8	13	16	12	14	22	20	31	35	32	33	49	53	77	120	232	482	837	1126	838	456	240	141	106	96	75	48	50	32	32	20	28	17	5	10	3	4	4	6	1	2	1	0	0
35-40	1	2	3	0	7	4	2	2	6	7	12	9	7	14	20	17	23	28	41	44	83	136	270	521	975	1367	920	430	220	134	112	83	64	43	44	27	20	12	10	13	8	6	0	2	1	2	0	1	0	0	0
40-45	0	0	1	0	2	0	3	5	1	3	1	5	4	5	9	16	19	38	33	57	84	165	294	445	760	1086	832	463	273	138	85	66	50	30	20	19	9	7	4	3	1	0	2	0	0	1	0	0	0	0	0
45-50	0	0	1	0	0	0	0	0	3	0	1	4	4	5	5	7	15	24	25	45	84	128	258	517	1337	2118	1321	590	223	115	74	44	28	24	16	11	12	5	4	1	1	0	1	1	0	1	0	0	0	0	0
50-55	0	0	0	1	0	0	0	1	0	1	2	3	3	3	3	7	12	11	14	26	40	77	209	480	1164	2128	1265	403	116	77	35	26	34	21	15	12	7	6	6	4	2	2	1	0	0	0	0	0	0	0	0
55-60	0	0	0	0	0	0	0	1	0	0	0	2	3	1	2	9	9	11	12	16	24	83	126	240	355	383	275	131	75	48	44	26	42	27	11	6	3	3	6	0	1	0	1	0	0	0	0	0	0	0	0
60-65	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	4	9	10	21	62	160	234	499	1210	2030	1110	381	191	101	69	41	41	31	10	4	6	3	1	2	1	0	0	0	0	1	0	0	0	0	0
65-70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	2	4	20	79	161	252	581	1224	2032	1338	519	222	94	48	42	25	9	13	5	1	0	3	2	0	0	0	1	0	0	0	0	0	0	0
70-75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2	20	55	89	117	253	289	245	136	62	29	15	7	7	4	3	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0
75-80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	6	9	10	16	12	3	0	1	2	0	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80-85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

DfT PEMS data - Euro 5 diesel vans

NOx mg/sec

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	NA	NA	NA	1.2	NA	NA	0.3	1.3	0.7	1.3	0.8	1.1	1.0	1.5	1.1	1.4	1.3	1.5	1.7	1.5	1.6	1.9	1.8	1.9	3.7	2.5	4.5	3.7	3.1	2.9	3.7	4.4	4.0	4.5	6.8	7.3	6.4	7.1	8.8	10.1	9.6	12.9	12.4	11.5	17.9	17.1	18.5	18.4	NA	NA	NA
5-10	NA	0.3	0.2	NA	1.2	1.5	0.8	0.5	0.6	0.9	1.3	0.8	0.7	1.0	1.0	1.3	1.2	1.4	1.6	1.6	1.5	1.7	1.6	1.9	2.5	2.6	3.1	3.2	4.3	4.3	6.0	6.2	7.1	8.0	8.4	9.2	10.6	10.4	10.8	13.9	11.9	14.6	15.1	14.8	14.1	18.1	23.4	19.7	23.4	27.2	20.8
10-15	0.5	0.6	1.4	0.5	1.9	0.9	0.8	0.5	1.0	0.6	0.8	0.6	0.5	0.8	1.0	0.9	1.0	0.9	1.1	1.1	1.3	1.2	1.4	1.9	2.6	3.0	3.5	4.3	5.9	5.7	7.3	8.4	11.2	12.2	13.5	15.0	16.0	19.7	21.0	20.6	24.8	24.3	26.7	21.1	25.1	35.3	35.7	40.1	NA	NA	29.4
15-20	0.9	1.1	0.9	1.1	0.6	0.5	1.1	0.4	0.6	0.7	0.5	0.4	0.7	0.5	0.5	0.5	0.7	0.8	0.8	1.1	1.2	1.3	1.7	2.7	3.5	4.3	4.9	5.6	7.5	8.6	11.5	13.3	14.1	17.1	17.0	20.9	18.9	24.2	24.7	26.4	28.2	36.5	33.3	44.8	46.7	47.9	58.8	60.7	74.3	36.0	NA
20-25	0.6	1.2	0.7	0.8	1.0	0.7	0.4	1.0	1.2	0.6	0.7	0.8	0.7	0.8	0.7	0.8	0.8	0.8	0.8	1.1	1.2	1.6	2.5	2.9	3.5	4.9	5.9	7.5	10.0	12.0	14.5	18.1	19.8	24.4	29.6	29.1	39.7	37.1	42.2	40.5	43.2	44.5	65.7	46.2	50.4	55.5	59.6	78.9	86.9	84.2	63.0
25-30	0.8	NA	0.4	0.0	0.4	0.5	0.7	0.6	0.5	0.8	0.7	0.8	0.5	1.1	1.0	0.8	0.6	1.1	1.2	1.1	2.1	2.1	2.4	3.6	4.5	6.0	7.3	10.4	13.3	15.9	18.3	22.1	26.2	30.6	34.0	37.8	48.6	58.6	62.4	57.3	65.1	91.4	78.0	104.8	75.8	50.1	102.6	NA	NA	105.7	NA
30-35	0.9	1.0	0.1	0.2	NA	0.2	0.2	0.4	0.7	1.3	0.8	0.6	0.3	0.4	0.7	0.9	0.7	1.1	0.7	1.4	2.0	1.9	2.2	2.9	4.7	5.3	9.5	10.8	19.3	24.1	29.3	30.9	39.8	38.5	55.8	39.8	58.4	61.5	94.7	105.4	113.9	88.3	99.7	118.4	114.5	85.2	142.9	NA	NA	NA	NA
35-40	NA	0.5	NA	0.0	0.9	NA	0.3	NA	0.4	0.7	0.5	0.3	0.3	0.8	0.6	0.5	0.5	0.4	1.5	1.2	1.3	3.6	3.8	4.6	6.9	10.1	12.8	15.0	19.1	25.9	32.0	49.0	39.4	51.8	88.1	66.5	68.1	91.4	99.2	118.6	114.2	100.1	97.6	100.4	80.3	NA	119.0	NA	NA	NA	NA
40-45	NA	NA	0.3	NA	NA	NA	1.3	0.6	0.9	0.4	0.5	1.1	0.3	0.5	0.4	0.6	1.0	1.3	1.0	1.9	2.8	4.3	5.4	7.5	11.3	15.6	21.3	28.7	34.6	43.8	58.5	55.7	57.0	70.2	78.7	84.6	70.6	107.2	108.7	86.7	96.9	112.5	74.6	85.2	77.8	NA	NA	NA	NA	NA	NA
45-50	NA	NA	NA	NA	NA	NA	NA	0.8	0.2	3.5	0.6	NA	0.9	1.1	1.7	1.5	1.0	2.5	1.3	3.0	3.0	4.8	5.9	6.7	8.9	14.5	21.5	26.3	38.5	62.3	50.0	63.3	70.1	90.0	74.1	56.9	113.0	121.6	164.2	108.5	76.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
50-55	NA	NA	NA	NA	NA	NA	NA	0.7	0.0	NA	NA	1.0	0.0	NA	0.7	0.4	0.5	2.5	2.1	2.4	1.7	2.6	5.4	8.5	8.8	17.6	19.6	34.9	38.7	82.8	47.8	70.3	106.3	109.9	141.4	157.2	188.0	58.9	53.5	72.4	128.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
55-60	NA	NA	NA	NA	NA	1.0	NA	0.8	NA	NA	NA	NA	NA	NA	0.3	0.8	0.3	0.3	1.6	1.5	1.5	3.2	4.8	8.4	15.6	23.9	27.1	50.2	54.0	61.9	91.3	98.3	112.7	124.1	116.6	24.5	NA	36.6	NA	132.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
60-65	NA	NA	NA	NA	NA	1.3	NA	NA	NA	NA	NA	NA	0.6	0.4	NA	NA	8.8	3.1	1.4	2.2	2.1	3.4	5.3	9.2	18.4	27.7	36.8	64.7	62.6	80.7	95.8	113.5	115.8	131.7	115.6	94.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
65-70	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.9	NA	NA	NA	NA	NA	2.9	5.3	3.0	2.8	4.2	6.7	7.7	12.6	19.4	33.0	51.2	66.0	86.1	97.6	106.5	105.3	125.1	137.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
70-75	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	5.3	1.7	4.0	10.3	8.7	14.5	22.4	33.3	49.3	64.9	83.3	180.2	198.7	129.2	195.9	212.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
75-80	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.2	7.2	6.8	12.4	8.5	26.3	28.2	43.4	38.1	52.1	121.4	196.6	222.3	141.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
80-85	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.6	NA	37.5	NA	24.6	95.3	123.1	103.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Number of observations (sample size in seconds)

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	0	0	0	1	0	0	1	4	2	6	10	10	16	8	21	31	40	40	54	59	74	82	96	171	219	2403	152	89	56	46	40	40	38	18	33	21	21	19	19	13	18	15	18	12	4	3	1	2	0	0	0
5-10	0	2	2	0	4	8	6	12	15	19	31	45	37	47	22	58	36	68	63	57	61	61	60	61	72	58	85	52	57	55	48	49	46	47	39	46	33	42	29	30	26	13	20	19	12	11	6	10	1	6	4
10-15	2	6	2	8	5	9	13	18	22	23	32	30	30	54	51	53	61	54	56	59	80	93	94	101	109	102	99	108	98	136	109	109	98	94	85	68	50	43	45	29	25	17	15	10	2	5	6	1	0	0	2
15-20	3	4	4	4	6	5	10	16	20	25	22	30	33	44	44	48	47	55	73	77	97	151	180	183	279	372	287	241	166	135	97	91	76	64	63	52	47	33	33	32	23	18	14	13	17	10	9	6	4	2	0
20-25	2	2	4	4	4	5	4	9	9	17	17	23	19	25	35	38	41	51	67	79	134	190	257	291	352	365	320	271	220	164	139	75	69	53	59	32	42	27	17	13	13	11	4	13	7	7	12	7	4	4	2
25-30	3	0	1	2	5	2	5	6	7	11	6	11	10	31	12	19	25	29	45	39	109	155	212	300	497	610	441	256	159	103	69	64	55	39	44	27	21	22	17	17	14	13	11	6	4	2	5	0	0	1	0
30-35	1	1	1	4	0	4	2	6	4	8	5	15	17	15	15	13	21	11	27	25	27	58	84	127	190	193	171	98	77	43	42	45	27	14	29	17	8	13	16	8	7	10	8	7	3	1	1	0	0	0	0
35-40	0	1	0	1	3	0	4	0	4	7	6	3	6	12	8	9	8	15	35	25	26	49	66	92	193	176	148	92	59	35	31	23	18	13	15	13	14	16	9	9	7	8	4	3	4	0	2	0	0	0	0
40-45	0	0	1	0	0	0	1	1	1	3	5	4	4	5	5	8	9	12	20	23	28	67	106	200	300	266	211	154	73	43	31	21	26	20	13	14	11	8	4	8	3	2	4	1	2	0	0	0	0	0	0
45-50	0	0	0	0	0	0	0	1	2	1	1	0	3	2	2	3	4	5	6	16	16	51	111	193	371	457	310	184	102	45	26	15	11	10	6	6	3	2	1	2	2	0	0	0	0	0	0	0	0	0	0
50-55	0	0	0	0	0	0	0	1	1	0	0	1	1	0	3	1	3	5	8	16	19	47	61	97	111	127	117	89	41	25	9	17	20	23	3	2	1	1	1	2	1	0	0	0	0	0	0	0	0	0	0
55-60	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	2	4	12	18	38	57	66	89	131	119	91	62	62	29	28	35	18	23	5	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
60-65	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	6	10	34	61	62	81	122	190	200	160	108	57	49	61	38	26	14	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65-70	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	4	1	10	22	49	45	64	127	153	167	178	118	82	46	47	21	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70-75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	12	21	19	14	35	50	88	78	48	41	21	8	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75-80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	9	6	10	6	7	4	18	8	12	34	30	10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80-85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	1	2	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

