Ammonia Emissions from Roads for Assessing Impacts on Nitrogen-sensitive Habitats

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Experts in air quality management & assessment

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1 Introduction

1.1 More than 15 years ago, Cape et al. (2004) measured the effects of traffic emissions of ammonia (NH_3) on roadside concentrations, showing that road traffic had a significant effect on ammonia concentrations as well as nitrogen deposition fluxes. The monitoring transects used by Cape et al (2004) extended up to 10 m from the roads and, over this distance, they showed that measured ammonia and co-located measured NO_2 concentrations declined at similar rates. The monitoring transects used by Cape et al. (2004) did not extend beyond 10 m from roads.

1.2 Following on from the Cape et al. (2004) study, the 2007 update to the air quality sections of the Design Manual for Roads and Bridges (DMRB) (HA207/07) explained that ammonia emissions from road vehicles can lead to significant additional nitrogen deposition in the immediate vicinity of roads; explaining that this meant, "*typically within 10 m*". It is not clear whether the reference to 10 m was linked to the results from Cape et al. (2004), although it is understood that at that time there had been no other robust ambient monitoring determining the roadside increment of ammonia. HA207/07 did not require the inclusion of traffic-related ammonia emissions in air quality assessments. The most recent update to the air quality sections of the DMRB (LA105) no longer mentions traffic-related ammonia emissions, and the assessment approach requires a calculation of the effect that road traffic has on nitrogen deposition calculated from NOx emissions. The contribution from ammonia emissions is not considered in LA105.

1.3 Internal guidance provided by Natural England to its officers, outlining its "*approach to advising competent authorities on the assessment of road traffic emissions under the Habitats Regulations*" (Natural England, 2018), describes an assessment methodology based on the assumption that the only traffic emission of relevance to nitrogen deposition is NOx. Furthermore, the approach which Natural England takes when considering the sensitivity of habitats to traffic-related impacts is often guided by its report on the "*Potential risk of impacts of nitrogen oxides from road traffic on designated nature conservation sites*" (Natural England, 2016). In relation to road traffic, this report solely considers emissions of NOx.

1.4 Guidance from the Institute of Air Quality Management (Holman et al., 2019) suggests that emissions of ammonia from road traffic are small and falling; although evidence to support this statement is not provided. The Guidance suggests that the impacts of road traffic emissions on nitrogen deposition should be calculated, but focuses on emissions of NOx, and does not consider the potential contribution of ammonia emissions.

1.5 This report presents evidence on the magnitude of ammonia emissions from road traffic and considers the potential contribution to nitrogen deposition near the roadside.

1.6 It is also explains that some of the measures which have been introduced to decrease NOx emissions from road vehicles will increase ammonia emissions. In order to test different fleet assumptions with regard to their effects on trends in nitrogen deposition at the roadside, a new emissions model has been generated to describe traffic-related ammonia emissions. A range of different assumptions regarding future petrolisation/hybridisation, and electrification of the passenger car fleet have then been tested with the likely effect on trends in roadside nitrogen deposition explored.

1.7 Ammonia emissions also play an important role in the formation of fine airborne particulate matter, but this has not been considered within this report, which deals solely with impacts on nitrogen-sensitive habitats.

2 Emissions Sources

2.1 Unlike NOx, ammonia is not released by combustion processes within vehicle engines. It is a by-product of systems which are fitted in order to reduce emissions of NOx.

2.2 New vehicles registered in the UK have to meet European type-approval emissions standards, referred to as "Euro" standards. These seek to control emissions of a number of pollutants, including NOx. The standards have become progressively more stringent and comprehensive over time and currently extend from ‘Euro 1’ to ‘Euro 6’ for cars and vans and Euro I to Euro VI for Heavy Duty Vehicles (HDVs). The Euro 1 and Euro I standards came into force in 1992. Euro VI has been mandatory for all new HDVs since January 2014. The Euro 6 standards are being delivered in a number of iterations, with implementation dates from 2014 until 2021. Ammonia is regulated for Euro VI HDVs, with an emission limit of 10 parts per million but is not currently regulated for other vehicles.

2.3 In petrol vehicles, NOx emissions are typically controlled using a three-way catalyst, which is designed to oxidise hydrocarbons and carbon monoxide (to form water and carbon dioxide) while reducing NOx to form unreactive nitrogen (N_2). However, if the conditions for these reactions are not optimal, then nitric oxide (NO) can be reduced to ammonia, which is then emitted via the vehicle’s exhaust. This typically occurs when an engine runs with a high fuel to air ratio; which is often when engines are cold and/or under particularly heavy load.

2.4 In diesel vehicles, NOx emissions are typically controlled using either a Lean NOx Trap (LNT) or Selective Catalytic Reduction (SCR). The LNT requires the periodic removal of stored NOx by operating with excess fuel and this can result in NO being reduced to ammonia. SCR relies on deliberately generating ammonia (the additive AdBlue is composed of urea in water, which is injected into the exhaust system). The ammonia then reacts with NOx, but it is possible for unreacted ammonia to “slip” and join the exhaust.

2.5 Ammonia emissions can be prevented either by better management of the NOx-control systems, or by fitting an ammonia slip catalyst.

3 Ambient Measurements

Monitoring Methods for Ammonia Concentrations

3.1 Ammonia is a difficult gas to measure in ambient air. Tang et al. (2001) explained that the low sampling rate of passive diffusion tubes (such as those often used for nitrogen dioxide) make them too uncertain for use at typical background ammonia concentrations where they can significantly overestimate concentrations. Martin et al. (2019) examined the performance of a range of different ammonia samplers and showed that some diffusion tubes showed clear bias. This study, again, noted that the low sampling rate of some tube-type samplers makes them too uncertain to use at background concentrations where they can significantly over-read.

3.2 Over-estimating ambient background concentrations is particularly problematic for any study which seeks to identify the contribution of a road to ambient concentrations. This is because these studies rely on comparing the roadside measurements with the background measurements; with the difference indicating the contribution of the road itself. If the background concentration is over-estimated, then the road increment will be under-estimated.

3.3 In the UK, the ‘reference’ method for measuring ambient ammonia concentrations is the DEnuder for Long-Term Atmospheric (‘DELTA’) (Connolly et al, (2016)). These monitors form the basis of Defra’s National Ammonia Monitoring Network (NAMN), and Acid Gases and Aerosols Network (AGANet). The MAMN also uses Adapted Low-cost Passive High Absorption (‘ALPHA’) samplers (Tang et al. 2001), which have been shown (e.g. Martin et al. (2019)) to provide accurate and reliable measurements even at low ambient background concentrations.

Roadside Ammonia Measurements

3.4 Cape et al. (2004) used ALPHA samplers to measure ammonia concentrations alongside roads and at representative background locations; subtracting the background values to indicate the vehicle-derived increment. These measurements, which were made during 2002-2003, are summarised in Figure 1. Results are presented as a function of numbers of vehicles on the surveyed roads so as to allow easier comparison between the studies (the measured roadside concentrations were much higher alongside very busy roads than alongside minor roads). It is clear that ammonia concentrations were higher than the local background concentration across all of these transects and that the concentrations were highest closest to roads. Cape et al. (2004) reported no other ammonia emission sources other than road vehicles along the roadways surveyed and it is clear from these measurements that road traffic was contributing significantly to the ambient ammonia concentrations.

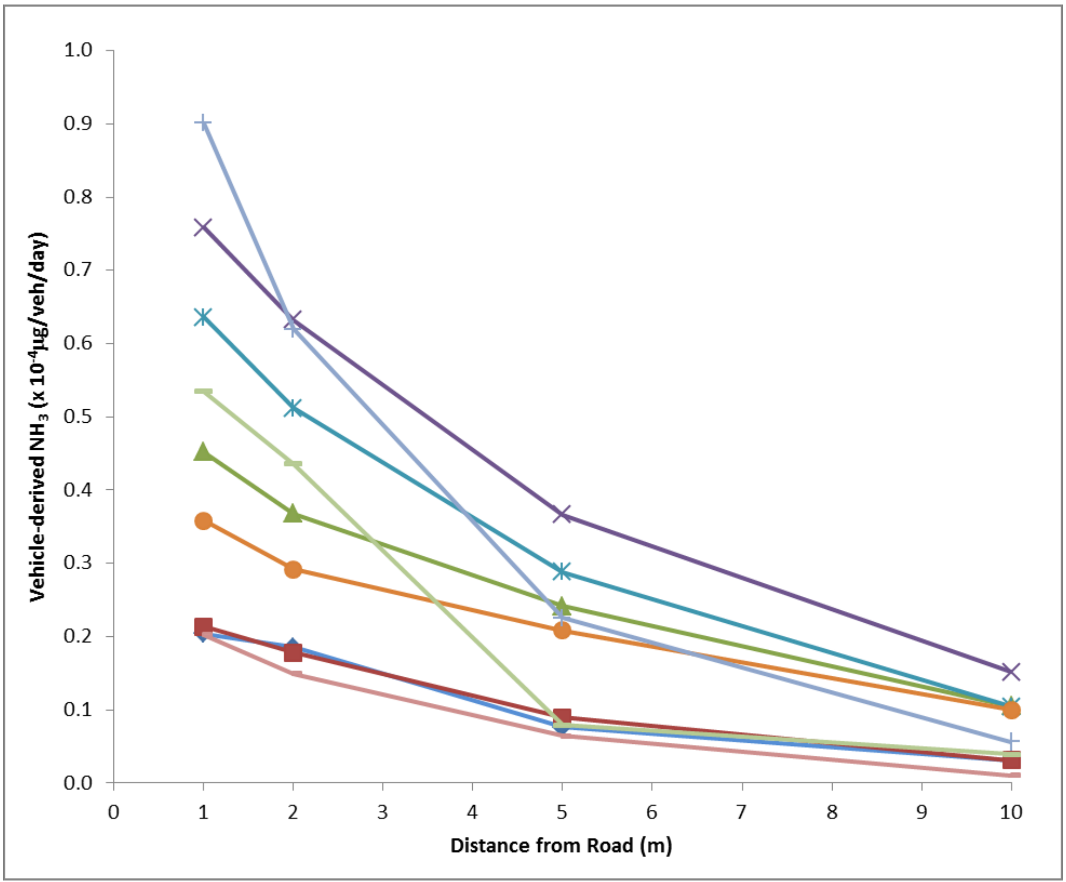

Figure 1: Roadside Increments (i.e. total concentration minus local background) of Ammonia over Nine Transects in 2002-2003 (data from Cape et al., 2004)).

3.5 No similar study to that carried out by Cape et al. (2004) was reported until 2018. Marner et al. (2018) used a network of ALPHA and DELTA II samplers, at 29 sites within Ashdown Forest in East Sussex, operated over a period of two years (summer 2014 to summer 2016). The network included sites adjacent to both major and minor roads, and background sites. This included three transects of ammonia monitors beside roads. Two of these were alongside the busy A22. The third transect was beside a minor road which makes it less useful for the type of analysis presented here. Figure 2 shows the two-year average measured ammonia concentrations vs distance from the A22. The results reported by Marner et al. (2018) are similar to those of Cape et al. (2004) in that they show very clearly that road traffic has contributed significantly to elevated ammonia concentrations close to the road.

3.6 As well as ammonia, all of the monitoring sites shown in Figure 2 also measured NO_2 concentrations. These measurements were used to calculate road-NOx concentrations using Defra's NOx from NO_2 calculator. Figure 3 shows that the spatial pattern in ammonia and NOx concentrations on moving away from the A22 is very similar, which is to be expected since both are primary pollutants released from the same emission source.

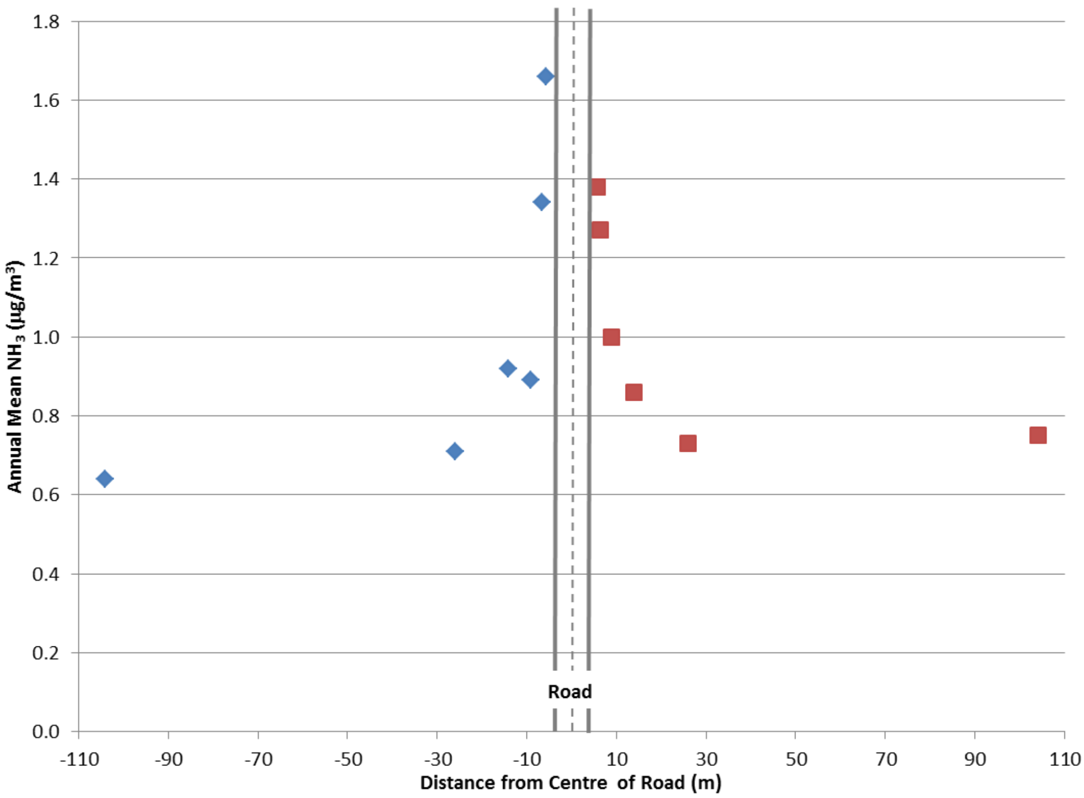

Figure 2: ALPHA Monitoring Results (µg/m^3) on Transects 1 (blue diamonds) and 2 (red squares) vs distance from the centre of road. Negative values are distance westward and positive values are distance eastward (calculated from Marner et al., 2018)

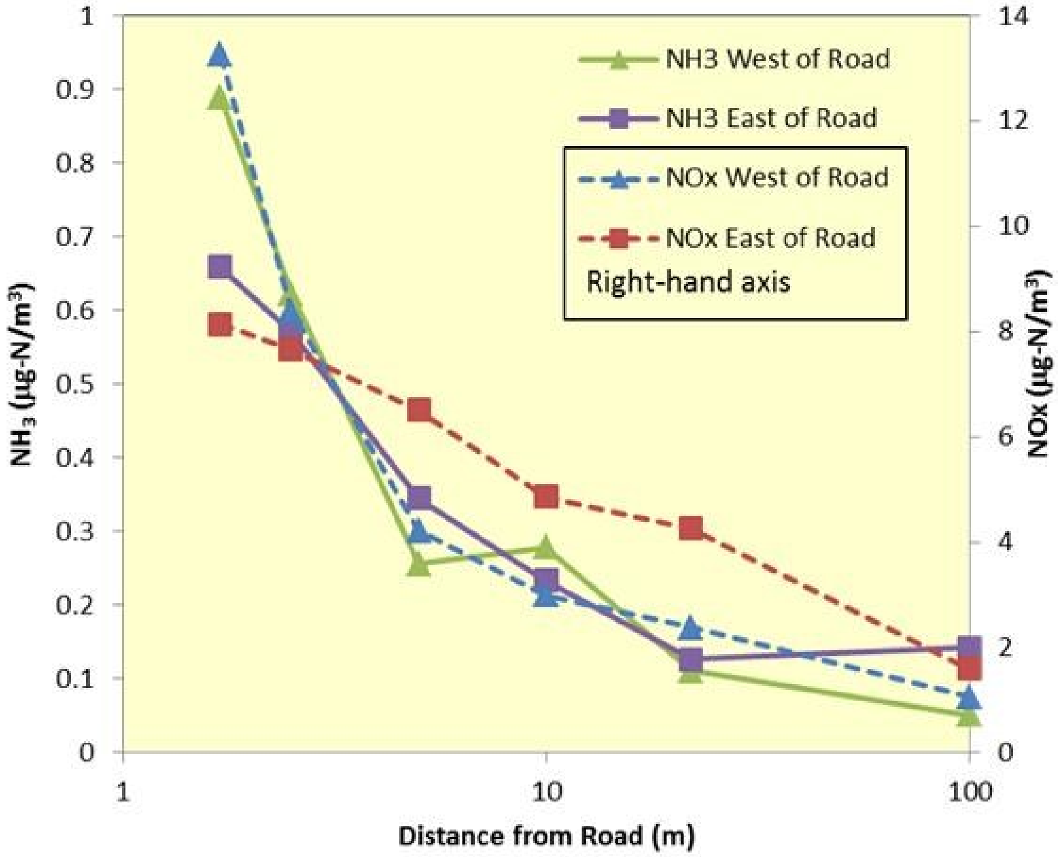

Figure 3: Two-year (2014-2016) average Ammonia and NOx concentrations along two transects running perpendicular to the A22 after subtracting measured background concentrations (calculated from Marner et al., 2018)

3.7 The NAMN includes two DELTA sites close to roads; one in central London (close to the junction of the A4 (Cromwell Road) and Queen's Gate and one in Edinburgh, at the St Leonard's monitoring station (ca. 35 m from the A7). Measurements in Edinburgh stopped in 2016. Since neither of these sites paired roadside and nearby background samplers, they cannot be used to isolate the effect of the nearby road. However, Figure 4 summarises the measurements made at these two sites between 2006 and 2019. There is no clear trend for total concentrations to either increase or reduce over this period, but is should be recognised that a large proportion of the values measured at both sites will not come from road traffic.

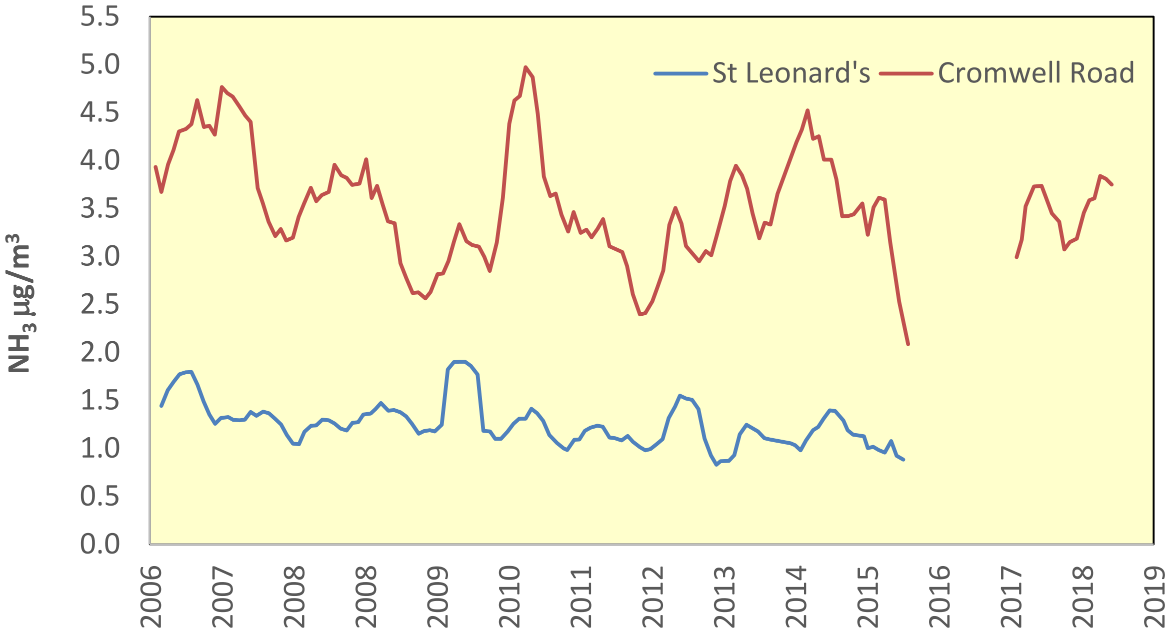

Figure 4: Rolling 6-month Mean Ammonia Concentrations at Edinburgh St Leonard's and London Cromwell Road, 2006 to 2019 (Taken from (Defra, 2020))

Contribution of Measured Roadside Ammonia to Nitrogen Deposition

3.8 When calculating nitrogen deposition, advice from Highways England (LA105), and the IAQM (Holman et al., 2019) is to multiply annual mean concentrations by annual mean deposition velocities. Both sources recommend using the deposition velocities set out in Table 1, which are taken from the air quality technical advisory group document AQTAG06 (AQTAG, 2012).

