Report

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A comparison of real driving emissions from Euro 6 diesel passenger cars with zero emission vehicles and their impact on urban air quality compliance

Urban air quality study: extension I

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A COMPARISON OF REAL DRIVING EMISSIONS FROM EURO 6 DIESEL PASSENGER CARS WITH ZERO EMISSION VEHICLES AND THEIR IMPACT ON URBAN AIR QUALITY COMPLIANCE

URBAN AIR QUALITY STUDY: EXTENSION I

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EXECUTIVE SUMMARY

This report describes an extension to the *Urban Air Quality Study* commissioned by Concawe that explored how urban air quality is affected by emissions from road transport and domestic combustion. In the first report a particular focus was placed on the impact of real driving emissions (RDE) on urban concentrations of nitrogen dioxide (NO_2) and particulate matter (PM_{10} and $PM_{2.5}$) and the effect this may have on compliance with ambient air quality limit values at European, national and regional level. The aim of this extension study is to determine how measured emissions from newer RDE compliant Euro 6 diesel passenger cars would affect the concentration of NO_2 in European urban environments. A comparison has also been made where the substitution of Euro 6d diesel passenger cars with zero exhaust emission equivalents is explored.

In 2017, Concawe commissioned Ricardo to collect data from literature sources and test a range of Euro 6 diesel passenger cars using the new on-road real driving emission test cycle to measure actual on-road emissions of NO_X for each of the Euro 6 categories; Euro 6b (pre and post 2015), Euro 6c and Euro 6d (Temp). The study showed that real world NO_X emissions from diesel passenger cars are significantly reduced by successive Euro 6 standards and suggests that the technical solutions available to Euro 6d cars will comply with the 80 mg/km EU NO_X emission standard for Euro 6 passenger cars under RDE test conditions.

Aeris Europe's AQUIReS+ model has been populated with the emissions data collected by Ricardo and used to model population exposure to concentrations of NO_2, $PM_{2.5}$ and PM_{10} across the 28 EU member states and 10 European cities: Antwerp, Berlin, Bratislava, Brussels, London, Madrid, Munich, Paris, Vienna and Warsaw.

The principal findings of the study are:

- In the natural turnover of the vehicle fleet, the significantly reduced NO_X emissions from Euro 6d diesel passenger cars will be as effective as zero emission vehicles in helping cities become compliant with air quality standards.
- For NO_2, $PM_{2.5}$ and PM_{10}, no appreciable effect on air quality compliance or population exposure is observed between any of the modelled diesel passenger car scenarios or their replacement with equivalent zero emission vehicles.
- NO_2 compliance issues in traffic "hot-spots" persist until 2030 in a number of European cities under all modelled scenarios. It is unlikely that measures targeting new diesel cars will address this issue.
- In the case of particulates, modern passenger car emissions are largely independent of the drive-train given that mechanical abrasion (brake, road and tyre wear) is the most significant source.
- It is important to identify the actual emission sources contributing to each unique area of non-compliance to effectively address outstanding issues, for example, domestic heating or urban power generation in addition to road transport and other sources.

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INTRODUCTION

This report describes an extension to the *Urban Air Quality Study* (Aeris Europe, 2016), a study commissioned by Concawe that explored how urban air quality is affected by the emissions from vehicles and domestic combustion. In the first report, a focus was placed on the impact of real driving emissions (RDE) on urban concentrations of nitrogen dioxide (NO_2) and particulate matter (PM_{10} and $PM_{2.5}$) and the effect this may have on compliance with ambient air quality limit values at European, national and regional level. This study focusses on the effect that RDE test compliant Euro 6d diesel passenger cars will have on urban air quality in major towns and cities within the EU. To achieve this, nearly 2,500[1] European air quality monitoring stations have been modelled and a detailed analysis of air quality compliance and population exposure in 10 European cities has been performed.

Since the publication of the first report, there continues to be much debate with respect to the impact of NO_2 on urban populations, particularly at levels exceeding EU air quality limit values. Although the nature and severity of health impacts are still being discussed, for example the work currently being undertaken by COMEAP in the UK (COMEAP, 2015 (a)), (COMEAP, 2015 (b)), (COMEAP, 2017), diesel vehicles have been singled out as the primary cause of non-compliance with NO_2 air quality limit values in the urban environment.

Historically, the modelling of urban air quality has often relied on the assumption that vehicles on the road perform similarly to the way they do in laboratory test environments, this can lead to an underestimation of the effect of the vehicle fleet and makes determining the direct contribution of vehicle emissions to concentrations difficult. The development of reliable portable emission measuring systems (PEMS) has enabled vehicle emissions to be monitored under real driving conditions and testing of early Euro 6 diesel passenger cars[2] has highlighted the difference in emission levels of nitrogen oxides (NO_X) between laboratory test cycles and real driving conditions. Emissions under real driving conditions were found to be on average, 5 to 7 times the legislated limit value (LLV) required for type approval (Yang, et al., 2015), this was despite those same cars having achieved type approval and passing laboratory emissions testing.

A requirement of Euro 6 legislation is that manufacturers verify the emissions performance of their vehicles under a real driving test cycle using PEMS. (2016/427/EC) It is common to express the degree of compliance with the legislated emissions limit using a conformity factor (CF), which is a simple coefficient of the legislated limit value of 80mg/km, for example a CF of 1 is equal to the LLV[3] while a CF of 2 would be two times the LLV or 160mg/km.

In 2017, Concawe commissioned Ricardo to gather data from literature as well as their own tests under real driving conditions to determine the emissions of a range of diesel passenger cars built to comply with Euro 6b, 6c and 6d-temp standards (2007/715/EC). **Table 1** shows the results of the Ricardo data for each Euro 6 class (Ricardo, 2018) expressed as diesel passenger car NO_X conformity factors.

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[1] Monitoring station data is from Member State submissions to the EEA and must meet data quality requirements

[2] For example, the testing performed by the Allgemeiner Deutscher Automobil-Club (ADAC) as part of its EcoTest program (ADAC, 2017)

[3] The Euro 6d RDE Conformity Factor from January 2020 is 1.

Table 1 Conformity factors for diesel passenger cars derived from the Ricardo study – Nitrogen Oxides (NO_X)[4]

	Euro 6b Pre-2015	Euro 6b Post-2015	Euro 6c	Euro 6d (temp)
Minimum NO_X	1.13	0.20	0.25	0.23
Maximum NO_X	17.25	5.35	3.65	1.29
Mean NO_X	6.70	2.19	1.43	0.73
Median NO_X	5.41	1.90	1.21	0.76

This study takes advantage of the NO_X emissions from the Ricardo study by using them as inputs to Aeris Europe's AQUIReS+ model to explore the impact on compliance and population exposure to nitrogen dioxide of real driving emissions from diesel passenger cars, now and into the near future. For particulate emissions ($PM_{2.5}$ and PM_{10}) there are no conformity factors, but this study does examine the impact of particulate matter emissions.

The emissions Base Case formulated for the original *Urban Air Quality Study* (Aeris Europe, 2016) was used as a starting point for all diesel passenger car scenarios, this is based on the January 2015 Thematic Strategy on Air Pollution Report #16 (TSAP16) Working Party for the Environment (WPE) Current Legislation Baseline Scenario (IIASA, 2015a), (IIASA, 2015b) associated with the EU Air Policy Review process (European Commission, 2011) as generated by IIASA's GAINS model. The emissions inventory and projections[5] considered in the Base Case are the most up to date European estimates available at the time of writing but do not take into account the effects of legislation for which the actual impact on future activity levels could not be quantified[6]. As a result, the Base Case should be considered as under-estimating anticipated emissions reductions. The baseline road transport emissions have been disaggregated using the fleet projections included in the TREMOVE[7] v3.3.2 'alternative' scenario (European Commission, 2015) (Fiorello, et al., 2009), and the emission factors of COPERT[8] v4.11. The effective Euro 6 diesel passenger car NO_X conformity factor in the Base Case is 2.8, this corresponds well with the measured Euro 6b (post 2015) mean emissions from the Ricardo study. To produce road transport emissions for each scenario, the Base Case Euro 6 NO_X conformity factors have been modified to reflect those listed in **Table 1**.

Whilst the overall methodology of this study is based on that described in the 2016 report, the AQUIReS+ model has been updated to include more air quality stations and additional data from existing EEA stations. The population exposure capabilities of AQUIReS+ include the exposure methodology described in the paper "Exceedance of air quality limit values in urban areas" (EEA, 2014 (a)). More details on this technique can be found in the methodology section of this report.

[4] (Ricardo, 2018) Expectations for Actual Euro 6 Vehicle Emissions. RD18-000697-2
[5] IIASA TSAP Report 16, WPE 2014 CLE for 2030 using the PRIMES 2013 Reference Activity Projection and COPERT v4.11 emission factors.
[6] For example, the Medium Combustion Plants Directive (MCPD) and the review of the National Emissions Ceilings Directive (NECD).
[7] TREMOVE v3.3.2 is a mature transport policy assessment model developed for the iTren 2030 project which covers all inland urban and inter-urban transport modes.
[8] The COPERT 4 methodology is part of the EMEP/EEA Air Pollutant Emission Inventory Guidebook for the calculation of air pollutant emissions. The emission factors generated are vehicle and country specific.

AIR QUALITY LIMIT VALUES

Ambient air quality limit values are referred to frequently throughout this study. Rather than describe them repeatedly, **Table 2** lists the limit values of relevance for $PM_{2.5}$, PM_{10} and NO_2. For those pollutants with more than one metric, the * indicates the statistically more significant limit, i.e. the metric that will usually be exceeded first or the "stricter" limit.

Table 2 EU Ambient Air Quality Limit Values

Pollutant	Frequency	Value (µg/m³)	Allowed Exceedances
Nitrogen Dioxide (NO_2)	Hourly Exceedance	200	18
Nitrogen Dioxide (NO_2)	Annual Mean *[9]	40	0
Particulate Matter ($PM_{2.5}$)	Annual Mean	25	0
Particulate Matter (PM_{10})	Daily Exceedance *[10]	50	35
Particulate Matter (PM_{10})	Annual Mean	40	0

[9] (de Leeuw & Ruyssenaars, 2011)
[10] (Buijsman, et al., 2005), (Stedman, et al., 2007)

GEOGRAPHIC COVERAGE AND RESOLUTION

Building on the 2016 study, this study extends the focus of urban air quality to every town and city in the EU with an air quality monitoring station that qualifies for inclusion in the AQUIReS+ model[11]. In some cases this means that smaller towns may be represented by a single station, however for larger cities and at national and EU scale it provides valuable insights. This study has generated results for EU countries individually, the EU-28 as a whole and in detail for the following cities:

- Antwerp
- Berlin
- Bratislava
- Brussels
- London
- Madrid
- Munich
- Paris
- Vienna
- Warsaw

The modelling of air quality management zones (AQMZ)[12] has been omitted in favour of a focus on urban areas (towns and cities) as this is more representative of the actual exposure of a population than the AQMZ approach. Using the AQMZ approach as adopted in the 2016 Urban Air Quality Study and elsewhere[13], can lead to a significant over-estimation of population exposure, this is because the whole population of a zone is considered exposed to non-compliant air quality levels if even a single road junction or air quality monitoring station is non-compliant. An example of this is given in the results section of this report.

[11] AQUIReS+ employs strict eligibility requirements for candidate air quality stations, these include a minimum number of valid measurements each year (similar to the ambient air quality directive) and measurements must cover a minimum time-frame. Full details can be found in the original Urban Air Quality Study.

[12] Air quality management zones are designated under the ambient air quality directive (2008/50/EC) and oblige Member States to divide their entire territory into zones. Zones can be regarded as the primary territorial units for assessment and management of air quality under the air quality directives. There are approximately 680 AQMZ in the EU, this number varies by pollutant (2008/50/EC, 2008).

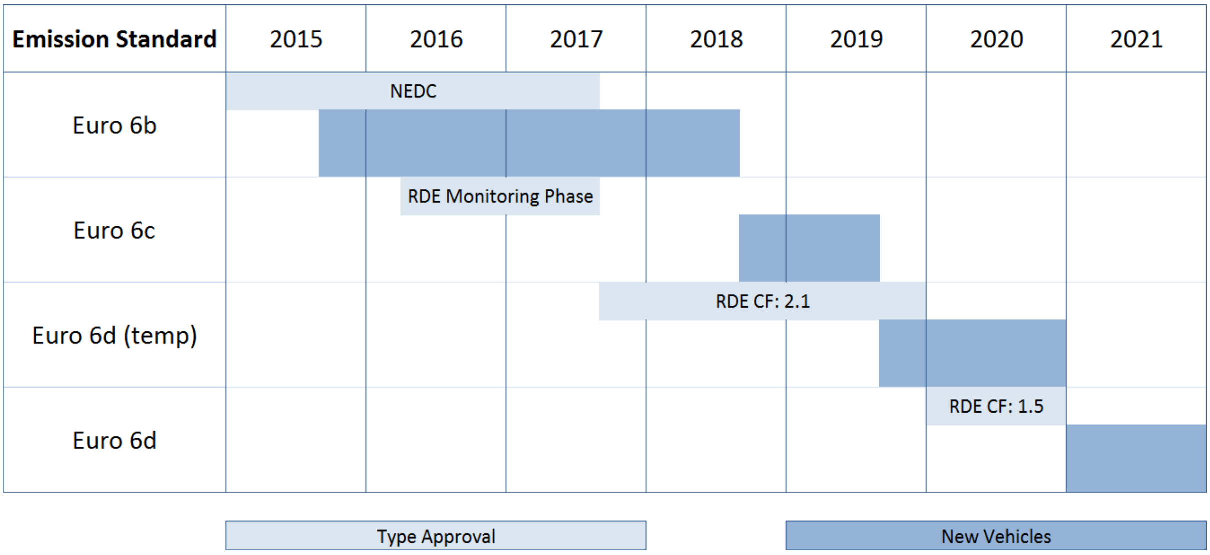
[13] For example "Modelling $PM_{2.5}$ impact indicators in Europe: Health effects and legal compliance" (Kiesewetter, et al., 2015)

NITROGEN DIOXIDE COMPLIANCE SCENARIOS

The following scenarios were generated using the Ricardo test data in **Table 1** to inform the NO_X emissions of Euro 6 diesel passenger cars. All scenarios are based on the original UAQ Base Case detailed in the *Urban Air Quality Study* and are used as inputs to AQUIReS+ to model the resultant changes in localised concentrations of NO_2 across Europe. In any scenario where the conformity factor is measured as being less than 1 the modelling has assumed a conformity factor of 1; this is shown in the relevant descriptions below. This pinning of the conformity factor to 1, even when testing indicates emissions are below the LLV, is a deliberate decision and designed to prevent exaggeration of the emissions reductions. It also serves to ensure that the model is reflecting the minimum effect that full compliance with the legislated emissions limits would have on air quality.

Figure 1 shows the timeframes for each of the Euro standards explored in this study. The "Type Approval"[14] shading indicates the window for manufacturers to obtain new model type approvals whilst the "New Vehicles" shading indicates that all applicable vehicles produced during that time must comply with the corresponding standard. These timeframes have been incorporated into each of the scenarios described below.

Figure 1 Euro standard and timeframe for new vehicle implementation[15]



The New European Driving Cycle (NEDC) laboratory test cycle will be replaced with the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) from September 2017 for Euro 6d (temp) type approvals and for all vehicles including Euro 6c from September 2018.

The RDE component of the WLTC test procedure is being introduced in three phases:

1. A monitoring period from April 2016 on new vehicle type approvals
2. Euro 6d (temp) type approvals with a conformity factor of 2.1
3. Euro 6d type approvals with a conformity factor of 1 + 0.5 measurement error margin

[14] Automotive type approval is the confirmation by an independent body that production samples of a design meet specified performance standards, including those set forth in EC directives and UN regulations. This includes testing, certification and production conformity assessment.

[15] The Euro 6d Conformity Factor from January 2020 is expressed as 1.5 for simplicity however it is actually 1 with a 0.5 margin of tolerance to allow for measurement uncertainties. The margin is subject to annual review.

RICARDO MEDIAN SCENARIO

In this scenario (**Table 3**) every Euro 6 diesel passenger car introduced in a specific year is assumed to conform to the median of the test results.

Table 3 Scenario – Ricardo Median

Scenario	Description	Years	CF
Ricardo Median	Euro 6 Diesel PCs registered before 2015 meet the **median** of the Ricardo test results: Euro 6b Pre-2015	Pre-2015	**5.41**
	Euro 6 Diesel PCs registered in 2015 and 2016 meet the **median** of the Ricardo test results: Euro 6b Post-2015	2015-2016	**1.90**
	Euro 6 Diesel PCs registered between 2017 and 2019 meet the **median** of the Ricardo test results: Euro 6c	2017-2019	**1.21**
	Euro 6 Diesel PCs registered from 2020 onwards meet the **median** of the Ricardo test results: Euro 6d temp but with an RDE of 1 rather than 0.76	2020+	**1**

RICARDO MEAN SCENARIO

In this scenario (**Table 4**) every Euro 6 diesel passenger car introduced in a specific year is assumed to conform to the mean of the test results.

Table 4 Scenario – Ricardo Mean

Scenario	Description	Years	CF
Ricardo Mean	Euro 6 Diesel PCs registered before 2015 meet the **mean** of the Ricardo test results: Euro 6b Pre-2015	Pre-2015	**6.70**
	Euro 6 Diesel PCs registered in 2015 and 2016 meet the **mean** of the Ricardo test results: Euro 6b Post-2015	2015-2016	**2.19**
	Euro 6 Diesel PCs registered between 2017 and 2019 meet the **mean** of the Ricardo test results: Euro 6c	2017-2019	**1.43**
	Euro 6 Diesel PCs registered from 2020 onwards meet the **mean** of the Ricardo test results: Euro 6d temp but with an RDE of 1 rather than 0.73	2020+	**1**

RICARDO EURO 6D MAXIMUM SCENARIO

This scenario (**Table 5**) mirrors the Ricardo Median scenario until 2020 from which time every Euro 6 diesel passenger car registered is assumed to conform to the maximum of the test results.

Table 5 Scenario – Ricardo Euro 6d Maximum

Scenario	Description	Years	CF
Ricardo E6DMax	Euro 6 Diesel PCs registered before 2015 meet the **median** of the Ricardo test results: Euro 6b Pre-2015	Pre-2015	**5.41**
	Euro 6 Diesel PCs registered in 2015 and 2016 meet the **median** of the Ricardo test results: Euro 6b Post-2015	2015-2016	**1.90**
	Euro 6 Diesel PCs registered between 2017 and 2019 meet the **median** of the Ricardo test results: Euro 6c	2017-2019	**1.21**
	Euro 6 Diesel PCs registered from 2020 onwards meet the **maximum** of the Ricardo test results: Euro 6d temp	2020+	**1.29**

RICARDO EURO 6D EARLY INTRODUCTION SCENARIO

This scenario (**Table 6**) mirrors the Ricardo Median scenario until 2018 from which time every Euro 6 diesel passenger car registered is assumed to conform to the median of the test results.