CATAPULT Connected Places

DfT PEMS data - Euro 6 Petrol cars

NOx mg/sec

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	NA	0.38	0.20	0.15	0.11	0.15	0.20	0.19	0.34	0.14	0.24	0.23	0.13	0.13	0.14	0.10	0.16	0.24	0.09	0.19	0.13	0.13	0.12	0.14	0.10	0.04	0.11	0.15	0.14	0.20	0.16	0.31	0.37	0.60	0.63	0.33	0.78	0.73	0.44	2.07	0.77	1.66	0.65	2.26	0.29	3.77	0.08	0.11	52.22	NA	0.26
5-10	0.17	0.20	0.11	0.18	0.19	0.12	0.32	0.19	0.20	0.09	0.11	0.22	0.20	0.13	0.13	0.13	0.17	0.12	0.12	0.22	0.11	0.25	0.40	0.33	0.30	0.56	0.52	0.72	0.49	0.48	0.35	0.39	0.22	0.30	0.65	0.35	0.36	1.20	0.65	1.23	0.86	0.85	1.55	0.90	0.98	1.60	0.59	2.47	1.62	0.20	0.29
10-15	0.33	0.11	0.17	0.11	0.13	0.21	0.36	0.19	0.27	0.10	0.14	0.17	0.14	0.16	0.10	0.12	0.09	0.11	0.10	0.08	0.13	0.08	0.11	0.25	0.28	0.25	0.29	0.40	0.55	0.79	0.83	0.52	0.69	0.83	0.71	0.94	1.75	1.75	1.68	3.21	1.84	2.97	6.00	0.56	1.20	5.36	0.60	5.50	16.55	NA	0.24
15-20	0.22	0.10	0.17	0.13	0.22	0.21	0.68	0.68	0.13	0.25	0.13	0.14	0.14	0.21	0.14	0.15	0.20	0.13	0.11	0.07	0.13	0.14	0.16	0.12	0.18	0.27	0.27	0.44	0.64	0.85	0.71	0.92	1.51	1.42	1.24	1.72	2.86	2.77	2.67	2.41	7.69	4.33	6.93	9.90	4.67	5.59	1.53	0.49	0.01	NA	NA
20-25	0.34	0.27	0.10	0.06	0.11	0.09	0.16	2.36	0.15	0.21	0.29	0.17	0.33	0.32	0.25	0.06	0.15	0.15	0.17	0.11	0.21	0.14	0.16	0.24	0.23	0.33	0.44	0.46	1.01	1.24	1.23	1.72	2.29	2.27	4.99	4.78	6.80	4.45	3.29	6.13	3.97	1.08	8.00	32.18	30.12	2.95	12.88	9.12	1.01	NA	NA
25-30	0.13	0.09	0.10	0.08	0.15	0.69	0.19	0.14	0.07	0.23	0.12	0.17	1.01	0.22	0.15	0.14	0.14	0.29	0.47	0.23	0.10	0.18	0.16	0.15	0.15	0.19	0.22	0.57	0.84	1.23	2.26	3.14	3.97	3.19	5.21	7.00	12.49	11.61	7.45	0.70	8.40	0.78	0.27	6.09	1.89	3.16	59.01	NA	1.54	NA	NA
30-35	0.19	0.01	0.47	0.04	0.19	0.49	0.11	0.54	0.23	0.24	0.06	0.19	0.16	0.09	0.40	0.06	0.15	0.07	0.23	0.18	0.20	0.23	0.14	0.42	0.71	0.49	0.99	1.50	1.06	1.77	2.11	5.34	6.54	1.82	5.87	3.01	12.46	17.22	14.24	6.74	0.00	0.76	30.05	0.93	NA	NA	NA	NA	NA	NA	NA
35-40	0.04	NA	0.25	0.09	0.04	0.12	0.03	0.13	0.07	0.02	0.12	0.38	0.09	0.41	0.16	0.05	0.09	0.16	0.18	0.28	0.16	0.13	0.32	0.35	0.29	0.40	0.32	1.40	2.22	3.55	1.86	6.16	4.88	0.45	2.98	11.27	27.38	22.71	16.24	-0.01	0.86	4.36	1.20	NA	0.28	NA	NA	NA	NA	NA	NA
40-45	NA	0.03	0.06	NA	NA	0.02	0.02	0.06	0.07	0.02	0.07	0.02	0.05	0.14	0.12	0.10	0.17	0.14	0.06	0.28	0.35	0.11	0.22	0.17	0.68	0.98	1.08	1.13	2.36	2.07	5.24	9.27	6.71	2.36	3.77	1.13	4.35	3.21	1.13	NA	1.63	0.65	NA	NA	NA	NA	NA	NA	NA	NA	NA
45-50	NA	NA	0.04	0.05	NA	0.00	0.02	0.07	NA	0.09	0.06	0.07	0.04	0.06	0.03	0.09	0.11	0.10	0.10	0.46	0.18	0.31	0.42	0.51	0.50	1.05	2.52	2.24	4.15	3.18	6.47	3.24	0.63	0.56	3.72	1.89	1.03	1.09	0.50	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
50-55	NA	NA	NA	0.02	0.01	0.03	0.06	0.30	0.10	0.07	0.13	0.03	0.01	0.14	0.09	0.06	0.04	0.09	0.09	0.06	0.08	0.11	0.12	0.24	0.61	0.37	0.54	1.00	1.87	3.98	2.31	2.62	2.19	0.76	1.33	1.44	1.70	0.69	0.20	0.18	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
55-60	NA	NA	NA	0.04	NA	NA	NA	NA	NA	0.08	0.04	NA	0.04	0.00	0.13	0.08	0.15	0.10	0.07	0.21	0.10	0.10	0.22	0.22	1.25	0.84	0.78	3.42	3.55	4.11	8.72	8.12	2.21	1.39	2.65	0.59	2.86	0.76	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
60-65	0.16	NA	NA	NA	NA	NA	NA	NA	NA	0.10	0.19	0.09	NA	0.02	0.03	0.23	0.07	0.10	1.29	0.48	0.43	0.39	0.43	1.02	1.01	1.34	1.80	4.74	8.74	6.70	8.81	6.25	4.07	3.98	2.94	3.15	4.03	6.53	NA	NA	NA	2.37	NA	NA	NA	NA	NA	NA	NA	NA	NA
65-70	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.21	NA	NA	NA	NA	NA	NA	0.07	0.04	0.78	0.70	0.25	0.41	0.37	1.36	0.95	0.67	2.52	4.16	3.11	5.54	2.69	3.83	2.85	3.55	6.40	4.07	8.88	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
70-75	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.22	0.27	0.18	0.25	0.09	1.14	2.50	1.47	2.64	3.66	5.97	3.81	4.79	6.70	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
75-80	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.02	0.07	NA	0.24	0.90	3.55	3.30	6.54	4.81	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Number of observations (sample size in seconds)

Acceleration (m/s2)

mph	-2.5					-2					-1.5					-1					-0.5					0					0.5					1					1.5					2					2.5
0-5	0	2	3	13	12	24	25	45	43	58	72	57	66	85	87	79	112	95	107	105	119	134	127	143	195	8004	224	167	135	132	118	97	80	94	96	102	100	98	94	97	63	53	35	24	28	8	2	2	1	0	1
5-10	10	12	31	30	49	67	63	65	75	75	67	60	58	62	50	46	57	57	47	54	60	60	65	78	70	89	91	94	108	114	113	96	114	98	96	97	75	78	94	87	67	76	57	52	43	30	24	17	12	3	3
10-15	15	13	31	23	31	61	51	56	58	94	105	77	119	107	105	106	114	124	163	175	167	153	145	190	179	212	232	213	249	267	297	327	343	298	257	203	172	143	97	68	50	30	23	18	13	7	7	5	4	0	1
15-20	8	5	7	14	25	31	36	50	63	64	72	106	117	130	134	143	150	170	181	234	285	314	422	521	652	733	652	562	578	524	419	328	350	301	225	175	154	113	97	62	47	35	23	19	7	6	4	1	1	0	0
20-25	1	2	6	5	14	14	18	12	25	37	41	56	67	77	88	79	121	120	172	213	290	459	629	803	1006	1195	1077	799	659	554	380	337	253	198	140	99	79	61	38	28	20	19	12	11	3	1	3	5	3	0	0
25-30	3	2	1	5	6	8	15	9	12	15	21	18	25	38	36	43	46	42	82	100	155	212	414	639	1092	1288	1053	640	403	261	181	149	99	95	88	56	50	27	23	16	6	4	3	2	1	1	3	0	1	0	0
30-35	3	1	4	6	3	11	5	8	12	8	16	11	18	17	28	14	31	23	32	43	54	99	176	270	522	774	497	299	186	130	110	71	63	49	46	31	39	23	12	4	2	5	4	1	0	0	0	0	0	0	0
35-40	3	0	3	1	2	7	3	4	2	7	9	16	10	9	5	17	18	19	29	36	60	78	154	363	689	957	608	286	178	107	80	76	67	31	25	21	14	8	3	1	6	3	2	0	1	0	0	0	0	0	0
40-45	0	1	3	0	0	2	1	5	4	3	1	8	9	9	6	7	15	12	22	40	67	71	108	165	298	359	318	217	138	79	78	52	42	28	23	21	6	2	1	0	2	1	0	0	0	0	0	0	0	0	0
45-50	0	0	4	4	0	1	3	1	0	5	3	1	5	7	9	8	12	13	30	26	92	132	204	268	461	605	534	317	178	167	104	63	31	15	14	9	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
50-55	0	0	0	1	1	2	2	1	2	2	1	3	1	1	9	6	9	14	21	46	122	215	329	462	910	1593	1152	544	283	177	98	79	33	17	8	5	4	2	1	1	0	0	0	0	0	0	0	0	0	0	0
55-60	0	0	0	2	0	0	0	0	0	3	1	0	2	2	7	3	8	4	8	14	34	75	105	103	130	204	162	96	71	68	45	29	13	14	10	5	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0
60-65	1	0	0	0	0	0	0	0	0	1	1	2	0	1	1	2	3	9	12	60	230	334	319	381	606	863	781	514	354	229	143	55	34	16	15	6	3	1	0	0	0	1	0	0	0	0	0	0	0	0	0
65-70	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	4	19	97	204	259	265	306	569	896	944	566	297	190	90	56	26	14	6	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70-75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	17	17	21	20	33	65	78	52	43	9	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75-80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	2	2	1	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex B: Mean NO_x emissions calculated for Highways England probe vehicle survey data (by link)

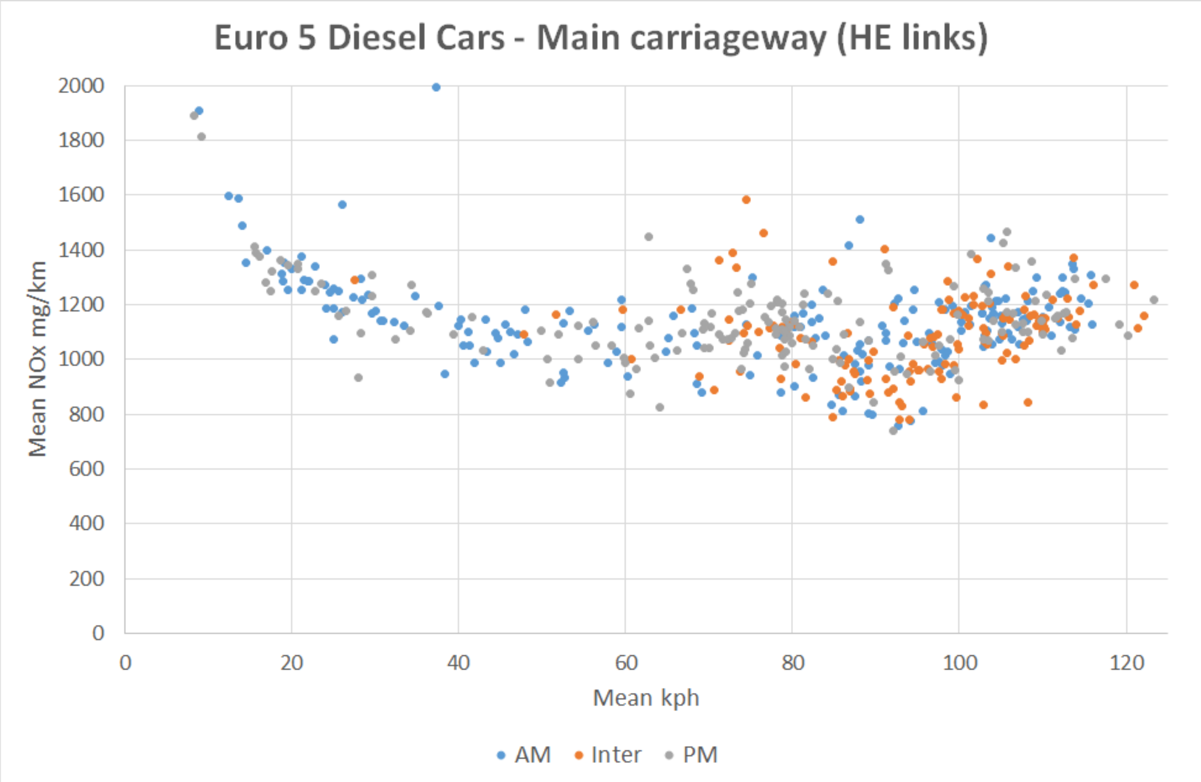

Figure B1: Calculated Euro 5 diesel car NO_x emissions – HE links – Main carriageway