Table 1: AQTAG(06) Annual Average Deposition Velocities for NO_2 and Ammonia

Chemical Species	Surface Type	Deposition Velocity (m/s)
NO_2	Grassland	0.0015
	Forest	0.003
Ammonia	Grassland	0.02
	Forest	0.03

3.9 In Figure 5, the measured ammonia concentrations from Figure 2, and the concurrent co-located NO_2 measurements, have had the local measured background values subtracted. The concentrations have then been multiplied by the simple deposition velocities given in Table 1 (assuming deposition to grassland). Figure 5 thus shows, based solely on measured concentrations combined with deposition velocities taken from the document recommended by Highways England, and the IAQM, that ammonia can contribute more than half of the local traffic-related increment of nitrogen deposition (the range in Figure 5 is for ammonia to make up between 40% and 68% of the total roadside traffic-related flux).

3.10 A more precise method of calculating nitrogen deposition from road traffic uses the 'big leaf' model (Smith et al. (2000). Figure 6 uses this approach, combined with dispersion modelling which was calibrated against local measurements[1] of both ammonia and NO_2, and shows the relative contribution that ammonia makes to local traffic-related nitrogen deposition. Along these two transect, ammonia contributes between 50% and 70% of the road increment to nitrogen deposition when deposition is calculated using the 'big leaf' approach.

[1] With the profile of concentrations vs distance from the road also fitted to the measurements.

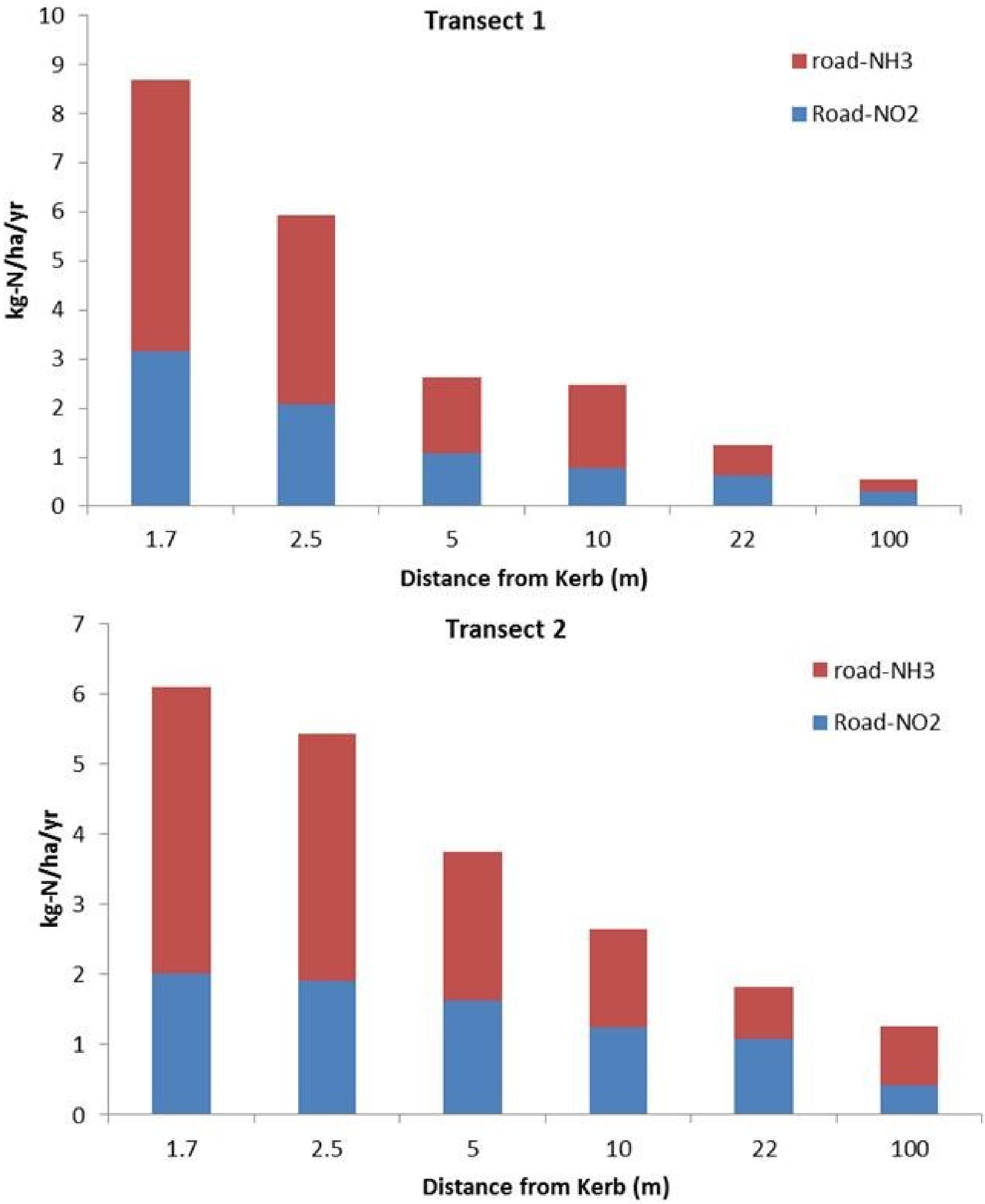

Figure 5: Local Traffic-related Increment of Nitrogen Deposition from Ammonia and NO_2 Beside the A22. Derived Solely from Measured Concentrations and 'AQTAG' Deposition Velocities (calculated from Marner et al., 2018)

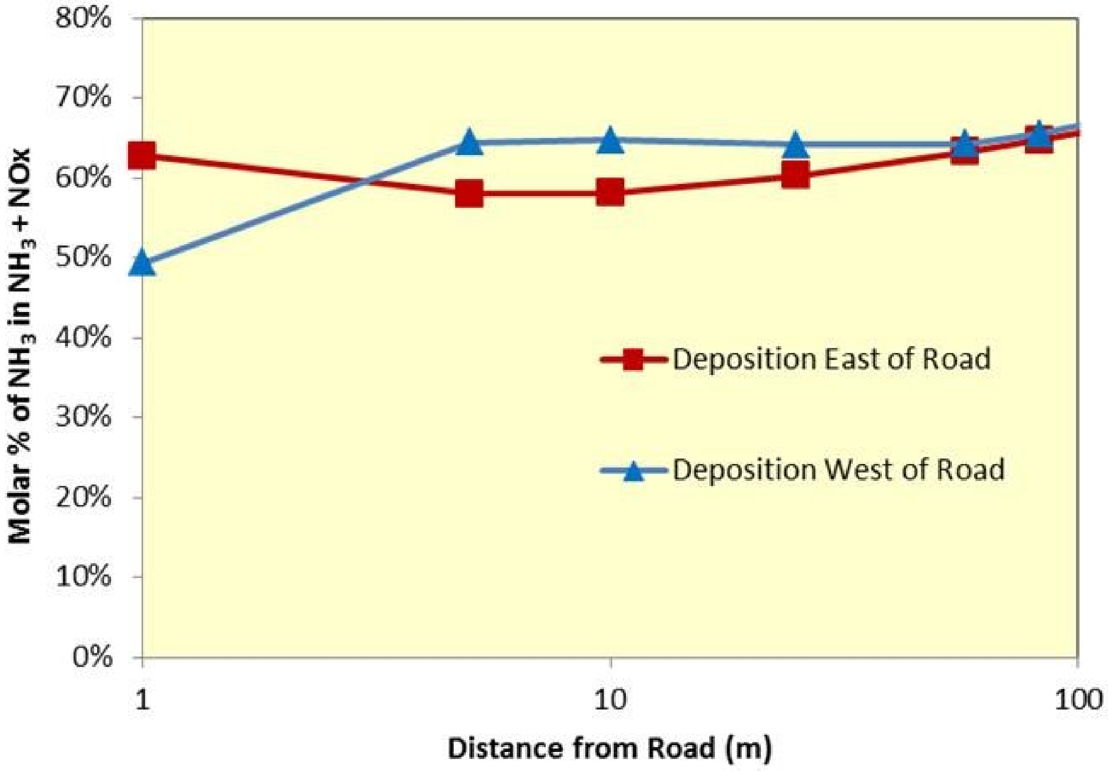

Figure 6: Relative Importance of Local Traffic-related Increment of Nitrogen Deposition from Ammonia and NOx beside the A22 (Calculated from the Results Presented in Marner et al., 2018 for Ecological Transects J and K - Detailed "AQC" Modelling)

3.11 The modelled transects in Figure 6 are co-located with transects of both NO_2 and ammonia measurements and so the relative rate of reduction in concentrations of both species are known with some confidence. The same study also reported results for numerous other modelled transects which were not co-located with measurement transects; although most were co-located with at least one ambient monitoring site. Results across all of the transects are summarised in Figure 7.

3.12 Across all of these transects, ammonia only contributed a relatively small amount (typically <10%) to the sum of NOx and ammonia concentrations (when expressed as nitrogen), but the relative rates at which ammonia and NO_2 deposit make the ammonia contribution to deposition more significant. Concentrations of NO_2 and ammonia both fall appreciably over the first 10 m when moving away from a road. Both pollutants then continue to fall over the next 90 m and beyond. Because the concentrations of both pollutants fall at similar rates, the relative contribution made by each pollutant to nitrogen deposition remains relatively constant.

3.13 Mechanistically there are reasons to expect the average rate of reduction of ammonia to be greater than that of NO_2, since it is a primary pollutant (NO_2 largely forms from NO by reaction with ozone) and because it deposits more rapidly than NO_2 and will thus also deplete more rapidly. However, this relationship is complex because each gas behaves differently at different times of day and at different times of the year. In practice, the ambient measurements do not show ammonia concentrations to fall significantly more rapidly than those of NO_2 and the model results (which take account of different diurnal and seasonal profiles as well as the measured relationships with distance from roads) suggest that the importance of ammonia to the total roadside flux actually increases slightly on moving away from the road (Figure 7).

3.14 Figure 7 is not intended to show whether or not traffic-related nitrogen deposition will be significant at 200 m from a road; rather it shows that the relative importance of traffic-related ammonia does not diminish in comparison with the importance of traffic-related NO_2. There is no basis, at any distance from a road, for calculating nitrogen deposition in relation to traffic-related NO_2 while excluding traffic-related ammonia. Assessments which do not include the contribution of traffic-related ammonia are likely to significantly under-predict the effects of road traffic on roadside nitrogen deposition.

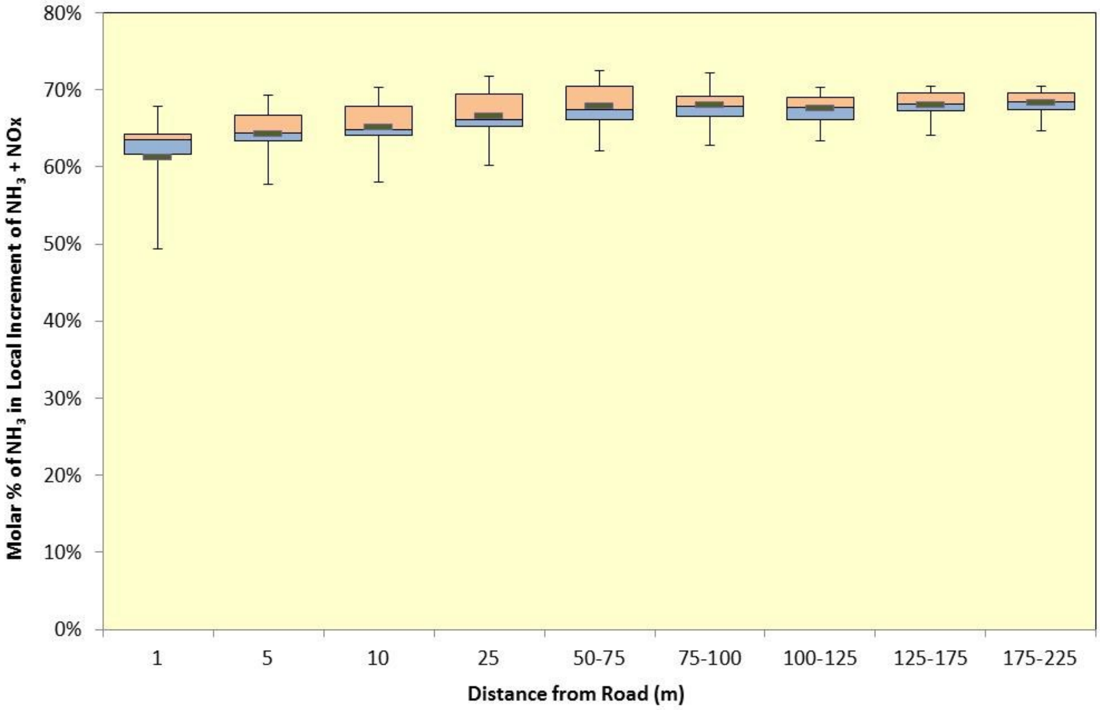

Figure 7: Relative Importance of Local Traffic-related Increment of Ammonia and NOx to Deposition Fluxes along 15 Different Roadside Transects in Ashdown Forest Assuming Uniform Sward Height (Calculated from the Results Presented in Marner et al., 2018 Detailed "AQC" Modelling)

4 Traffic-related Ammonia in the Future

4.1 The significance of traffic-related ammonia should not be a surprise. In the USA, measurements collected using remote sensing have shown that, for some time, ammonia emissions from petrol cars and trucks have exceeded those of NOx. Figure 8 summarises some results from remote sensing carried out in the USA during 2013. This figure summarises the results from 21,000 individual measurements made in a location likely to be characterised by fully-warmed engines[2] and shows the relative contribution of NOx and ammonia to the total nitrogen emitted from petrol vehicles. Vehicles manufactured prior to the year 2000 emitted vastly more NOx than ammonia, but declines in NOx emissions from newer models significantly outstripped declines in ammonia emissions. Thus, since 2007, average ammonia emissions have been significantly greater than NOx emissions when viewed in terms of nitrogen. It should be stressed that the interpretation of these data is not that ammonia emissions have been increasing over time; it is that reductions in NOx emissions have outpaced reductions in ammonia emissions.

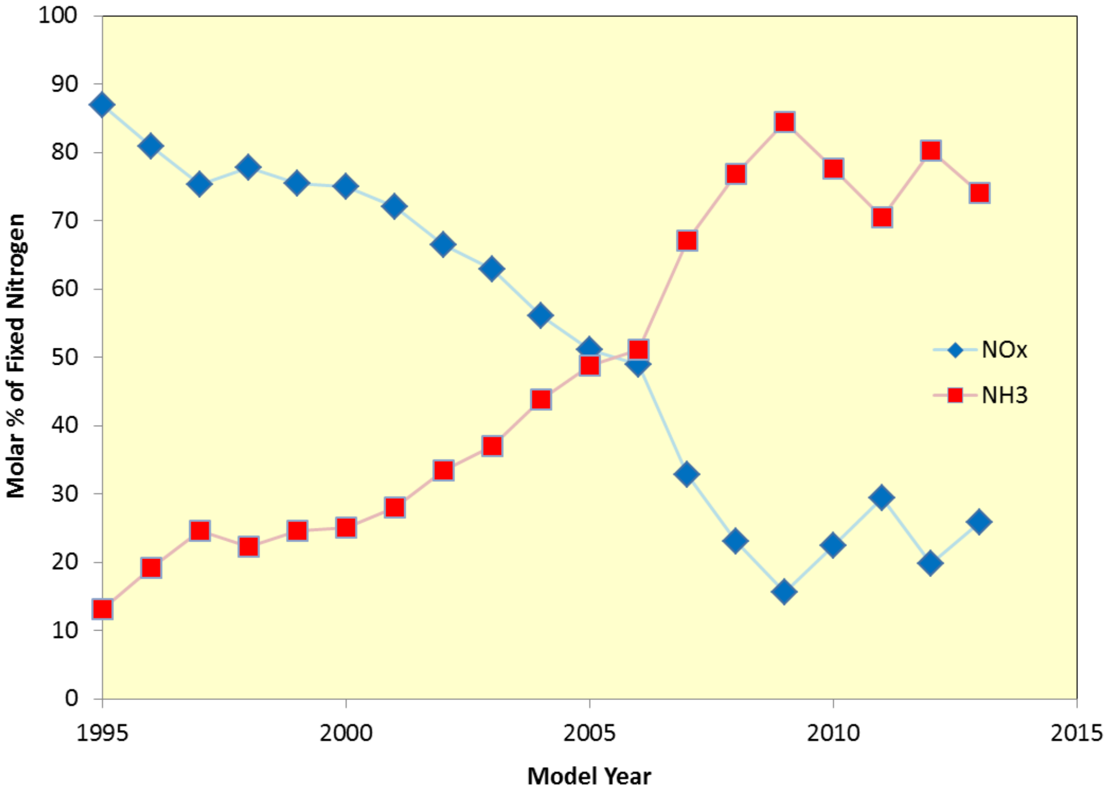

Figure 8: Relative Importance of NOx and Ammonia to Total NOx+Ammonia Emissions from Different-age Petrol Cars Measured in Tulsa in 2013 (Derived from Bishop and Steadman (2015))

2 mean speed 39 kph with an uphill gradient.

Emissions factors for Ammonia from Road Traffic

4.2 How ammonia emission from the vehicle fleet will change over time can only be predicted by understanding how different types of vehicle contribute to the fleet-total emissions, and how the numbers of these vehicles are likely to change in the future.

EEA Guidebook/COPERT Emissions Factors

4.3 In the UK, current- and future-year emissions factors for NOx are often taken from Defra's Emissions Factors Toolkit (EFT)[3]. These NOx emissions factors are referenced to average vehicle speeds and take account of the anticipated effect of emissions-controls for NOx (for example, the predicted NOx emissions from a Euro 6 diesel car are much lower than those from a Euro 3 diesel car). The emissions factors underpinning the EFT are ultimately derived from the EU Emissions Inventory Guidebook (the 'EEA Guidebook'[4]) and the Computer Programme to calculate Emissions from Road Transport (COPERT) model[5]. The EFT combines vehicle-specific emissions factors with estimates of the relative proportion of different types of vehicle within the fleet. It also contains projections of how the vehicle fleet is predicted to change over time; thus allowing for predictions of NOx emissions in the future.

4.4 The EFT does not include emissions factors for ammonia, but the EEA Guidebook does. These have been used in the UK National Atmospheric Emissions Inventory (NAEI)[6]. Table 2 summarises the fleet-weighted traffic-related ammonia emissions contained within the NAEI for 2017. Euro class-specific ammonia emissions factors (i.e. not fleet-weighted) from the EEA Guidebook itself are discussed further in Paragraph 4.18, below.

4.5 The Netherlands Organisation for Applied Scientific Research (TNO) reviewed the EEA Guidebook emissions factors for ammonia in 2015 and reached the conclusion that they significantly under-predict the true amount of ammonia emitted from vehicles. As part of this review, they pointed out anomalies in the EEA Guidebook emissions factors, such as the expectation that a bus without SCR will emit exactly the same amount of ammonia as a bus with SCR. Given the extreme engineering difficulty of ensuring ammonia slip from SCR remains zero at all times, this seems highly unlikely. Examples of the under-read that TNO considered likely are shown in Figure 9 and Figure 10. The TNO dataset did not extend to Euro 6/VI vehicles.

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3 Natural England has recently expressed the view that AQC's CURED model provides a more appropriate method of calculating NOx emissions than Defra's EFT ((Natural England, 2018), (Planning Inspectorate / WDC, 2019)), but CURED is ultimately based on the same dataset as the EFT itself.