Table 6 Scenario – Ricardo Euro 6d, Early Introduction

Scenario	Description	Years	CF
Ricardo E6DEarly	Euro 6 Diesel PCs registered before 2015 meet the **median** of the Ricardo test results: Euro 6b Pre-2015	Pre-2015	**5.41**
	Euro 6 Diesel PCs registered in 2015 and 2016 meet the **median** of the Ricardo test results: Euro 6b Post-2015	2015-2016	**1.90**
	Euro 6 Diesel PCs registered in 2017 meet the **median** of the Ricardo test results: Euro 6c	2017	**1.21**
	Euro 6 Diesel PCs registered from **2018** onwards meet the **median** of the Ricardo test results: Euro 6d temp but with an RDE of 1 rather than 0.76	2018+	**1**

ZERO EXHAUST EMISSION PASSENGER CARS FROM 2020 SCENARIO

This scenario (**Table 7**) mirrors the Ricardo Median scenario until 2020 from which time every Euro 6 diesel passenger car registered emits zero exhaust emissions; this is the equivalent of replacing all new diesel passenger car sales with electric vehicles.

Table 7 Scenario – Zero Exhaust Emission Passenger Cars from 2020

Scenario	Description	Years	CF
ZEV Scenario	Euro 6 Diesel PCs registered before 2015 meet the **median** of the Ricardo test results: Euro 6b Pre-2015	Pre-2015	**5.41**
	Euro 6 Diesel PCs registered in 2015 and 2016 meet the **median** of the Ricardo test results: Euro 6b Post-2015	2015-2016	**1.90**
	Euro 6 Diesel PCs registered between 2017 and 2019 meet the **median** of the Ricardo test results: Euro 6c	2017-2019	**1.21**
	All Diesel PCs registered from 2020 onwards are replaced with **zero exhaust emission** vehicles undertaking the same activity.	2020+	**0**

PARTICULATE MATTER COMPLIANCE SCENARIOS

Particulate matter is highly distinct from NO_2, whereas vehicular NO_x is produced solely by combustion processes within the engine, particulates are emitted as a result of both combustion and mechanical processes, e.g. brake wear, tyre wear and road abrasion. All modern road vehicles produce very small quantities of particulates from combustion due to effective particulate filters and other emissions abatement processes within the engine. Effectively, current diesel combustion engines and electric vehicles produce similar levels of particulates (Timmers & Achten, 2016).

Particulate matter is also formed by chemical reactions and physical aggregation processes in the atmosphere, the contribution from these secondary sources and the emissions that lead to their formation is discussed in the Methodology section.

To help quantify the effect of replacing diesel passenger cars with zero exhaust emission vehicles two particulate matter scenarios have been considered. The first uses the UAQ Base Case described earlier, the second models the elimination of all diesel exhaust emissions for new passenger cars registered from 2020. This is the equivalent of replacing all new diesel passenger car sales with electric vehicles. This scenario is detailed in **Table 8**.

Table 8 Particulate matter scenarios

Scenario	Description
Base Case	UAQ Base Case (See page. 15)
ZEV Scenario	All diesel passenger cars registered from 2020 onwards are replaced with **zero exhaust emission** cars undertaking the same activity.

METHODOLOGY

This study utilises the same tools and methodology as described in the *Urban Air Quality Study* (Aeris Europe, 2016). Please refer to that document for a more detailed description of the methodology, models and data sources, in particular Chapter 5 and the AQUIReS+ model. What follows is a brief discussion of enhancements made to the AQUIReS+ model since the 2016 study and the most relevant background information.

AQUIRES+

AQUIReS+ is a suite of tools developed by Aeris Europe that together provide a modular integrated assessment model (IAM). AQUIReS+ is able to incorporate a wide-range of exogenous data sources in order to build emissions profiles[16] at country and grid level and relate those emissions to concentrations at individual measuring stations. An important feature of AQUIReS+ is the ability to account for localised traffic, environmental and topographical effects at each measuring station across Europe by analysing the measurement history of specific stations and their proximity to key air quality influences.

NO_X AND NO/NO_2 RATIOS

Nitrogen oxide (NO_X) is comprised of nitric oxide (NO) and nitrogen dioxide (NO_2). NO is considered non-harmful to health at atmospheric concentrations, however NO can be converted to NO_2 once released to the atmosphere. The rate of this oxidisation and the opposite reactions converting NO_2 to NO are subject to many criteria (Hagenbjörk, et al., 2017) (Kimbrough, et al., 2017) and can have a significant effect on overall NO_2 concentrations (Kurtenbach, et al., 2012).

In urban environments, the direct emission of NO_2 from road transport has become an important contributor to NO_2 concentrations at roadside locations and the proportion of NO_2 in NO_X emissions from a diesel vehicle is significantly higher than the proportion found in the emissions of an equivalent gasoline vehicle (Pastramas, et al., 2014). NO_2 emissions are also influenced by engine size and exhaust after-treatments such as catalytic converters, as a result, direct NO_2 emissions from diesel engines have increased from approximately 5% in older vehicles to between 12% and 70% dependent on the vehicle (EEA, 2013). This proportion continues to evolve and analysis of measurement data shows that for a given NO_X emission the proportion emitted as direct NO_2 is highly variable (Carslaw, et al., 2016).

The atmospheric chemistry that oxidises NO to NO_2, the evolution of vehicle fleets from gasoline to diesel, and the emission abatement technologies present in a vehicle are all significant factors in determining the atmospheric NO_2 concentration for a given mass of NO_X emissions. AQUIReS+ incorporates all of these factors, on an annualised basis, to produce a NO_X to NO_2 concentration profile at each modelled location. This is achieved through a number of techniques including the incorporation of measured NO, NO_2 and NO_X concentrations and an evaluation of region specific vehicle fleet characteristics. Ultimately it allows the model to account for the factors described above at any given physical location within the geospatial resolution of the input data.

DATA DISCUSSION AND AVAILABILTY

AQUIReS+ uses measuring station data obtained from the AirBase and e-Reporting systems, both maintained by the European Environment Agency (EEA). These systems hold air quality measurement data submitted by every EU Member State and some other European countries. At the time of modelling, the most up to date, complete, ratified datasets available from the EEA were for 2014, however not every country had submitted complete data for every year. No other measurement data was included in the modelling performed for this

[16] Emission profiles are explained in more detail in the *Urban Air Quality Study* (Aeris Europe, 2016).

study in an attempt to ensure that only ratified, official data was used and that each country is represented using equivalent data.

The Air Quality Directive includes guidelines on air quality measurement data required to be submitted for regulatory purposes, including population and areal coverage. Therefore the air quality stations submitted by a country are intended to be representative of the air quality in a given area; hence modelling based on the officially submitted set of stations is likely to be more representative of an area (country or city) as a whole than if additional stations are included. This representativeness is particularly important when comparing countries or cities. This situation can be illustrated using Germany as a representative example, for the 2010 measurement year, 439 stations measuring NO_2 were available from the EEA however data available from the Umwelt Bundesamt (Umwelt Bundesamt, 2017) shows measurements available from some 489 NO_2 stations.

Additionally, not all data recorded at a station is necessarily submitted, for example whilst NO_2 data is widely submitted, NO_X data is not submitted to anywhere near the same degree, despite the fact that the same NO_2 stations almost certainly measure NO. The reasons for this are unclear.

BASE CASE EMISSIONS

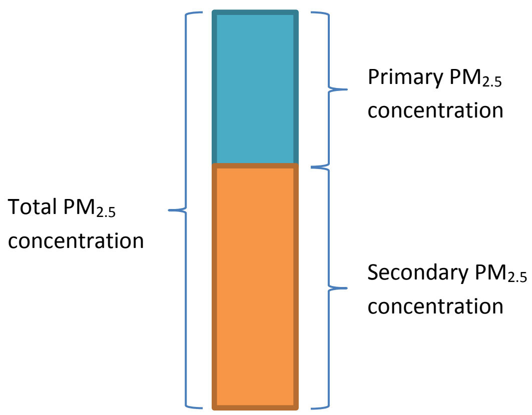
The emissions Base Case formulated for the original *Urban Air Quality Study* (Aeris Europe, 2016) was used as a starting point for all diesel passenger car scenarios, this is based on the January 2015 Thematic Strategy on Air Pollution Report #16 (TSAP16) Working Party for the Environment (WPE) Current Legislation Baseline Scenario (IIASA, 2015a), (IIASA, 2015b) associated with the EU Air Policy Review process (European Commission, 2011) as generated by IIASA's GAINS model. The emissions inventory and projections[17] considered in the Base Case are the most up to date European estimates available at the time of writing but do not take into account the effects of legislation for which the actual impact on future activity levels could not be quantified[18]. As a result, the Base Case should be considered as under-estimating anticipated emissions reductions. The baseline road transport emissions have been disaggregated using the fleet projections included in the TREMOVE[19] v3.3.2 'alternative' scenario (European Commission, 2015) (Fiorello, et al., 2009), and the emission factors of COPERT[20] v4.11. The effective Euro 6 diesel passenger car NO_X conformity factor in the Base Case is 2.8, this corresponds well with the measured Euro 6b (post 2015) mean emissions from the Ricardo study.

EMISSIONS SCENARIOS

Each emission scenario has been generated using conformity factors derived from the real driving emissions data described in **Table 1** and detailed by scenario in **Table 3** through to **Table 8**. The scenarios were produced in the form of emission attenuation profiles[21] that describe the overall shape of a country's emissions over time. In the case of nitrogen dioxide the relevant emissions are the oxides of nitrogen (NO_X), comprised of NO and NO_2. In the case of particulate matter the emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3) and non-methane volatile organic compounds (NMVOC) in addition to direct particulate emissions are used. These other emissions are required because a significant, but varying portion of the total particulate matter (PM) concentration derives from these secondary sources.

The relationship between emissions of PM, SO_2, NO_X, NH_3 and NMVOCs and the concentration of particulate matter is particularly complex. PM is made up of a primary and a secondary component illustrated in **Figure 6**; primary PM is emitted as particulates at source, any subsequent transformation is a result of physical processes e.g. agglomeration. Secondary PM is formed from pre-cursor emissions undergoing chemical and physical transformations in the atmosphere. This means that much of the PM measured at an air quality measuring station may have been emitted as a different chemical elsewhere; this includes transboundary sources so the emissions from all countries have to be taken into account.

Figure 2 **$PM_{2.5}$ source apportionment showing primary and secondary split**



[17] IIASA TSAP Report 16, WPE 2014 CLE for 2030 using the PRIMES 2013 Reference Activity Projection and COPERT v4.11 emission factors.
[18] For example, the Medium Combustion Plants Directive (MCPD) and the review of the National Emissions Ceilings Directive (NECD).
[19] TREMOVE v3.3.2 is a mature transport policy assessment model developed for the iTren 2030 project which covers all inland urban and inter-urban transport modes.
[20] The COPERT 4 methodology is part of the EMEP/EEA Air Pollutant Emission Inventory Guidebook for the calculation of air pollutant emissions. The emission factors generated are vehicle and country specific.
[21] Emission attenuation profiles are explained in more detail in the *Urban Air Quality Study* (Aeris Europe, 2016).

The formation of secondary PM and supporting methodology are detailed more thoroughly in the original *Urban Air Quality Study*. For a background and history of the source-receptor concept used to determine the impact of transboundary emissions please read *EMEP Status Report 1/2004* (METNO, 2004). Secondary PM is mostly sized less than 2.5 microns in diameter and can make up a significant portion of PM_{10} concentrations (typically 60%). Concentrations in air of PM_{10} are also affected by resuspension of particles as a result of physical action, e.g. wind and road transport activity in streets.

NITROGEN OXIDES EMISSIONS

Figure 3 shows the Base Case emissions of nitrogen oxides in Germany from all diesel passenger cars split by Euro standard. These emissions are the same as those used as the Base Case in the original *Urban Air Quality Study*. Every country in the study possesses a unique vehicle fleet composition and subsequent emissions profile; however the evolution of emissions over time is quite similar. Germany has been chosen as a representative example to illustrate these trends.

Figure 3 Diesel passenger car NO_X emissions in Germany - Base Case

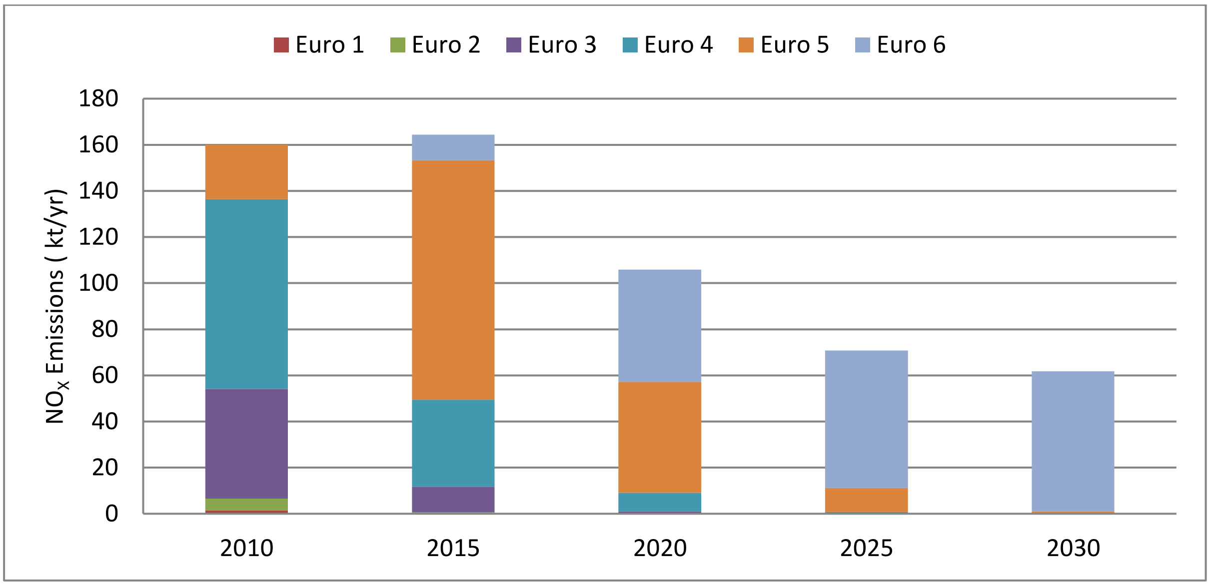


Figure 4 shows diesel passenger car emissions in Germany with the Euro 6 diesel passenger car emissions modified to reflect the Ricardo Median scenario detailed in **Table 3**. The effect is a reduction in Euro 6 diesel passenger car emissions from 2015 onwards with a nearly two-thirds reduction by 2030 as a result of

Figure 4 NO_X emissions from diesel passenger cars in Germany from the Ricardo Median Scenario

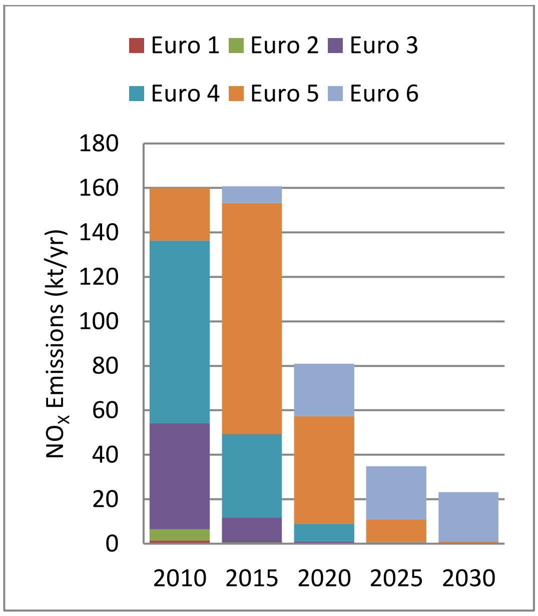
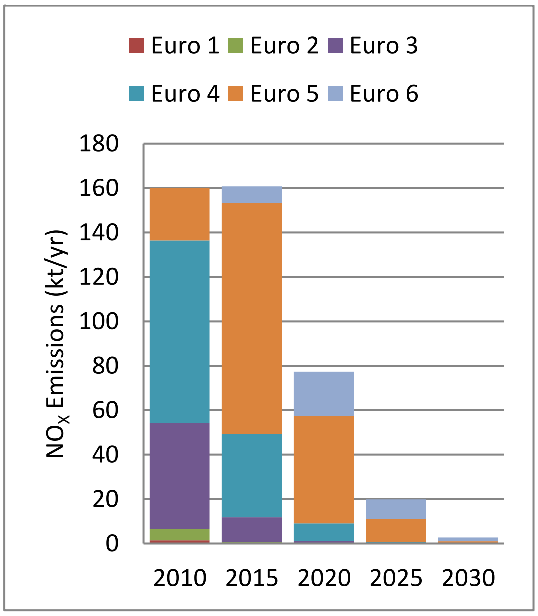


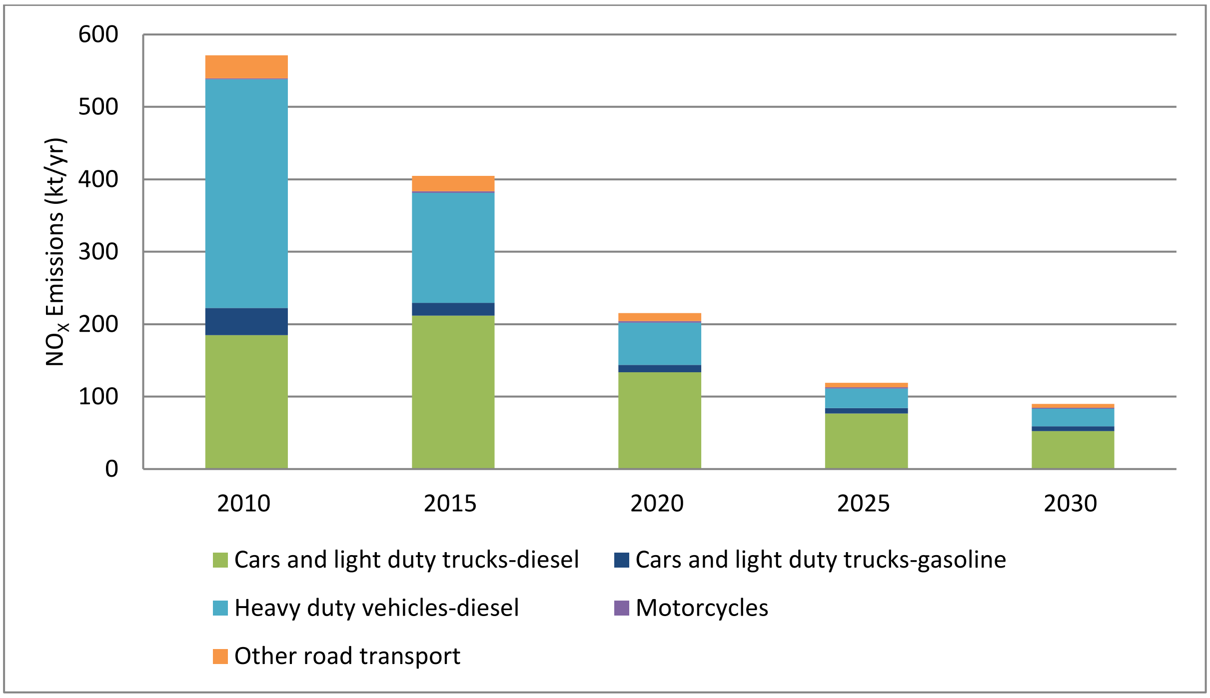
Figure 5 NO_X emissions from diesel passenger cars in Germany under the ZEV Scenario



improved emissions from diesel car technologies. **Figure 5** shows the diesel passenger car emissions in Germany modified to reflect the ZEV scenario in **Table 7**. This is the equivalent of replacing all new diesel car registrations with zero emission equivalents, e.g. battery or fuel cell electric vehicles. The residual Euro 6 emissions observed post 2020 are a result of pre 2020 diesel passenger cars still present in the fleet.