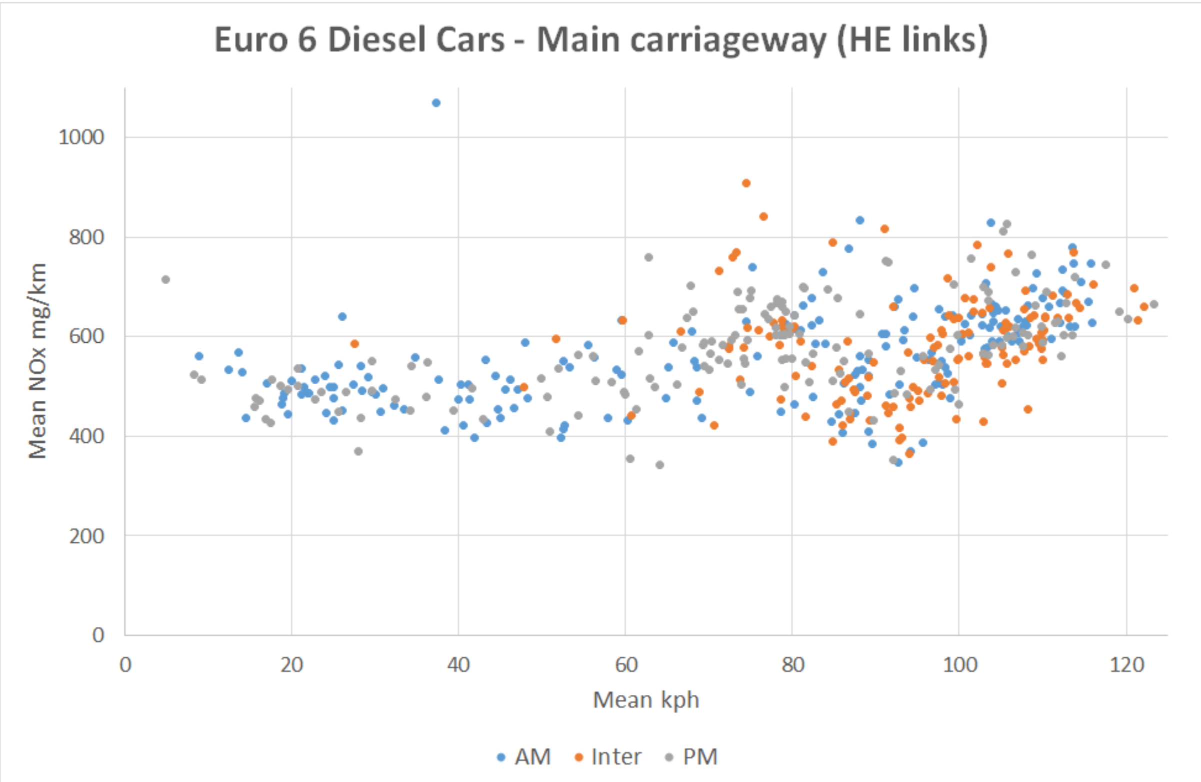

Figure B2: Calculated Euro 6 diesel car NO_x emissions – HE links – Main carriageway

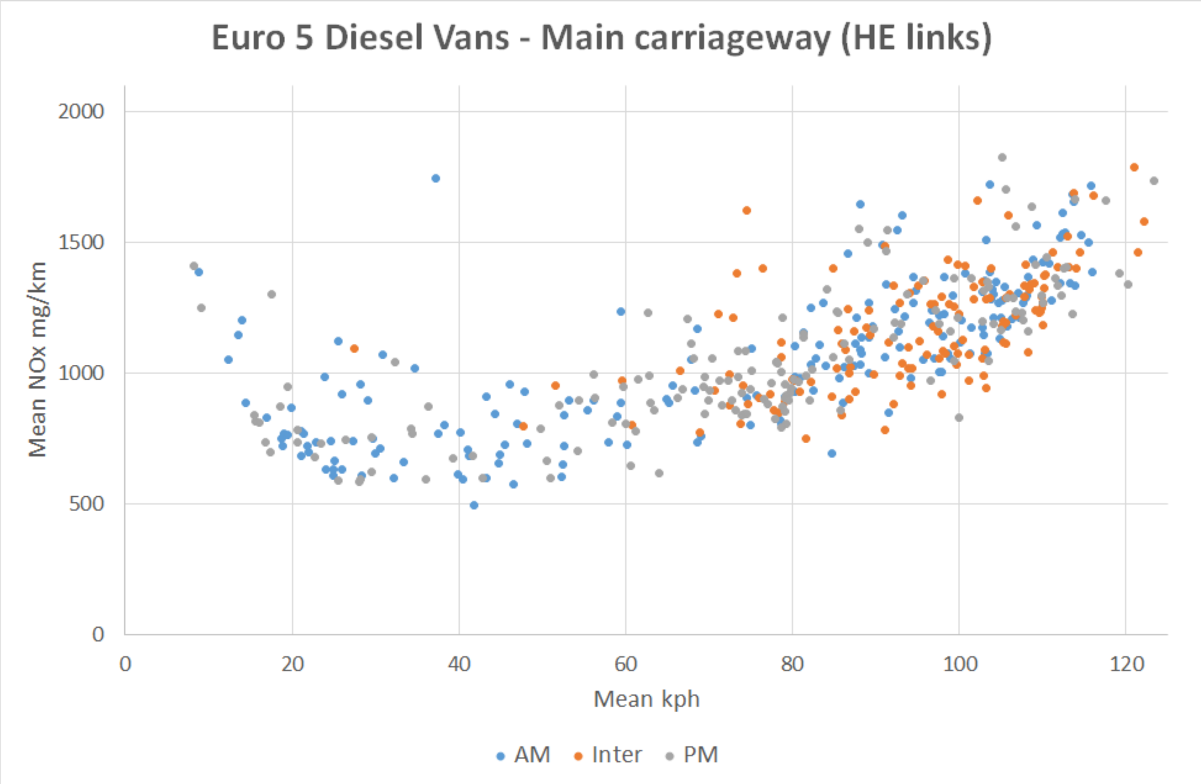

Figure B3: Calculated Euro 5 diesel van NO_x emissions – HE links – Main carriageway

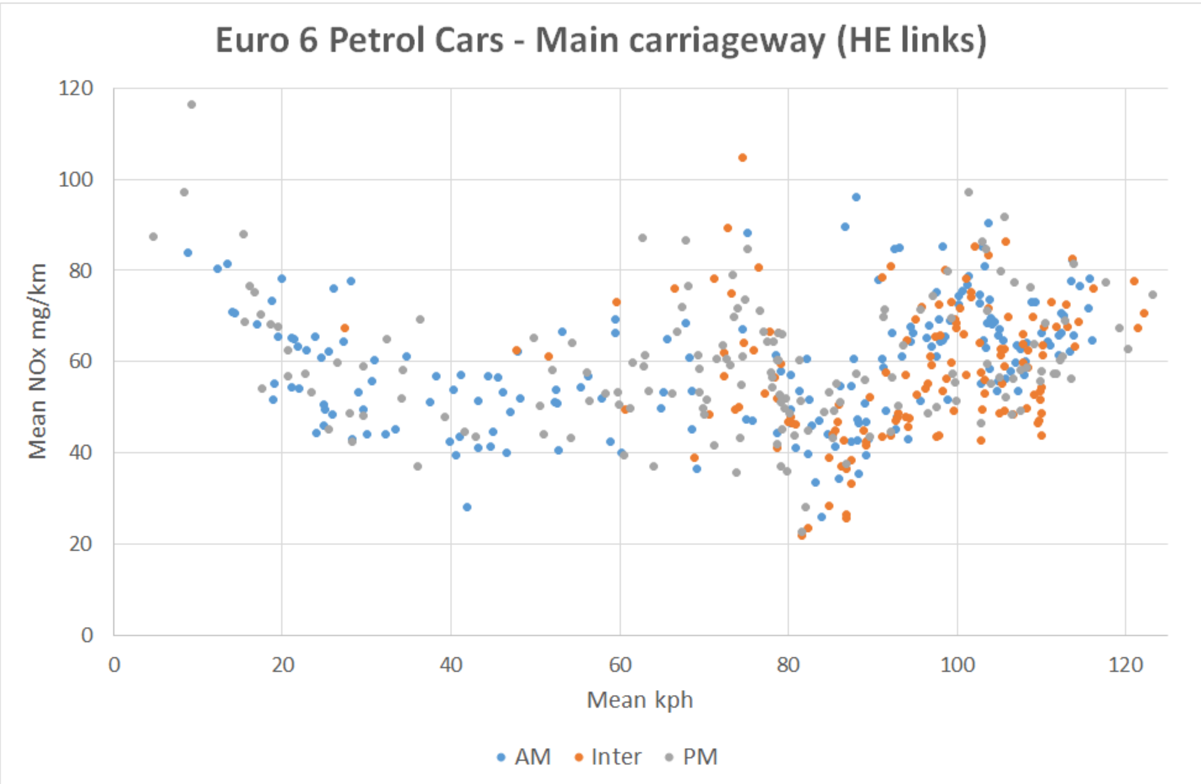

Figure B4: Calculated Euro 6 petrol car NO_x emissions – HE links – Main carriageway

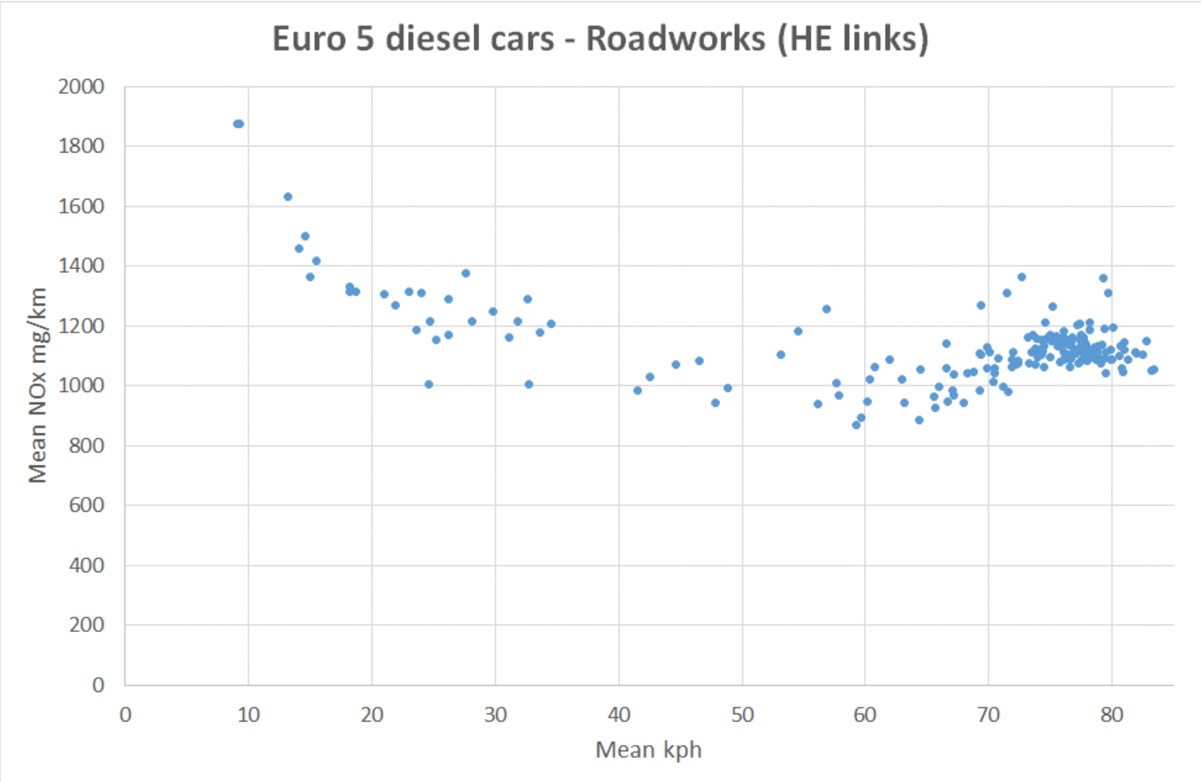

Figure B5: Calculated Euro 5 diesel car NO_x emissions – HE links – Roadworks (50mph)