4 https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

5 The same emissions factors are used in both the Guidebook and COPERT. They are often referred to as COPERT emissions factors but within this current report are referred to as the EEA Guidebook emissions factors.

6 https://naei.beis.gov.uk/

Table 2: Fleet-weighted Ammonia Emissions Factors within the UK NAEI [a]

Vehicle Type	Ammonia (g/v/km)
Petrol cars	0.015
Diesel cars	0.003
Petrol LGVs	0.020
Diesel LGVs	0.003
Rigid HGVs	0.009
Artic HGVs	0.009
Buses	0.003
Motorcycles	0.002

[a] Includes a contribution for cold starts

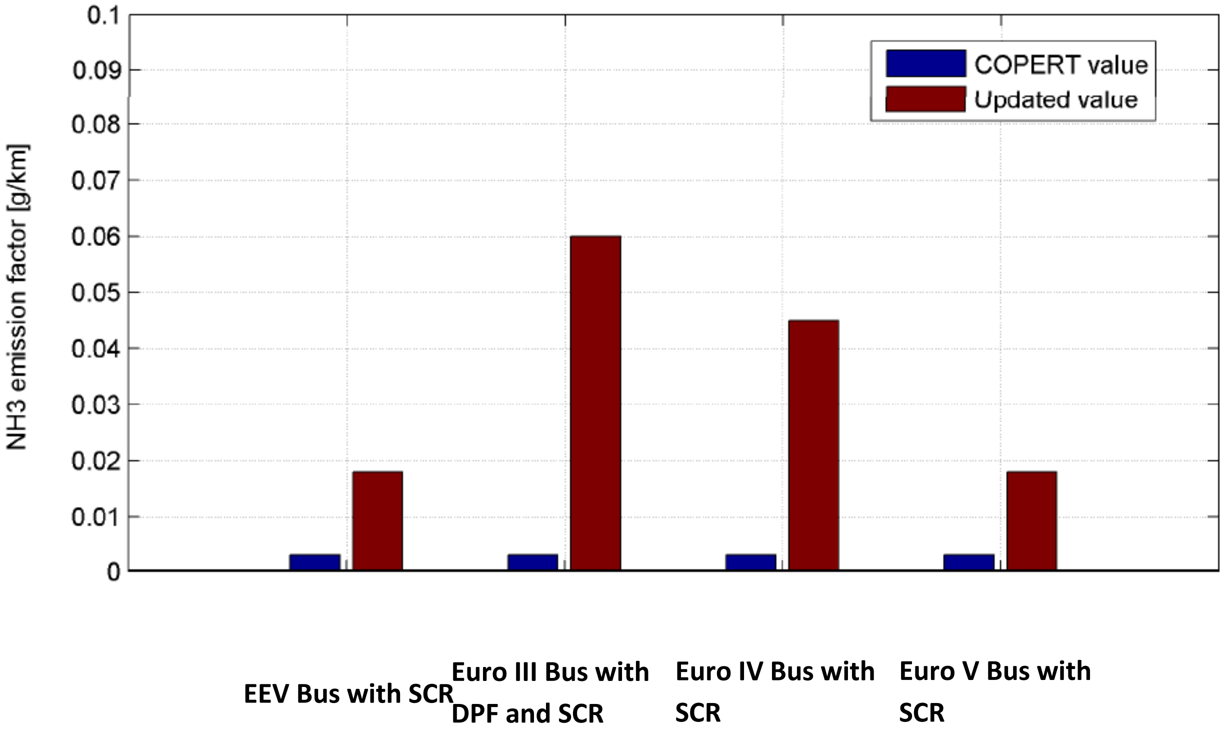


Figure 9: Comparison of COPERT (i.e. EEA Guidebook) and TNO Updated Ammonia Emissions factors for Buses/Coaches on Rural Roads (TNO, 2015) (amended to give English translations of TNO vehicle descriptors)

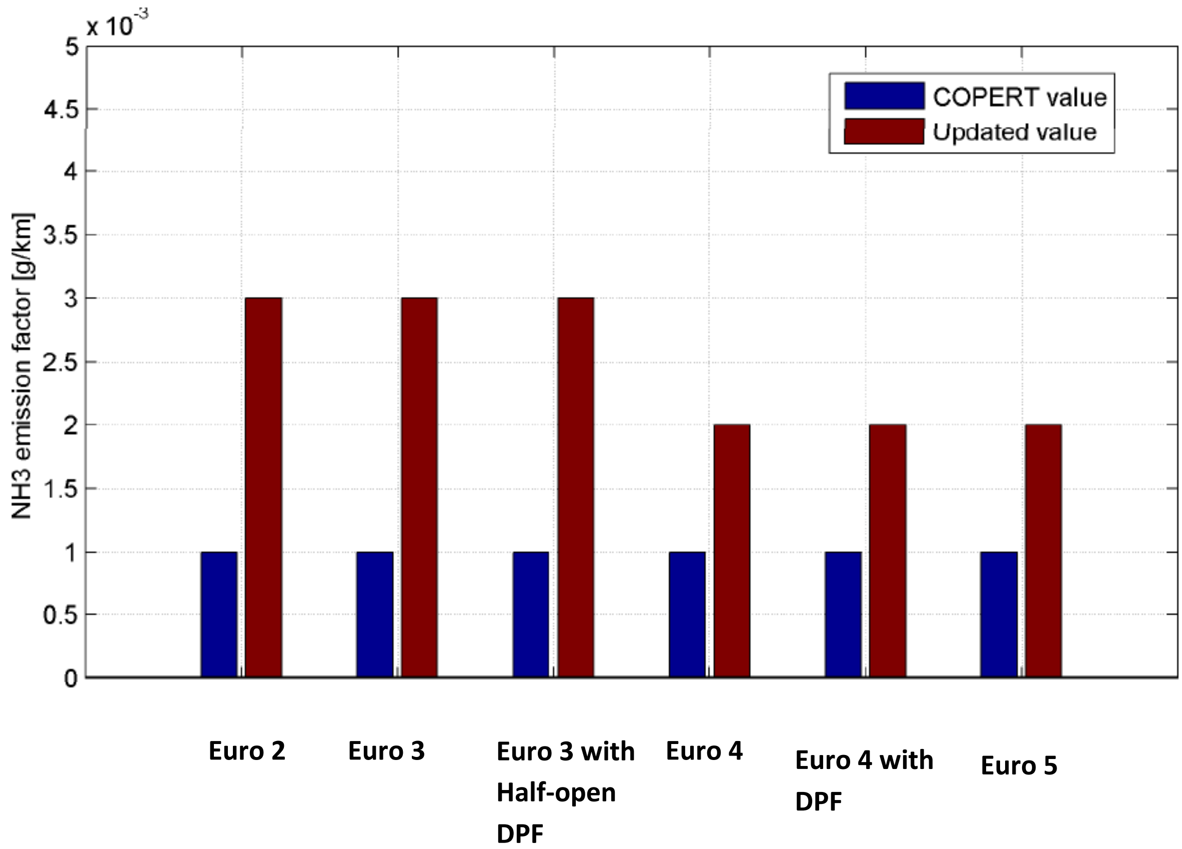


Figure 10: Comparison of (i.e. EEA Guidebook) and TNO Updated Ammonia Emissions factors for Passenger Cars on Rural Roads (TNO, 2015) (amended to give English translations of TNO vehicle descriptors)

4.6 A further test of the emissions factors from Table 2 has been carried out as part of this current study by comparing them against the ambient measurements described in Paragraph 3.5. In order to do this, it is necessary to use a predictive dispersion model. This inevitably introduces additional errors, but these have been kept to a minimum. As well as ambient concentrations of ammonia, the monitoring described in Marner et al. (2018) includes a network of Automatic Traffic Counters (ATCs) providing flow details, diurnal profiles, and vehicle fleet composition statistics for the roads alongside the monitors. The ADMS-Roads dispersion model has been used to predict the traffic component of ammonia concentrations at the 28[7] ammonia monitors described in Paragraph 3.5 which are more than 2 m from roads[8]. The overall model configuration is described in Marner et al. (2018). A detailed approach was taken to setting up the model and this was

[7] Some of the sites were represented by both an ALPHA and a DELTA monitor, thus the number of monitors is greater than the number of monitoring sites.

[8] It is considered that including sites which are less than 2 m from roads risks introducing additional artefacts owing to uncertainties around vehicle wake effects.

reviewed by the team responsible for Defra's national modelling of critical loads exceedances (see Marner et al., 2018 for further details)[9]. Figure 11 summarises the results.

4.7 There is clearly a correlation between measured and modelled ammonia concentrations, but this is to be expected since traffic-related emissions are a function of traffic volumes; thus higher emissions are predicted, and higher concentrations are measured, alongside the busiest roads. However, the model under-predicts the concentrations of ammonia measured close to roads by a factor of almost three (i.e. the predictions are ca. 1/3rd of the measurements). Whilst there are clearly other factors which might cause the dispersion modelling to underpredict concentrations[10], this comparison provides further reason to question the traffic-related ammonia emissions factors in the EEA Guidebook.

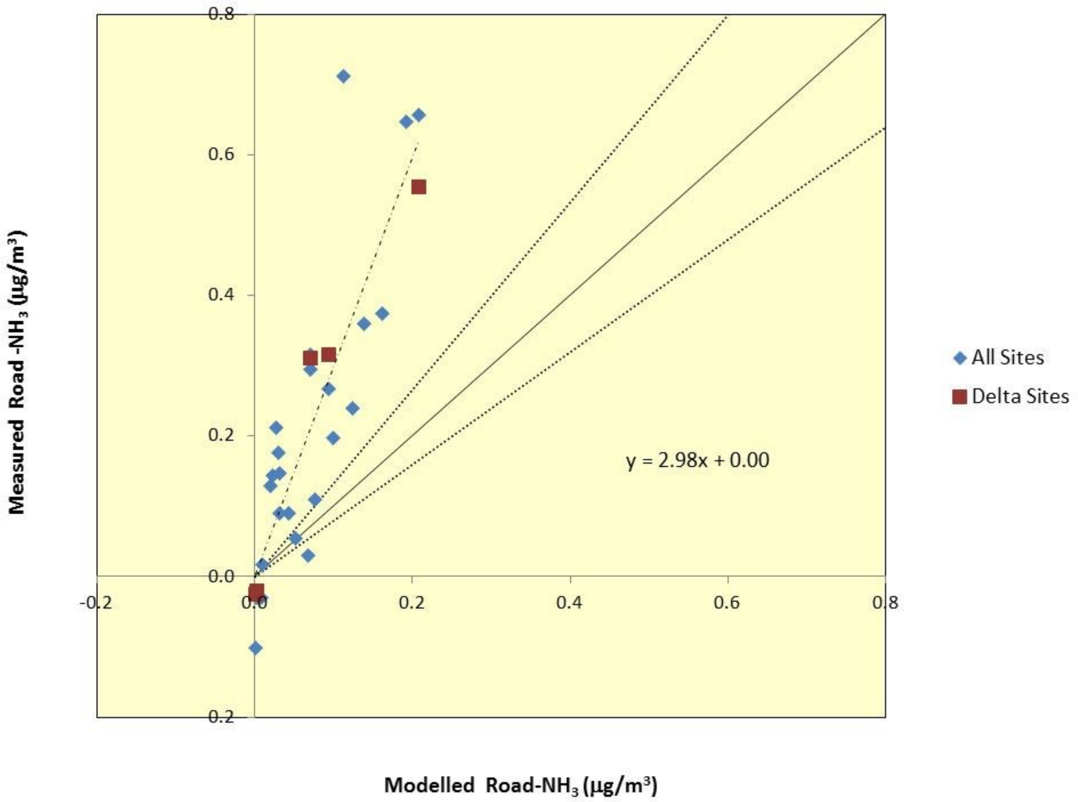


Figure 11: Measured vs NAEI-Modelled Road-Ammonia (also showing 1:1 line, +/- 25% lines, and OLS regression best-fit line)[11]

9 The only difference to the modelling presented here and that described in Marner et al., 2018 is the use of the NAEI emissions factors for NH_3.

10 It is also noted that Marner et al., (2018) also found that NOx concentrations were systematically underpredicted; suggesting bias in the EFT emissions factors for NOx.

11 Non-road 'background' component of measured NH_3 taken to be the intercept of the best-fit line, which is 0.623 $\mu g/m^3$. This background has then been subtracted from the measurements for clarity of presentation. The monitoring sites include roadside and background locations, which is why some of the measurements are negative (i.e. these monitors are all several hundred metres from roads and the 'background' value which has been subtracted is effectively a statistical average)

4.8 Another reason to doubt the NAEI ammonia emissions factors comes from recent remote sensing measurements made in the UK. Rose (2018) analysed the chemical composition of approximately 300,000 individual exhaust plumes. Samples were taken in more than 20 different locations across the UK and cover a range of different driving conditions (i.e. speeds, acceleration and gradients). Automatic Number Plate Recognition (ANPR) cameras were used to identify the type of vehicle which produced each exhaust plume. The results are summarised in Figure 12. These results are expressed per kg of fuel consumed and so cannot be directly compared with the emissions in Table 2. However, qualitatively, they give reason to question the NAEI statistics. For example, Table 2 suggests that ammonia emissions (in g/km) from articulated HGVs are just 3 times higher than those from diesel cars, while Figure 12 shows that emissions (in g/kg fuel) from >12te HGVs are 3 to 6 times higher than those from diesel cars. If both datasets were correct then large HGVs must, on average, consume less fuel per km than diesel passenger cars; anecdotally, this seems highly unlikely. In any event, Figure 12 shows that there is considerable variation in ammonia emissions between different Euro standards. This is further highlighted by Figure 13, which shows how emissions from diesel cars have increased over time, with this being predominantly driven by ammonia slip from SCR-equipped vehicles.

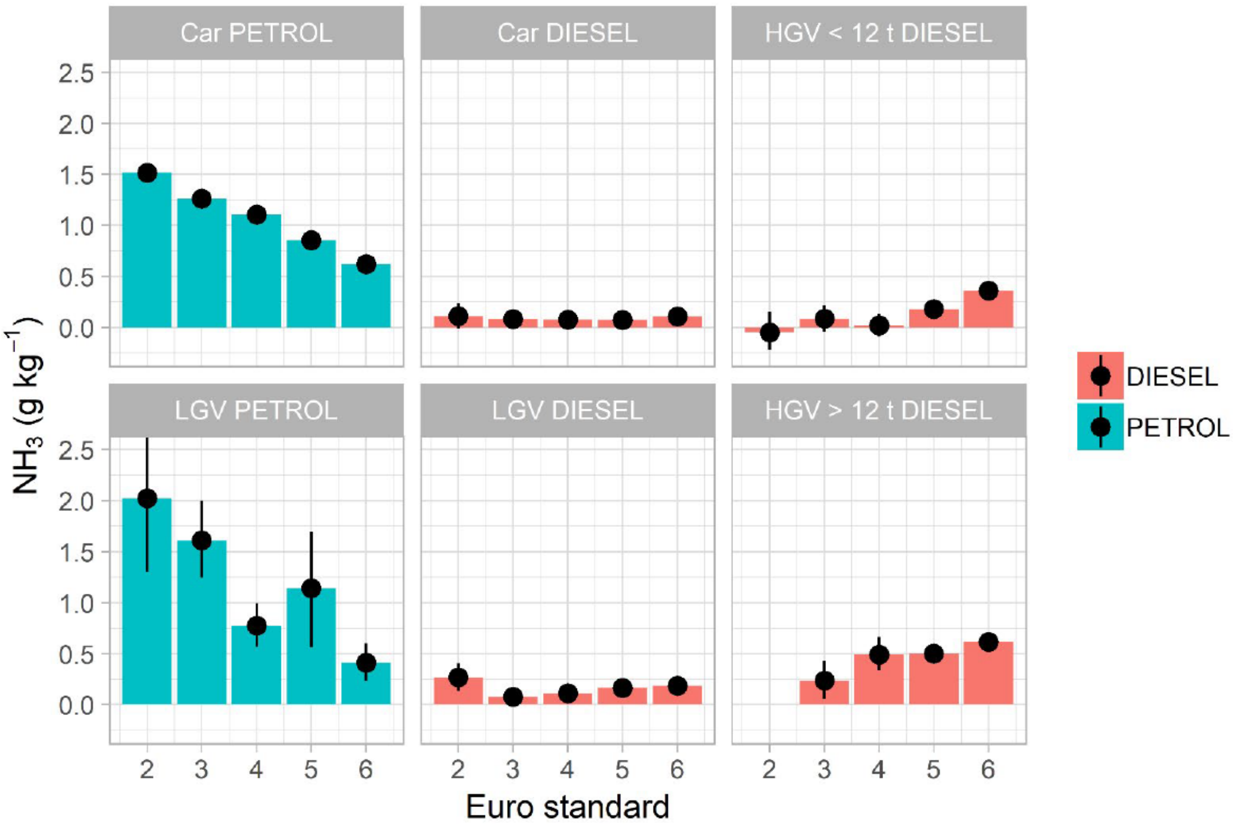


Figure 12: Summary of emissions of Ammonia in grammes per kilogramme of fuel from different classes of vehicle. Uncertainty intervals relate to the 95% confidence interval in the mean. (From Rose, 2018)

4.9 Given that current forecasts for reductions in traffic-related NOx emissions are related to predicted changes to the vehicle fleet, it seems sensible to take account of the likely consequential effect that these changes to the fleet will have on ammonia emissions.

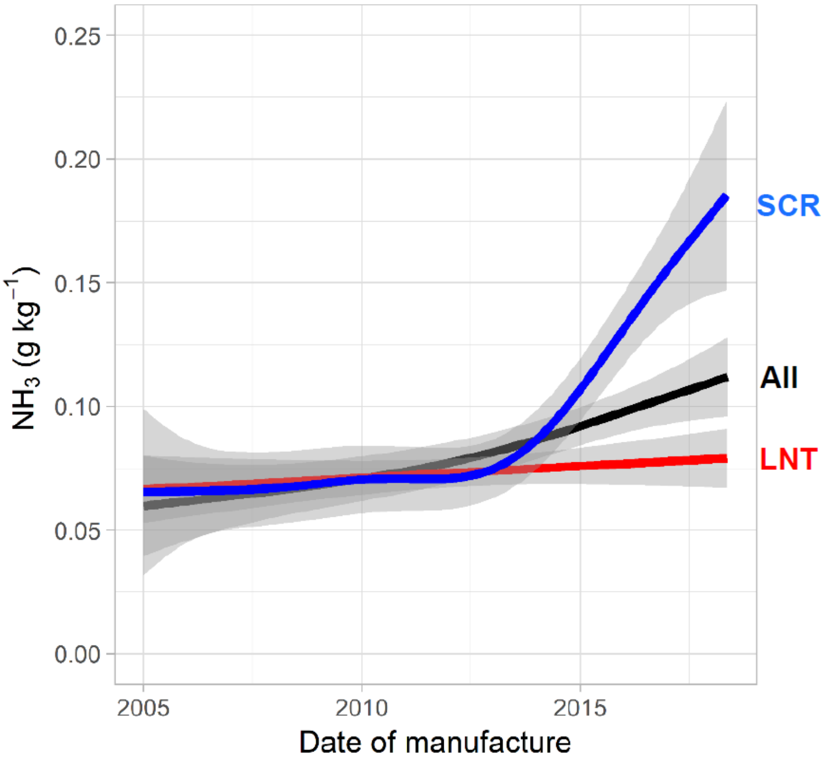


Figure 13: Ammonia Emissions from Diesel Passenger Cars by Year of Manufacture and NOx-Control Technology. SCR = Selective Catalytic Reduction and LNT = Lean NOx Trap (from Rose, 2018).

Declines in Ammonia from Petrol Vehicles

4.10 The work by Bishop and Stedman (2015) showed that, despite increasing in relative terms, emissions of ammonia per vehicle have been reducing in absolute terms since around 2005. Similarly, the measurements reported by Rose (2018) in Figure 12 show that ammonia emissions from later models of petrol vehicle tended to be lower (on a fuel-specific basis) than those from older models. This finding should, however, be treated with some caution. Because the measurements in Figure 12 were all made relatively recently, the older-model vehicles tended to also be older vehicles, while the later-model vehicles tended to be younger. Thus while Figure 12 shows that, at the time of testing, newer petrol cars emitted, on average, less ammonia than older models, it is not clear whether this trend is because newer vehicles are inherently cleaner, or because ammonia emissions increase as vehicles age. There have been improvements to catalyst design over the period separating Euro 2 and Euro 6 vehicles which might be expected to reduce emissions per vehicle. However, there is also evidence that catalysts degrade over time and thus produce higher levels of ammonia emissions when aged.