Although the emission reductions in the above figures appear significant, it must be remembered that road transport is not the only source of nitrogen dioxide emissions and diesel passenger cars are just one, albeit an important component of the overall vehicle fleet. **Figure 6** shows the total road transport emissions split by vehicle category; this shows that from 2015 onwards diesel cars and light-duty trucks make up the largest single emissions category. The total NO_X emissions in **Figure 6** are represented by the *Road Transport* component in **Figure 7** which shows the total emissions of nitrogen oxides in Germany split by key sector.

Figure 6 Total vehicle fleet NO_X emissions in Germany split by vehicle category – Base Case



From the emissions totals in **Figure 7**, it can be seen that while emissions from road transport reduce significantly over time, the emissions from other sectors remain much more constant. This means that the contribution of non-transport sectors to urban concentrations of NO_X and consequently NO_2 becomes proportionally more important; of particular note is residential combustion (e.g. central heating) which, from 2025, contributes well over half the equivalent mass of NO_X emissions as road transport.

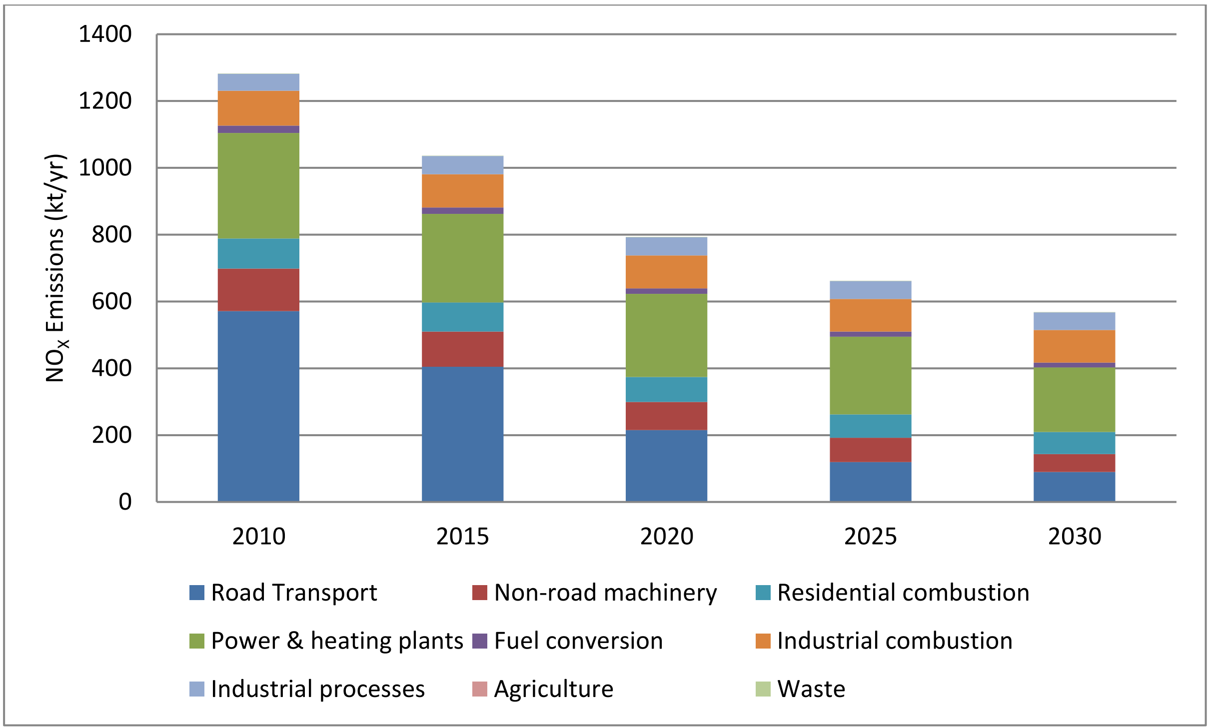
Non-urban emission sources are represented in most of the other sectors and generally have less effect on urban NO_X concentrations given that they tend to be located away from urban centres, however they may still contribute to urban background concentrations. The AQUIReS+ model factors the effect of non-urban sources as well as the varying proportion of NO_2 and NO in NO_X from different sources. This helps to more accurately model the effect of newer road transport technologies as well as account for the proximity of each emissions source.

Much of the change in road transport emissions is a result of a significant reduction in heavy duty vehicle (HDV) emissions, which in turn are a result of Euro VI emissions regulations delivering successful on the road NO_X emissions reductions. In part this is due to the SCR technology used, but it is also due to the framing of the legislation. The ICCT published a comprehensive briefing (ICCT, 2016) on the differences between HDV and light duty vehicle (LDV) real world NO_X emissions and they concluded:

"The best available data shows that the introduction of Euro VI standards significantly reduced real-world NO_X emissions from heavy-duty vehicles. Significant changes between Euro IV/V and Euro VI that likely contributed to that improvement include:

1. *Addition of an off-cycle test during type approval.*
2. *Improved type-approval test cycle that includes cold start and lower load conditions as well as transient and high-load conditions.*
3. *PEMS test for in-service conformity testing, with limited restrictions on the boundary conditions used during the test and subsequent data processing."*

Figure 7 NO_X Emissions in Germany by key sector (IIASA GAINS TSAP16 CLE WPE Scenario) – Base Case



PARTICULATE MATTER EMISSIONS

Figure 8 shows the $PM_{2.5}$ emissions of diesel passenger cars by Euro standard over time in Germany, again Germany has been chosen as a representative example. This is the Base Case as used in the original *Urban Air Quality Study*. From 2020 onwards the non-exhaust component becomes dominant; this is primarily composed of particles from brake wear, tyre wear and road abrasion. As the non-exhaust component is produced independently of the vehicle powertrain a switch to zero emissions vehicles will not affect this aspect and may actually increase this number as a function of increased vehicle mass (Timmers & Achten, 2016). No attempt has been made to modify emissions in the ZEV scenario to take into account vehicle mass.

Figure 8 Primary $PM_{2.5}$ emissions from diesel passenger cars in Germany - Base Case

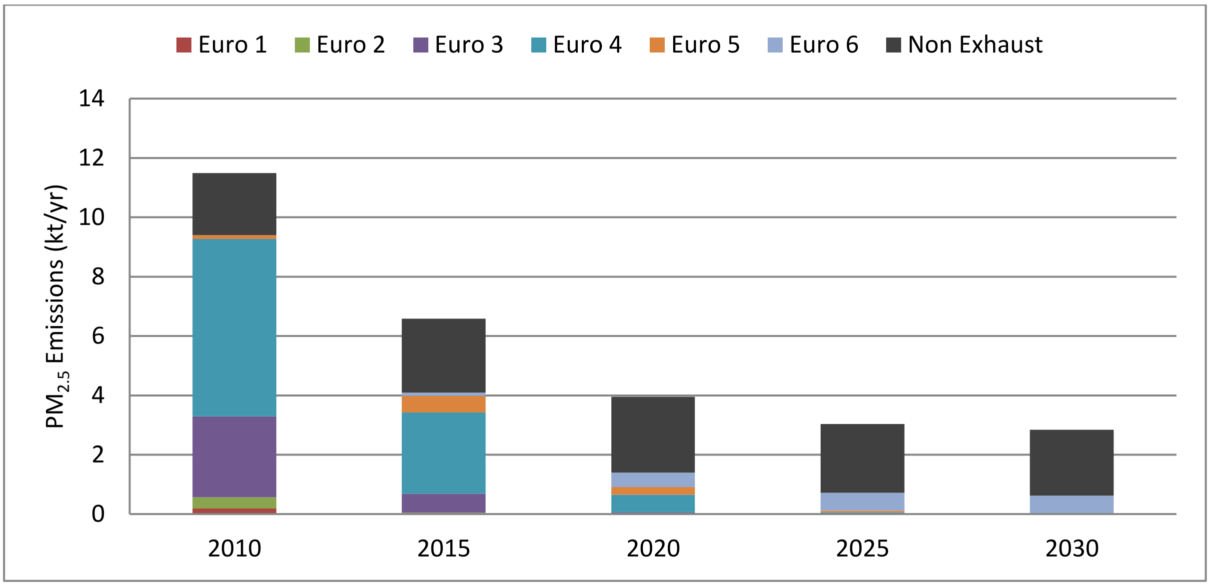
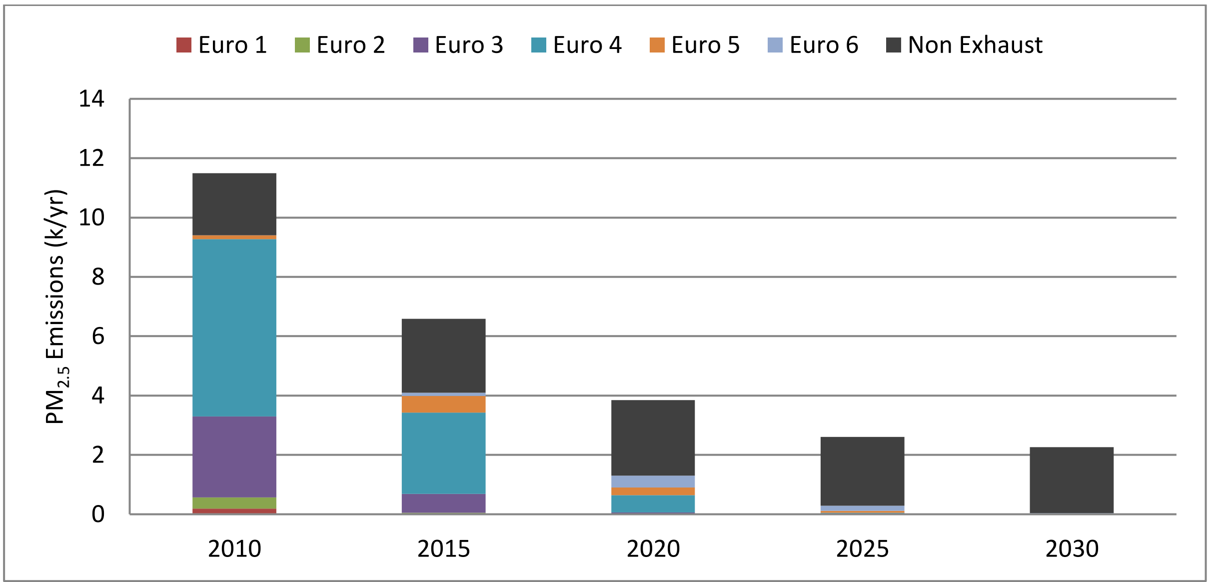


Figure 9 shows the $PM_{2.5}$ emissions in Germany for the portion of the vehicle fleet made up of diesel passenger cars modified to reflect new diesel passenger car registrations from 2020 being replaced with zero emission equivalents (the ZEV scenario). It is assumed that vehicle activity remains the same, i.e. the same distance is driven in each city and driving habits don't change. By 2020 non-exhaust emissions dominate.

Figure 9 Primary $PM_{2.5}$ emissions from diesel passenger cars in Germany, replacing all new registrations of PCD with ZEVs from 2020



Road transport is not the only source of particulate emissions and diesel passenger cars are just one component of the overall vehicle fleet. **Figure 10** shows the total road transport emissions split by vehicle category; this shows that from 2015 onwards the non-exhaust fraction dominates the overall emissions of particulates. The total $PM_{2.5}$ emissions in **Figure 10** are represented by the *Road Transport* component in **Figure 11** which shows the total emissions of $PM_{2.5}$ in Germany split by key sector. From this it can be seen that the contribution from residential combustion is already an important source of particulates, roughly equal to that of all traffic in 2010 and becomes the dominant source from 2015.

Figure 10 Total vehicle fleet Primary $PM_{2.5}$ emissions in Germany split by vehicle category – Base Case

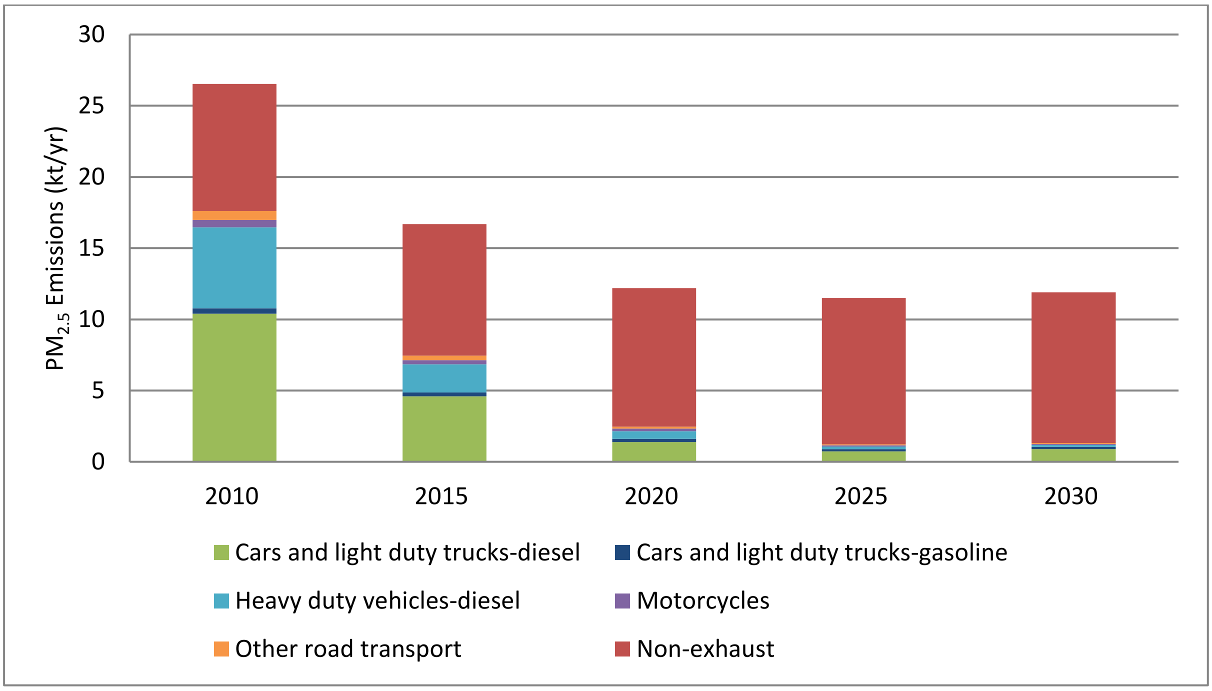
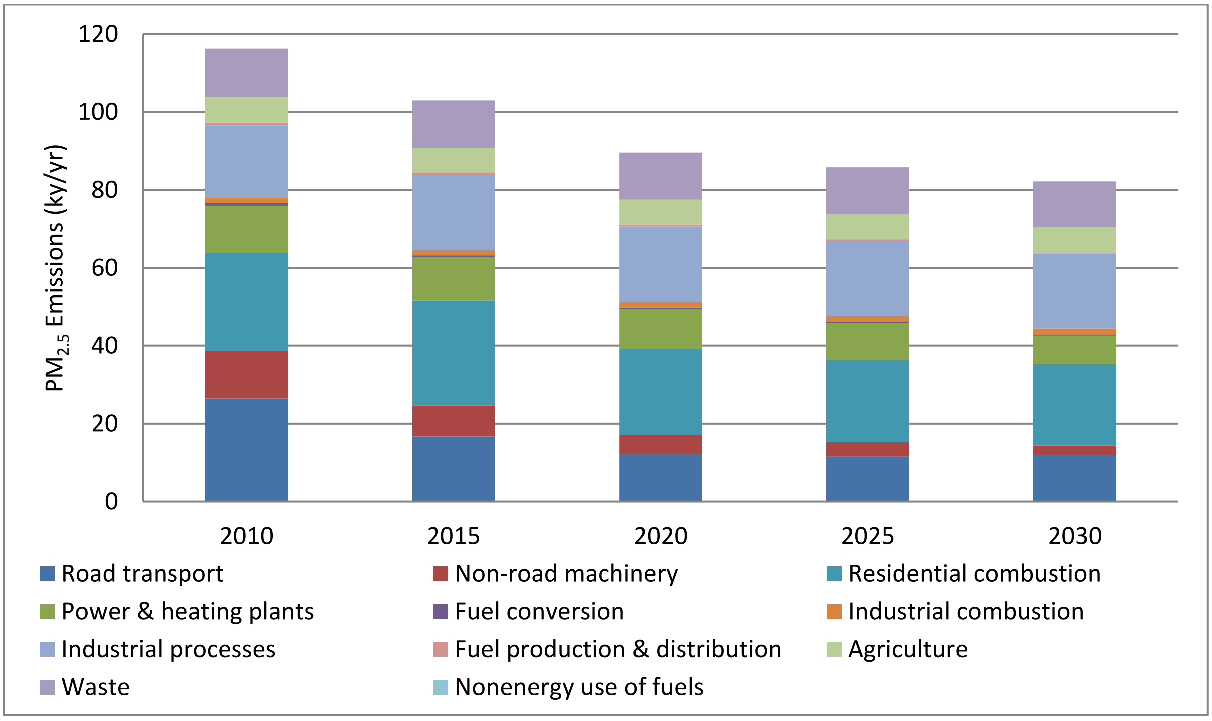


Figure 11 Primary $PM_{2.5}$ emissions in Germany by key sector (IIASA GAINS TSAP16 CLE WPE Scenario) – Base Case



MODELLING POPULATION EXPOSURE

AQUIReS+ includes the population exposure methodology described in the paper "Exceedance of air quality limit values in urban areas" (EEA, 2014 (a)). This methodology is a procedure for assigning a portion of the urban population to roadside monitoring stations and the remainder to background monitoring stations within a single contiguous urban area. By determining the compliance state of each station it is then possible to estimate the portion (if any) of the population exposed to air quality levels exceeding legislated limits.

The proportion assigned to traffic stations is, on average, the 5% of the urban population that lives within 100 metres of a major road (ENTEC, 2006). This percentage varies from country to country and complete details are available in the EEA report and **Appendix A: Urban Population Living Close to Major Roads**.

The Urban Audit (UA) data collection (Eurostat, 2014) was used to determine the geographical boundaries of cities and the population within each city (Eurostat, 2016) for each year. Using this data and air quality measuring station data available from the European Environment Agency's AQ E-Reporting System (EEA, 2017) and the legacy AirBase system (EEA, 2014 (b)) it is possible to geographically allocate measuring stations to cities across Europe. Only those stations classified as 'urban traffic', 'suburban traffic', 'urban background' or 'suburban background' are used for population exposure as neither 'industrial' or 'rural' stations are deemed representative of urban residential areas.

To help ensure robustness of the modelling, all of the eligibility criteria for monitoring stations detailed in the 2016 Urban Air Quality Study are maintained, this includes a minimum of 75% valid measurements per year at each station as well as at least three years of measurements.