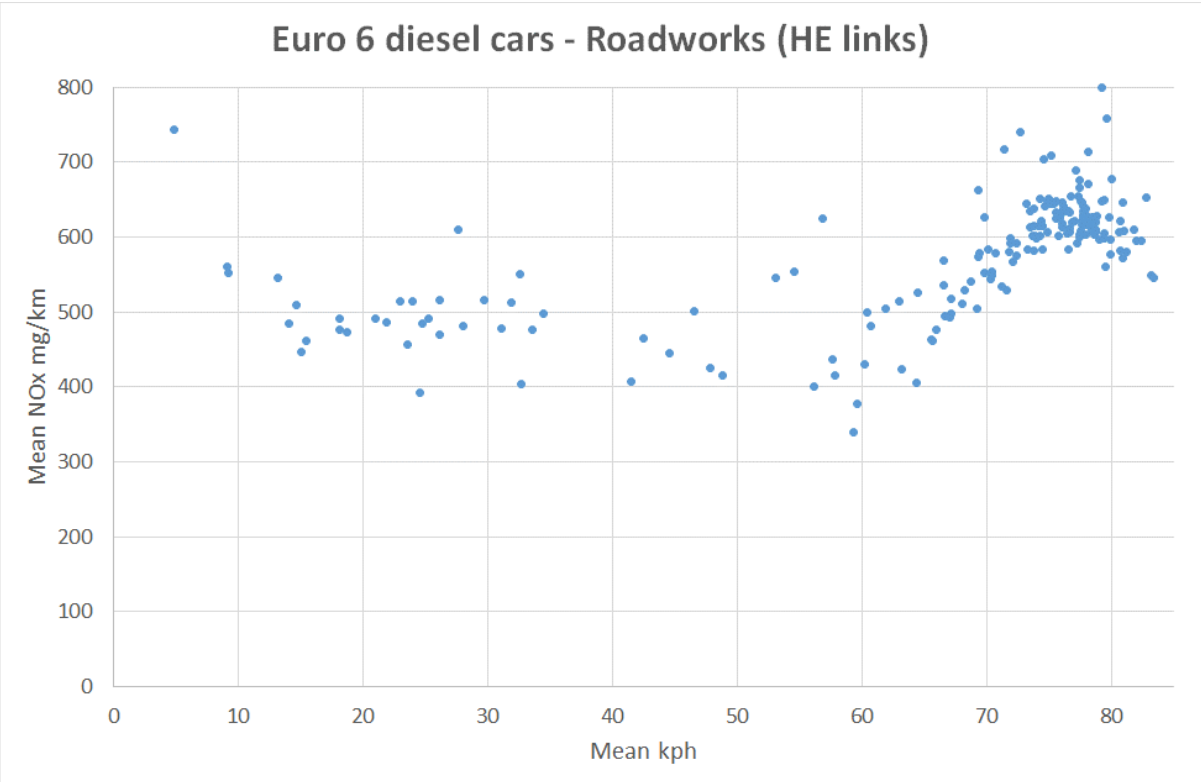

Figure B6: Calculated Euro 6 diesel car NO_x emissions – HE links – Roadworks (50mph)

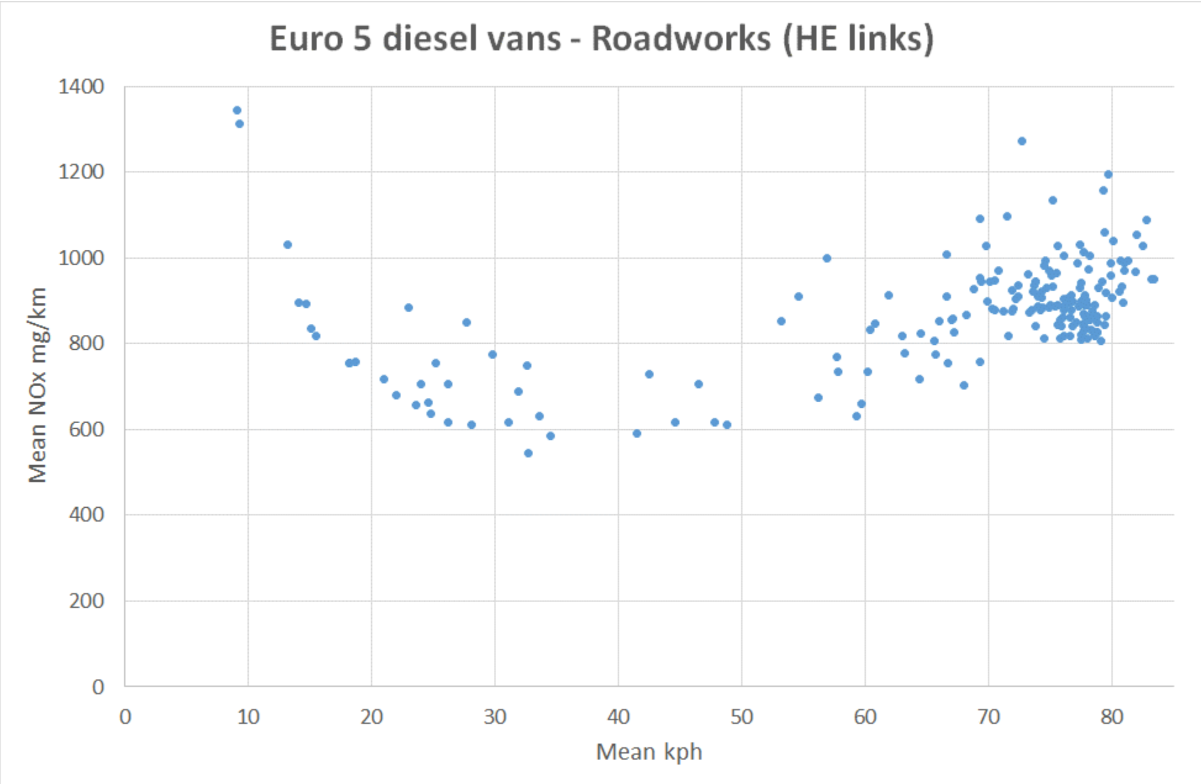

Figure B7: Calculated Euro 5 diesel van NO_x emissions – HE links – Roadworks (50mph)

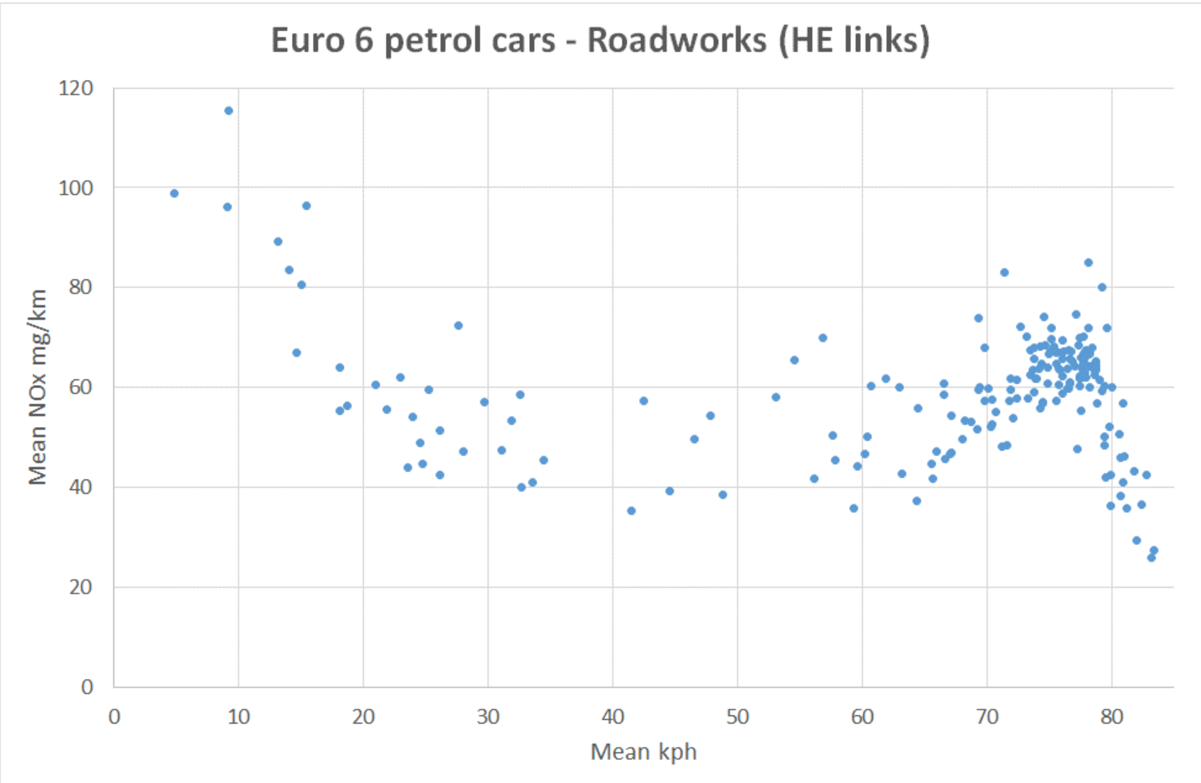

Figure B8: Calculated Euro 6 petrol car NO_x emissions – HE links – Roadworks (50mph)