4.11 Figure 14 and Figure 15 are reproduced from the TNO (2015) report and show how ammonia emissions from a given Euro standard of petrol car are expected to increase over time. In the same way, Figure 16, which is reproduced from Rose (2018) disaggregates the data for petrol cars from Figure 12 as a function of approximate vehicle mileage and shows a pattern of increasing ammonia emissions with increased vehicle mileage within each Euro standard. This pattern does appear, from Figure 16, to be somewhat diminished for the Euro 5 and Euro 6 models, but because few high-mileage vehicles were tested, it is difficult to be confident as to how these vehicles will behave in the future. It certainly seems very likely that Euro 6 petrol cars will emit more ammonia on average when they are old than when they are new, and only new models have currently been tested.

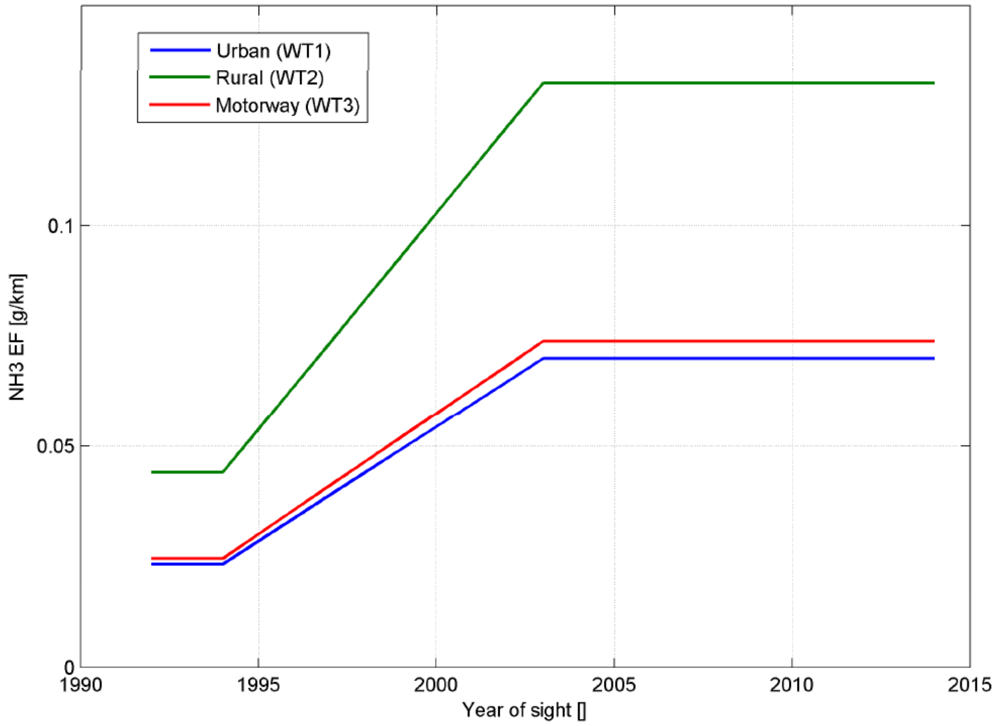


Figure 14: Ageing Effects on Ammonia Emissions from Euro 1 Petrol Passenger Cars (from TNO, 2015)

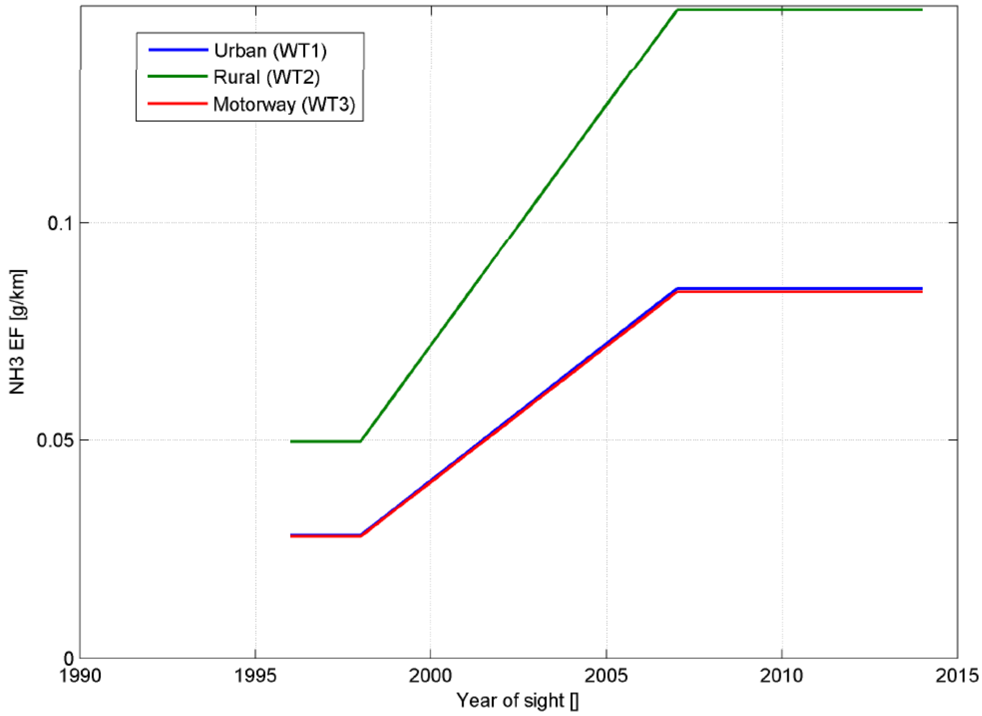


Figure 15: Ageing Effects on Ammonia Emissions from Euro 2 Petrol Passenger Cars (from TNO, 2015)

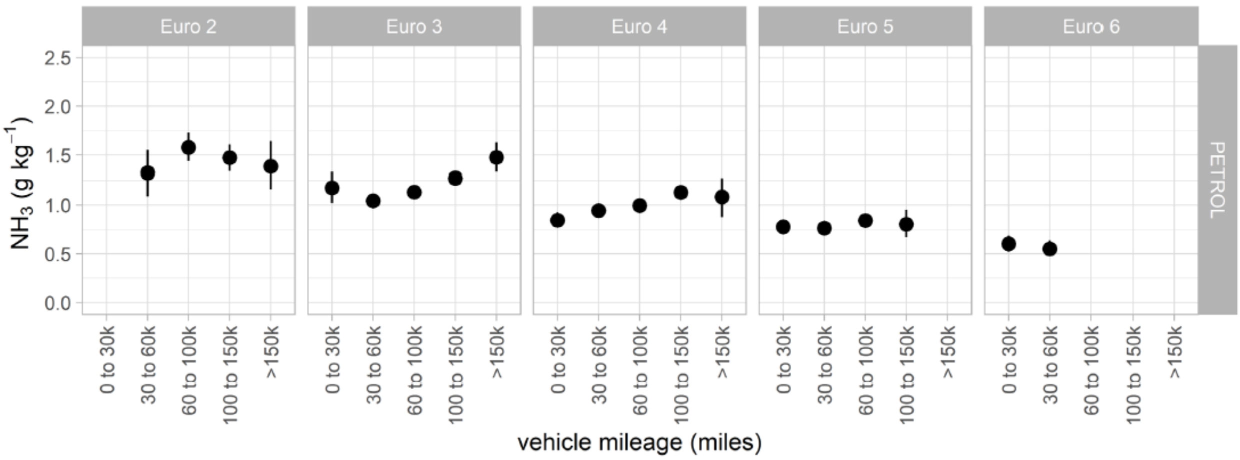


Figure 16: Ammonia Emissions from Petrol Cars as a Function of Vehicle Mileage (from Rose, 2018)

Impacts of Vehicle Electrification

4.12 Vehicles running solely on electricity have no exhaust emissions. Thus, a move toward a fully-electric vehicle fleet can reasonably be expected to significantly reduce traffic-related ammonia emissions. There are, however, some reasons to be cautious of the trend toward fleet electrification. The first is that widespread use of battery-electric[12] HDVs is, based on current knowledge, unlikely to be possible. The second is that for many manufacturers and consumers, moving to an electric vehicle currently means moving to a hybrid-electric vehicle.

Emissions from Hybrid Vehicles

4.13 As explained in Section 2, ammonia emissions from petrol cars typically occur in sub-optimal conditions for engine management; which is often when engines are cold and under heavy load. Temporal profiles of NOx emissions have shown that a large proportion of trip-total NOx can be emitted during relatively brief periods; again when conditions do not favour the performance of the emissions-control system. Similar data for ammonia emissions are not currently available, but it is far from unreasonable to expect a similar pattern; with very brief periods accounting for a large proportion of the ammonia being released.

4.14 Measurements of NOx emissions from plug-in hybrid vehicles have shown that trip-average NOx emissions **can** be higher if the vehicle is charged before use than if it is run with a discharged battery (e.g. Ehrenberger (2017)). This is because starting a trip under battery power can cause the petrol engine to be instantly required to produce significant power whilst fully cold. In this situation, a relatively brief period of sub-optimal engine management can cause more NOx to be released than has been saved during the start of the trip. It should be stressed that while this phenomenon has been observed, it is not yet clear how common it is. Again, similar data are not available for ammonia, but it is not unreasonable, given the importance of cold-start and heavy-load conditions for ammonia emissions, to expect that trip-average emissions from a hybrid vehicle might be comparable to those from a conventional vehicle if the trip is sufficiently long for the petrol engine to be required[13].

4.15 Thus, at present, it cannot be reliably assumed that trip-average ammonia emissions from a hybrid vehicle, particularly one driving in a rural location which is typical of many nitrogen-sensitive habitats, will be lower than those from a conventional vehicle. It is, however, noted that many hybrid vehicles tend to be petrol-hybrid rather than diesel-hybrid. Given that ammonia emissions from petrol cars tend to be significantly higher than those from diesel cars (Figure 12), a move from diesel toward hybrid-petrol cars might significantly increase fleet-average ammonia emissions.

4.16 On 4th February 2020, the UK Government announced an aspiration to remove the exemption for hybrid vehicles in its plans to phase out the sale of petrol and diesel cars. As noted in Paragraph 4.12, phasing out of all combustion-fuelled cars will remove all ammonia emissions from cars and so if this aspiration is delivered upon, then emissions from cars are likely to fall appreciably.

12 The term 'battery electric' is used in this report to describe a vehicle that runs solely on electricity, as distinct from a hybrid vehicle which is assumed to also have an internal combustion engine.

13 This assumes that plug-in hybrid vehicles will be charged before use, which is not always the case (https://themilesconsultancy.com/new-analysis-plug-hybrid-car-mpg-emissions-expected-spark-debate-suitability-fleet-operation). A plug-in hybrid vehicle which is not charged will behave similarly to conventional vehicle; albeit that it may be less efficient.

AQC-Derived Emissions Factors

4.17 In order to allow tentative predictions regarding trends in traffic-related ammonia emissions over time, a traffic-related ammonia emissions model has been developed. This model is based on the remote sensing results of Rose (2018), published real-world fuel consumption data, and the ambient measurements described in Section 2. The precise approach is described in Appendix A1. Given that it is not currently possible to predict the rate of reduction in ammonia from petrol cars in the future, it has been assumed that all future conventional petrol cars will have the same emissions as the average petrol car in 2015[14]. Similarly, it has been assumed that hybrid vehicles have the same emissions as their conventional equivalents. Further details are given in Appendix A1. The predicted emissions per vehicle are summarised in Figure 17. These emissions factors have been compared directly against those in the EEA Guidebook for equivalent vehicle categories in Appendix A2. These comparisons are described below:

Diesel Cars

4.18 Figure A2.1, in Appendix A2 shows that the derived emissions factors for diesel cars are all higher than those in the EEA Guidebook. This agrees with the previous conclusions of TNO (2015). Furthermore, while EEA Guidebook assumes equivalent emissions from Euro 5 through all of the Euro 6 subcategories, the derived emissions factors assume that ammonia emissions increase; principally because of the expected increased use of SCR.

Petrol Cars

4.19 Figure A2.2 in Appendix A2 shows that the derived emissions factors are lower than those in the EEA Guidebook for Euro 1 and Euro 2 petrol cars, similar for Euro 3 and Euro 4 vehicles, and higher for Euro 5 and Euro 6 vehicles. This is considered to principally reflect the increased recognition of the effect of catalyst ageing in the derived emissions factors. Failure to adequately account for the effect of catalyst ageing would cause life-average emissions from late-model and future vehicles to be under-predicted.

Diesel Light Goods Vehicles

4.20 Figure A2.3 in Appendix A2 shows that the derived emissions factors for diesel LGVs are all substantially higher than those in the EEA Guidebook; with the differences greatest for very old (pre Euro 3) and future (post-2021) vehicles.

Petrol Light Goods Vehicles

4.21 Petrol LGVs are not currently predicted to make up an appreciable fraction of the fleet in any year, but Figure A2.4 in Appendix A2 nevertheless compares the two emissions datasets for these vehicles. The pattern is very similar as described for petrol cars, with the EEA Guidebook values

[14] On a rural road in England according to the NAEI fleet proportions. As explained in Appendix A1, 2015 has been used since the model has been calibrated for this year. The emissions are thus weighted most significantly to those from the current Euro 5 car fleet.

being higher than the derived emissions factor for pre-Euro 3 vehicles and much lower for Euro 5 and Euro 6 vehicles. Again, fundamentally, this is considered to reflect differences in the approach taken to the effects of catalyst ageing, with the derived emissions factors being significantly more precautionary.

Heavy Duty Vehicles

4.22 Finally, Figure A2.5 in Appendix A2 compares the two emissions datasets for HDVs. Most of the derived emissions factors are significantly higher than those in the EEA Guidebook; the exceptions being for small older HGVs and small Euro VI HGVs, where the EEA Guidebook values are highest.

Overall

4.23 Overall, the conclusions of this comparison against the EEA Guidebook data are in agreement with those reported by TNO (2015). It is thus considered that these emissions factors provide a useful means of predicting ammonia emissions from roads and, as such, they have been made available to download from https://www.aqconsultants.co.uk/resources in an easy to use emissions factor tool (Calculator for Road Emissions of Ammonia (CREAM)).

4.24 It should be recognised that these emissions factors remain uncertain. Using them to make future-year predictions will clearly be an improvement on any assessment which omits ammonia. They are also considered to be more robust than the emissions factors contained in the EEA Guidebook, which risk significantly under-predicting ammonia emissions. The emissions factors contained in the CREAM model can be considered to provide the most robust estimate of traffic-related ammonia possible at the present time, but they may be updated in the future as more information becomes available.

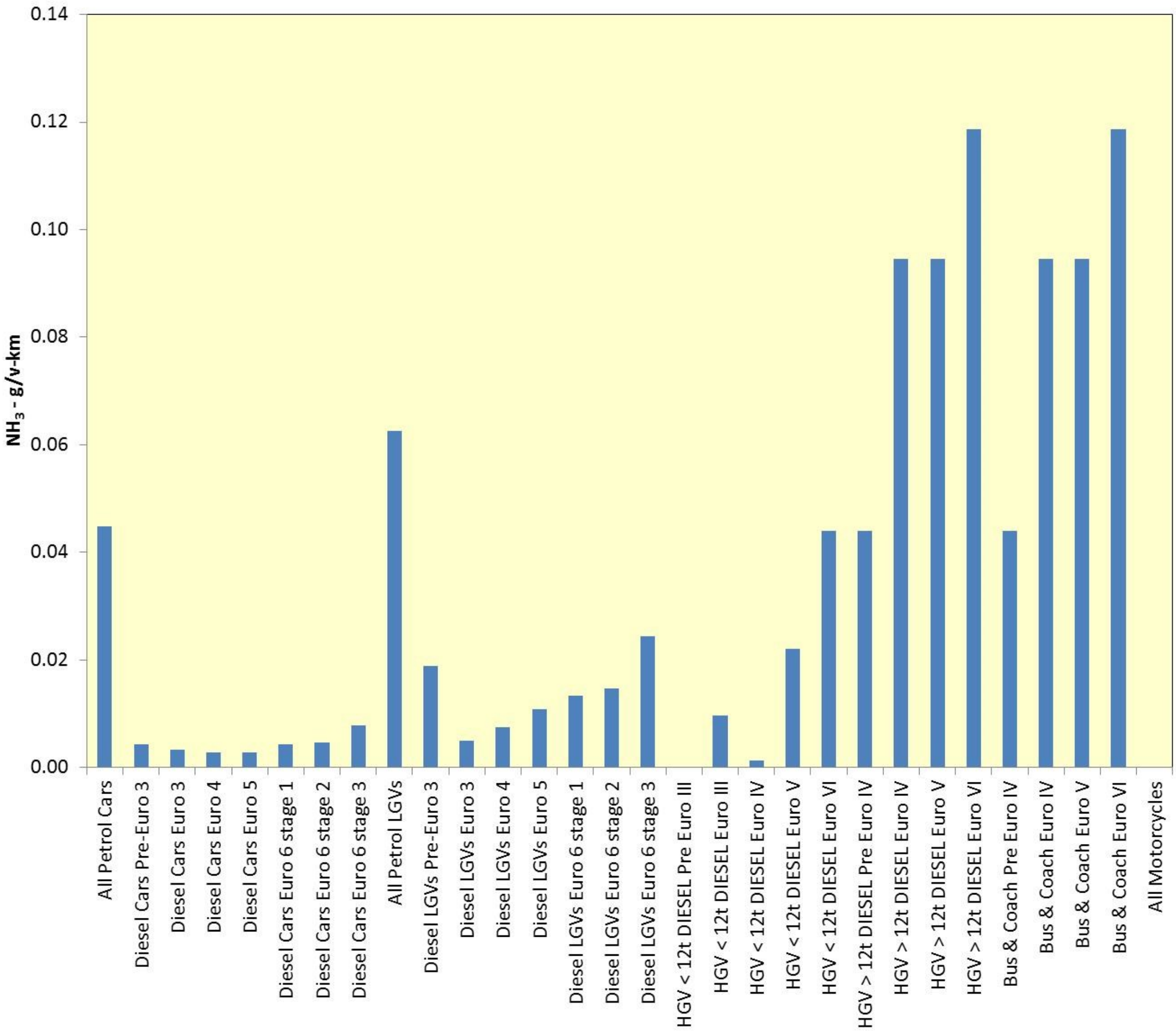


Figure 17: Calculated Ammonia Emissions per Vehicle

Future-year Forecasts

Forecasts using EFT-Equivalent Vehicle Fleet Projections

4.25 Figure 18 shows how, using the CREAM emissions factors, average ammonia emissions per vehicle are predicted to change over the period 2017 to 2030 (based on the NAEI/EFT fleet composition projections for a rural area in England outside of London)[15]. Projections are given for a range of different percentages of HDVs. At low (<8%) proportions of HDVs, ammonia emissions are predicted to fall until 2020. After 2020, emissions per vehicle are predicted to increase, with these increases being most rapid for fleets with fewer HDVs. Thus, ammonia emissions per vehicle in 2030 are predicted to be between 15% and 23% higher than those in 2017, based on the NAEI/EFT rural fleet projection assumptions.

[15] 2017 is chosen as the start year to allow comparison with EFT V9.0, which provides predictions for 2017 to 2030.

4.26 The predicted increase in ammonia emissions per vehicle will occur alongside (and is directly linked to) a reduction in NOx emissions per vehicle. In terms of nitrogen deposition, a key question is whether the reductions in NOx will outweigh the increases in ammonia, such that total roadside traffic-related nitrogen deposition will fall. Figure 19 shows how, at the kerbside, the effect of forecast (in EFT V9.0) NOx emissions reductions and the forecast ammonia increases will interact (assuming AQTAG(06) deposition velocities). While it is quite clear that omitting ammonia from the assessment would significantly over-predict the rate of reduction in traffic-related nitrogen deposition at the roadside, it is also clear that the forecast reductions in NOx emissions more than offset the forecast increase in ammonia emissions such that total roadside nitrogen deposition will continue to fall (even in the absence of reductions in emissions from other sectors). It should, however, be noted that Figure 19 assumes no traffic growth over the period 2017 to 2030 and that most of the predicted improvements occur prior to 2024 (deposition fluxes are predicted to increase marginally between 2028 and 2030).