The population represented by each monitoring station is then calculated using these equations from the "Exceedance of air quality limit values in urban areas" paper, for each year of modelling and pollutant:

Traffic population per station = $((P_{tj} / 100) \times Pop_i / n_{it})$

Background population per station = $((P_{bj} / 100) \times Pop_i / n_{ib})$

Where: i = city
j = country
n_{it} = Total number of traffic stations
n_{ib} = Total number of background stations
P_{tj} = Traffic population %
P_{bj} = Background population %
Pop_i = Total city population

Note: $P_{tj} + P_{bj} = 100\%$

CONCENTRATION AND DISTANCE FROM ROAD

The EEA population exposure model described above (and used in this study) assumes a constant concentration of each pollutant up to 100 metres from the road when determining the portion of the urban population exposed to traffic influences. This is not necessarily the case and a discussion related to this limitation and suggestions for improving this methodology can be found in **Appendix B: Concentration and Distance from Road.**

RESULTS

NITROGEN DIOXIDE

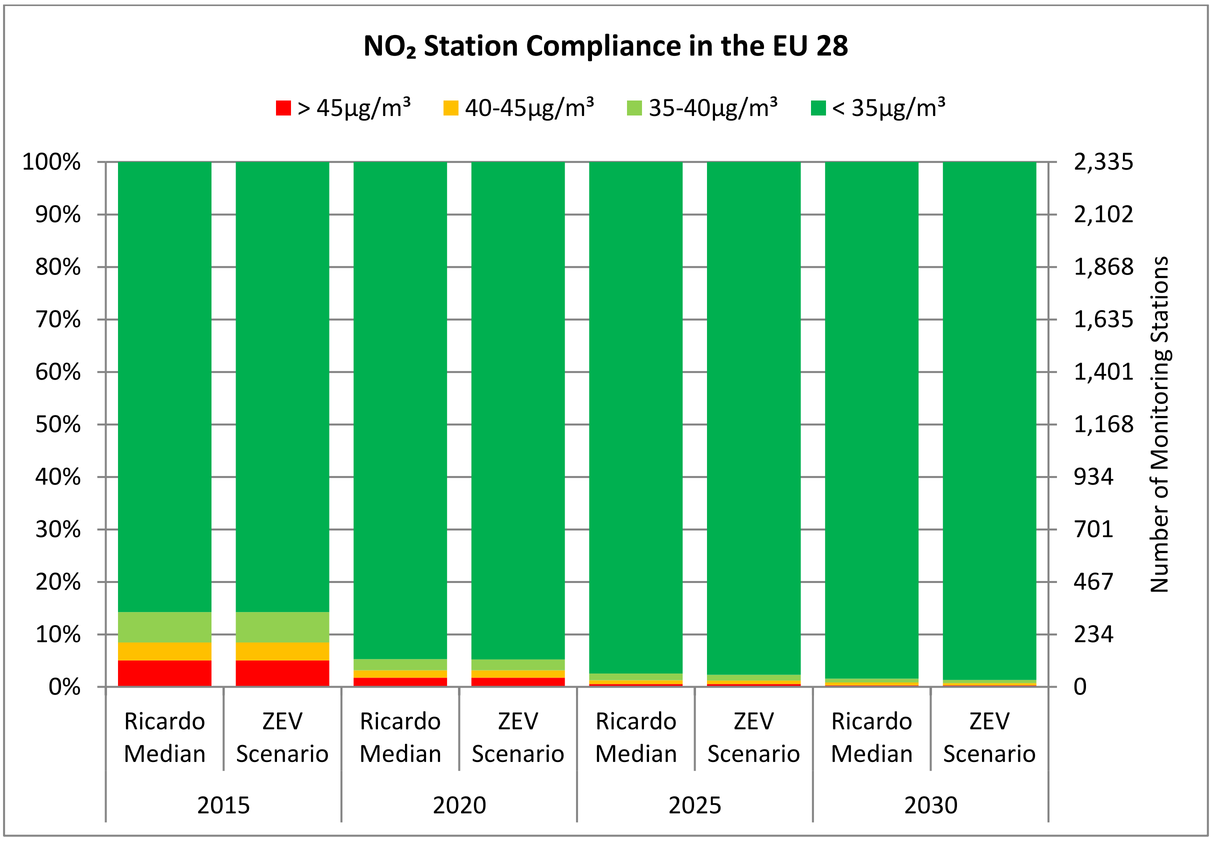
This section highlights the important considerations, findings and trends revealed by this study. For an explanation of the methodology linking NO_X emissions to NO_2 concentrations please see the main Urban Air Quality Study (Aeris Europe, 2016). For the sake of clarity and to avoid repetition, in addition to the Base Case, only the Ricardo Median scenario and the ZEV scenario are discussed. These have been chosen as they illustrate the effect that the largest reduction in emissions would have against an average emissions scenario however the general conclusions are consistent for the other diesel scenarios which were investigated. Additional results of this and other scenarios are available in the appendices.

COMPLIANCE AT EU LEVEL

By aggregating each Member State's air quality monitoring stations, an overall picture of compliance across the EU 28 can be produced. **Figure 12** illustrates this EU 28 compliance picture and shows that by 2020 roughly 2% of stations are predicted to be non-compliant with a further 1.5% predicted to be possibly non-compliant. This is observed in both the Ricardo Median and the ZEV scenario which both exhibit a similar evolution of compliance over time. The difference in the overall number of stations achieving compliance between the two scenarios is just above 0% in 2020, less than 0.1% in 2025 and 0.2% in 2030.

This strongly suggests that NO_2 non-compliance across the EU 28 is unrelated to Euro 6d diesel passenger cars given that their substitution with zero emission equivalents has a negligible effect on overall compliance.

Figure 12 **NO_2 station compliance across the EU 28 for the Ricardo Median and ZEV scenarios**

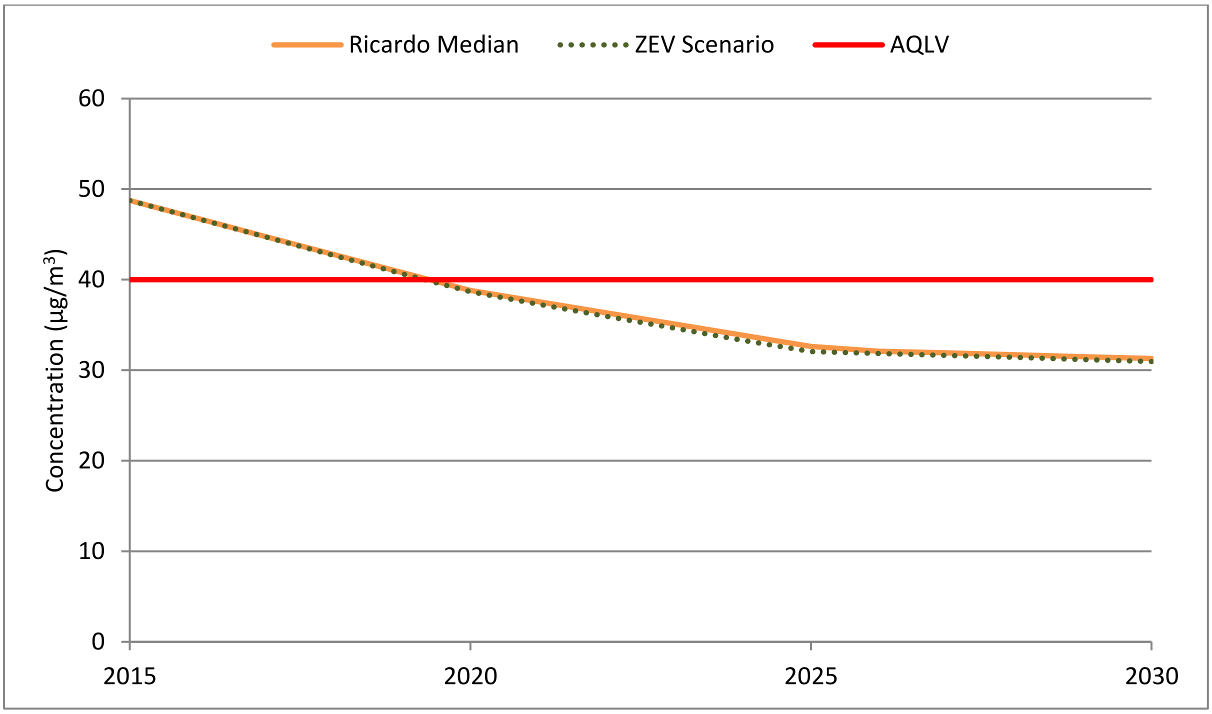


COMPLIANCE AT COUNTRY LEVEL

Compliance at country level has been analysed in two ways; the first is by taking the single highest station in a given country and noting the compliance situation of that station. This suffers from the same potential problem as the AQMZ described earlier where over-estimation of population exposure can occur. The second is to determine how many non-compliant stations there are in a country both in absolute terms and as a percentage of total stations in that country.

For example, in the case of Belgium[22] the chart in **Figure 13** shows the highest modelled station concentrations in each year.

Figure 13 Highest modelled NO_2 station in Belgium, by year



This shows that even the highest predicted concentration in Belgium is below the limit value by 2020, with no difference between the ZEV scenario and Ricardo Median scenario in compliance terms. **Figure 14** presents the same chart for Germany, this shows that the highest station in Germany never reaches compliance. In this case knowing the number of non-compliant stations can be informative. This is shown in **Figure 15** and indicates that the residual compliance problem is limited to 5 representative[23] stations in 2025 (~1% of the total number of NO_2 stations in Germany) and that these stations remain non-compliant even in the ZEV scenario.

[22] Both Belgium and Germany have been chosen as illustrative examples only.
[23] Please see the Methodology section for a brief discussion on stations and the representativeness.

Figure 14 Highest modelled NO_2 station in Germany, by year

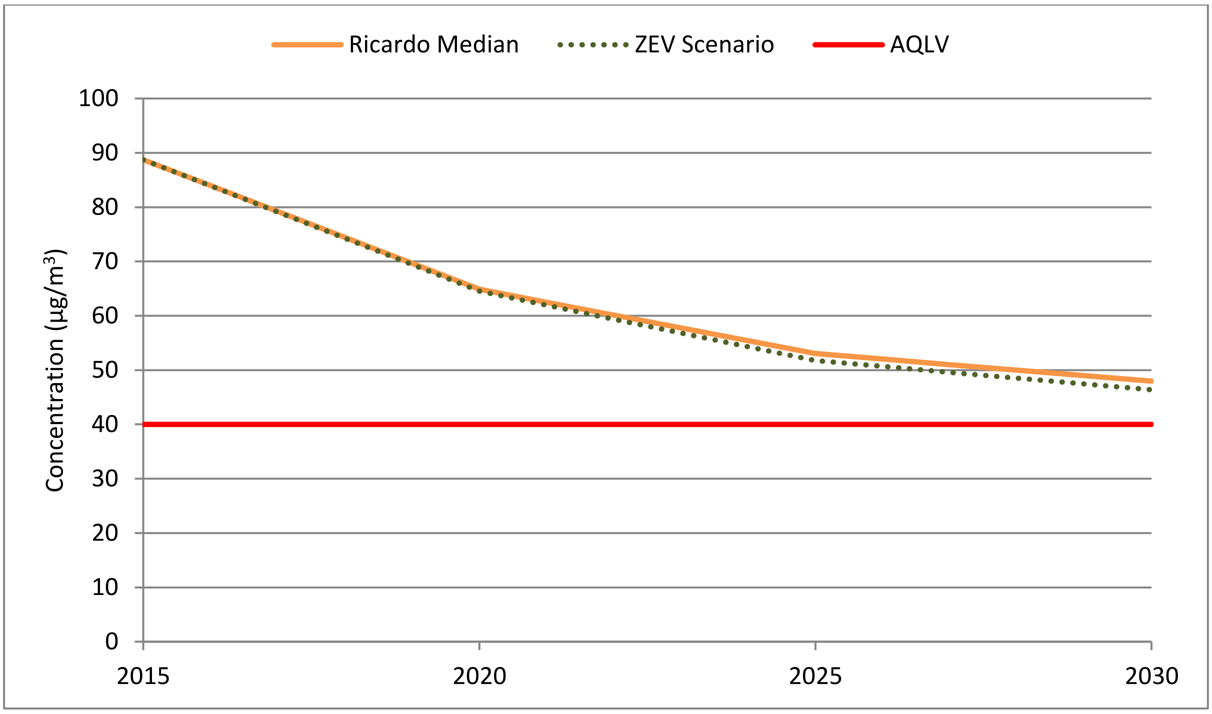
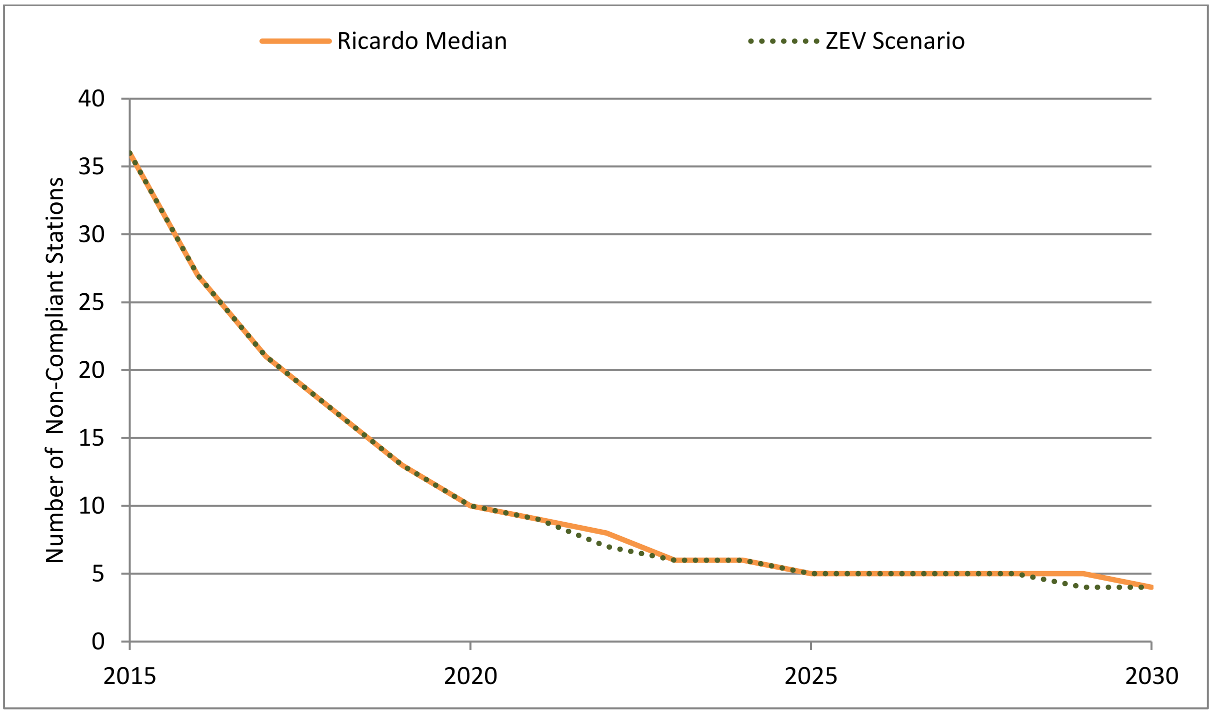
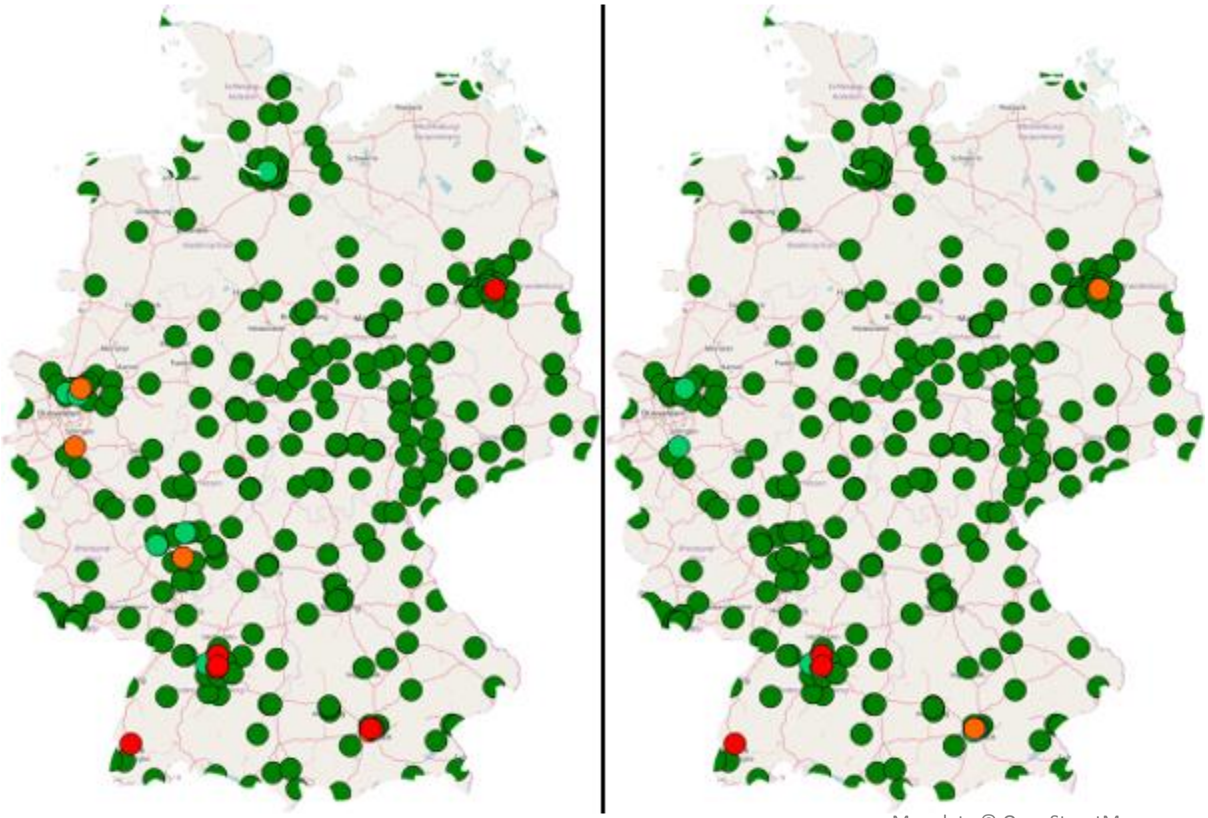


Figure 15 Number of non-compliant NO_2 stations in Germany by year – total modelled stations: 330



With the knowledge that there are only 5 out of over 300 representative stations in Germany that fail to achieve compliance in 2025 an idea of the geographical distribution of the stations is useful, this is illustrated in **Figure 16** where the compliance hot-spots are highlighted in red. This shows that by 2025, non-compliance is largely limited to traffic stations in Stuttgart and Freiburg. This suggests that a localised targeting of the issues in those areas might be needed to resolve the residual non-compliance.

Figure 16 Germany NO_2 AQ station compliance in 2020 (left) and 2025 (right) – Ricardo Median Scenario



Map data © OpenStreetMap

COMPLIANCE AT CITY LEVEL & POPULATION EXPOSURE

Larger cities and urban agglomerations contain a number of air quality monitoring stations that measure a range of pollutants. The location of each station is intended to be representative of human exposure to the pollutants they measure. For example, a traffic station in an urban environment will record hourly readings of nitrogen dioxide as short term exposure is expected at a traffic location. Similarly an urban background station will record the ambient background concentration as that is relevant for the exposure of the general urban population (2008/50/EC).

In other words, people tend to spend a short amount of time at the roadside exposed to traffic concentrations compared to the amount of time spent away from the roadside in homes and workplaces. Hence an hourly metric is used for roadside exposure and an annual mean for ambient long term exposure. In keeping with other literature and the previous study, the annual mean will be used for all NO_2 stations in this study for assessing compliance and population exposure.

The air quality management zone[24] (AQMZ) approach as adopted in the Urban Air Quality Study (Aeris Europe, 2016) and in other papers, for example "Modelling $PM_{2.5}$ impact indicators in Europe: Health effects and legal compliance" (Kiesewetter, et al., 2015) means that an entire AQMZ is deemed non-compliant if a single station is non-compliant. An analysis of monitoring stations within a city often reveals that the station recording the maximum concentration in a given year sometimes records a significantly higher value than the second highest and subsequent stations. This makes the AQMZ approach even more likely to exaggerate population exposure. This is illustrated in **Figure 17** which shows the highest and second highest recorded concentrations in Madrid from 2000 until 2014, in some years the difference between the two maximum stations approaches 20µg/m^3.