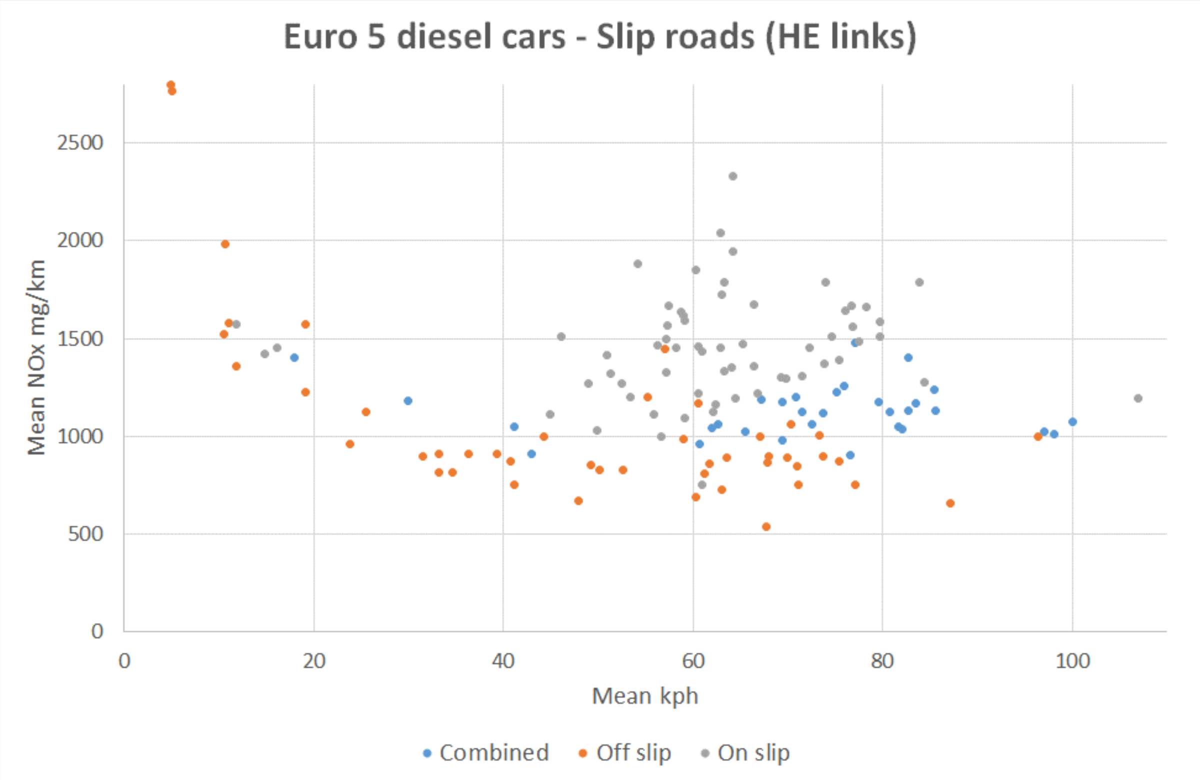

Figure B9: Calculated Euro 5 diesel car NO_x emissions – HE links – Slip roads

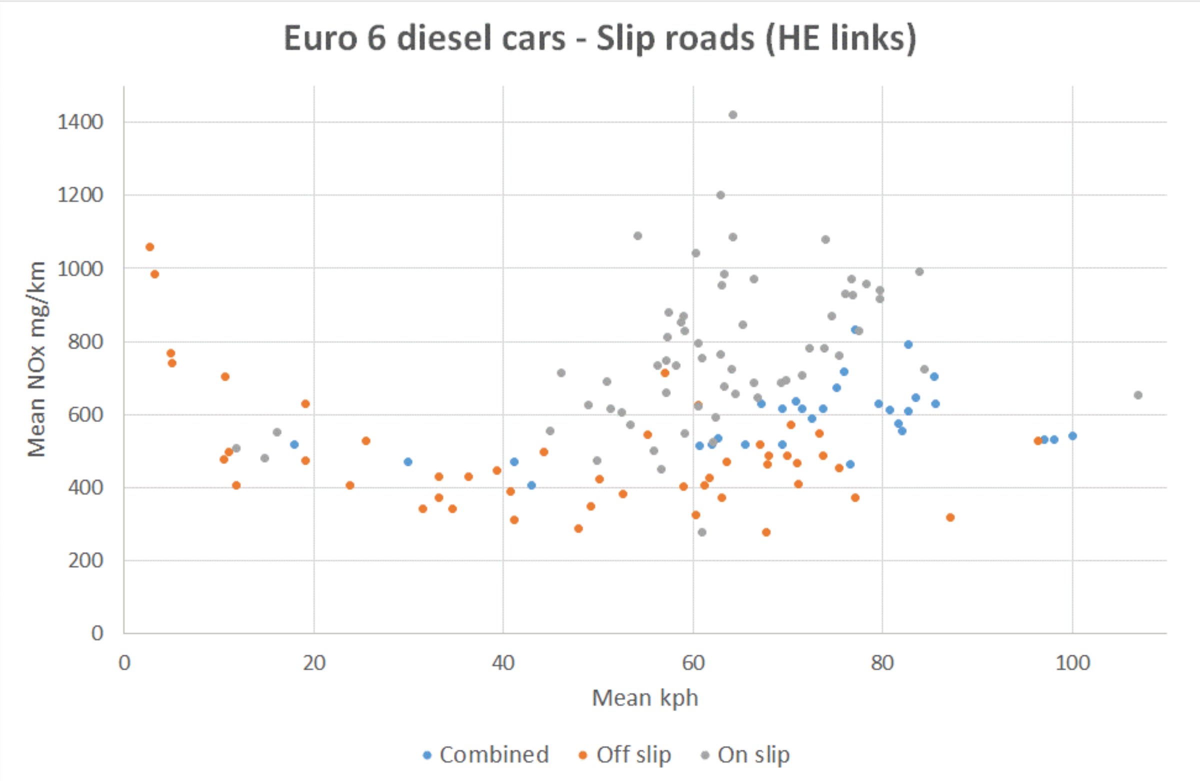

Figure B10: Calculated Euro 6 diesel car NO_x emissions – HE links – Slip roads

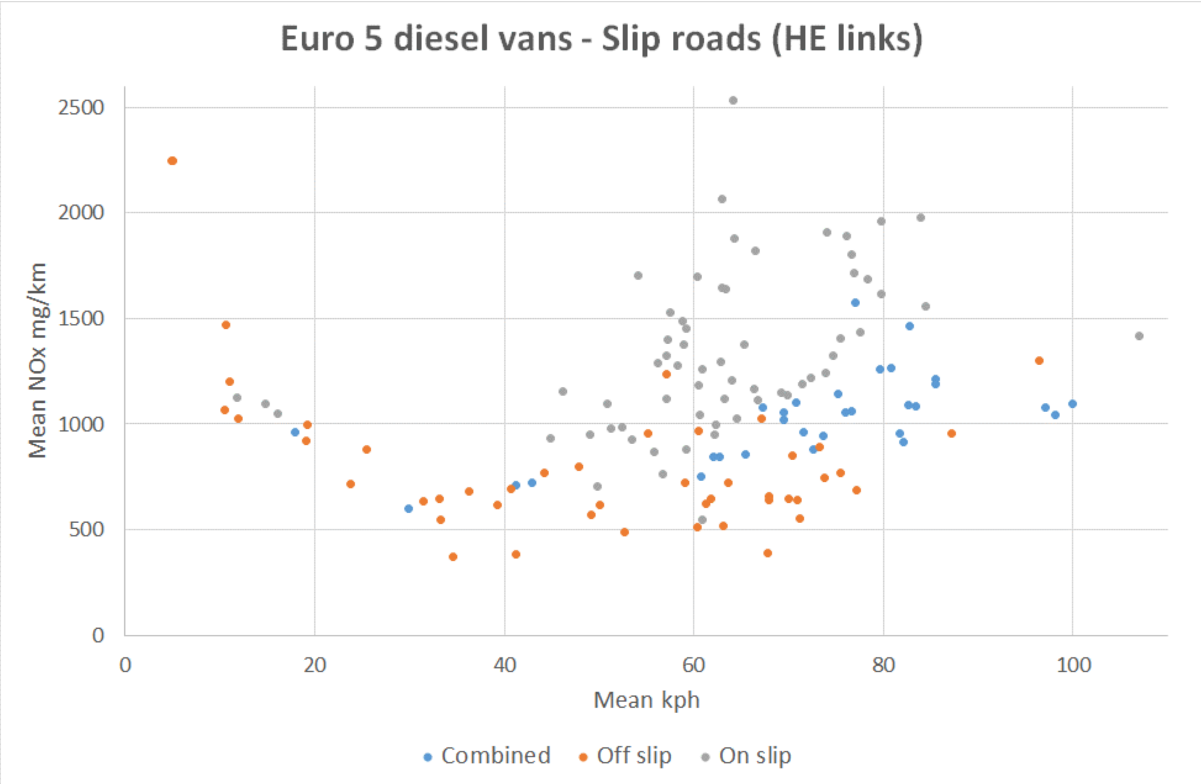

Figure B11: Calculated Euro 5 diesel van NO_x emissions – HE links – Slip roads

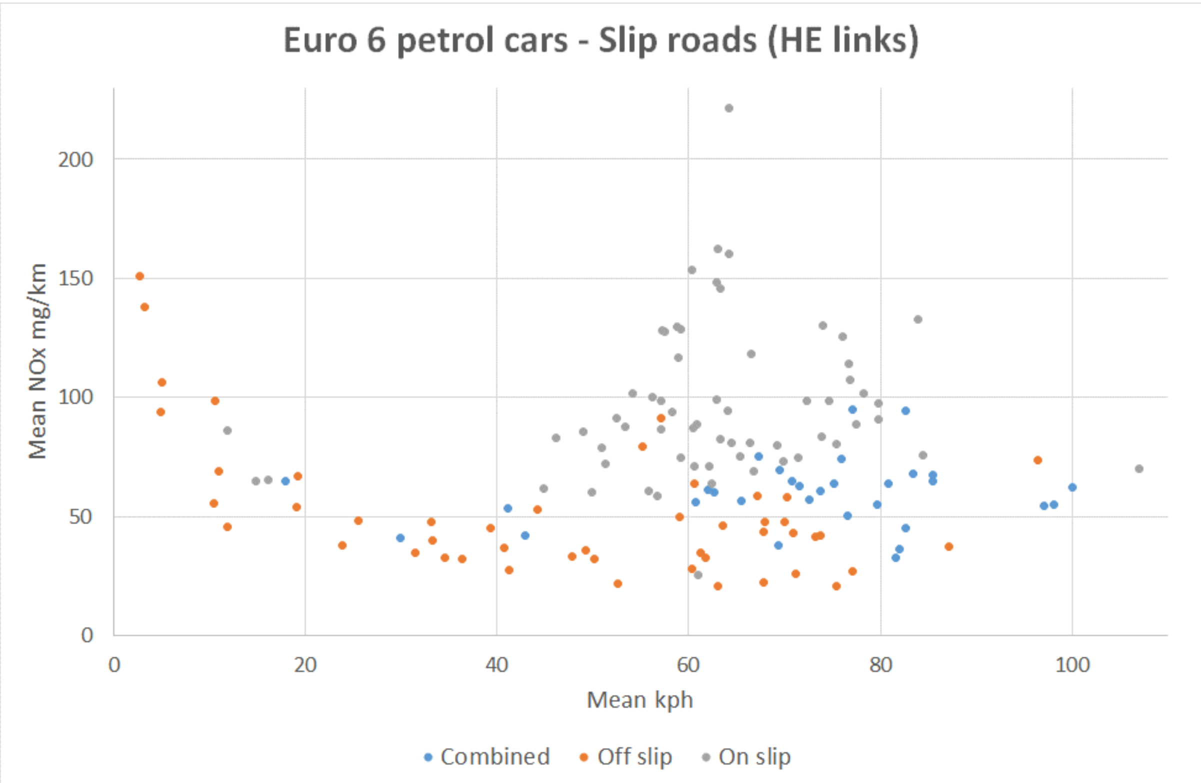

Figure B12: Calculated Euro 6 petrol car NO_x emissions – HE links – Slip roads

Annex C: Further investigation of the 'harmonica' effect

The 'harmonica' effect was reviewed to provide additional confidence in the results. It is hypothesised that the higher emission rate (NO_x mg/km) observed for diesel cars in the speed range 40 – 50mph is a consequence of (a) the DfT / DVSA PEMS emissions data (emission map) **and/or** (b) increased vehicle dynamics in this speed range in the Highways England survey data.