4.27 A significant degree of caution is needed if extrapolating the results in Figure 19 out to represent other study areas, since assumptions which have been made regarding NO_2 :NOx quotients and NOx model adjustment factors will be site-specific and will alter the trends; however the assumptions made have been chosen to be broadly representative.

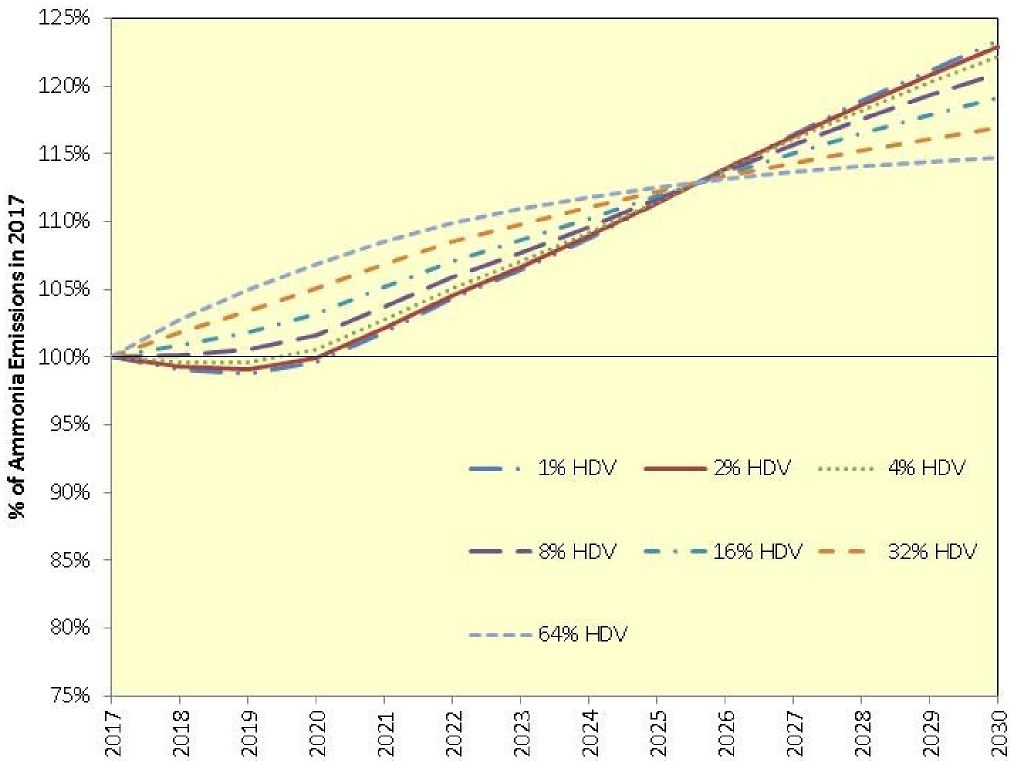


Figure 18: Forecast Ammonia Emissions per Vehicle – 2017 to 2030 (assuming England (outside London) rural fleet composition from the 2016 NAEI/EFT and no change in total traffic volumes over time)

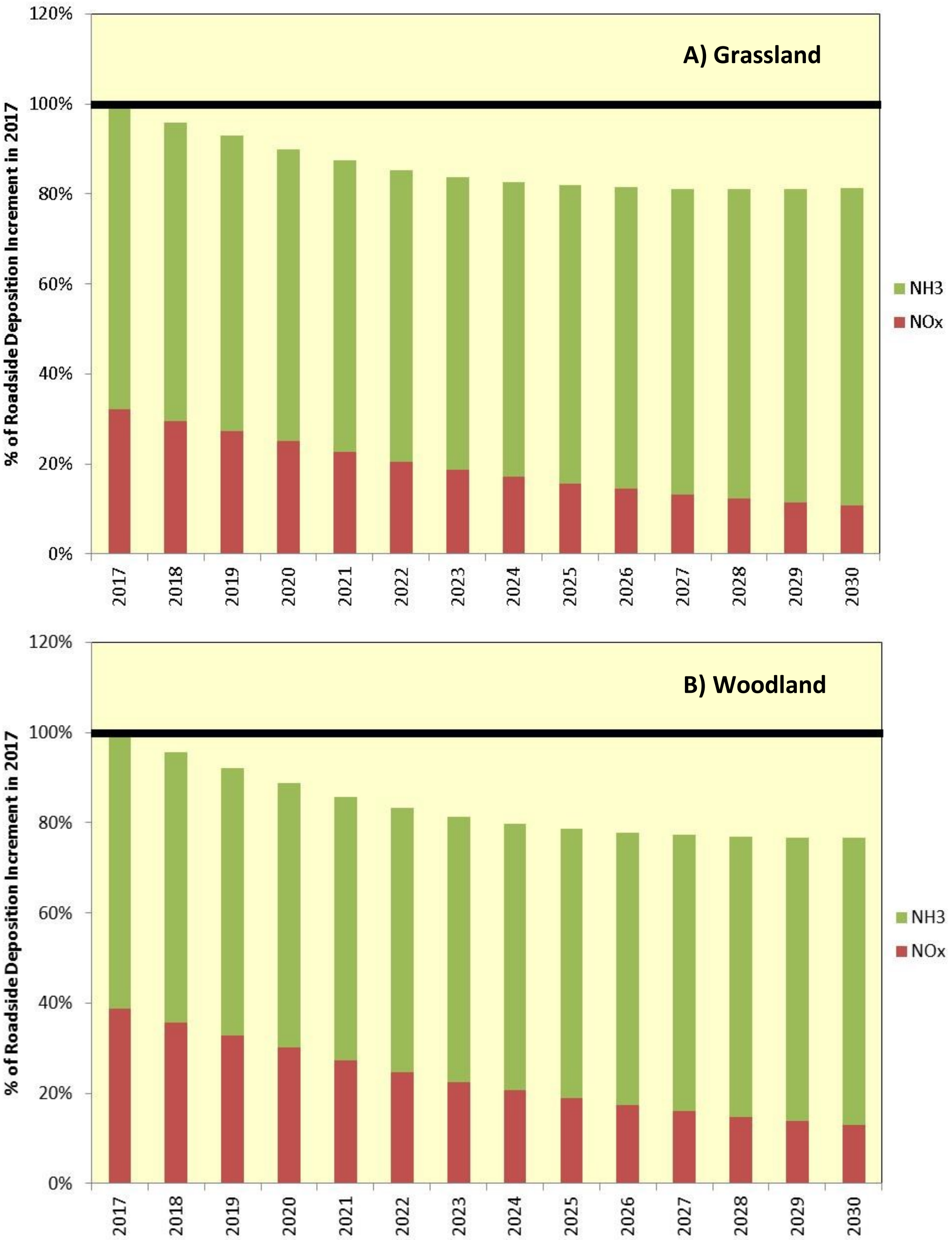


Figure 19: Forecast Trend in Traffic-related Nitrogen Deposition at the Roadside for NOx and Ammonia - using AQTAG(06) Deposition Velocities to A) Grassland and B) Woodland. Assuming default rural fleet projections from the 2018-based NAEI/EFT, with NOx Emissions Calculated Using EFT V9.0. Calculations assume that NO_2 at the roadside comprises 63% of NOx. NOx Emissions have been assigned 50% additional weighting, since EFT-based NOx Modelling often has an adjustment applied of approximately this scale, following verification against local measurements[16].

16 If NOx emissions are not uplifted then the rate of overall decline in nitrogen deposition is smaller, but deposition is still predicted to be lower in 2030 than in 2017.

Forecasts using Alternative Vehicle Fleet Projections

4.28 The current (2018-based) NAEI (and thus EFT V9.0) predicts a very slow rate of uptake of battery-electric vehicles. For example, it predicts that only 2.1% of cars on England's urban roads will be battery-electric in 2030, with 0% assumed to be battery-electric on rural roads and motorways. By comparison, the National Grid's Future Energy Scenarios (FES) predictions[17], which allow for the Government's Road to Zero strategy[18], suggest that up to 34% of cars could be electric by 2030 (11.8m of 32.9m), and as much as 97% by 2040 (31.9m of 32.9m). Even the lower-uptake scenarios presented in the FES report forecast over 5% of cars to be electric in 2030, and 48% in 2040. These predictions pre-date the UK Government's February 2020 announcement of a desire to phase out the sale of all new petrol and diesel vehicles by 2035. This suggests that the NAEI/EFT assumptions on future electric vehicle uptake in the medium to long-term may be pessimistic.

4.29 In the shorter term, the NAEI/EFT suggests that, on England's urban roads, 0.167% of cars would be electric in 2018, with this increasing to 0.210% in 2019, representing a 26% year-on-year increase over an already very low proportion (with zero battery-electric cars on rural roads). By comparison, the Society of Motor Manufacturers and Traders (SMMT)[19] report battery-electric car sales of 28,259 in January to October 2019, while for the same period in 2018 sales were 12,555. This represents a 125% year-on-year increase. SMMT data indicate a battery-electric car market share of 0.6% in January to October of 2018 and 1.4% in January to October of 2019. While these figures are not directly comparable to the vehicle-km based proportions in the NAEI/EFT, they do suggest that the NAEI/EFT may underestimate the current uptake of battery-electric vehicles.

4.30 At the same time that battery-electric vehicle uptake may be under-predicted, it seems possible that the NAEI/EFT may over-estimate the role of diesel cars in the future. The NAEI/EFT predicts that the proportion of diesel cars in the fleet has risen consistently since 2013, and will continue to do so until at least 2022. By contrast in September 2019 diesel sales were reported to have declined for the 29th month in a row[20]. Thus, if the future role of diesel is over-predicted, while the future role of petrol is under-predicted, then NOx emissions in the future are likely to be over-predicted, while ammonia emissions are most likely to be under-predicted.

4.31 Figure 20 shows the 2018-based NAEI/EFT fleet projections for rural roads in England.

17 http://fes.nationalgrid.com/media/1363/fes-interactive-version-final.pdf

18 https://www.gov.uk/government/publications/reducing-emissions-from-road-transport-road-to-zero-strategy

19 https://www.smmt.co.uk/vehicle-data/car-registrations/

20 https://www.am-online.com/news/market-insight/2019/09/05/uk-new-car-sales-dropped-in-august-as-diesel-orders-continued-decline

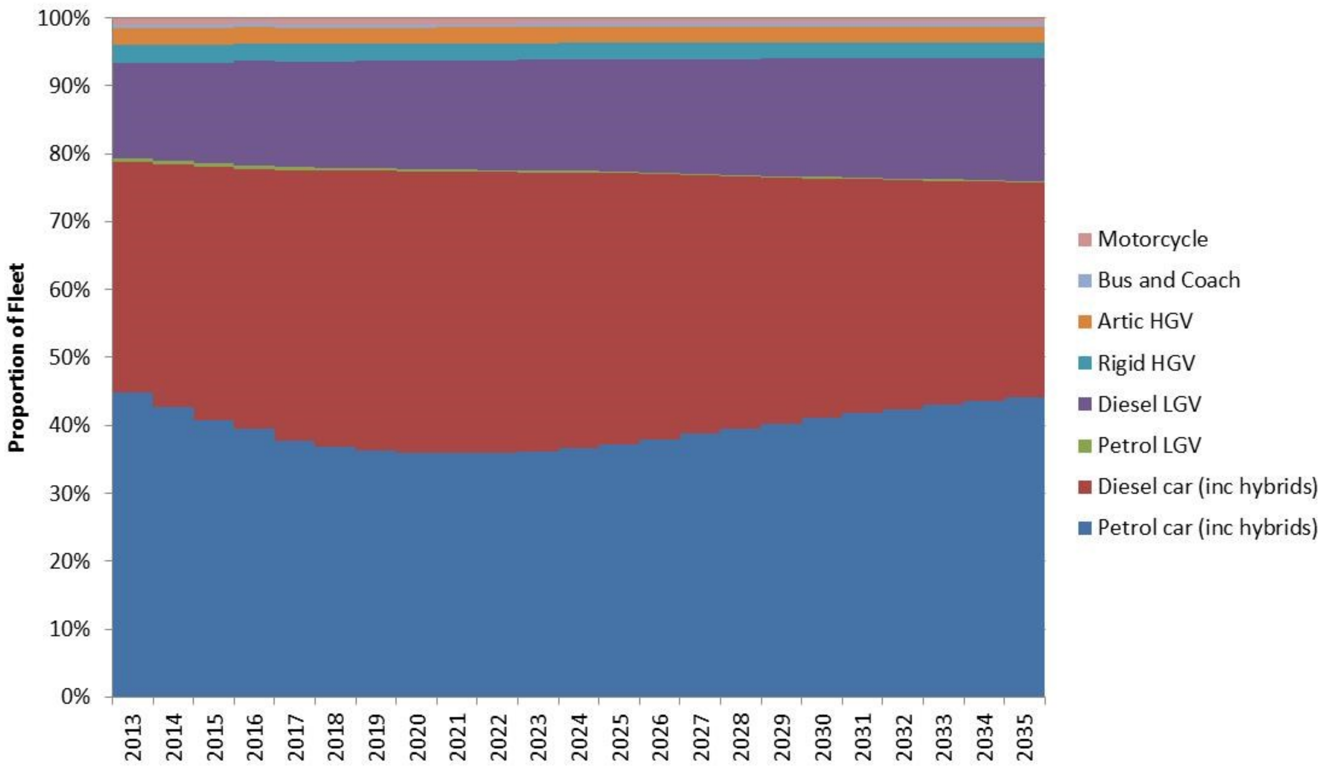


Figure 20: 2018-based NAEI/EFT Fleet Composition Projection for Rural Roads in England

Test of Increasing Petrol Car Uptake

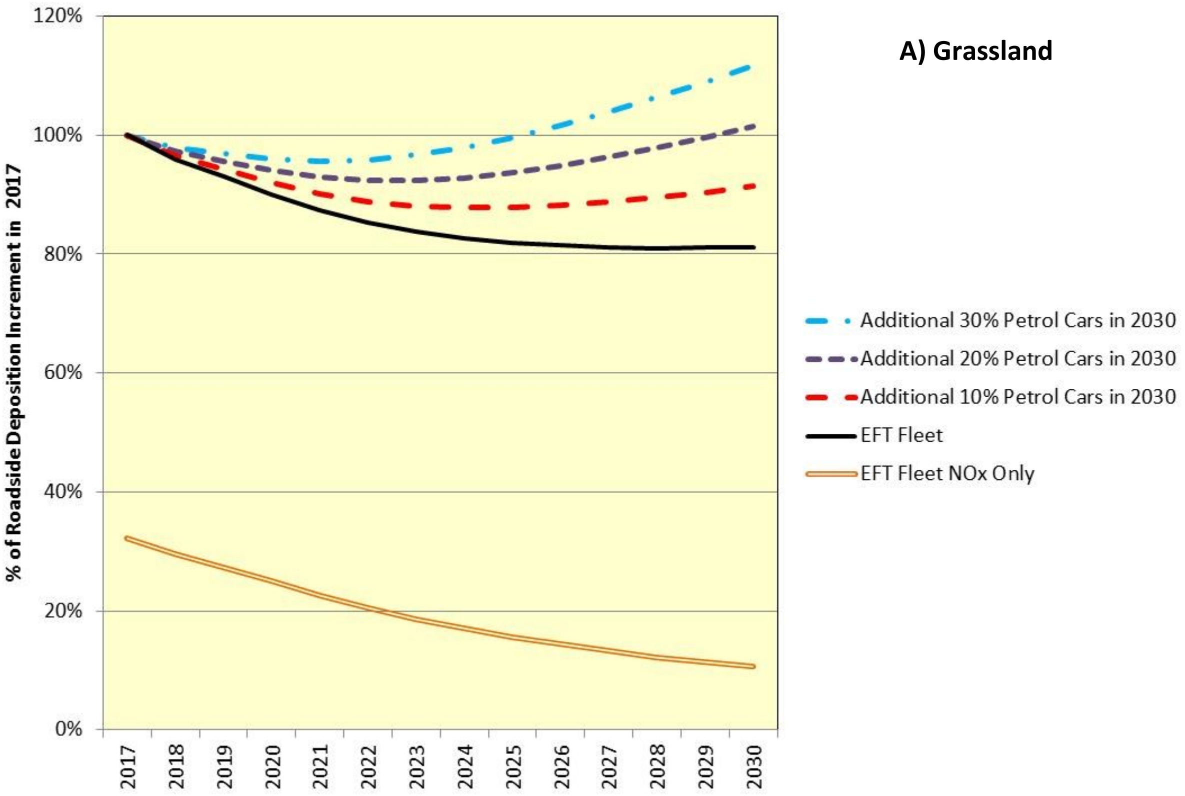
4.32 Given uncertainty regarding the petrol/diesel split of the car fleet in the future (particularly in light of anticipated growth in the number of petrol-hybrid vehicles), a series of sensitivity tests has been carried out. These sensitivity tests re-calculate the deposition values from Figure 19, but assume various different end points for the proportion of petrol cars within the total car fleet in 2030. The additional uptake, over and above that assumed in the NAEI/EFT, is then assumed to occur linearly between 2017 and 2030. For example, one of the tests assumes 10% additional petrol cars in 2030. The NAEI/EFT assumes that petrol cars make up 41% of the car fleet in 2030 and so this has been increased to 51%. The petrol fleet in 2018 has then been increased by 0.8% (10% / 13 years) while the petrol fleet in 2019 has been increased by 1.5% (10% / 13 years x 2). Diesel car proportions have been reduced in direct response to the assumed increase in petrol. This adjusted fleet has then been used to calculate NOx emissions (in EFT V9.0) and ammonia emissions (in the CREAM model). Deposition fluxes are calculated as described for the NAEI fleet in Figure 19. Trends in total roadside traffic-related nitrogen deposition fluxes for four alternative fleet assumption scenarios are given in Figure 21.

4.33 Figure 21 shows that, so long as the uptake of petrol and petrol-hybrid vehicles in 2030 has not been under-predicted by more than 10%, roadside traffic-related nitrogen deposition fluxes will continue to be lower in 2030 than in 2017[21]; albeit that even a 10% difference causes the trend in deposition to be

21 Assuming no traffic growth over this period.

upward from about 2025/2026 onward. If the move to petrol vehicles has been underestimated in the NAEI/EFT by more than 20%, then roadside traffic-related nitrogen deposition fluxes in 2030 will be higher than in 2017 even without any increase in vehicle numbers over the intervening period.

4.34 Again, it should be noted that these projections are quite sensitive to assumed NO_2:NOx quotients and also to the up-weighting applied to NOx emissions (set at 150%). It should also be noted that, for the reasons explained in Paragraph 4.15, petrol-hybrid cars are assumed to have the same emissions performance as conventional cars. In practice it is quite possible that both trip-average and instantaneous ammonia emissions from a petrol hybrid car will be higher than those from a conventional vehicle, but on balance it seems likely that they will be lower; causing Figure 21 to err on the side of pessimism. Finally, the likely reduction in ammonia emissions from moving to Euro 6 petrol cars from earlier petrol cars (see Paragraph 4.10) has not been included because it is not currently possible to robustly quantify the effect of this. Thus, on balance, these projections are considered likely to err on the side of caution, and thus potentially over-predict the increases in traffic-related ammonia emissions over this period. They can thus be considered robust. It is not possible to provide equally robust predictions at this time that do not tend toward over-predicting emissions in the future.