The potential exaggeration of population exposure from the AQMZ approach is illustrated in **Figure 18** for the city of Munich. Here a single modelled non-compliant traffic station in 2025 results in the entire population of Munich being classed as exposed to non-compliant ambient air quality, despite all the other stations, both traffic and background, forecast to record compliant air quality. To avoid this over estimation of population exposure a more refined approach has been adopted in this study, the results of which, applied to Munich, are shown in **Figure 19**. This method of population exposure is based on an EEA methodology and is discussed in more detail in the Methodology section.

[24] Air quality management zones are designated under the ambient air quality directive (2008/50/EC) and oblige Member States to divide their entire territory into zones. Zones can be regarded as the primary territorial units for assessment and management of air quality under the air quality directives. There are approximately 680 zones across the EU member states (2008/50/EC).

Figure 17 The two highest NO_2 concentrations in Madrid – measured concentration by year

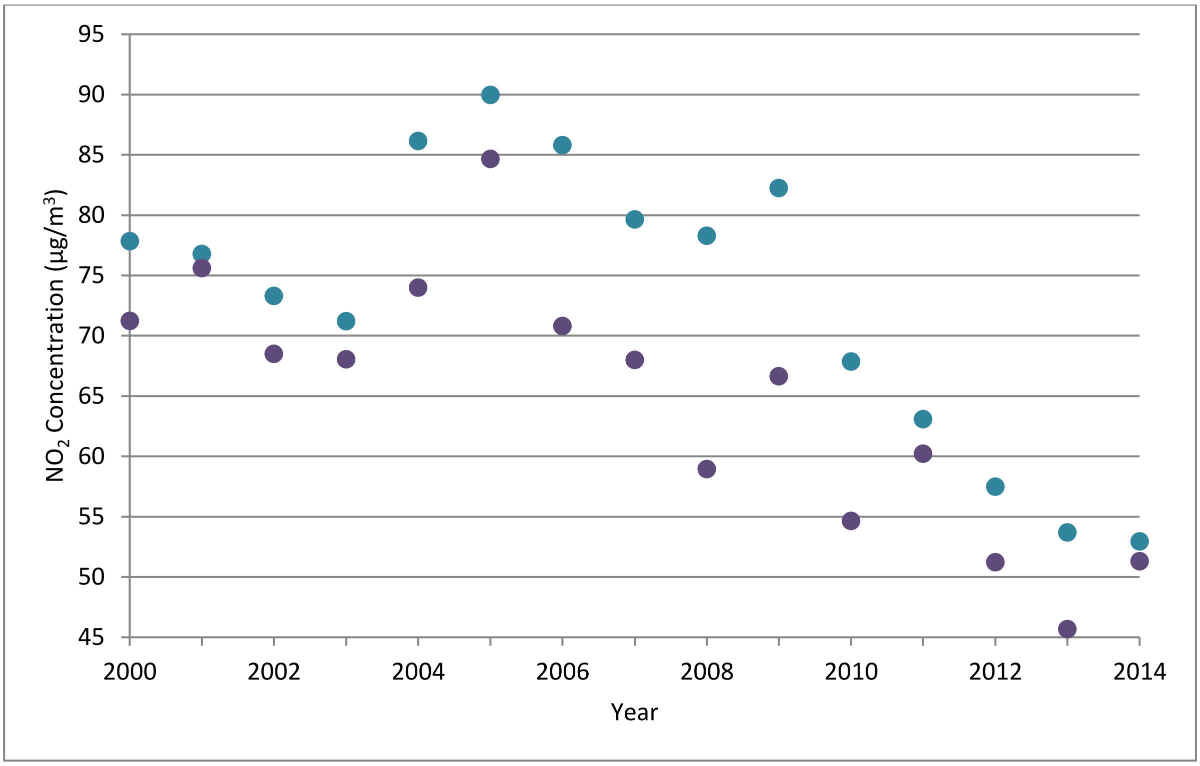
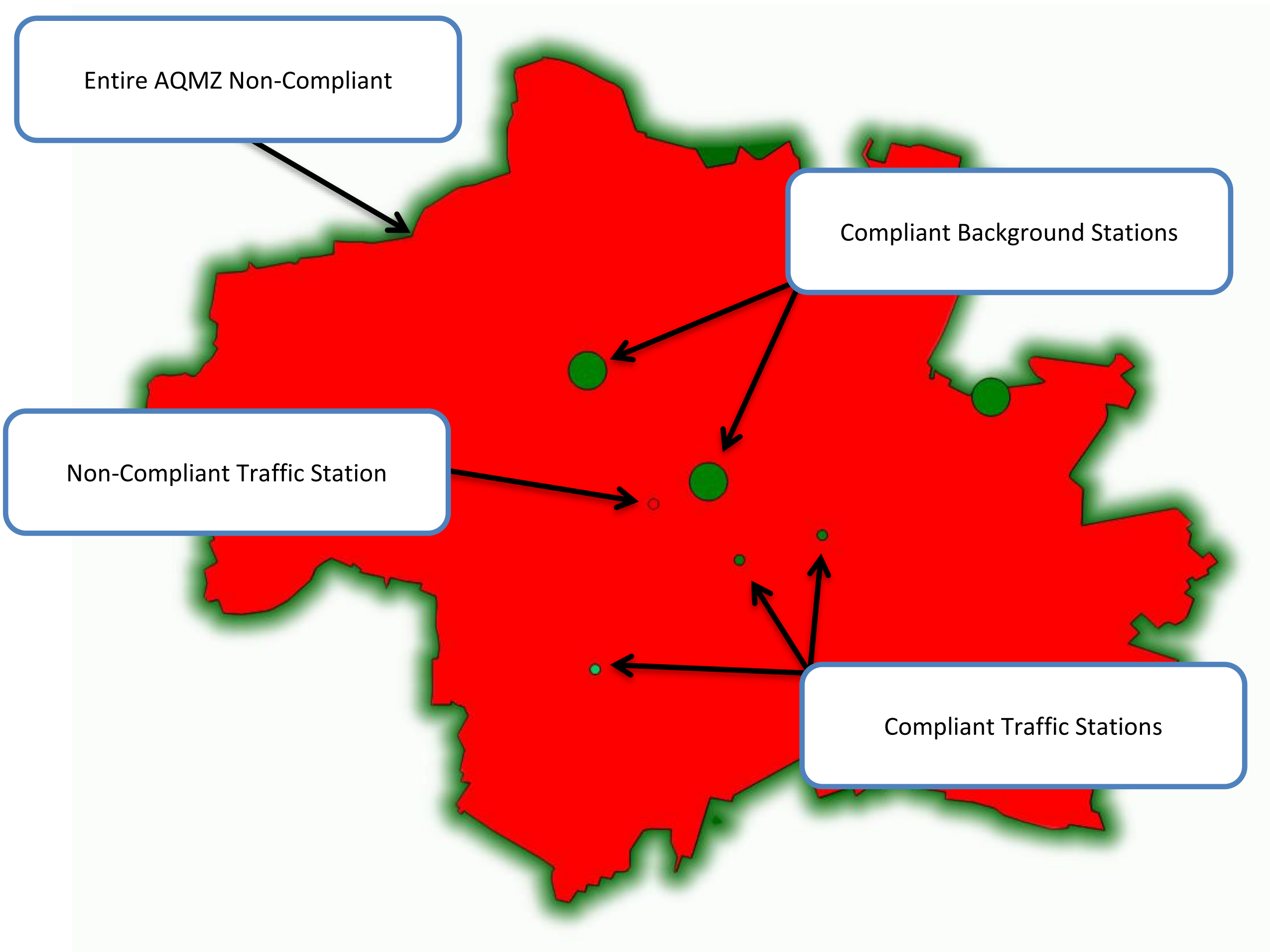
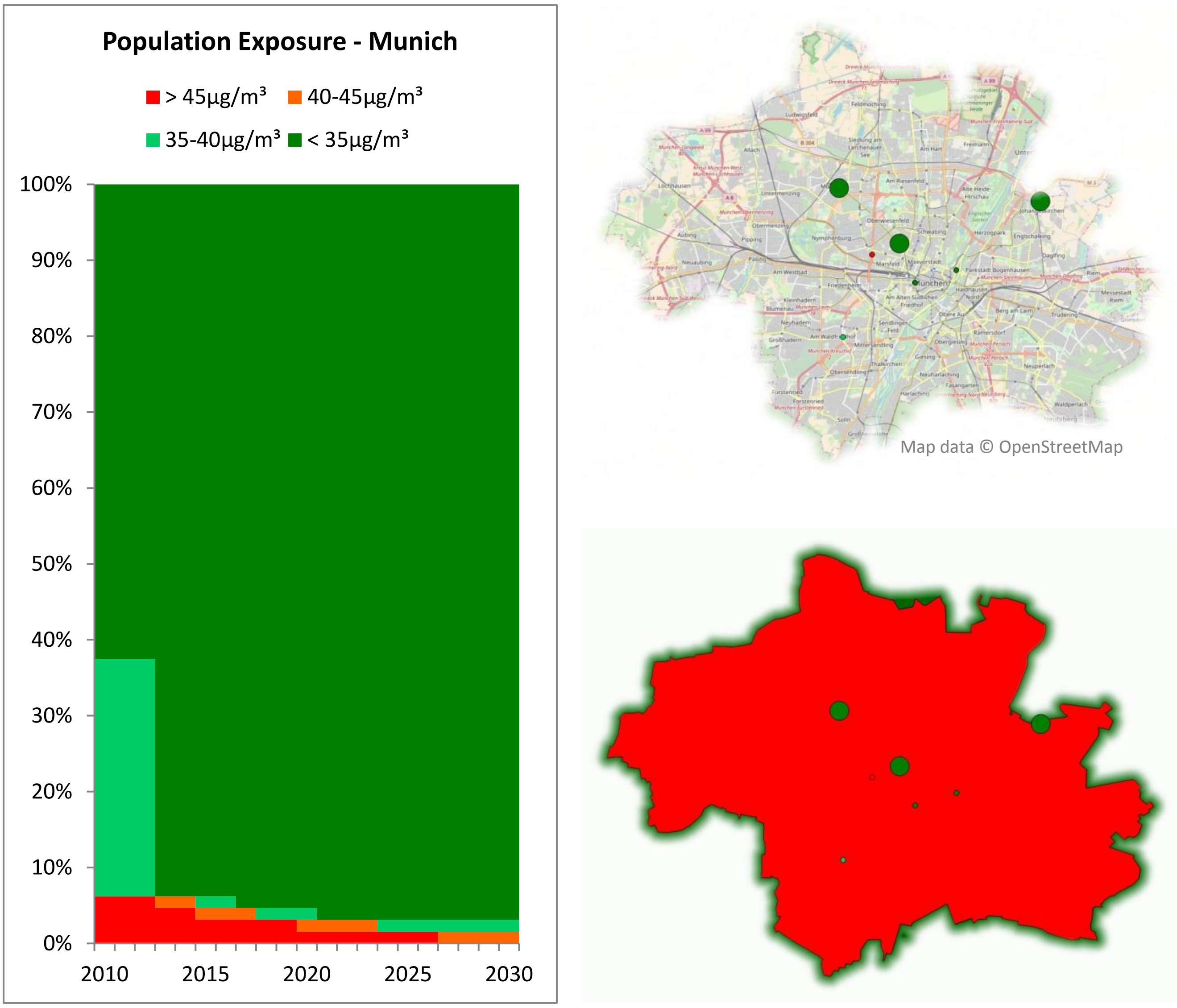


Figure 18 Munich – predicted NO_2 compliance in 2025 – UAQ Base Case, AQ stations superimposed on the Munich AQMZ



All of the representations in **Figure 19** use the same compliance scale which introduces an uncertainty either side of the limit value to indicate that within a few micrograms of the limit value it is possible that a station could be predicted as non-compliant when actually compliant or vice-versa. To illustrate the significant difference in moving from the AQMZ approach to the EEA approach described above, the modelled population of Munich exposed to non-compliant air in 2025 changes from 100% to less than 2%. As shown in the chart, this is a more reasonable figure considering that the non-compliant station is representing a roadside concentration and all the other stations in the city are modelling compliance. The stations are shown in the top-right with a street map background to aid legibility, the large circles represent background stations and the small circles traffic stations.

Figure 19 Population exposure to NO_2 in Munich, EEA Methodology vs AQMZ – 2025 – UAQ Base Case



EFFECT ON POPULATION EXPOSURE IN MUNICH: RICARDO MEDIAN -VS- ZEV SCENARIO

Figure 20 shows the exposure of the population of Munich[25] according to the Ricardo Median Scenario (**Table 3**) and the ZEV Emissions scenario (**Table 7**). No difference in compliance between the two is seen until 2022 and even then, the only difference is the shift of a single year forward in the ZEV scenario. Ultimately both scenarios result in the same level of population exposure in 2025 and 2030. Analysing the two stations responsible for this subtle shift shows that the concentrations modelled at each station for the two scenarios are very close; this is shown in **Figure 21**. The same level of exposure is observed even in the highest emissions scenario modelled, the "Ricardo 6D Maximum Scenario".

Figure 20 Population exposure to NO_2 in Munich – Ricardo Median Scenario and Zero Emission Vehicle Scenario

[25] Munich has been chosen as a city representative of other cities. These findings are therefore relevant to other cities and illustrate a general trend.

Figure 21 Munich – two highest NO_2 AQ stations illustrating the negligible difference in response between the Ricardo Median and ZEV scenarios

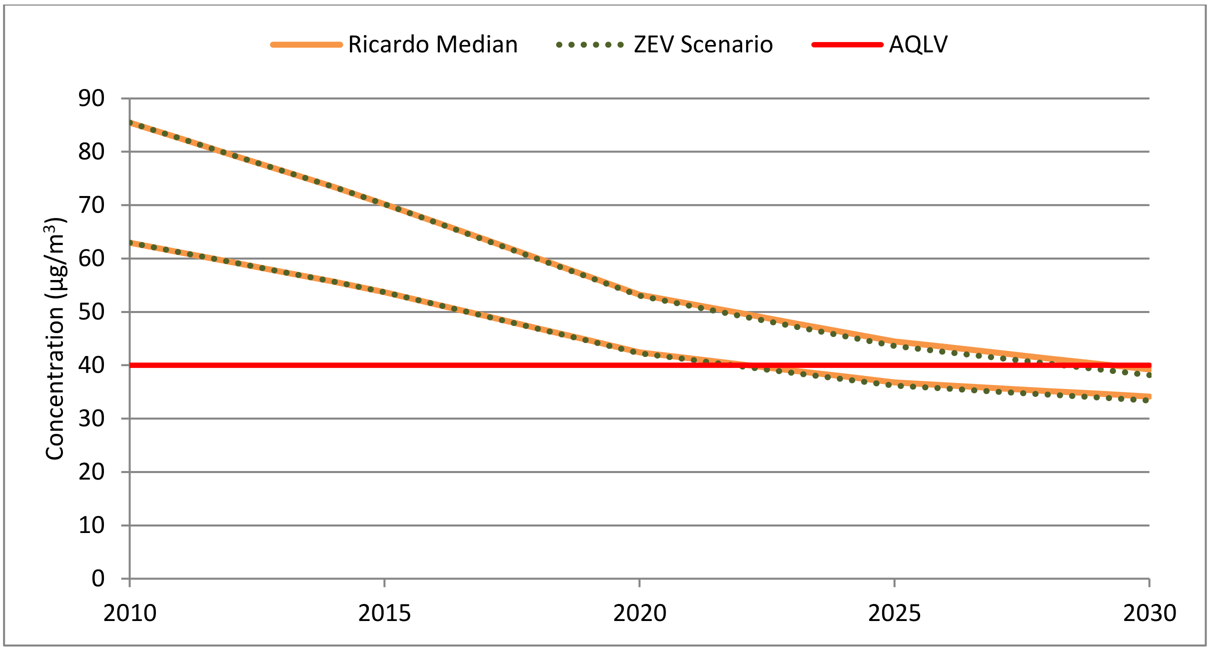


Figure 21 illustrates the marginal difference in urban NO_2 concentration that results from replacing all new registrations of diesel passenger cars with zero emission equivalents starting in 2020. The two stations are traffic stations, both located at high activity locations and both influenced primarily by traffic sources. Given their location, these are the type of stations that would be most affected by any measure that reduces traffic emissions.

PARTICULATE MATTER

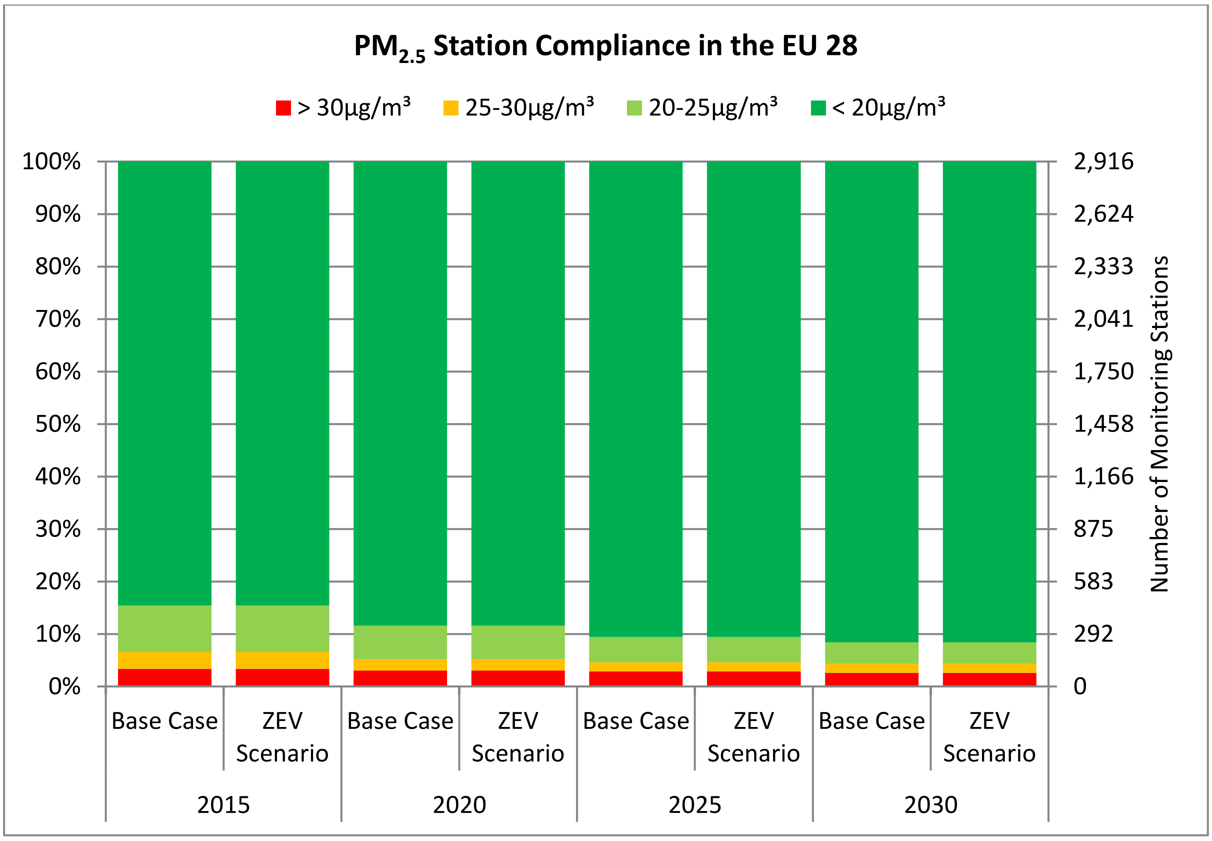
This section highlights the important considerations, findings and trends observed during this study for particulate matter. For an explanation of the modelling methodology please see the main *Urban Air Quality Study* (Aeris Europe, 2016). Further results are available in the appendices. Please see the Nitrogen Dioxide results section (Page 23) for limitations of the AQMZ population exposure approach and how an EEA methodology has been used to more realistically model population exposure.