(a) DfT / DVSA PEMS emissions data

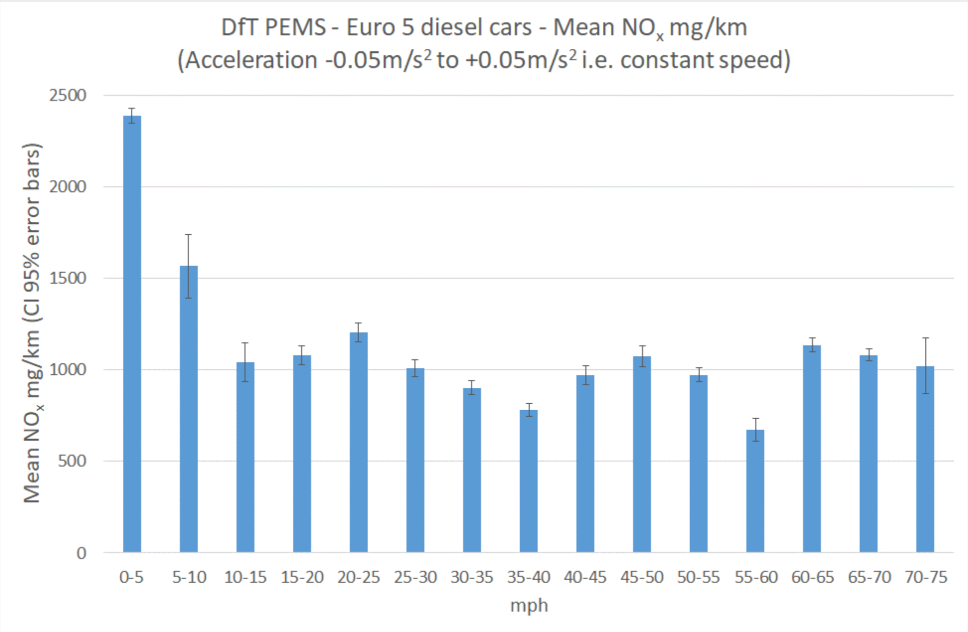

Figure C1: Euro 5 diesel car NO_x emissions at constant speed

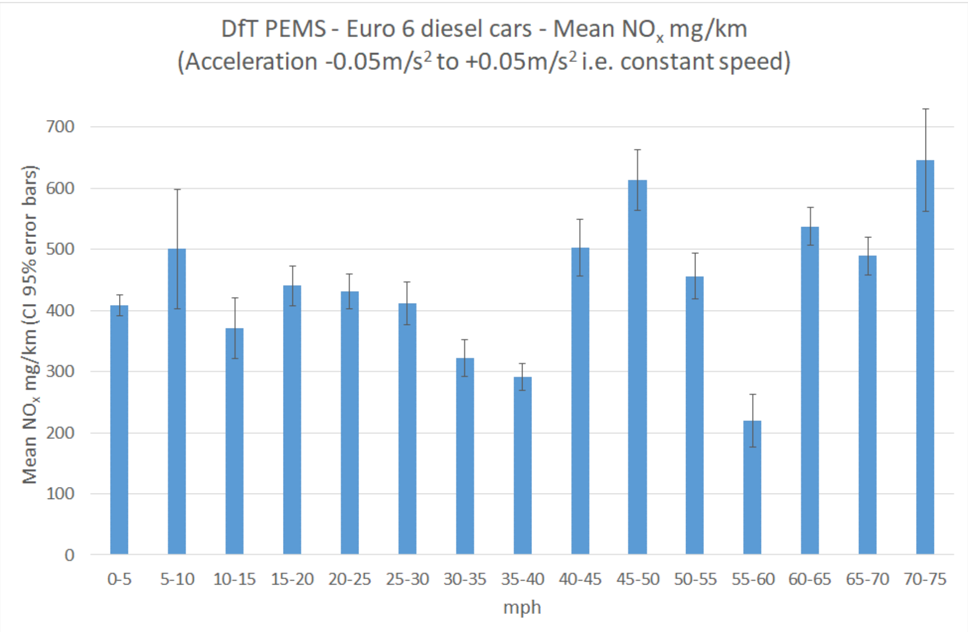

Figure C2: Euro 6 diesel car NO_x emissions at constant speed

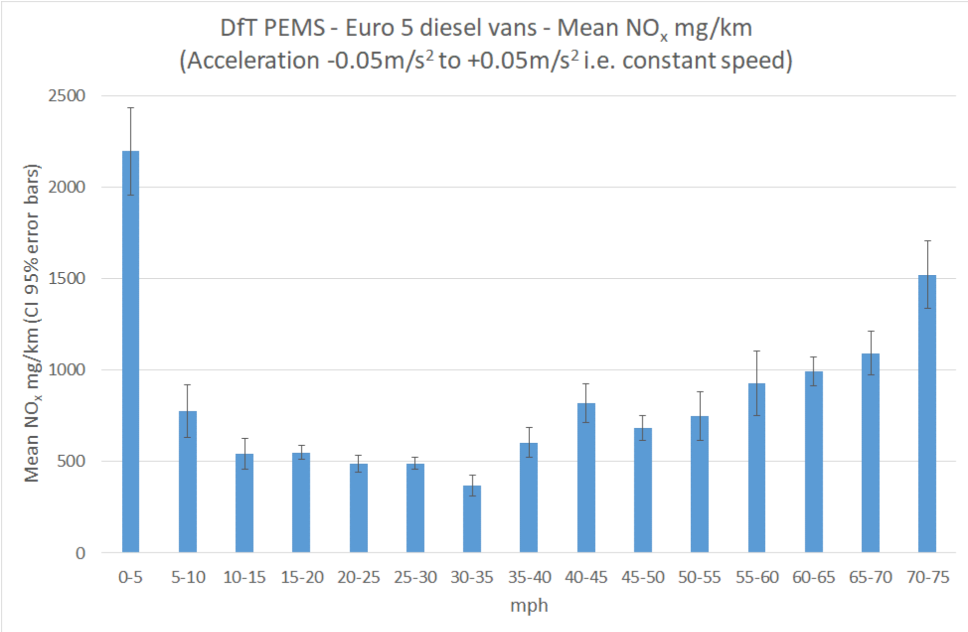

Figure C3: DfT PEMS Euro 5 diesel van NO_x emissions at constant speed

Figures C1, C2 and C3 present the DfT / DVSA PEMS emissions data for Euro 5 and Euro 6 diesel cars, and Euro 5 diesel vans operating at constant speed and zero acceleration (technically, data within an acceleration range of minus 0.05m/s^2 to plus 0.05 m/s^2). It can be seen that emissions of NO_x in the emissions map from diesel cars are elevated in the speed range 40 – 55mph, particularly for the Euro 6 diesel cars. NO_x emissions for the Euro 5 diesel vans (a small sample of only 5 vehicles) generally increase as speed increases above 50mph. The error bars indicate the 95% confidence interval about the mean. It should be noted that the lower emissions rate observed in the speed range 55 – 60mph for diesel cars coincides with a relatively smaller sample size in this speed bin. However, the calculated 95% confidence interval, whilst larger due to the smaller sample size, falls well below the adjacent speed bins.

(b) Highways England test track PEMS emissions data

A similar analysis is presented for the PEMS data collected by Highways England at Bruntingthorpe Aerodrome and Proving Ground (Figure C4). Two significant caveats apply to these results. Firstly, the sample size (number of vehicles tested) is generally very small, with the exception of Euro 5 diesel cars. Secondly, the nature of the test track environment means that vehicles cannot cruise at constant speed for any appreciable period (the test track is essentially a 2.8 km runway, with a perimeter road running parallel). Therefore, vehicles are only operating at constant speeds for short periods of time (perhaps between 10 and 30 seconds at a time depending on speed). The planned drive cycle for the test track PEMS tests is presented in Figure C5.

Figure C4: Highways England off-road PEMS survey test route at Bruntingthorpe Aerodrome and Proving Ground

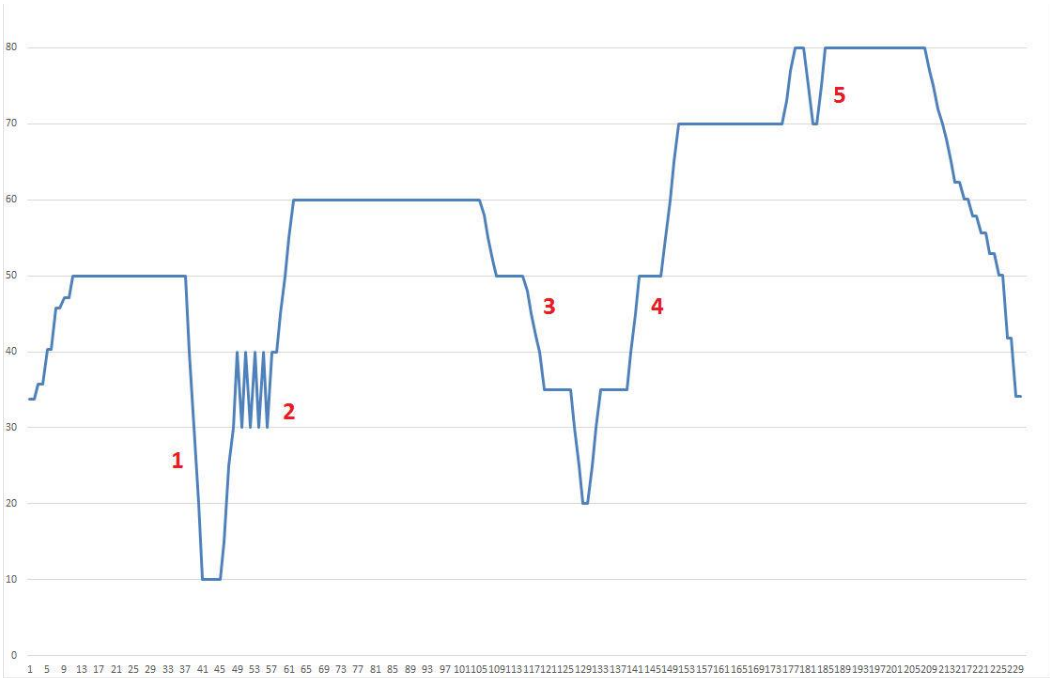

Figure C5: Planned drive cycle on the test track at Bruntingthorpe

Figures C6 and C7 present the results for Euro 5 and Euro 6 diesel cars respectively. The Euro 6 diesel car results should be treated with caution because they only represent two vehicles. However, both sets of results display higher NO_x emissions in the speed range 35 to 55mph, with reduced emissions between 55 and 60mph. Emissions then increase above 60mph.

Figures C8, C9, and C10 present the results for Euro 4, 5, and 6 diesel vans respectively. Again, care should be taken because of the small sample size (4, 5, and 3 vehicles only). Nevertheless, similar patterns are seen in these results, with generally higher NO_x emissions between 35 and 50/55mph, and reduced emissions in the speed range 55 to 65mph. The results for the Euro 5 diesel vans exhibit some instability between 55mph and 70mph, with a localised peak at 60-65mph. It may be the case that higher speeds may be dominated by the lighter Euro 5 vans, which might explain the apparent reduced emissions above 65mph (the heavier vans would struggle to reach these speeds within the confines of the test track). Results would need to be produced by individual vehicle to clarify this issue. Therefore, it is not known at this stage what influence the constrained test track conditions may have on these results, when making comparisons with 'on-road' PEMS data.

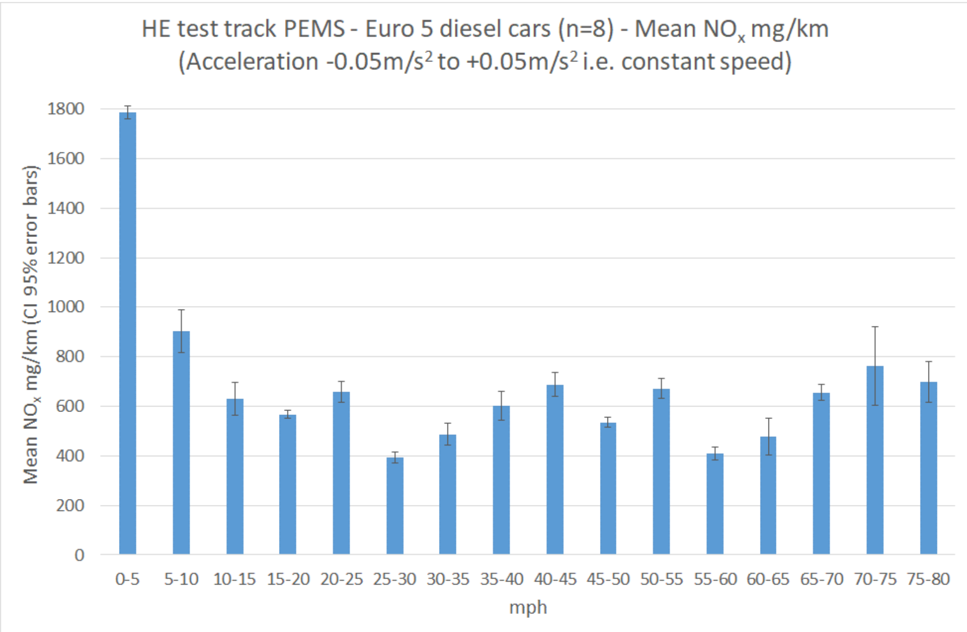

Figure C6: Highways England test track PEMS Euro 5 diesel car NO_x emissions at constant speed

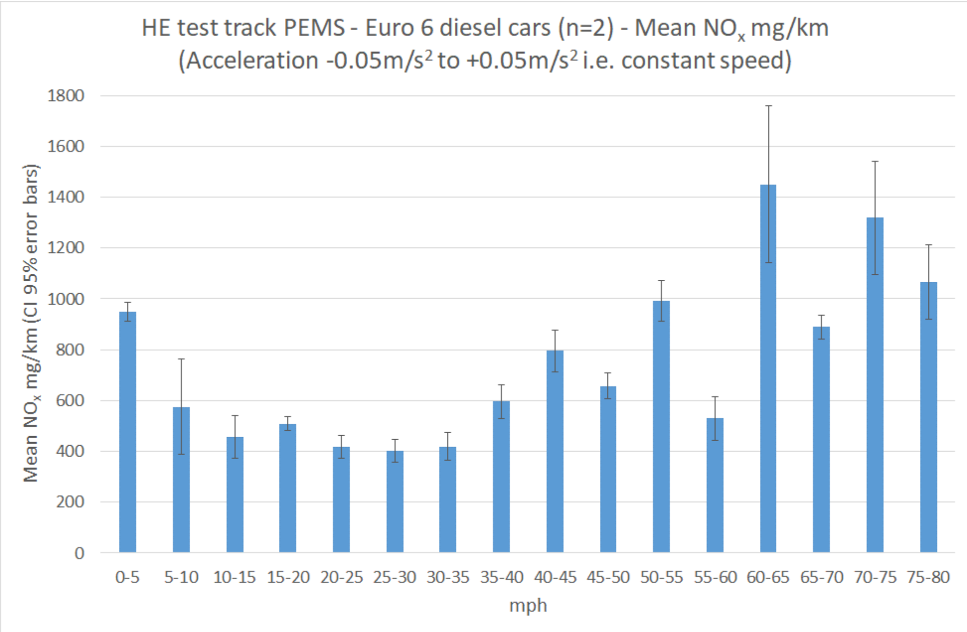

Figure C7: Highways England test track PEMS Euro 6 diesel car NO_x emissions at constant speed