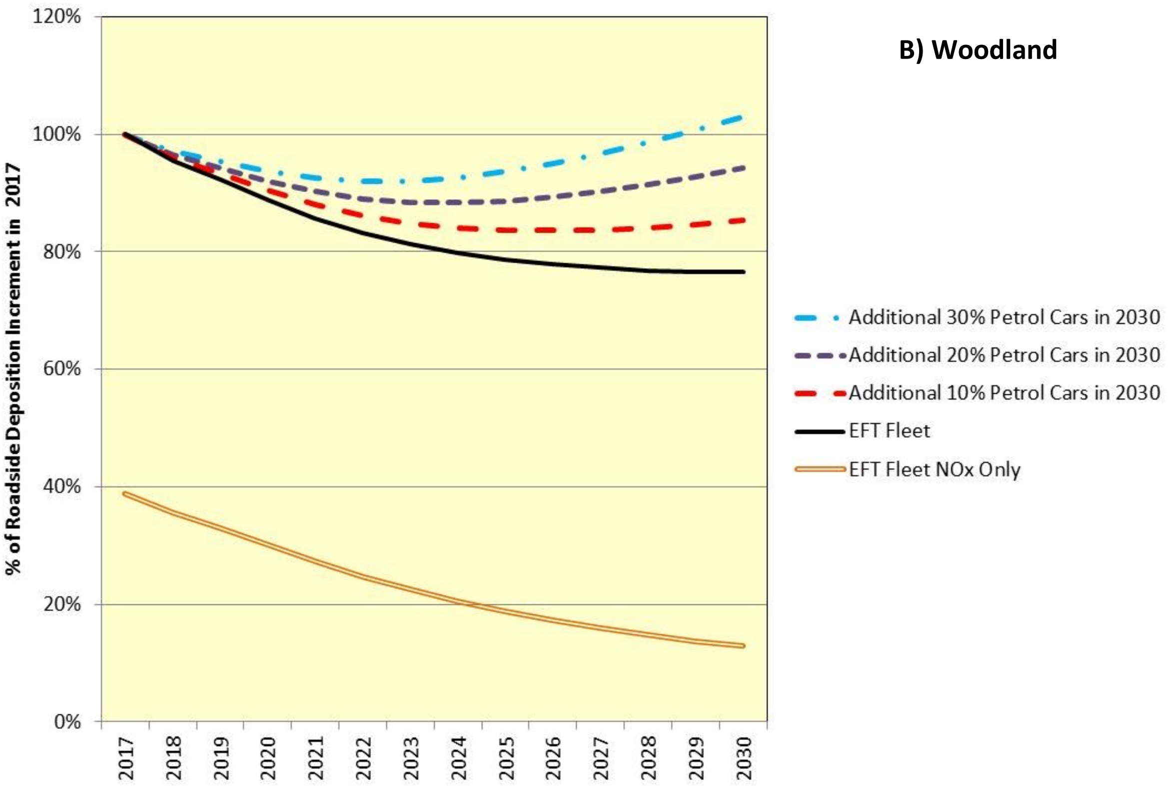


Figure 21: Four Different Projections for Roadside Traffic-related Nitrogen Deposition based on Different Petrol (+petrol-hybrid) car Uptake (also showing NAEI/EFT-based projection based on NOx only) (model assumptions as per Figure 19)

Test of Increasing Battery-electric Car Uptake

4.35 It is currently expected that sales of battery-electric cars will have to increase in order for the UK to meet its climate change commitments. As shown in Figure 20, the current NAEI/EFT fleet assumes that there will be no battery electric cars on rural roads in 2030. Since, unlike hybrid vehicles, battery-electric cars can be guaranteed to have zero exhaust emissions, it is worthwhile considering the effects of different rates of penetration of battery-electric cars.

4.36 Four separate alternative scenarios have been modelled: one in which 20% of passenger cars will be battery-electric in 2030, one in which 40% of passenger cars will be battery electric in 2030, and one (for the sake of completeness) in which all cars will be battery electric in 2030. The uptake of battery-electric vehicles has been simply assumed to be linear (e.g. the 20% uptake scenario assumes 1.5% (20% / 13 years) of cars will be electric in 2018, with this rising to 3.1% (20% / 13 years x 2) in 2019 etc.). In each case, vehicles are assumed to migrate in equal measures from the petrol and diesel car fleet and the non-car fleet is assumed not to change from that in the NAEI/EFT. All other model assumptions are the same as described previously (for Figure 19 and Figure 21).

4.37 The results are shown in Figure 22. The rate of forecast reduction in traffic-related nitrogen deposition at the roadside is clearly significantly increased if a greater uptake of battery-electric vehicles is assumed. However, even assuming 100% electric cars in 2020, local traffic-related nitrogen deposition at the roadside remains higher than the deposition associated with NOx emissions only from the NAEI/EFT fleet (i.e. assuming no battery electric vehicles). This is because the impacts of ammonia emissions from the non-car (i.e. LGV + HDV) fleet in 2030 are predicted to be greater than the impacts of NOx emissions from the car fleet; meaning that even removing all car emissions does not close the gap caused by omitting ammonia from a modelling assessment.

Conclusion

4.38 The precise trajectories shown in Figure 19, Figure 21, and Figure 22 will be highly dependent on study-specific assumptions and should only be viewed as indicative of what site-specific modelling might show in the absence of growth in total traffic volumes. They nevertheless provide a useful indication of how changes to the future fleet might affect deposition at the roadside. Growth in traffic volumes over this period would clearly erode any of the improvements shown in Figure 19, Figure 21, and Figure 22; with such effects being road-specific.

4.39 In practice, while the projections given in Figure 21 (additional petrol cars) are considered most likely to over-predict deposition in the future, those in Figure 22 which assume full electrification are likely to under-predict. What is clear is that, unlike the trend in roadside NOx concentrations, the trend in roadside nitrogen deposition fluxes is unlikely to be driven by the Euro standards, but by the challenges and opportunities around fleet electrification. A significant move to petrol-based hybrid vehicles may well drive roadside nitrogen deposition fluxes higher despite reductions in NOx emissions. On the other hand, significant uptake of battery-electric vehicles is likely to deliver significant improvements in roadside nitrogen deposition.

4.40 It is not within the scope of this report to evaluate the likelihood of universal uptake of battery-electric cars and the infrastructure, technological, and commercial challenges associated with this. Until such time as national forecasts are updated, it does not seem unreasonable to continue to make future predictions using the CREAM model and the NAEI/EFT fleet compositions. These predictions fall between the higher and lower ranges of what might happen as a result of fleet-electrification, but a full realisation of the UK Government's current aspirations should make these predictions worst-case.

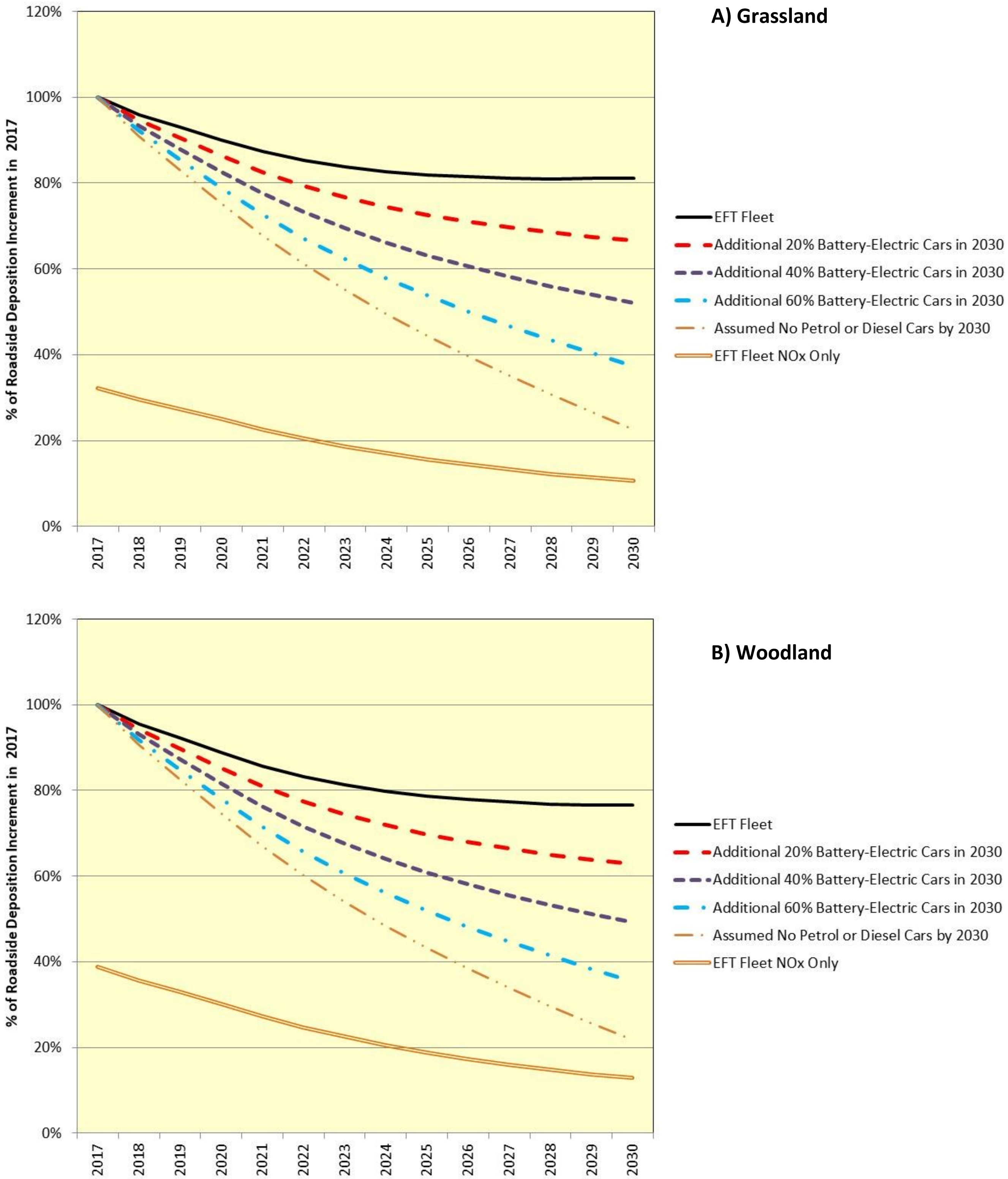


Figure 22: Five Different Projections for Roadside Traffic-related Nitrogen Deposition based on Different Battery-electric car Uptake (also showing NAEI/EFT-based projection based on NOx only) (model assumptions as per Figure 19)

5 Summary and Conclusions

5.1 Guidance on assessing the impacts of traffic emissions on roadside nitrogen deposition issued by Highways England, Natural England, and the Institute of Air Quality Management all focus on assessing the NOx component and do not include the ammonia component. However, the only recent UK study which identifies the traffic-related component of concentrations at the roadside using robust ambient measurements suggests that ammonia is at least equally as important as NOx in terms of roadside nitrogen deposition.

5.2 Ammonia is not produced by combustion within vehicle engines. It is produced by emissions controls systems that are used to reduce emissions of NOx, which have been implemented in response to a tightening of the European type approval standards (Euro Standards) for vehicles. As such, traffic-related ammonia emissions can be seen as a direct consequence of the NOx reductions being delivered through the Euro standards.

5.3 Modelling studies frequently combine model-specific NOx emissions factors with projections regarding how the vehicle fleet will evolve in the future and thus predict the rate at which NOx emissions from road traffic will reduce. In order to make equivalent predictions for ammonia it is necessary to define representative emissions factors. However, previous studies have shown that the emissions factors included in the EEA Emissions Inventory Guidebook are likely to under-predict ammonia emissions from vehicles. A more robust set of emissions factors has thus been developed, and are described in this report. In the absence of more robust information, these emissions factors are considered to be the best currently available.

5.4 Combining the vehicle fleet projections in the National Emissions Inventory (NAEI) with the derived ammonia emissions factors (along with the NOx emissions factors contained in Defra's Emissions Factors Toolkit (EFT)) shows that the importance of traffic-related ammonia is likely to increase sharply over the next few years. This is because NOx emissions per vehicle are predicted to reduce rapidly, while ammonia emissions per vehicle increase. Based on the default NAEI/EFT vehicle fleet for rural roads, ammonia is predicted to contribute up to 87% of local traffic-related nitrogen deposition at the roadside in 2030. Thus, inclusion of these more robust ammonia emissions factors significantly reduces the scale of reductions in roadside nitrogen deposition that would be predicted if traffic-related ammonia is excluded, or if the EEA Guidebook (NAEI) emissions factors are used.

5.5 It is considered that the predicted future-year fleet composition in the NAEI is incompatible with aspirations which have been made by the UK Government regarding electrification of the vehicle fleet. It also does not seem to align with recent observations regarding sales of diesel vehicles. A range of different alternative fleet projections have thus been tested. One group of assumptions is based around the possibility that fewer miles will be driven by diesel cars in the future, with more miles driven by petrol or petrol-hybrid vehicles. The second group of assumptions assumes a much greater uptake of battery-electric vehicles (i.e. not hybrids).

5.6 In the increased petrolisation/hybridisation scenarios, NOx emissions are predicted to fall while ammonia emissions are predicted to increase. This is partly because there is currently no empirical evidence that hybrid vehicles will emit less ammonia than non-hybrid vehicles (which in turn relates to the likely importance for ammonia of the brief period of starting a petrol engine from cold). The net effect is that increased petrolisation/hybridisation is likely to cause roadside nitrogen deposition to increase. In the increased fully-electric scenarios, emissions of NOx and ammonia are both predicted to fall appreciably, but not to the point that ignoring ammonia emissions altogether might be justified.

5.7 An overriding message from these tests is that while trends in NOx emissions in the near future may be shaped by the current Euro standards, the same cannot be said for total nitrogen deposition at the roadside. Trends in roadside nitrogen deposition, whether they are increases or decreases, will be driven by how the UK responds to the challenges and opportunities around electrification of the vehicle fleet.

5.8 It is not within the scope of this report to comment on the likelihood of wholescale electrification of the fleet over the next 10 years but, on balance, future-predictions which use the ammonia emissions factors presented in this report, together with the vehicle fleet projections from the NAEI, are likely to be conservative (i.e. risk over-predicting rather than under-predicting). Using the same fleet projections together with EEA Guidebook emissions factors is expected to under-predict ammonia emissions in the future, and thus over-predict the rate of decline in nitrogen deposition at the roadside.

5.9 The emissions factors used in this study are available to download from https://www.aqconsultants.co.uk/resources in an emissions factor tool (Calculator for Road Emissions of Ammonia (CREAM) V1A).

5.10 Given the importance of traffic-related ammonia to understanding the scale of change in nitrogen deposition at the roadside across the UK, it would be helpful if paired roadside and background ammonia measurements were established, and/or existing monitoring sites were retained. Unlike the case for NOx, where the UK has a large number of high-quality monitoring sites and patterns can be observed over time, high-quality ammonia monitoring in this way in the UK in recent years has been operated by an individual local council. It would also be helpful to extend current measurements of tailpipe NOx emissions to include ammonia.

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7 Appendices

A1 Derivation of Traffic-related Ammonia Emissions Factors

A1.1 There are no results from direct testing of ammonia emissions from vehicles made over representative drive cycles which are considered suitable to generate robust, fleet-wide emissions factors for use in the UK. The approach has thus been to combine the results from remote sensing, real-world fuel consumption data, and ambient ammonia measurements. Each of these steps is described below.

Remote-sensing of Ammonia Emissions

A1.2 The remote-sensing data were those reported by Rose (2018), which are described in Paragraph 4.8, and summarised in Figure 12, of the main report.

A1.3 The NAEI provides vehicle fleet projections for three different categories of Euro 6 diesel car ("Euro 6 up to 2016", "Euro 6 2017-2019" and "Euro 6 2020+"). This is because the EEA Guidebook provides alternative NOx emissions factors for each of these categories. The categories broadly coincide with different stages of the Euro 6 standard (Euro 6a/b, Euro 6d-TEMP and Euro 6d) but are not intended to align specifically with them. In order to use the NAEI fleet projection data, ammonia emissions from each of the three Euro 6 categories has been estimated.

A1.4 Figure 13 of the main report shows that ammonia emissions from diesel cars tend to be much higher when NOx is controlled using SCR than when it is controlled using LNT. The increased demands of the Euro 6 d-temp and Euro 6 d-final emissions standards are such that it is currently reasonable to expect their delivery to be associated with an increased use of SCR. The assumption has thus been made that ammonia emissions for the "Euro 6 up to 2016" category are those taken from in Figure 12. Emissions for the "Euro 6 2017-2019" category are taken to be those for "All" vehicles at the far right-hand side of Figure 13. Ammonia emissions for the "Euro 6 2020+" category are assumed to be those for SCR vehicles only at the far right-hand side of Figure A1.2.

A1.5 The NAEI also breaks the vehicle fleet into three different time periods for Euro 6 diesel LGV. The approach has been to take the results from Figure 12 as representing the first time period for each LGV category, and then to uplift this value by the same relative proportions as used for Euro 6 diesel cars as described in paragraph A1.4. These assumptions will clearly introduce uncertainty, since the technology mix for future vehicles cannot be defined, but the approach is considered reasonable in the absence of better information.

A1.6 The Rose (2018) study did not specifically identify ammonia emissions from buses. It has been assumed that these are the same as those for HGVs >12 te.

Fuel Consumption

A1.7 Because the remote sensing data are expressed per kg of fuel consumed, the next step has been to determine representative fuel consumption statistics. Fuel consumption values for passenger cars have been taken from the EQUA® index mile per gallon (mpg) values published by Emissions Analytics[22]. The full database of tested vehicles was downloaded in December 2019 and the tested[23] fuel consumption figures are summarised in Figure A1.1. These represent the average fuel consumption during each individual test. Each test covers more than 3.5 hours of driving, covering urban, rural, and motorway roads, as well as ‘sporty’, ‘high-load’ and ‘eco-driving’ elements. Results are collected on a second-by-second basis and normalised to represent the average congestion levels on the test route.

A1.8 As shown in Figure A1.1, the number of Euro 6 vehicles sampled is significantly greater than the number of earlier vehicles. However, Figure A1.1 also shows that there is no clear trend for the average fuel consumption to change with different Euro standards. The approach has thus been to take the average fuel consumption for all diesel cars tested (52 g/km, averaged over 4,665 vehicles) to represent all diesel cars; and to take the average fuel consumption for all petrol cars tested (55 g/km, averaged over 2,480 vehicles) to represent all petrol cars.

[22] https://equaindex.com/equa-fuel-economy-index/. The EQUA index provides numerical values for average fuel consumption, allowing these to be used directly (unlike for NOx emissions where only an emissions ‘rating’ is given).

[23] This resource publishes both tested and forecast fuel consumption data. Only the tested data were used.

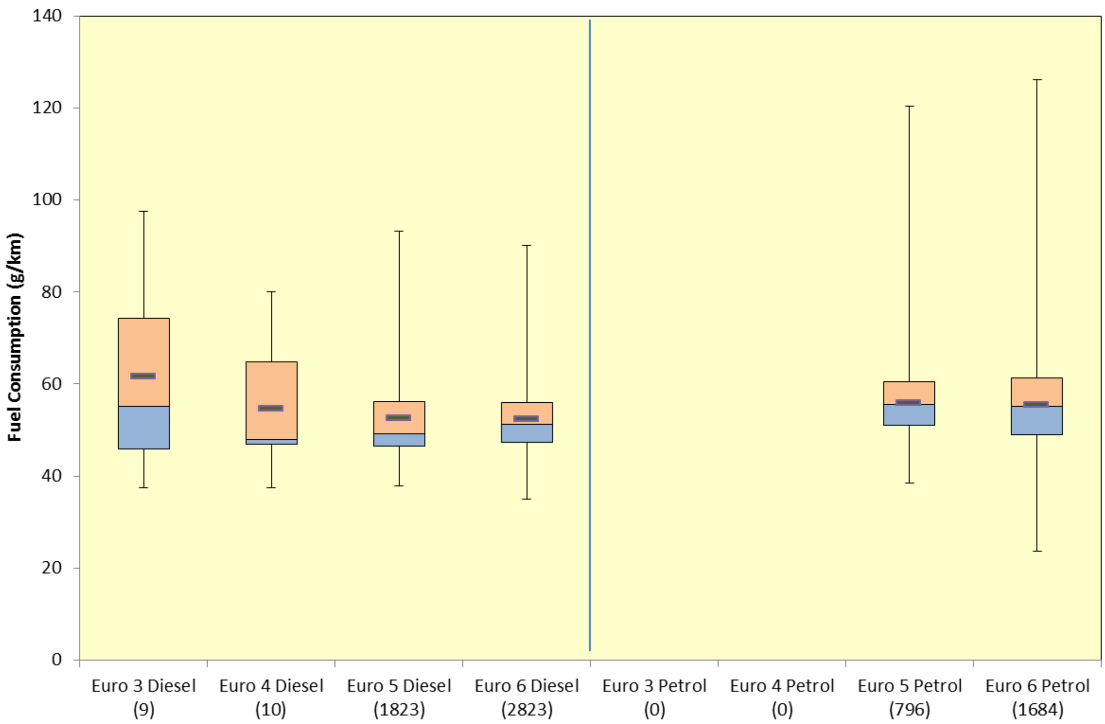

Figure A1.1: Measured Fuel Consumption from Different Classifications of Passenger Car (values in parentheses are the number of individual vehicles tested) (Derived from EQUA® Index data)[24]

A1.9 The EQUA® index does not include fuel consumption of HGVs. The Freight Transport Association (FTA) represents a range of sectors involved in operating goods vehicles, including hauliers, suppliers, retailers, local authorities etc. Its members operate more than half of the UK HGV fleet. Each year, the FTA carries out a survey of its members, covering information such as haulage trends, wage trends, and operating costs. This includes fuel consumption for different vehicle types. The most recent data published by the FTA are summarised in Table A1.1.