Given the similar particulate emissions from Euro 6 diesel passenger cars and zero emissions vehicles (the reasons for this are discussed earlier in this report) it is not expected that there will be any change in air quality as a result of diesel passenger car replacement by zero emission vehicles. This is confirmed by the results which show no appreciable change in compliance for all particulate metrics.

PARTICULATE MATTER ($PM_{2.5}$)

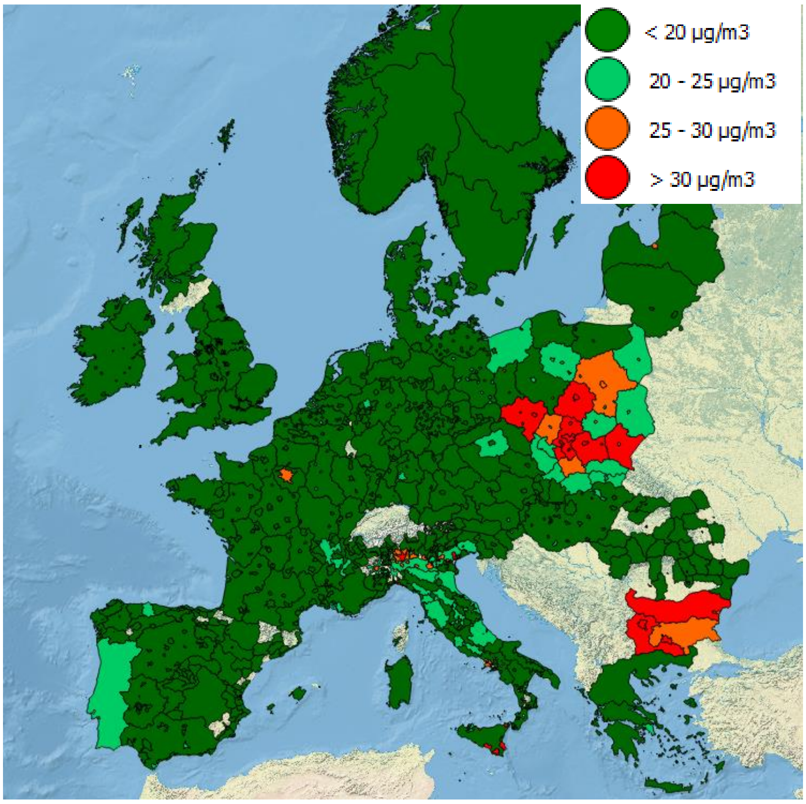
By aggregating each Member State's air quality monitoring stations, an overall picture of compliance across the EU 28 can be produced. **Figure 22** illustrates this EU 28 compliance picture and shows that by 2020 roughly 3% of stations are predicted to be non-compliant with a further 2% predicted to be possibly non-compliant. This is observed in both the Base Case and the ZEV scenario which both exhibit a similar evolution of compliance over time. There is no difference in compliance between the two scenarios. This strongly suggests that non-compliance across the EU 28 is unrelated to Euro 6d diesel passenger cars given that their substitution with zero emission equivalents has no effect on overall compliance.

Figure 22 $PM_{2.5}$ station compliance across the EU 28 for the Base Case and ZEV scenario



By 2020 there are predicted to be regions of non-compliance with the $PM_{2.5}$ 25µg/m³ annual mean limit value in Poland, Romania, the Po Valley region of Italy, southern Italy and Paris, this is illustrated in **Figure 23**.

Figure 23 $PM_{2.5}$ - European AQMZ compliance with the 25µg/m³ annual mean limit value in 2020 – UAQ Base Case



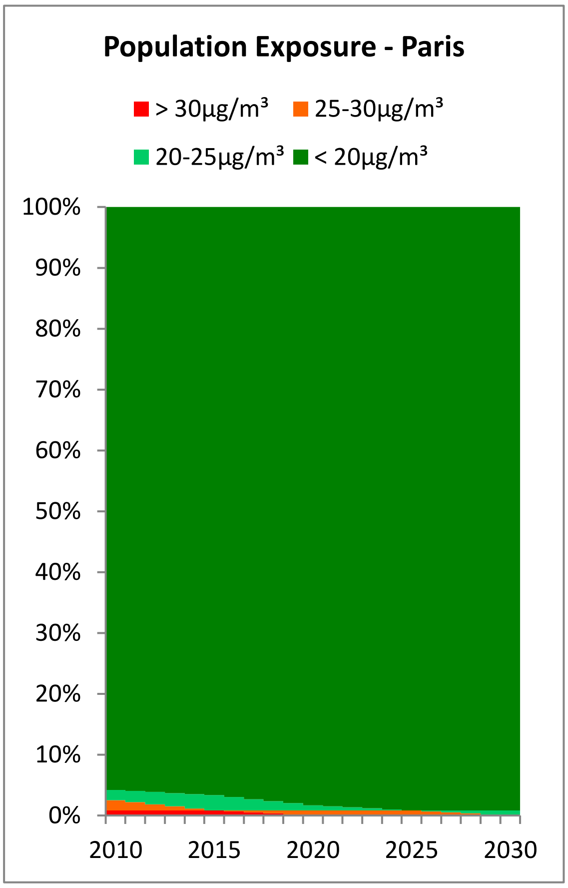
The previous study analysed the reasons for non-compliance in Eastern Europe and the domestic burning of wood and coal was determined to be the primary cause.

The Po Valley region is host to a number of high emitting industries and this is responsible for the non-compliance in that region (INEMAR - ARPA Lombardia, 2017).

Out of the ten cities studied in this report, two indicated non-compliance with the $PM_{2.5}$ limit value in 2020: Paris and Warsaw.

In Paris a single non-compliant station is modelled to exceed the annual air quality limit value by 2.5µg/m³ in 2020 and the portion of Parisian population exposed to this concentration is illustrated in **Figure 24**.

Figure 24 $PM_{2.5}$ population exposure in Paris UAQ Base Case

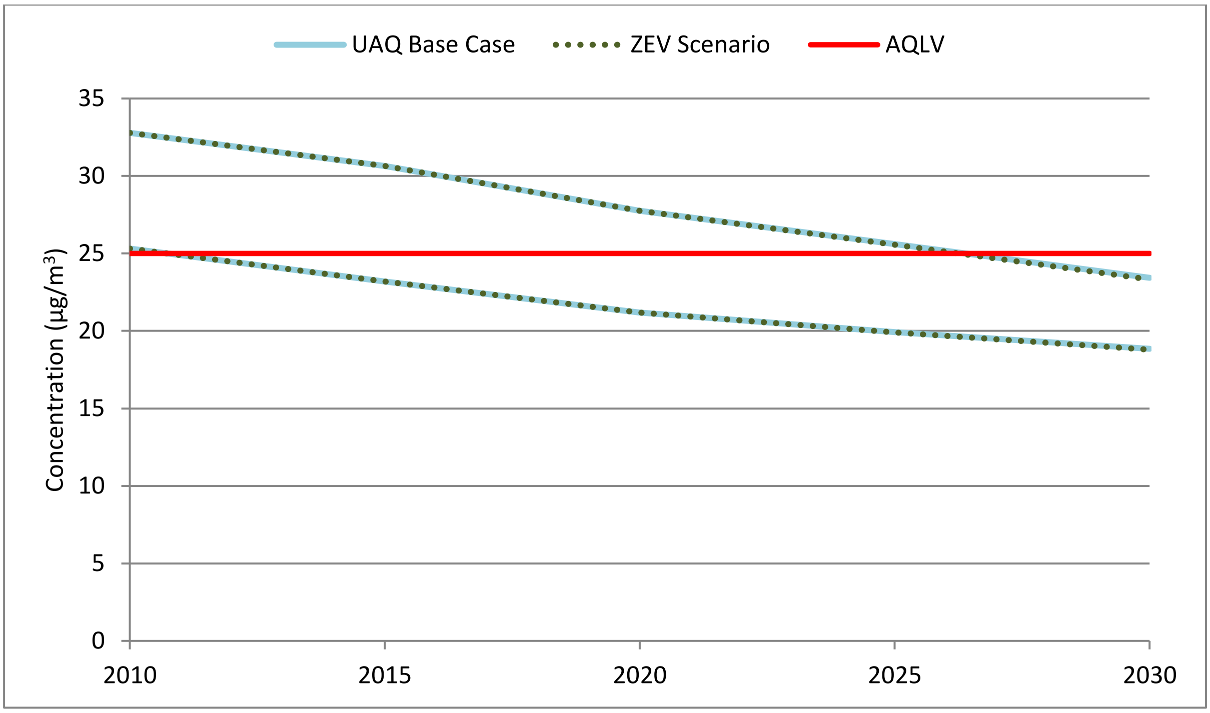


Warsaw experiences a high degree of primary $PM_{2.5}$ emissions from domestic combustion (IOS-PIB, 2016) and the single station modelled to be non-compliant in 2020 shows significant annual mean variability, this could indicate strong local sources are being observed at this station which exceeds the limit value by 3µg/m³ in 2020.

It should be noted that both the station in Paris and the station in Warsaw are non-compliant within the ±5µg/m³ uncertainty band of the model results. It is therefore not certain that either of these stations will actually be non-compliant.

Figure 25 shows the two highest traffic stations in Paris with concentrations modelled in the UAQ Base Case and the ZEV Scenario. The difference in concentration between the two scenarios is a fraction of a microgram and almost impossible to distinguish on the chart. This is in keeping with the very small overall reduction in emissions that replacing Euro 6d diesel passenger cars with zero emission vehicles is predicted to effect.

Figure 25 Paris – two highest $PM_{2.5}$ AQ stations illustrating the difference in response between Euro 6 diesel passenger cars and ZEVs



The conclusion for $PM_{2.5}$ with respect to the current annual air quality limit value of 25µg/m^3 is that there is little to no non-compliance in urban environments and the non-compliance that is observed is not a result of the exhaust emissions from diesel passenger cars.

PARTICULATE MATTER (PM_{10})

Particulate Matter less than 10 microns in diameter (PM_{10}) presents a compliance issue distinct from that of $PM_{2.5}$ in that the dominant metric for non-compliance is the daily exceedances of 50µg/m^3 rather than the 40µg/m^3 annual mean limit value. It is therefore necessary to use the daily exceedances of PM_{10} to model compliance or there is a risk of underestimating any potential issues. This is briefly discussed on page 7 and the original *Urban Air Quality Study* describes the AQUIReS+ methodology used to determine PM_{10} exceedances.

The principal areas of PM_{10} non-compliance with the daily exceedance limit are Eastern Europe, the Po valley and isolated industrial areas as shown in **Figure 26**. These areas are similar to the areas experiencing exceedances of the $PM_{2.5}$ annual mean value. Some cities are also modelled to be non-compliant with the PM_{10} daily exceedance limit but the same caveats as described for $PM_{2.5}$ apply with any urban non-compliance being highly marginal and unlikely a result of new diesel passenger cars given that no appreciable compliance improvement is observed when zero emission vehicles are substituted. This is shown in **Figure 27** for Paris.

Figure 26 PM_{10} - European AQMZ compliance with the allowable 35 daily exceedances of 50µg/m^3 (average of all stations in the zone) in 2020

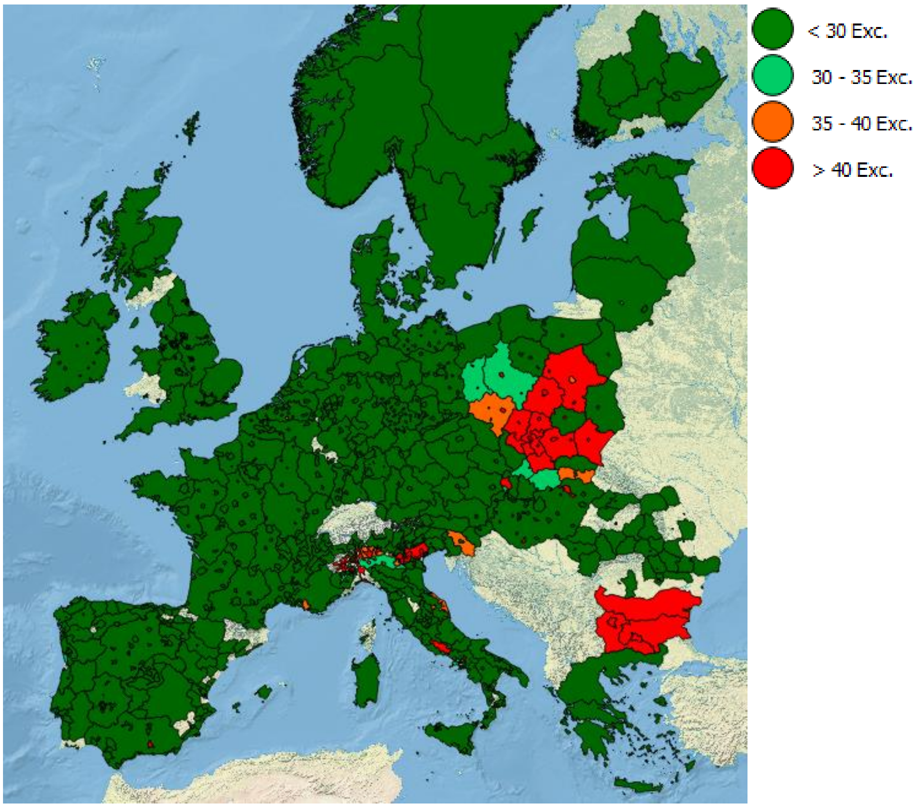
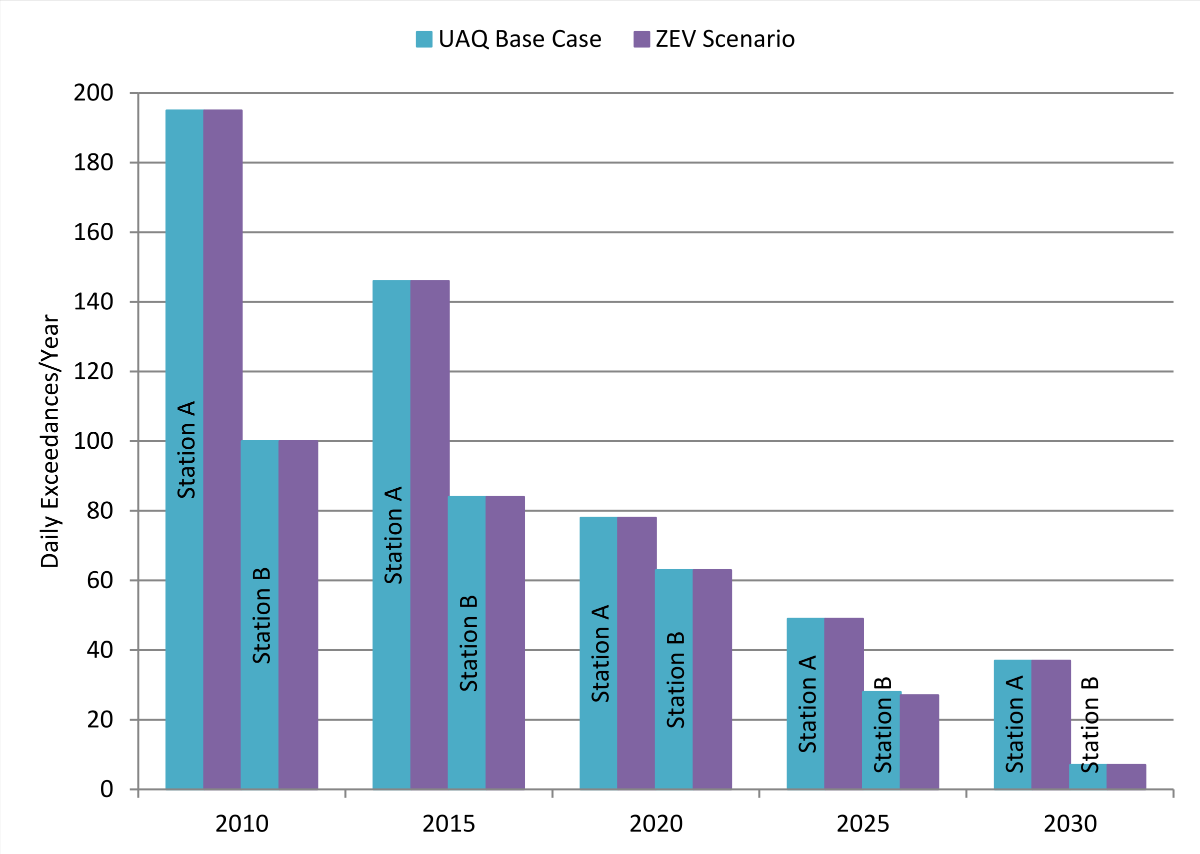


Figure 27 Paris – two highest PM_{10} exceedance AQ stations with response to zero emission vehicles – (35 exceedances allowed)



CONCLUSIONS

The aim of this study is to determine how the real driving emissions of Euro 6 diesel passenger cars would affect the concentration of nitrogen dioxide (NO_2) in European urban environments and in turn, the compliance outlook for these urban areas. In addition to this, as an exploration of the possibilities for accelerating compliance, the substitution of new Euro 6 diesel passenger cars with zero emission equivalents was explored for two key pollutants, nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$ and PM_{10}) in the same urban environments.

To facilitate these aims, a series of NO_X emissions scenarios were formulated based on modifying a benchmarked emission "Base Case" based on the EU's Thematic Strategy on Air Pollution emissions forecast (IIASA, 2015a), (IIASA, 2015b), with the results of the real driving emissions study conducted by Ricardo (Ricardo, 2018). A further scenario designed for both NO_X and $PM_{2.5}$ simulated the effect of replacing all new diesel passenger car registrations across Europe with zero emission vehicles. The methodology used in the 2016 *Urban Air Quality Study* (Aeris Europe, 2016) was updated to include newly available data and to perform a population exposure analysis based on an air quality station attribution model developed by the EEA (EEA, 2014 (a)). This method of population exposure allows for finer determination of an exposed population than the air quality management zone approach used in other studies, including the 2016 Study.

The results of the real driving emissions study conducted by Ricardo indicate that for diesel passenger cars driven under real driving conditions, the latest Euro 6 technologies deliver a significant reduction in the emissions of nitrogen oxides compared to pre-2015 vehicles. This reduction in emissions means that both Euro 6d diesel cars and zero emission cars have an almost identical effect on compliance with ambient air quality limit values and consequent population exposure. This holds true for all of the pollutants examined: NO_2, $PM_{2.5}$ and PM_{10}. Therefore, the choice of drive train (diesel or electric) in new passenger car registrations will have negligible impact on compliance with air quality limit values in European urban environments.