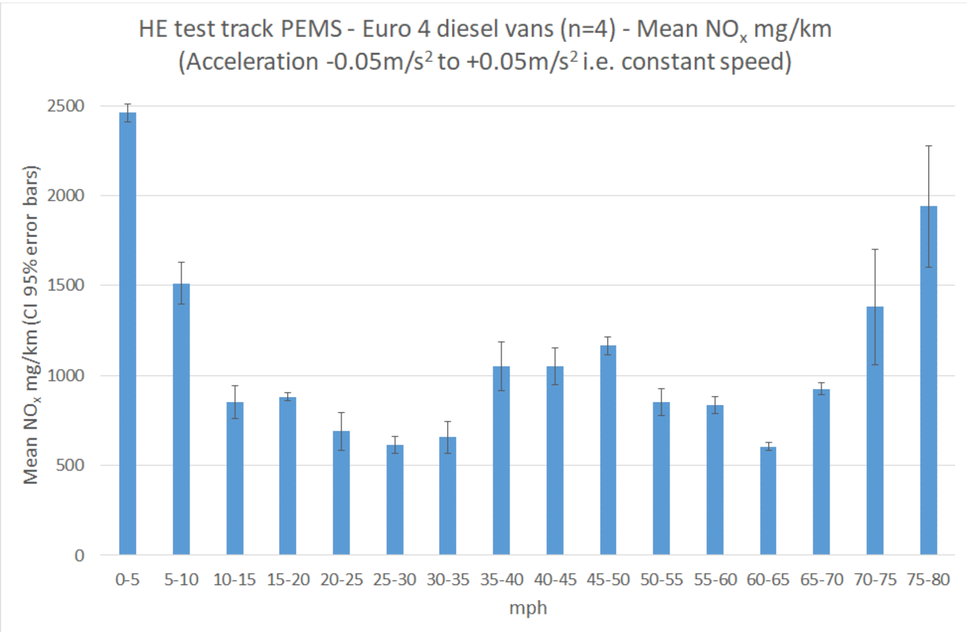

Figure C8: Highways England test track PEMS Euro 4 diesel van NO_x emissions at constant speed

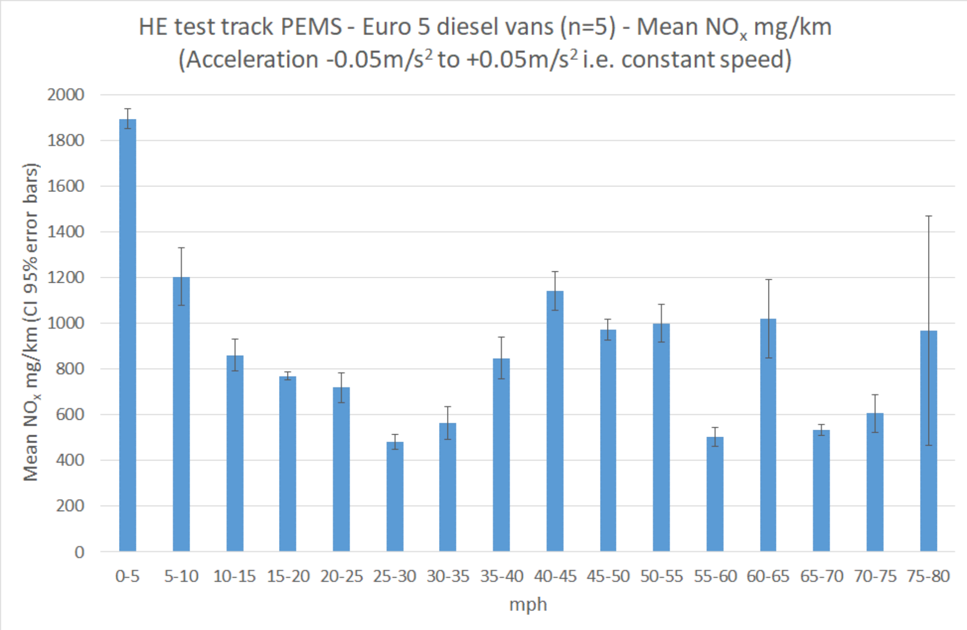

Figure C9: Highways England test track PEMS Euro 5 diesel van NO_x emissions at constant speed

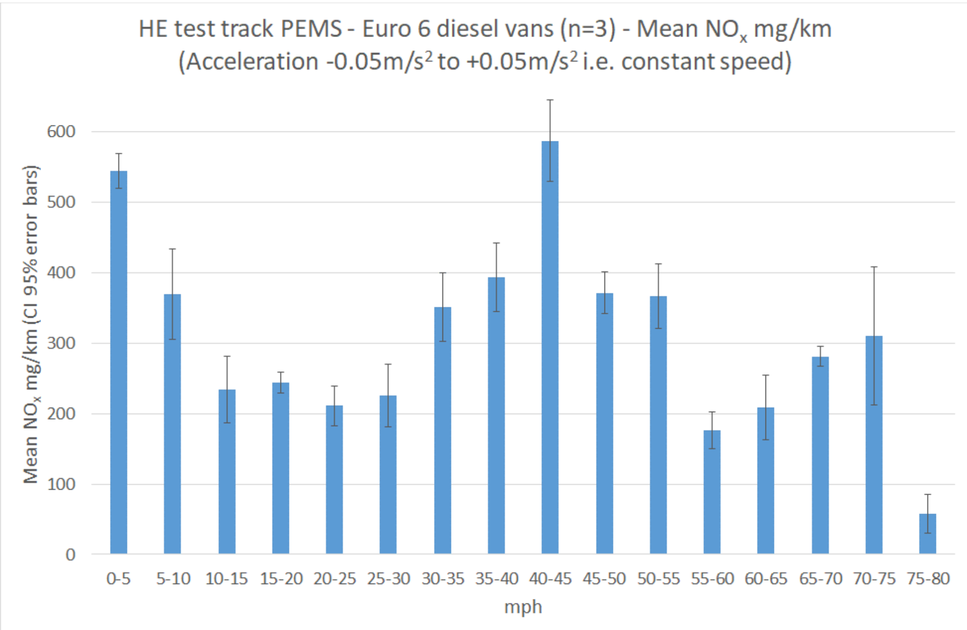

Figure C10: Highways England test track PEMS Euro 6 diesel van NO_x emissions at constant speed

(c) Highways England survey data vehicle dynamics

Figure C11 presents the standard deviation of observed speeds from the Highways England instrumented vehicle survey data, aggregated to the Highways England survey 'links'. The figure presents the average standard deviation within each speed bin, and the standard deviation weighted by link length. It can be seen that there is a larger standard deviation (increased vehicle dynamics) in the 50 – 55mph speed bin, relative to the adjacent speed bins. It can reasonably be expected that a higher degree of vehicle dynamics will result in elevated NO_x emissions, relative to a situation with lower vehicle dynamics (lower standard deviation of speed) at the same mean link speed.

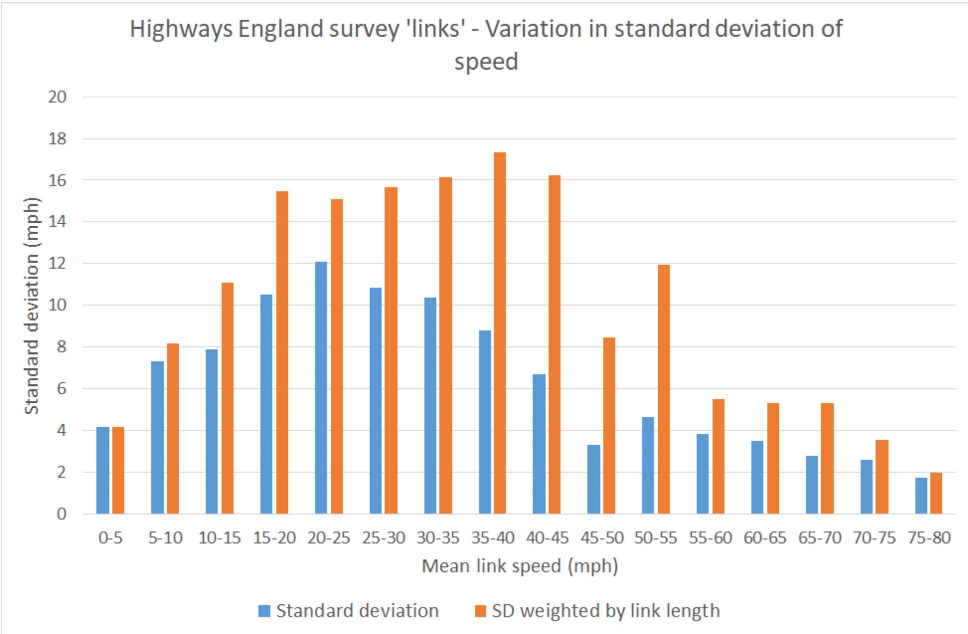

Figure C11: Highways England survey 'links' – Variation in standard deviation of speed

Therefore, the calculated NO_x emission rates by speed bin for the Highways England main carriageway links, as presented in Figures C12 and C13, will be a consequence of both (a) the emission maps derived from the DfT / DVSA PEMS data, and (b) the variation in observed vehicle dynamics by speed. In these cases, it would appear that the variation in NO_x emissions by speed in the DfT / DVSA emissions map is dominant.

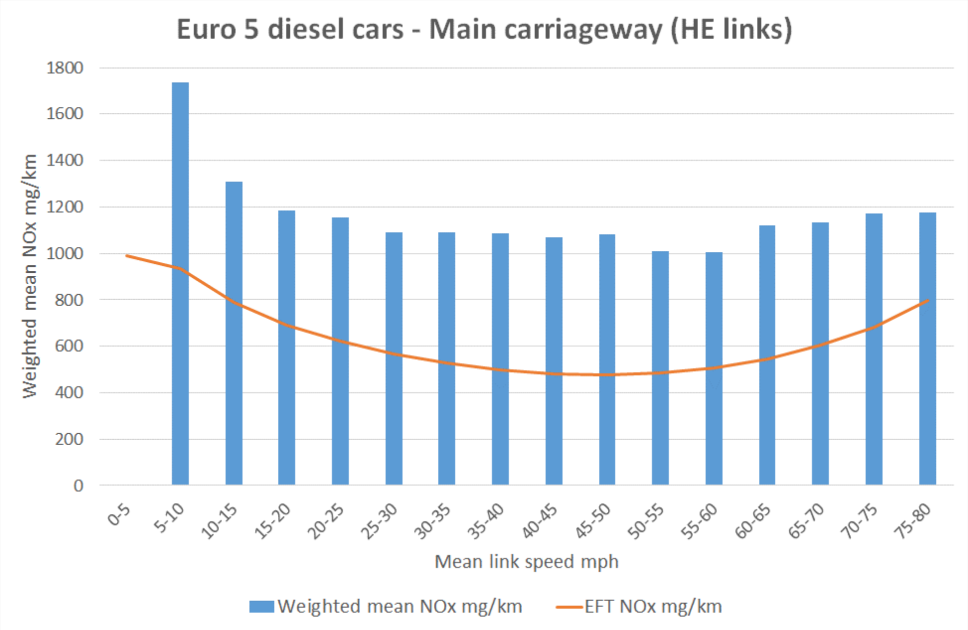

Figure C12: Highways England motorway link NO_x emissions data by speed bin – Euro 5 diesel cars