[24] Published values in miles per gallon converted to g/km based on an assumption of 1,192 litres per tonne for diesel and 1,340 litres per tonne for petrol, as reported in the 2018 version of the UK Greenhouse Gas Conversion Factors for Company Reporting (https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018). The 2018 values were used in preference to the 2019 data to be more consistent with the many of the measurements, however the differences are trivial in the context of other uncertainties.

Table A1.1: Average Fuel Consumption Values for Commercial Vehicles (Freight Transport Association, 2018)

Vehicle Class	Vehicle Subclass	Average Reported Fuel Economy (miles per gallon)
LGV	na	26
HGV	7.5te	16
	10-12te	13
	12-14te	13
	16-18te	12
	26te rigid	10
	32 te rigid tipper	8
	33te artic	9
	38te artic	8.5
	32.5te artic	9
	40te artic	7.6
	44 te artic	8.2

A1.10 The vast majority of LGVs on UK roads run on diesel (for example, the NAEI predicts that diesel LGVs made up 98% of all vehicle-kilometres travelled by LGVs on rural roads in 2019). The LGV fuel consumption values in Table A1.1 are thus taken to represent diesel-LGVs. The EQUA® Index also covers LGVs, but at the time that this analysis was prepared, results were only published for 49 vehicles and it was thus considered that the FTA data were more representative and robust. However, in the absence of any other real-world fuel consumption data for petrol-LGVs, the EQUA® Index values have been used. These represent tests from just two vehicles[25] and so will be particularly uncertain. However, because the number of petrol-LGVs in the overall vehicle fleet is so low, this uncertainty will have minimal impact on the emissions calculated from the fleet as a whole.

A1.11 Where necessary, the fuel consumption statistics have been combined with the 2018 UK-average HGV fleet composition values taken from the current (2018-based) NAEI in order to predict fleet-weighted average fuel consumption figures. The fuel consumption values used are set out in Table A1.2.

25 A 2015 Mercedes Citan and a 2016 Volkswagen Caddy.

Table A1.2: Average Fuel Consumption Values for Commercial Vehicles (Freight Transport Association, 2018)

Vehicle Class	Assumed Fuel Consumption (g/km)	Derived From
Petrol Cars	55	EQUA® Index[22]
Diesel Cars	52	
Petrol LGV	64	
Diesel LGV	91	(Freight Transport Association, 2018)
HGV <12 te	153	
HGV >12 te	243	

Calibration against Ambient Measurements

A1.12 The ammonia remote-sensing data have been combined with the measured fuel consumption statistics in order to provide an initial estimate of ammonia emissions from each vehicle type in g/km. These are set out in Table A1.3. There are many sources of uncertainty in these values. Furthermore, it is expected that the ammonia emissions factors will often be used as inputs to the ADMS-Roads dispersion model but that users will not be able to carry out local model verification against robust measurements (since it is uncommon to carry out robust roadside ammonia measurements paired with robust background ammonia measurements). The next step has thus been to verify the initial ammonia g/km emissions rates in Table A1.3 against the ambient measurements described in Paragraph 3.5.

Table A1.3: Ammonia Emissions Factors Based on Remote Sensing and Fuel Consumption Data (prior to model calibration)

Vehicle Type	Euro Standard	Ammonia (g/km)	Vehicle Type	Euro Standard	Ammonia (g/km)
Petrol Cars	Pre-Euro 1	0.084	HGV < 12t DIESEL	Pre-Euro I	0.000
	Euro 1	0.084		Euro I	0.000
	Euro 2	0.084		Euro II	0.000
	Euro 3	0.069		Euro III	0.012
	Euro 4	0.061		Euro IV	0.002
	Euro 5	0.047		Euro V	0.027
	Euro 6	0.034		Euro VI	0.055
Diesel Cars	Pre-Euro 1	0.005	HGV > 12t DIESEL	Pre-Euro I	0.055
	Euro 1	0.005		Euro I	0.055
	Euro 2	0.005		Euro II	0.055
	Euro 3	0.004		Euro III	0.055
	Euro 4	0.004		Euro IV	0.117
	Euro 5	0.004		Euro V	0.117
	Euro 6	0.005		Euro VI	0.147
Petrol LGVs	Pre-Euro 1	0.130	Bus & Coach	Pre-Euro I	0.055
	Euro 1	0.130		Euro I	0.055
	Euro 2	0.130		Euro II	0.055
	Euro 3	0.103		Euro III	0.055
	Euro 4	0.049		Euro IV	0.117
	Euro 5	0.073		Euro V	0.117
	Euro 6	0.026		Euro VI	0.147
Diesel LGVs	Pre-Euro 1	0.023	Motorcycle	All	0.000
	Euro 1	0.024			
	Euro 2	0.024			
	Euro 3	0.006			
	Euro 4	0.009			
	Euro 5	0.013			
	Euro 6	0.016			

A1.13 As explained in Paragraph 4.6 of the main report, as well as ambient concentrations of ammonia, the monitoring described in Marner et al. (2018) includes a network of Automatic Traffic Counters (ATCs) providing flow details, diurnal profiles, and vehicle fleet composition statistics for the roads alongside the monitors. The ADMS-Roads dispersion model has been used to predict the traffic component of ammonia concentrations at the 28[26] ammonia monitors described in Paragraph 3.5 which are more than 2 m from roads[27]. The overall model configuration is described in detail in Marner et al. (2018). A detailed approach was taken to setting up the model and this was reviewed by the team responsible for Defra's national modelling of critical loads exceedances (see Marner et al., 2008 for further details)[28].

A1.14 Figure A1.2 shows the total measured ammonia concentrations vs the modelled road-ammonia (predicted using the emissions factors in Table A1.3) at all of the monitoring sites (except the six monitors within 2m of roads). Some of these monitoring sites are a long way from roads (i.e. 'background sites'). The intercept of the line is at 0.625 μg/m^3. This value has thus been taken to represent the average concentration of ammonia in the study area wherever the road contribution is zero (i.e. the background concentration).

A1.15 In order to show the measured vs modelled road component of ammonia, the 'background' concentration of 0.625 μg/m^3 has been subtracted from the measurements. Figure A1.3 shows the results of this. The slope of the line (0.8053) is the same in both Figure A1.2 and Figure A1.3, with the only difference between these two figures being the point of the intercept on the Y axis. This comparison thus suggests that the road increment of ammonia has been over-predicted by around 19% (i.e. 1 – 0.8053 = 0.1941). Given the way in which the emissions factors have been derived, an agreement to within around 19% is considered to be relatively encouraging. Furthermore, the predictions are clearly superior to those derived using EEA Guidebook emissions factors, which under-predicted by almost three times. It is nevertheless considered appropriate to adjust the emissions by the slope of the line in Figure A1.2. Thus, all emissions, from all vehicle types, have been reduced by 19.47%.

A1.16 Figure A1.4 shows the final performance of the model, once the non-road (background) component (0.625 μg/m^3) has been added, and the traffic-related ammonia emissions have all been multiplied by 0.8053. There is no significant residual bias and all but one of the predicted concentrations is within 25% of the measured value. Table A1.4 confirms that model performs well using the appropriate statistical tests.

26 Some of the sites were represented by both an ALPHA and a DELTA monitor, thus the number of monitors is greater than the number of monitoring sites.

27 It is considered that including sites which are less than 2 m from roads risks introducing additional artefacts owing to uncertainties around vehicle wake effects. Six monitoring sites are within 2 m of roads and have thus been omitted from the analysis.

28 The only difference to the modelling presented here and that described in Marner et al., 2018 is the use of the emissions factors in Table A1.3 for NH_3.

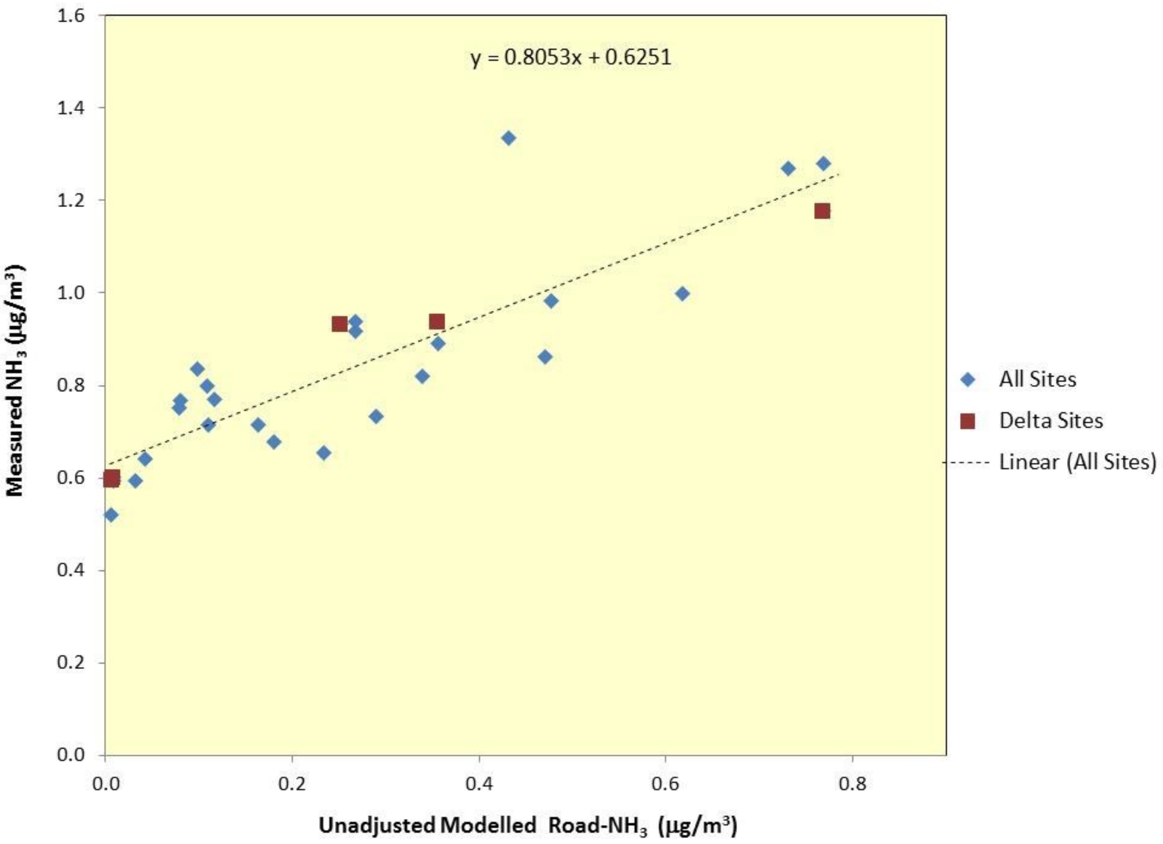

Figure A1.2: 2-Year Mean Measured Ammonia vs Concurrent Modelled Unadjusted Road-Ammonia

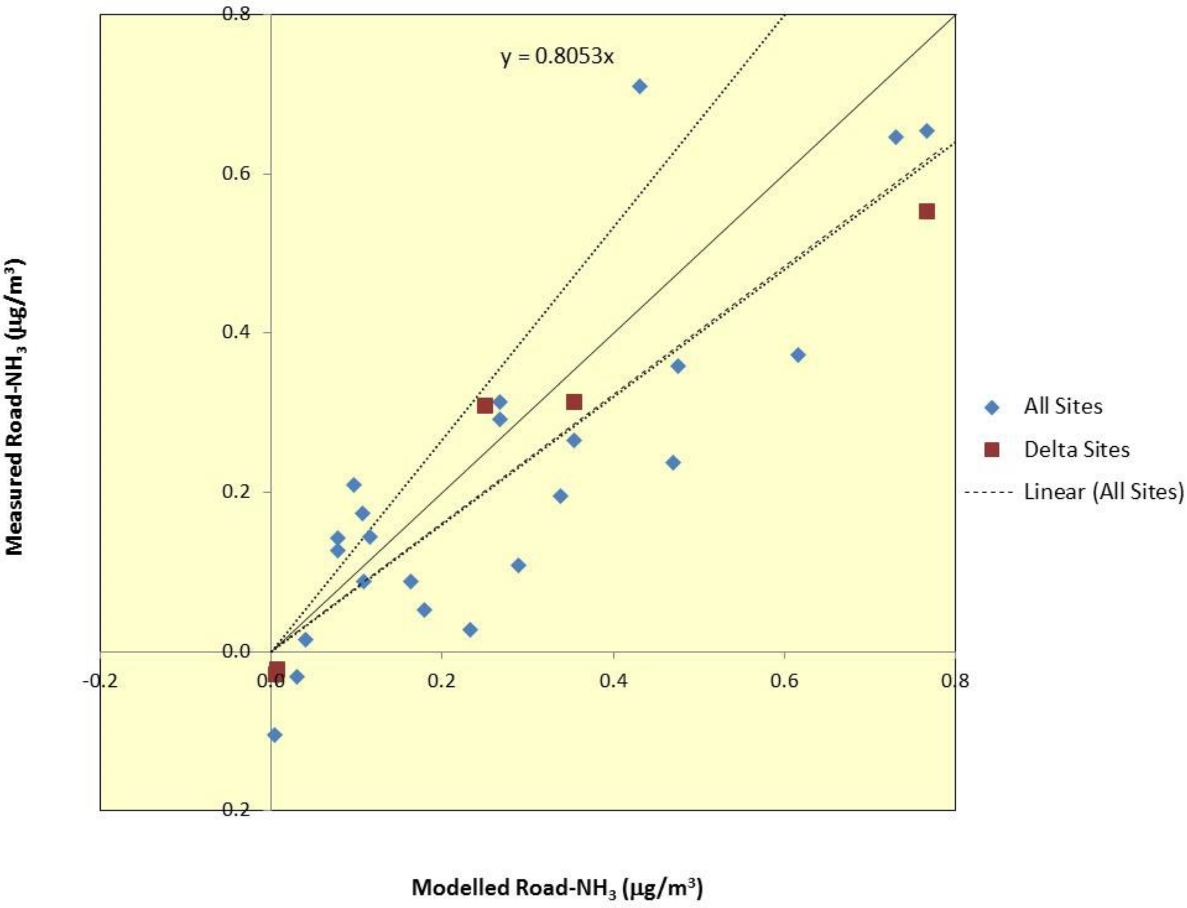

Figure A1.3: Measured vs Modelled Road-Ammonia (also showing 1:1 line, +/- 25% lines, and OLS regression best-fit line)[29]

29 Non-road 'background' component of measured NH_3 taken to be the intercept of the best-fit line, which is 0.6251 µg/m^3. This background has then been subtracted from the measurements for clarity of presentation.

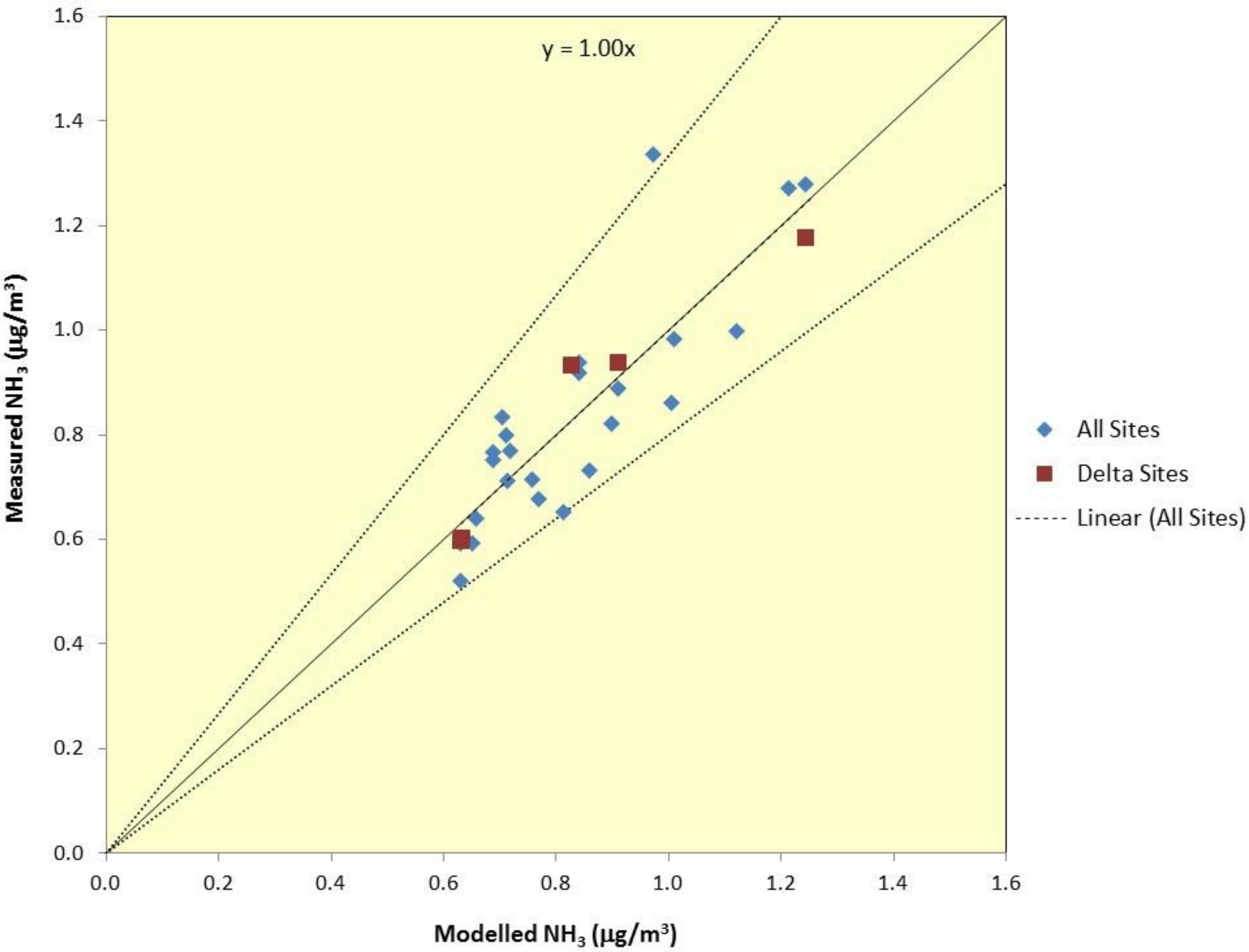

Figure A1.4: 2-Year Mean Measured Ammonia vs Concurrent Modelled Adjusted Total Ammonia (also showing 1:1 line, +/- 25% lines, and OLS regression best-fit line)

Table A1.4: Summary of Model Performance

Statistic	Value
Correlation Coefficient	0.87
Root Mean Square Error (RMSE)	0.11
Fractional Bias	-0.00002
number sites >25%	0
number sites <25%	1
number sites within 25%	28
% sites within 25%	97%

Forecasting Emissions from Petrol Cars in the Future

A1.17 As explained in Paragraphs 4.10 and 4.11 of the main report, ammonia emissions from petrol vehicles when tested as new may not provide a good indication of the average emissions over the lifetime of the vehicle. Ageing of the catalyst is thought to provide at least one of the reasons why the recorded emissions from older petrol cars are higher than those from new petrol cars. Over time, the petrol car fleet is likely to become increasingly populated by Euro 6 vehicles but, in broad terms, the average age of the fleet is unlikely to change appreciably.