The indistinguishable impact of replacing the new diesel passenger car portion of the vehicle fleet with zero emission cars is observed at both city and national level, however in both scenarios there remains residual NO_2 non-compliance in a number of European cities. It is therefore vital that local analyses are performed to determine the specific emission sources contributing to non-compliance and if road traffic is identified as a legitimate target for achieving compliance it is probable that a focus on those vehicles and sources known to emit high volumes of NO_X such as older buses, LDV or pre-Euro VI HDV vehicles are likely to be effective options. It is unlikely that any measure that targets newer Euro 6 diesel passenger cars will bring these small areas into compliance.

In the case of particulates, emissions from modern passenger cars are largely independent of the drive train as mechanical abrasion (brake, road and tyre wear) is the most significant source. This means that both electric and newer diesel passenger cars produce essentially equivalent emissions for a given vehicle weight and driving habit. Therefore any areas experiencing $PM_{2.5}$ or PM_{10} non-compliance will be unlikely to see any improvement regardless of the vehicle technology employed in new vehicles.

Given the above observations, from an air quality perspective, it is unlikely that excluding newer Euro 6 diesel passenger cars from cities will result in earlier compliance or a reduction in population exposure. Instead there is a need to identify the real sources of non-compliance to effectively address outstanding issues and it is highly likely that this will require tailored local measures targeting specific elements of road transport, for example replacing older vehicles with new vehicles regardless of powertrain, or non-transport sources, for example residential combustion or small-scale power generators found in many large buildings (DEFRA, 2017).

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APPENDIX A: URBAN POPULATION LIVING CLOSE TO MAJOR ROADS

Percentage of the urban population in each country living close to major roads – taken from "Exceedance of air quality standards in urban areas" (EEA, 2014 (a))

Country ISO2	Percentage of population living close to major roads	Percentage of population exposed to background concentrations
AT	6.4	93.6
BE	7.4	92.6
BG	3.6	96.4
CH	5.0	95.0
CY	5.0	95.0
CZ	4.5	95.5
DE	6.2	93.8
DK	6.6	93.4
EE	2.8	97.2
ES	5.3	94.7
FI	3.8	96.2
FR	4.2	95.8
GB	5.8	94.2
GR	4.0	96.0
HR	4.1	95.9
HU	4.7	95.3
IE	4.9	95.1
IS	0.7	99.3
IT	4.9	95.1
LI	2.5	97.5
LT	2.3	97.7
LU	9.1	90.9
LV	3.8	96.2
MT	5.0	95.0
NL	6.4	93.6
NO	1.9	98.1
PL	3.4	96.6
PT	3.8	96.2
RO	2.4	97.6
SE	2.2	97.8
SI	4.9	95.1
SK	5.7	94.3
TR	5.0	95.0

APPENDIX B: CONCENTRATION AND DISTANCE FROM ROAD

The EEA population exposure model used in this report assumes a constant concentration of each pollutant up to 100 metres either side of the road when determining the portion of the urban population to assign to traffic stations. It also somewhat simplifies the fact that different pollutants have distinct dispersion characteristics. However this is not the case in reality, and it is important to consider that the distance from an emissions source can have a significant effect on the concentration observed. Whilst these factors may not make a significant difference in all cases, when discussing nitrogen dioxide in urban environments the effect can be significant. Research by a number of authors using measurement data recognises that the relationship between kerbside concentrations of NO_2 and reductions with distance from the road can be expressed using logarithmic relationships e.g. (AQEG, 2004), (Gilbert, et al., 2003, pp. 43-46), (Hickman, et al., 2002), (Pleijel, et al., 2004, pp. 261-264), with up to a 25% reduction in concentration over the first 10 metres. This relationship between NO_2 concentrations and distance from road is described as essentially linear on a log-linear scale between 10cm from the kerb and 140m from the kerb (Laxen & Marner, 2008).

Figure 28 NO_2 normalised concentration profile [26]

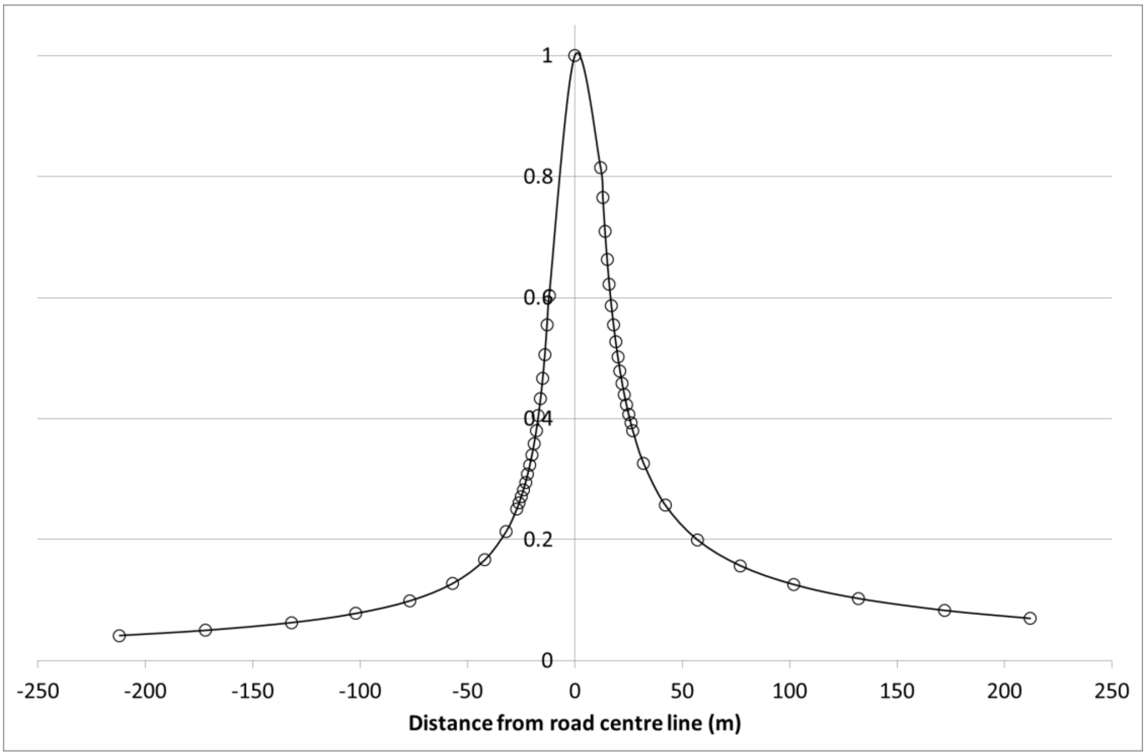


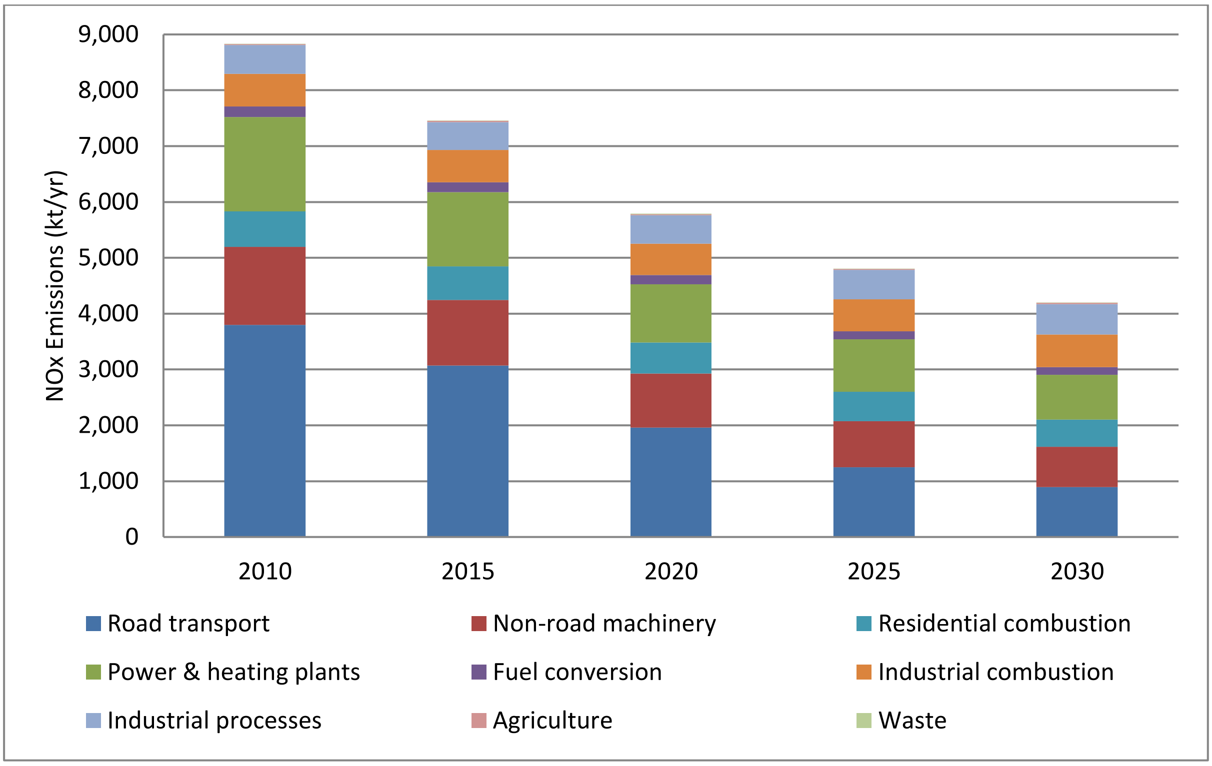
Figure 28 is taken from a DEFRA Technical Report (DEFRA, 2015) and shows an example normalised concentration profile for NO_2 with distance from the road centreline. From this we can determine that at 20 metres from the road centreline the concentration is halved and at 100 metres (as used in the EEA methodology adopted in this study) the concentration is essentially at background levels (roughly 10% of the road concentration). By applying a concentration measured at kerbside[27] to the whole population within 100 metres of a road the result is almost certainly an over-estimation of the population exposed to these higher concentrations. This issue will continue to grow in importance as the scale at which the modelling of population exposure in cities becomes finer. For the purposes of this study, the estimate of population exposure to non-compliant concentrations is likely to be higher than in reality.

[26] DEFRA Technical Report, December 2015, Annex B, Figure B.2 – Example normalised concentration profile
[27] Traffic stations must be located within 10 metres of the kerbside (2008/50/EC)

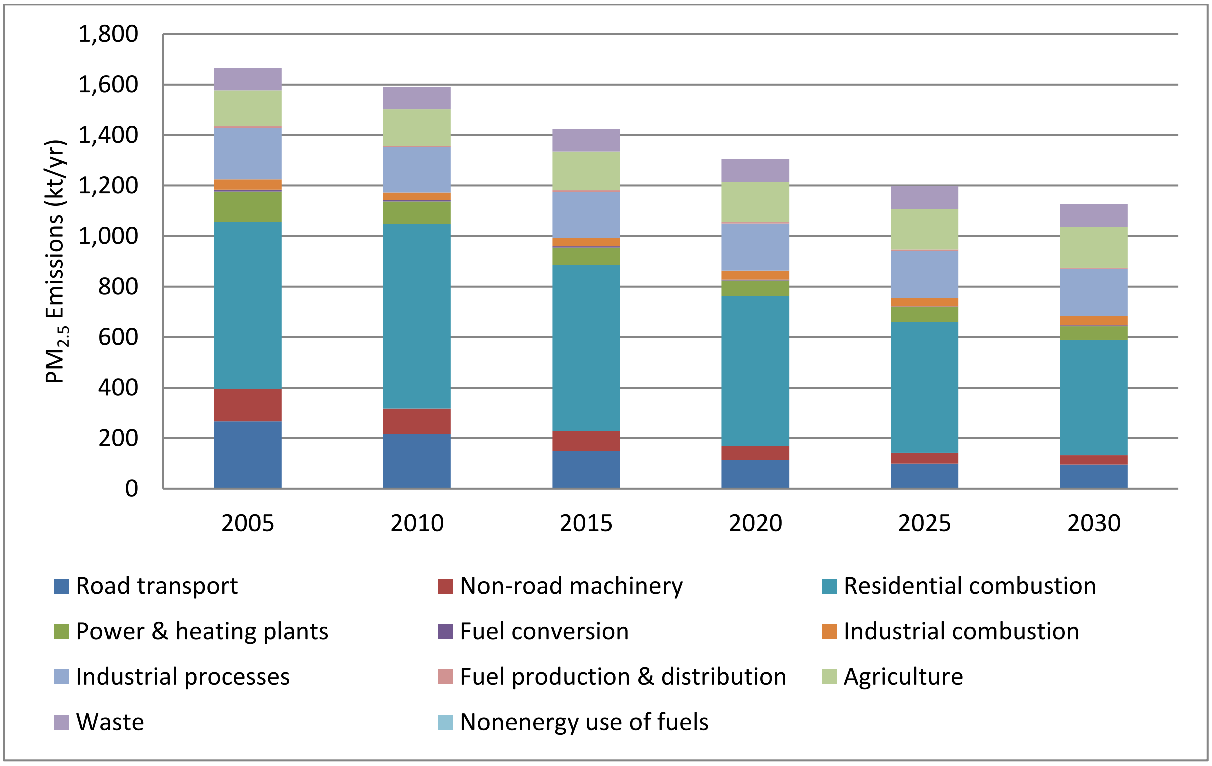
APPENDIX C: DATA AND RESULTS - EU28

EMISSIONS

EU28 BASE CASE NO_X EMISSIONS BY KEY SECTOR (IIASA GAINS TSAP16 CLE WPE SCENARIO)



EU28 BASE CASE $PM_{2.5}$ EMISSIONS BY KEY SECTOR (IIASA GAINS TSAP16 CLE WPE SCENARIO)



NO_2 COMPLIANCE AT AIR QUALITY STATIONS – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 40µg/m^3 annual mean air quality limit value

	UAQ Base Case			Ricardo Median			Ricardo Mean		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	1868	294	230	1868	294	230	1868	294	230
2011	1915	269	208	1915	269	208	1915	269	208
2012	1954	253	185	1954	253	185	1954	253	185
2013	1983	242	167	1983	242	167	1983	242	167
2014	2015	234	143	2015	234	143	2015	234	143
2015	2044	224	124	2045	225	122	2045	224	123
2016	2086	205	101	2091	201	100	2089	203	100
2017	2132	174	86	2143	165	84	2142	165	85
2018	2176	143	73	2193	129	70	2189	133	70
2019	2220	111	61	2233	107	52	2231	109	52
2020	2250	96	46	2259	92	41	2258	91	43
2021	2262	89	41	2275	81	36	2275	81	36
2022	2277	81	34	2286	81	25	2285	82	25
2023	2288	78	26	2298	72	22	2297	73	22
2024	2301	70	21	2317	59	16	2317	59	16
2025	2318	58	16	2328	52	12	2327	53	12
2026	2320	58	14	2336	44	12	2335	45	12
2027	2328	52	12	2345	37	10	2344	38	10
2028	2337	44	11	2350	33	9	2350	33	9
2029	2345	36	11	2354	30	8	2354	30	8
2030	2347	37	8	2354	31	7	2354	31	7

These totals include all stations in the model domain, that is the EU28 + NO, CH, IS, MK

	Ricardo E6DMax			Ricardo E6DEarly			ZEV Scenario		
Year	Compliant	Uncertain	Non-Compliant	Compliant	Uncertain	Non-Compliant	Compliant	Uncertain	Non-Compliant
2010	1868	294	230	1868	294	230	1868	294	230
2011	1915	269	208	1915	269	208	1915	269	208
2012	1954	253	185	1954	253	185	1954	253	185
2013	1983	242	167	1983	242	167	1983	242	167
2014	2015	234	143	2015	234	143	2015	234	143
2015	2045	225	122	2045	225	122	2045	225	122
2016	2090	202	100	2091	201	100	2091	201	100
2017	2143	164	85	2144	164	84	2144	164	84
2018	2192	130	70	2194	128	70	2195	127	70
2019	2233	107	52	2233	108	51	2234	107	51
2020	2259	92	41	2260	91	41	2261	90	41
2021	2275	81	36	2275	81	36	2276	81	35
2022	2285	82	25	2287	80	25	2287	82	23
2023	2297	73	22	2298	73	21	2302	69	21
2024	2317	59	16	2318	58	16	2318	59	15
2025	2327	53	12	2329	51	12	2334	46	12
2026	2335	45	12	2337	43	12	2342	40	10
2027	2344	38	10	2345	37	10	2349	33	10
2028	2348	35	9	2350	33	9	2354	31	7
2029	2354	30	8	2354	30	8	2354	31	7
2030	2354	31	7	2354	31	7	2359	27	6

These totals include all stations in the model domain, that is the EU28 + NO, CH, IS, MK

$PM_{2.5}$ COMPLIANCE AT AIR QUALITY STATIONS – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 25µg/m³ annual mean air quality limit value

	UAQ Base Case			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	2234	510	105	2234	510	105
2011	2274	476	99	2274	476	99
2012	2314	442	93	2314	442	93
2013	2354	409	86	2354	409	86
2014	2394	375	80	2394	375	80
2015	2434	341	74	2434	341	74
2016	2456	321	72	2456	321	72
2017	2479	300	70	2479	300	70
2018	2501	280	68	2501	280	68
2019	2524	259	66	2524	259	66
2020	2546	239	64	2546	239	64
2021	2559	227	63	2559	227	63
2022	2571	216	62	2571	216	62
2023	2584	204	61	2584	204	61
2024	2596	193	60	2596	193	60
2025	2609	181	59	2609	181	59
2026	2615	177	58	2615	177	58
2027	2621	172	56	2621	172	56
2028	2626	168	55	2626	168	55
2029	2632	163	53	2632	163	53
2030	2638	159	52	2638	159	52

These totals include all stations in the model domain, that is the EU28 + NO, CH, IS, MK

PM_{10} COMPLIANCE AT AIR QUALITY STATIONS – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 40µg/m^3 annual mean air quality limit value

	UAQ Base Case			ZEV Scenario		
Year	Compliant	Uncertain	Non-Compliant	Compliant	Uncertain	Non-Compliant
2010	2150	256	98	2150	256	98
2011	2174	238	92	2174	238	92
2012	2198	220	86	2198	220	86
2013	2222	203	79	2222	203	79
2014	2246	185	73	2246	185	73
2015	2270	167	67	2270	167	67
2016	2284	155	65	2284	155	65
2017	2299	143	62	2299	143	62
2018	2313	131	60	2313	131	60
2019	2328	119	57	2328	119	57
2020	2342	107	55	2342	107	55
2021	2348	102	54	2348	102	54
2022	2354	97	53	2354	97	53
2023	2361	92	51	2361	92	51
2024	2367	87	50	2367	87	50
2025	2373	82	49	2373	82	49
2026	2374	82	48	2374	82	48
2027	2375	82	48	2375	81	48
2028	2375	81	47	2376	81	47
2029	2376	81	47	2377	80	47
2030	2377	81	46	2378	80	46