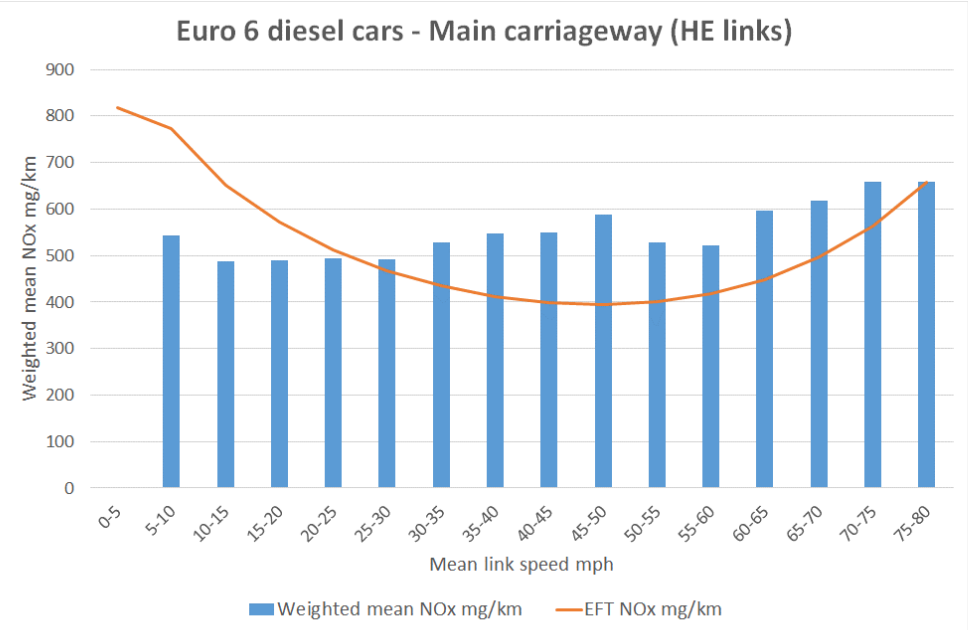

Figure C13: Highways England motorway link NO_x emissions data by speed bin – Euro 6 diesel cars

(d). Required 'uplift' to account for 'harmonica' effect during light congestion (30-50mph speed band).

From the previous calculations in sections 9 and 10, applying PEMS emission rates to the Highways England vehicle dynamics survey data at a 'link' resolution, emission rates were calculated for each of the proposed speed bands, as illustrated again in Figure C14.

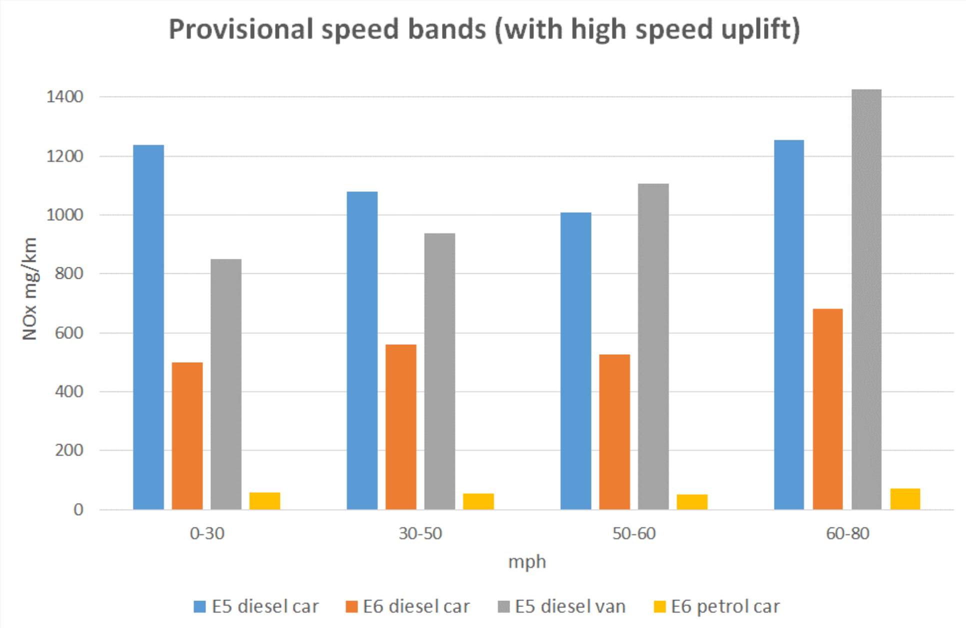

Figure C14: Provisional speed bands (with high speed uplift)

Relative differences in emission rates during 'free flow' and 'light congestion' can be derived from Figure C14. These factors can then be applied to EFT 'free flow' emission values to estimate EFT emission rates values for 'light congestion'. Table C1 presents a set of such factors derived from the DfT / DVSA PEMS data and Highways England 'link' vehicle dynamics data.

Table C1: Speed band NO_x mg/km emission rates derived from DfT / DVSA PEMS data and Highways England 'link' vehicle dynamics data

Speed band (mph)	**E5 diesel car**	**E6 diesel car**	**E5 diesel van**	**E6 petrol car**
0-30 (heavy congestion	1237	498	849	57
30-50 (light congestion)	1081	561	938	55
50-60 (free flow)	1009	525	1107	51
60+ (high speed)	1254	680	1427	70
Factor ('Free flow' to 'Light congestion)	1.07	1.07	0.85	1.09

Annex D: Comparison of EFT and TNO assumptions regarding high speed light vehicle NOx emissions

TNO has indicated, based on Dutch PEMS data, that a 15% to 20% increase in light vehicle NO_x emissions is to be expected for every 10kph increase above 100kph. This assumption has been compared with EFTv8 to assess the level of consistency in the rate of change (gradient) of NO_x emissions as speed increases above 100kph. Figure D1 presents this comparison, assuming a common emissions rate at 100kph, for Euro 5 diesel cars, Euro 6 diesel cars, and Euro 5 diesel vans (class III).

The blue columns are the EFTv8 predicted emission rates at 10kph increments. The red columns present the expected (TNO) emissions rates if NO_x emissions increase by 15% for every 10kph increase above 100kph. Similarly, the grey columns present the expected (TNO) emissions rates if NO_x emissions increase by 20% for every 10kph increase above 100kph.

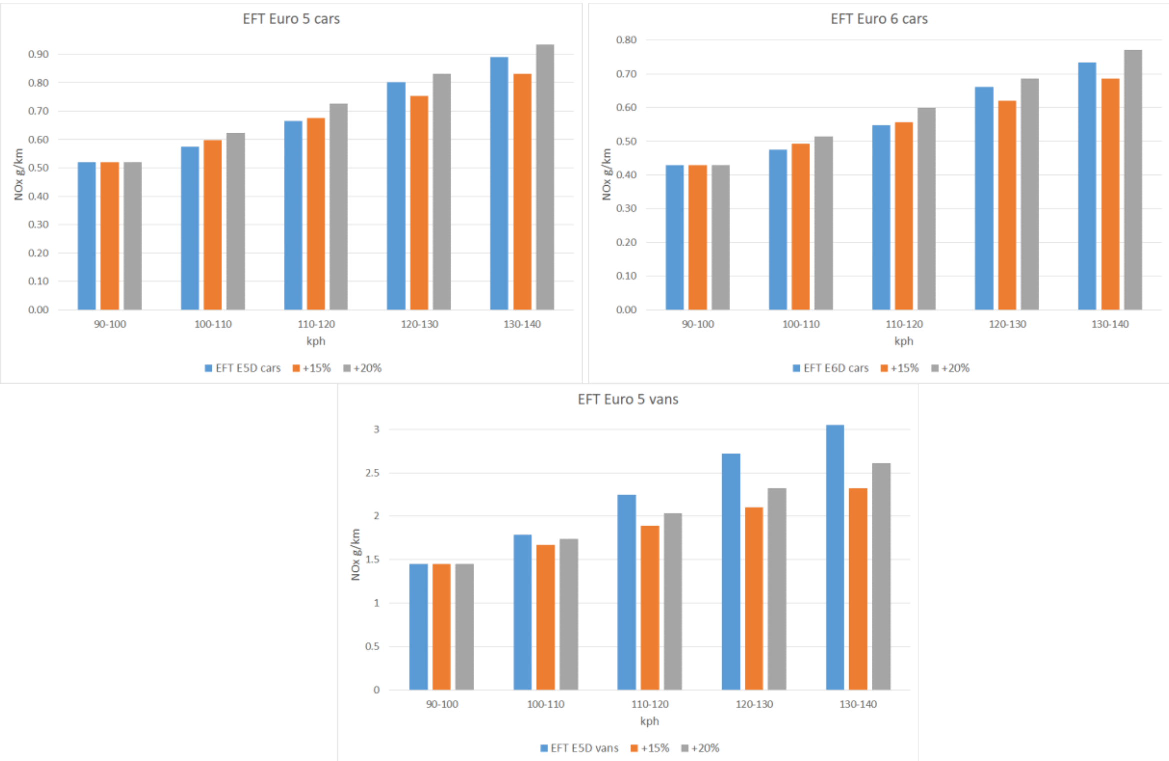

Figure D1: Comparison of EFT and TNO higher speed NO_x gradient assumptions

It can be seen that for Euro 5 and Euro 6 diesel cars, the TNO 15% and 20% increase values generally straddle the predicted EFT values.

To calculate the appropriate emission rate for the proposed >60mph speed band, it is necessary to know the proportions of light vehicles travelling at speeds greater than 60mph, and the associated EFT emission rates. The distribution of speeds can be derived from published DfT statistics (TSGB Table SPE0111). Table D1 presents the mean EFT emission rates by 5mph speed band above 60mph, and the proportions of motorway (free flow) traffic operating within these speed bands.

Table D1: EFT light vehicle emission rates and traffic proportions

	EFT emission rates (g/km)				DfT traffic proportions (%)	
mph	Euro 5 diesel cars	Euro 6 diesel cars	Euro 5 diesel vans		Car	Van
50-60	0.498	0.411	1.308		12.9	13.9
60-65	0.546	0.450	1.615		14.1	13.7
65-70	0.601	0.496	1.933		21.8	20.2
70-75	0.681	0.561	2.318		21.9	20.4
75-80	0.791	0.653	2.704		14.1	14.6
80-85	0.887	0.732	2.996		7.5	8.3
85-90	0.890	0.734	3.121		4.1	5.3

Table D2 presents the calculated EFT light vehicle emissions rates for a 60mph+ speed band, applying the emission rates and traffic proportions from Table D1. Finally, Table D3 presents a comparison of the calculated emission rates from Table D2 with the speed band emission rates derived by Highways England from EFT (originally averaging from 96 – 130kph for the 'high speed' band, but also now including the mean value averaged from 96 – 140kph).

Table D2: Calculated light vehicle emission rates for 60mph+ speed band from Table 1

	Euro 5 diesel cars	Euro 6 diesel cars	Euro 5 diesel vans
60+mph	0.685	0.565	2.295

Table D3: Comparison with EFT light vehicle speed band values calculated by Highways England

	Euro 5 diesel cars	Euro 6 diesel cars	Euro 5 diesel vans
0-30mph	0.742	0.613	1.261
30-50mph	0.499	0.411	1.083
50-60mph	0.497	0.410	1.300
EFT 60-81mph*	0.664	0.548	2.167
60+mph	0.685	0.565	2.295
	97.0%	97.0%	94.4%
EFT 60-87mph**	0.714	0.589	2.366
60+mph	0.685	0.565	2.295
	104.3%	104.3%	103.1%

*EFT emission rates averaged from 96kph to 130kph (81mph)

**EFT emission rates averaged from 96kph up to 140kph (87mph)

It can be seen from Table D3 that if the 'high speed' band is calculated from EFT as a simple average of the values between 96kph and 130kph, the resultant NO_x emission rates will be approximately 3% too low for diesel cars, and 5.6% too low for diesel vans (class III). In contrast, if the 'high speed' band is calculated from EFT as a simple average of the values between 96kph and 140kph, the resultant NO_x emission rates will be approximately 4.3% too high for diesel cars, and 3.1% too high for diesel vans (class III).

Annex E: Mean NO_x emissions calculated for Highways England probe vehicle survey data (by link) – Slip roads

	On slip (link count = 62)	**Off slip (link count = 48)**	**Combined links (link count = 31)**
Euro 5 diesel car	1454 mg/km	1192 mg/km	1127 mg/km
Euro 6 diesel car	767 mg/km	487 mg/km	587 mg/km
Euro 5 diesel van	1333 mg/km	950 mg/km	1026 mg/km
Euro 6 petrol car	96 mg/km	52 mg/km	60 mg/km

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