A1.18 There is currently no way to robustly predict how ammonia emissions from petrol cars in the future might change from those in the current fleet. The assumption has thus been made that the current fleet-weighted average ammonia emissions for petrol cars apply to all current and future petrol cars. Table A1.5 shows the assumed make-up of the petrol car fleet used to calibrate the model. The emissions in Table A1.3 have been weighted by the proportions in Table A1.5 to calculate the fleet-weighted average emission from petrol cars in the calibration dataset. The two largest components of this fleet are Euro 4 and Euro 5 vehicles. The fleet-weighted average ammonia emission, following calibration using the factor from Figure A1.3, is 0.045 g/km and so it has been assumed that all petrol cars in the future will emit 0.045 g/km of ammonia.

Table A1.5: Assumed Make-up of the Petrol Car Fleet in 2015

Euro Standard	Proportion of Fleet
Pre-Euro 1	0.0%
Euro 1	0.1%
Euro 2	1.1%
Euro 3	8.2%
Euro 4	11.8%
Euro 5	16.3%
Euro 6	3.2%

A1.19 For the reasons explained in Paragraphs 4.13 to 4.15, there is currently no robust basis for assuming that the trip-average ammonia emissions from a petrol-hybrid vehicle will be any different from those from a standard petrol vehicle. It has thus been assumed that the same emission rate applies to both hybrid and non-hybrid vehicles. This is the same as the approach taken in the EEA Guidebook.

Final Derived Ammonia Emissions Factors

A1.20 Table A1.6 sets out the derived emissions factors for traffic-related ammonia. These values are also shown graphically in Figure 17 in the main report. Similar to the EEA Guidebook values, and because of the way in which they have been derived, these emissions factors are not speed-dependent and thus cover all driving speeds. There are some omissions in the dataset, most notably for motorcycles, but in most situations motorcycle numbers will be sufficiently small that this will make little difference to the fleet-total emissions. These emissions factors are compared directly against those in the EEA Guidebook for equivalent vehicle categories in Appendix A2. As explained in Paragraph 4.23 of the main report, the results of this comparison are qualitatively consistent with the findings of TNO in 2015 (TNO, 2015)

A1.21 As explained in Paragraph 4.23 of the main report, using the emissions factors in Table A1.6 to make future-year predictions will clearly be an improvement on any assessment which omits ammonia. These emissions factors are also considered to be more robust than those contained in the EEA Guidebook. They can be considered to provide the most robust estimate of traffic-related ammonia possible at the present time, but may be revisited as further information becomes available.

Table A1.6: Derived Emissions Factors for Traffic-related Ammonia (Emissions per vehicle in mg per km travelled)

Vehicle Type	Ammonia Emission (mg/km)
All Petrol Cars	44.76
Diesel Cars Pre-Euro 3	4.24
Diesel Cars Euro 3	3.30
Diesel Cars Euro 4	2.83
Diesel Cars Euro 5	2.83
Diesel Cars Euro 6 stage 1	4.24
Diesel Cars Euro 6 stage 2	4.70
Diesel Cars Euro 6 stage 3	7.79
All Petrol LGVs	62.54
Diesel LGVs Pre-Euro 3	18.92
Diesel LGVs Euro 3	4.98
Diesel LGVs Euro 4	7.47
Diesel LGVs Euro 5	10.79
Diesel LGVs Euro 6 stage 1	13.28
Diesel LGVs Euro 6 stage 2	14.71
Diesel LGVs Euro 6 stage 3	24.41
HGV < 12t Diesel Pre Euro III	0.00
HGV < 12t Diesel Euro III	9.63
HGV < 12t Diesel Euro IV	1.38
HGV < 12t Diesel Euro V	22.01
HGV < 12t Diesel Euro VI	44.02
HGV > 12t Diesel Pre Euro IV	43.95
HGV > 12t Diesel Euro IV	94.50
HGV > 12t Diesel Euro V	94.50
HGV > 12t Diesel Euro VI	118.67
Bus & Coach Pre Euro IV	43.95
Bus & Coach Euro IV	94.50
Bus & Coach Euro V	94.50
Bus & Coach Euro VI	118.67
All Motorcycles	0.00

A2 Comparison with EEA Guidebook (COPERT) Emissions

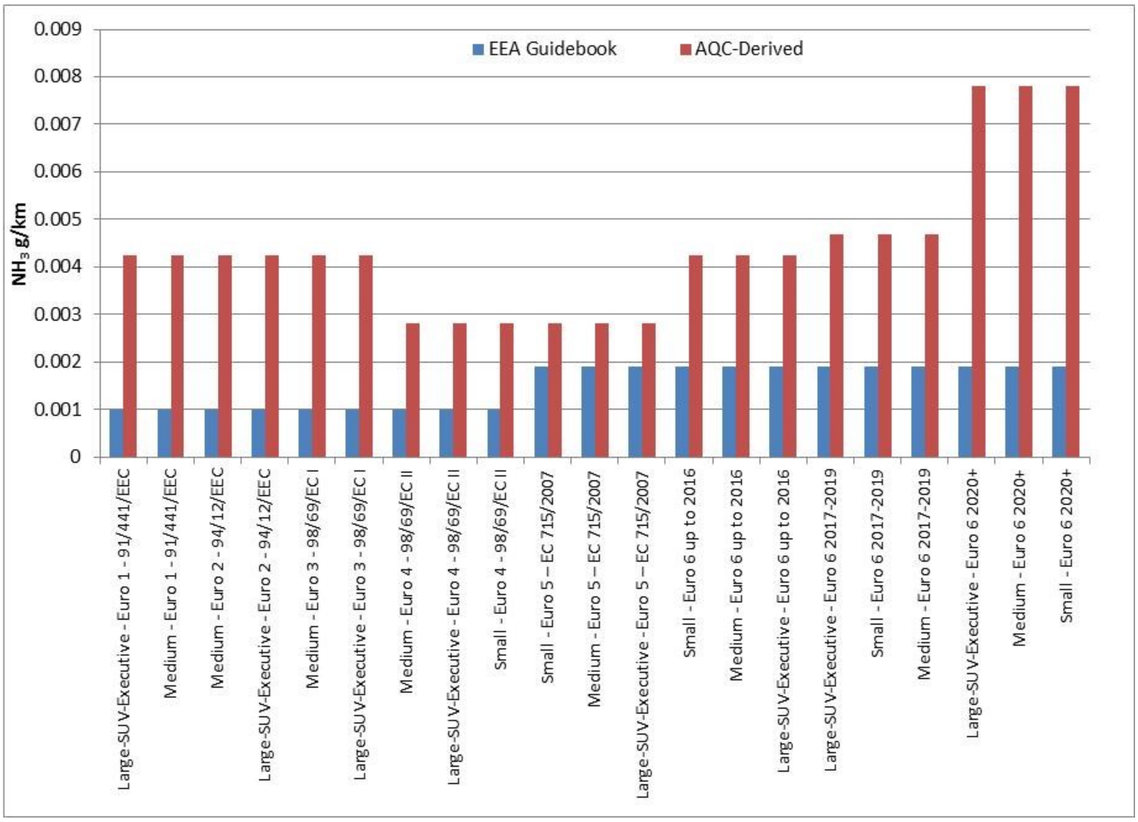

Figure A2.1: EEA Guidebook and AQC-Derived Ammonia Emissions for Diesel Passenger Cars

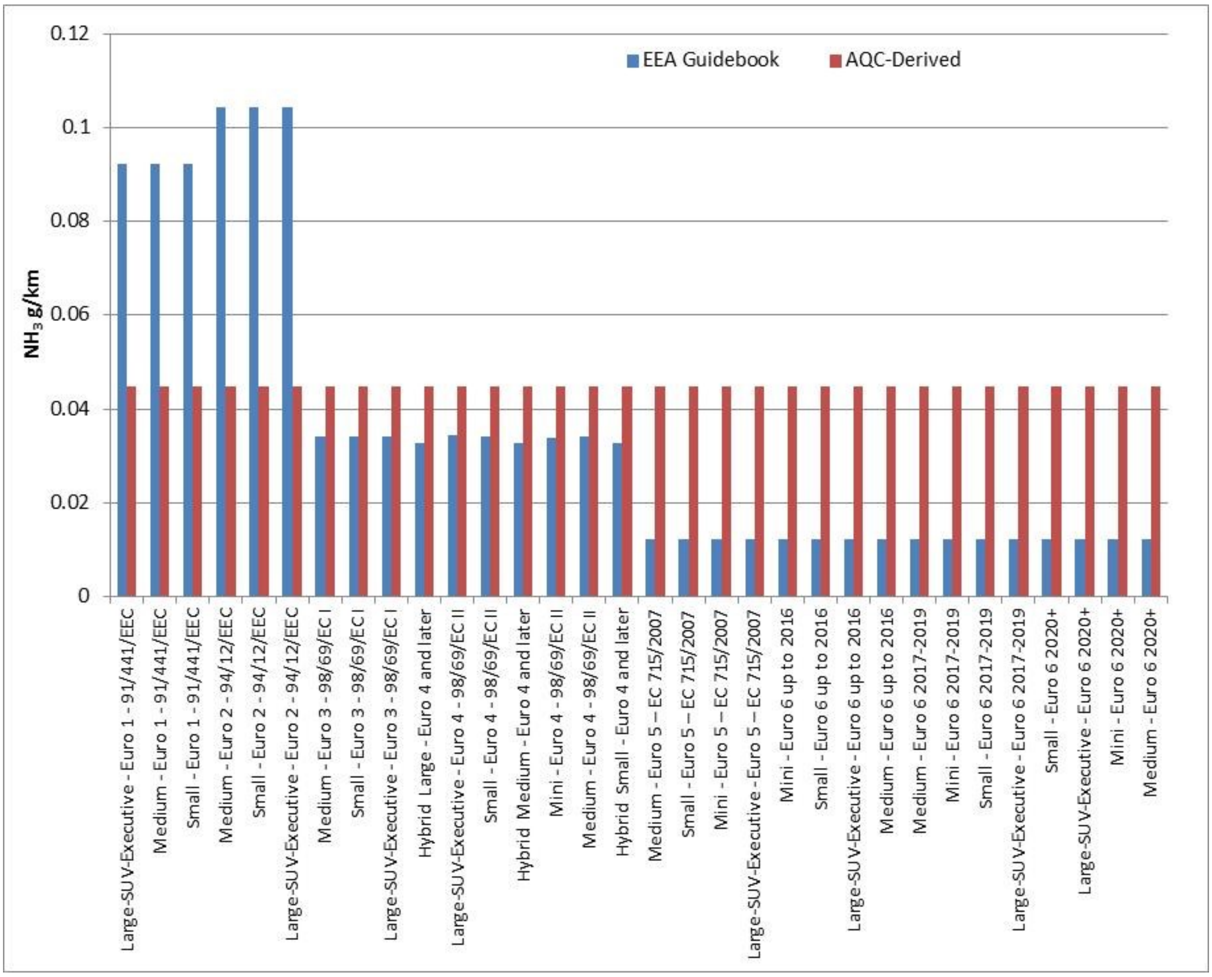

Figure A2.2: EEA Guidebook and AQC-Derived Ammonia Emissions for Petrol Passenger Cars

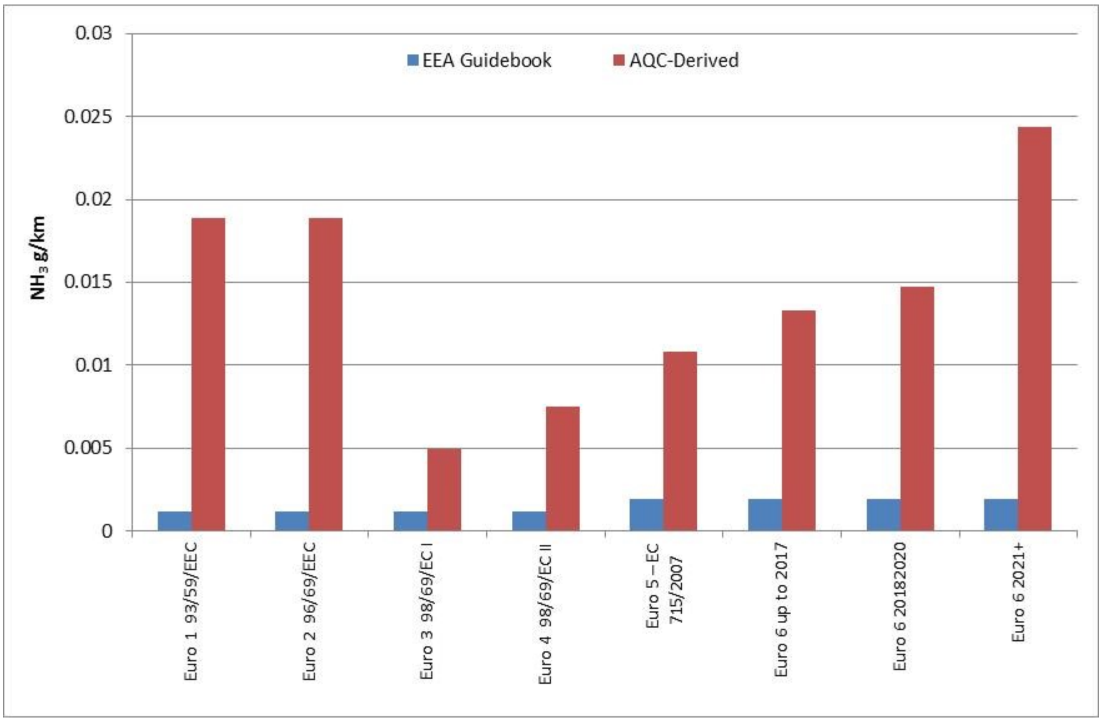

Figure A2.3: EEA Guidebook and AQC-Derived Ammonia Emissions for Diesel LGVs

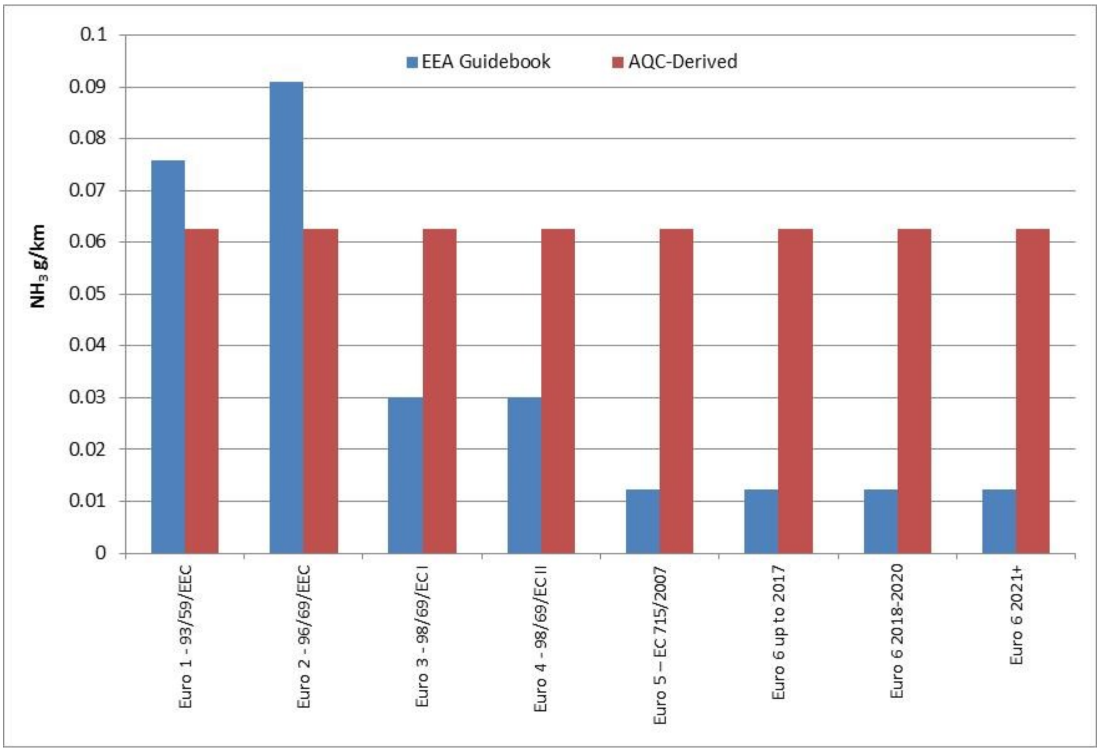

Figure A2.4: EEA Guidebook and AQC-Derived Ammonia Emissions for Petrol LGVs

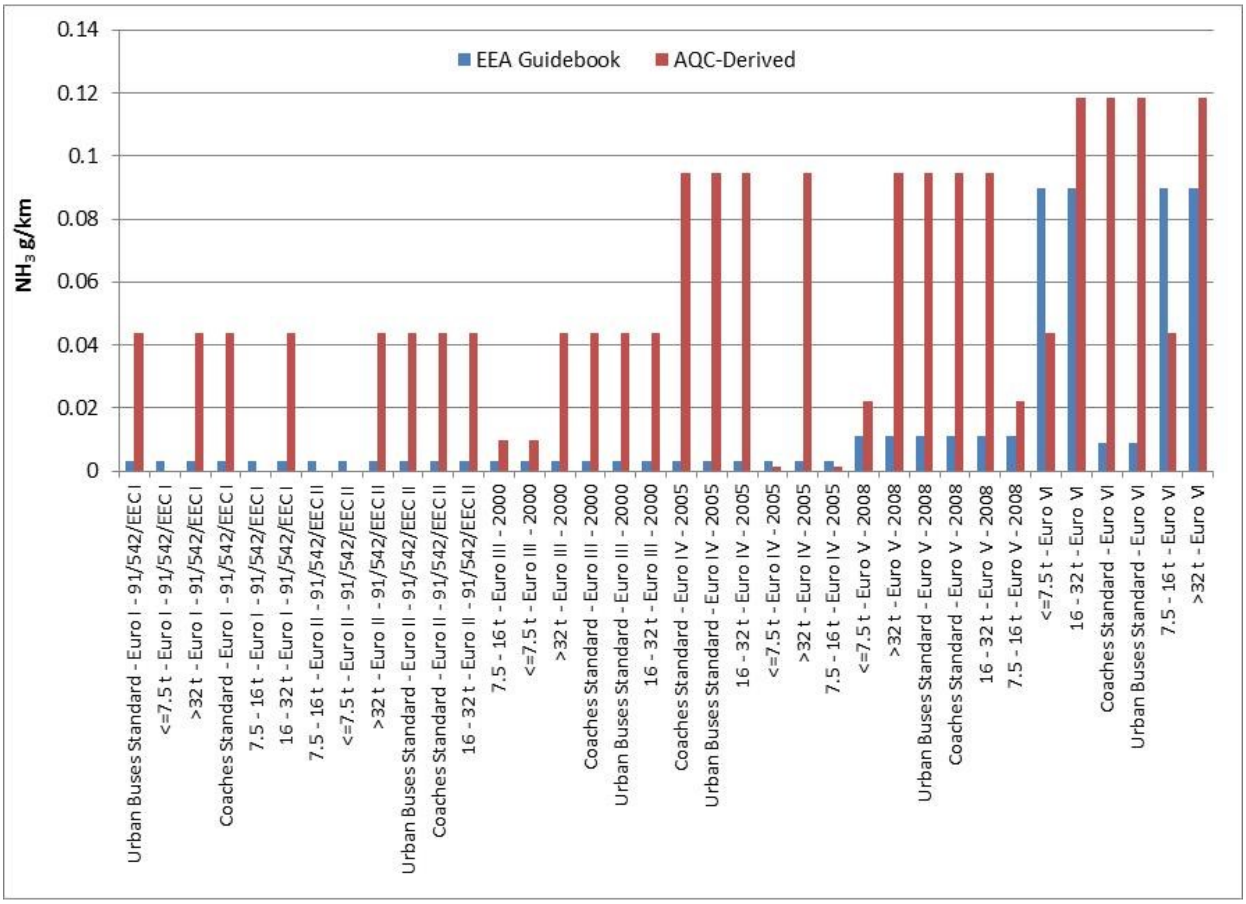

Figure A2.5: EEA Guidebook and AQC-Derived Ammonia Emissions for HDVs[30]

[30] The 7.5te to 16te HGV category in the Guidebook has been compared against the <12 te HGV category in the derived emissions factors.