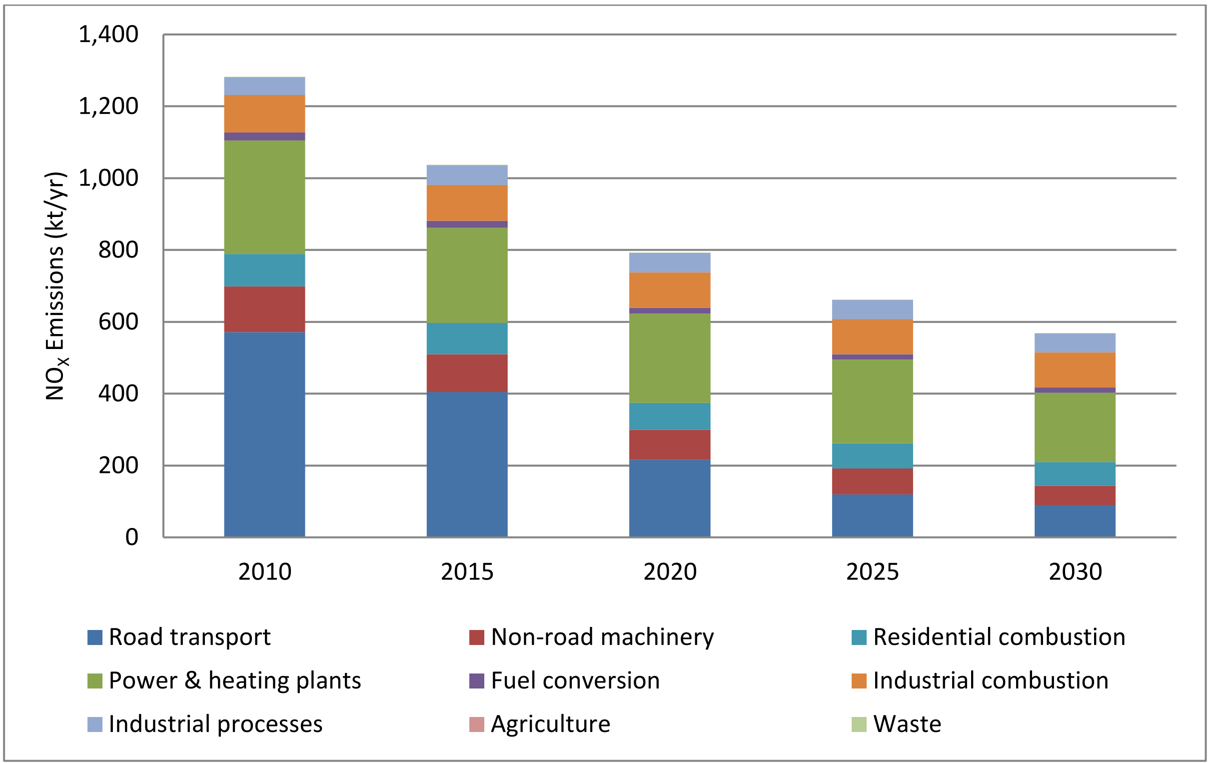
These totals include all stations in the model domain, that is the EU28 + NO, CH, IS, MK

APPENDIX D: DATA AND RESULTS - GERMANY

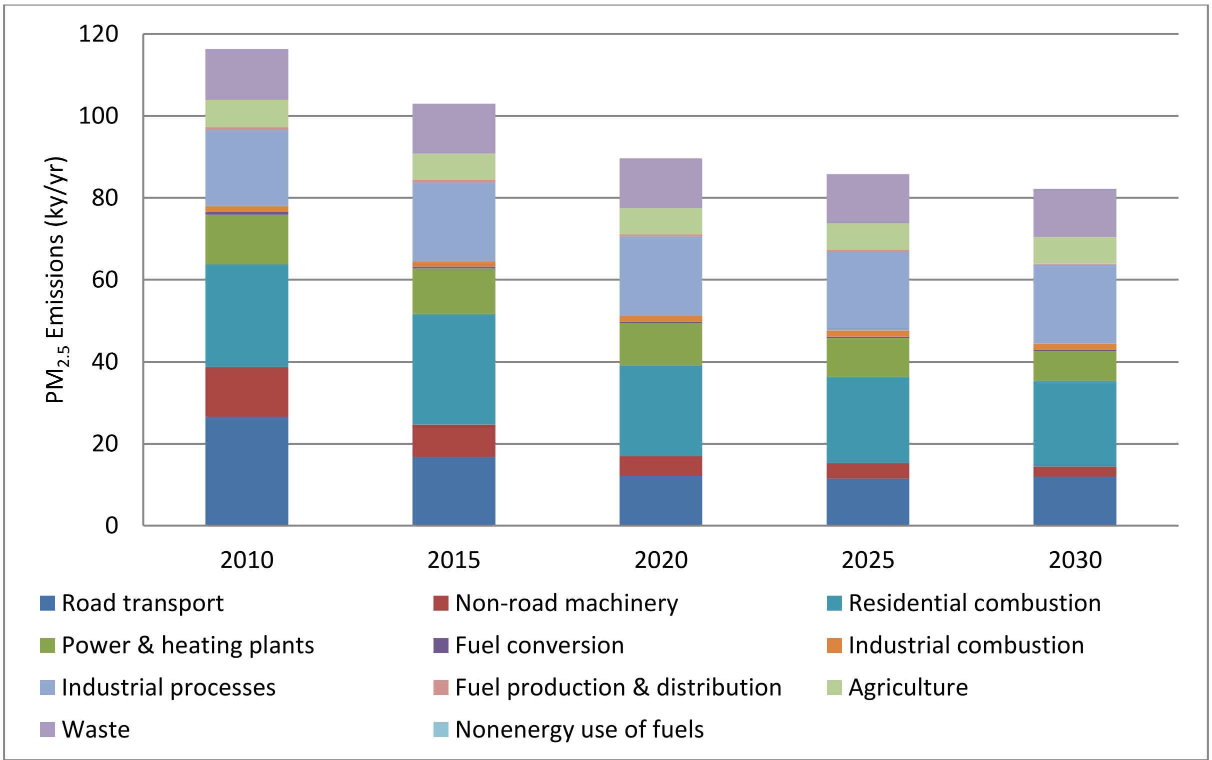
Germany has been chosen as a representative example of an EU Member State to illustrate general trends

EMISSIONS

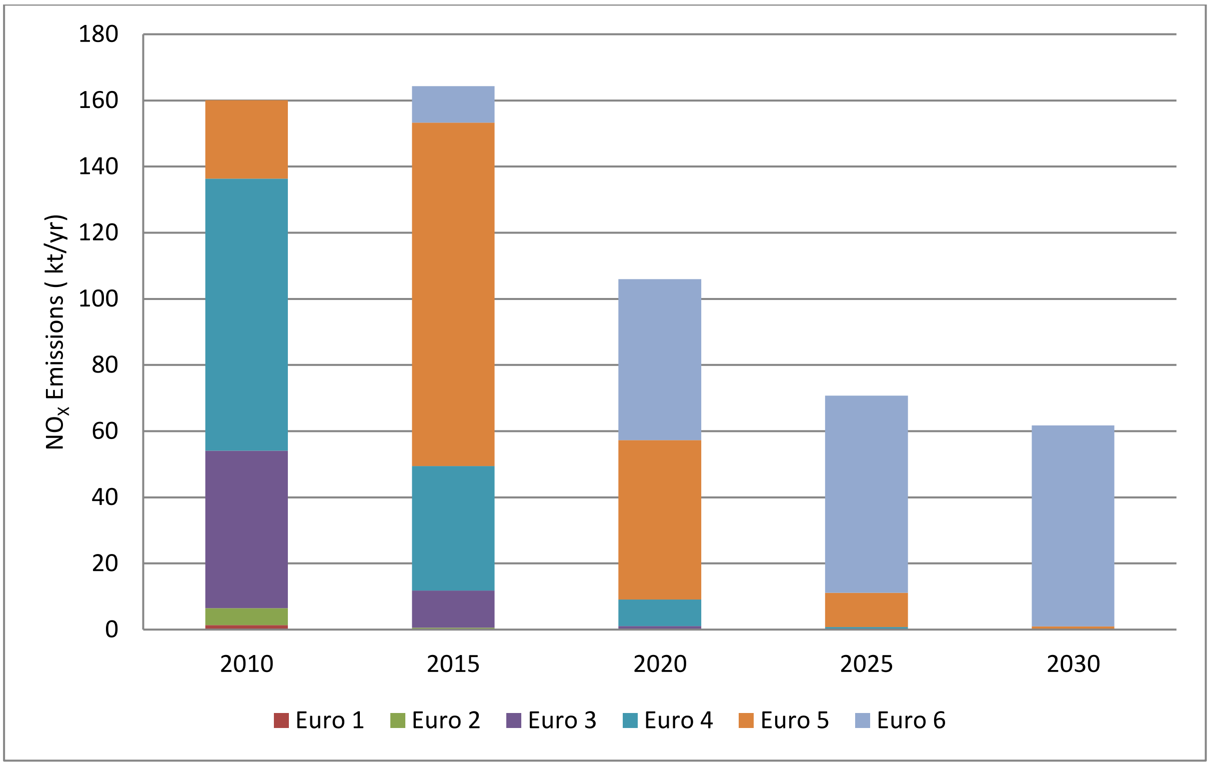
GERMANY BASE CASE NO_X EMISSIONS BY KEY SECTOR (IIASA GAINS TSAP16 CLE WPE SCENARIO)



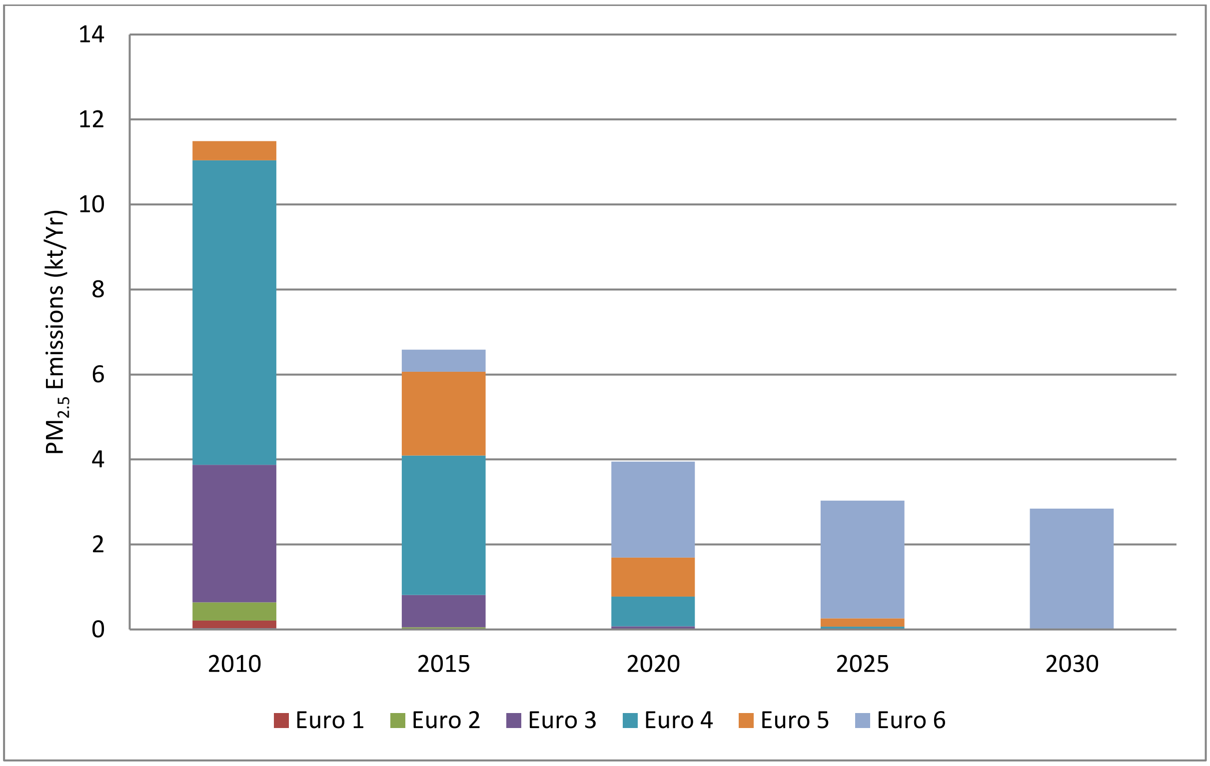
GERMANY BASE CASE $PM_{2.5}$ EMISSIONS BY KEY SECTOR (IIASA GAINS TSAP16 CLE WPE SCENARIO)



GERMANY BASE CASE, DIESEL PASSENGER CAR NO_X EMISSIONS BY EURO STANDARD



GERMANY BASE CASE, DIESEL PASSENGER CAR $PM_{2.5}$ EMISSIONS BY EURO STANDARD



NO_2 COMPLIANCE AT AIR QUALITY STATIONS IN GERMANY – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 40µg/m^3 annual mean air quality limit value

	UAQ Base Case			Ricardo Median			Ricardo Mean		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	247	34	49	247	34	49	247	34	49
2011	252	36	42	252	36	42	252	36	42
2012	257	36	37	257	36	37	257	36	37
2013	260	38	32	260	38	32	260	38	32
2014	266	39	25	266	39	25	266	39	25
2015	274	37	19	274	37	19	274	37	19
2016	280	36	14	280	36	14	280	36	14
2017	289	30	11	290	29	11	290	29	11
2018	296	24	10	299	21	10	298	22	10
2019	303	18	9	307	17	6	307	17	6
2020	311	14	5	314	11	5	314	11	5
2021	314	11	5	316	9	5	316	9	5
2022	316	9	5	317	8	5	317	8	5
2023	317	8	5	317	9	4	317	9	4
2024	317	9	4	317	9	4	317	9	4
2025	317	9	4	318	9	3	318	9	3
2026	317	9	4	320	7	3	320	7	3
2027	318	9	3	320	8	2	320	8	2
2028	320	7	3	321	7	2	321	7	2
2029	320	7	3	323	5	2	323	5	2
2030	321	7	2	323	5	2	323	5	2

	Ricardo E6DMax			Ricardo E6DEarly			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	247	34	49	247	34	49	247	34	49
2011	252	36	42	252	36	42	252	36	42
2012	257	36	37	257	36	37	257	36	37
2013	260	38	32	260	38	32	260	38	32
2014	266	39	25	266	39	25	266	39	25
2015	274	37	19	274	37	19	274	37	19
2016	280	36	14	280	36	14	280	36	14
2017	290	29	11	290	29	11	290	29	11
2018	299	21	10	299	21	10	299	21	10
2019	307	17	6	307	17	6	308	16	6
2020	314	11	5	315	10	5	315	10	5
2021	316	9	5	316	9	5	316	9	5
2022	317	8	5	317	8	5	317	9	4
2023	317	9	4	317	9	4	317	9	4
2024	317	9	4	317	9	4	317	9	4
2025	318	9	3	319	8	3	320	7	3
2026	320	7	3	320	7	3	320	8	2
2027	320	8	2	320	8	2	321	7	2
2028	321	7	2	321	7	2	323	5	2
2029	323	5	2	323	5	2	323	5	2
2030	323	5	2	323	5	2	324	4	2

$PM_{2.5}$ COMPLIANCE AT AIR QUALITY STATIONS IN GERMANY – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 25µg/m^3 annual mean air quality limit value

	UAQ Base Case			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	434	22	0	434	22	0
2011	437	19	0	437	19	0
2012	440	16	0	440	16	0
2013	444	12	0	444	12	0
2014	447	9	0	447	9	0
2015	450	6	0	450	6	0
2016	451	5	0	451	5	0
2017	451	5	0	451	5	0
2018	452	4	0	452	4	0
2019	452	4	0	452	4	0
2020	453	3	0	453	3	0
2021	453	3	0	453	3	0
2022	453	3	0	453	3	0
2023	454	2	0	454	2	0
2024	454	2	0	454	2	0
2025	454	2	0	454	2	0
2026	454	2	0	454	2	0
2027	454	2	0	454	2	0
2028	455	1	0	455	1	0
2029	455	1	0	455	1	0
2030	455	1	0	455	1	0

PM_{10} COMPLIANCE AT AIR QUALITY STATIONS IN GERMANY – TOTALS OF ALL STATIONS BY SCENARIO

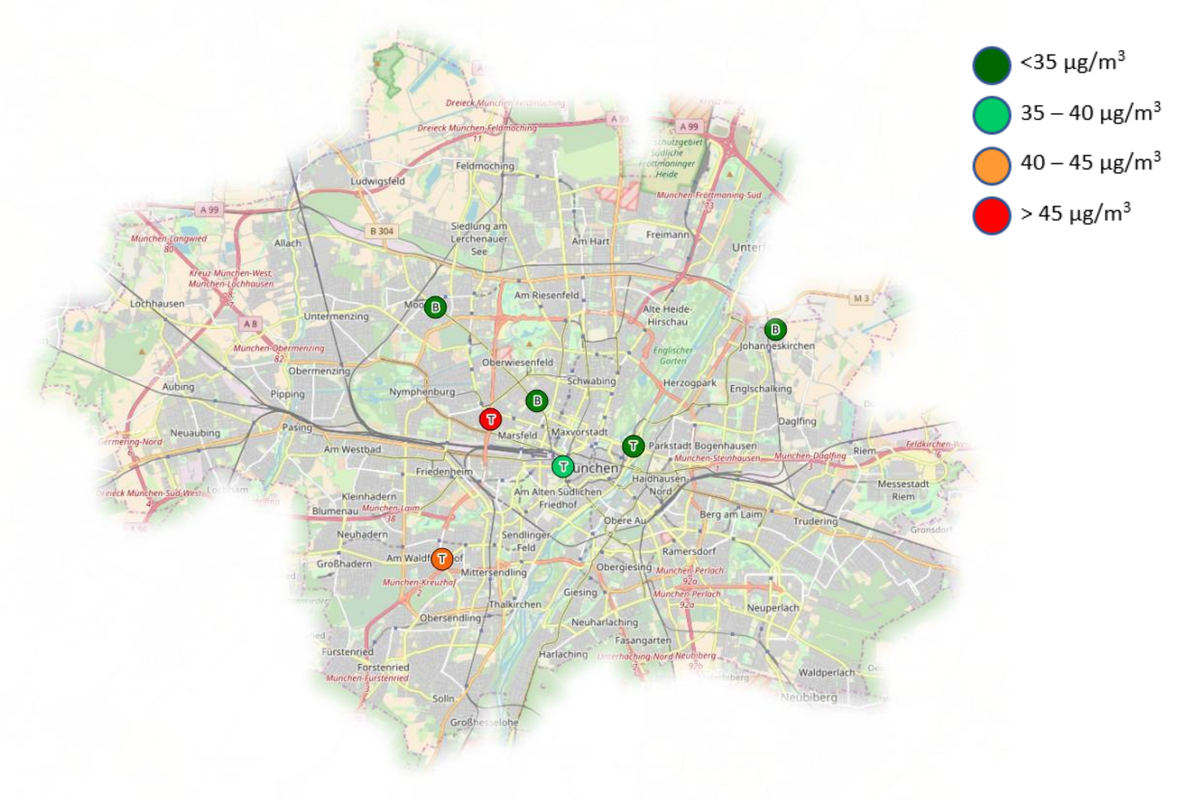
Compliance with the 40µg/m^3 annual mean air quality limit value

	UAQ Base Case			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	414	10	0	414	10	0
2011	415	9	0	415	9	0
2012	416	8	0	416	8	0
2013	418	6	0	418	6	0
2014	419	5	0	419	5	0
2015	420	4	0	420	4	0
2016	421	3	0	421	3	0
2017	421	3	0	421	3	0
2018	422	2	0	422	2	0
2019	422	2	0	422	2	0
2020	423	1	0	423	1	0
2021	423	1	0	423	1	0
2022	423	1	0	423	1	0
2023	423	1	0	423	1	0
2024	423	1	0	423	1	0
2025	423	1	0	423	1	0
2026	423	1	0	423	1	0
2027	423	1	0	423	1	0
2028	423	1	0	423	1	0
2029	423	1	0	423	1	0
2030	423	1	0	423	1	0

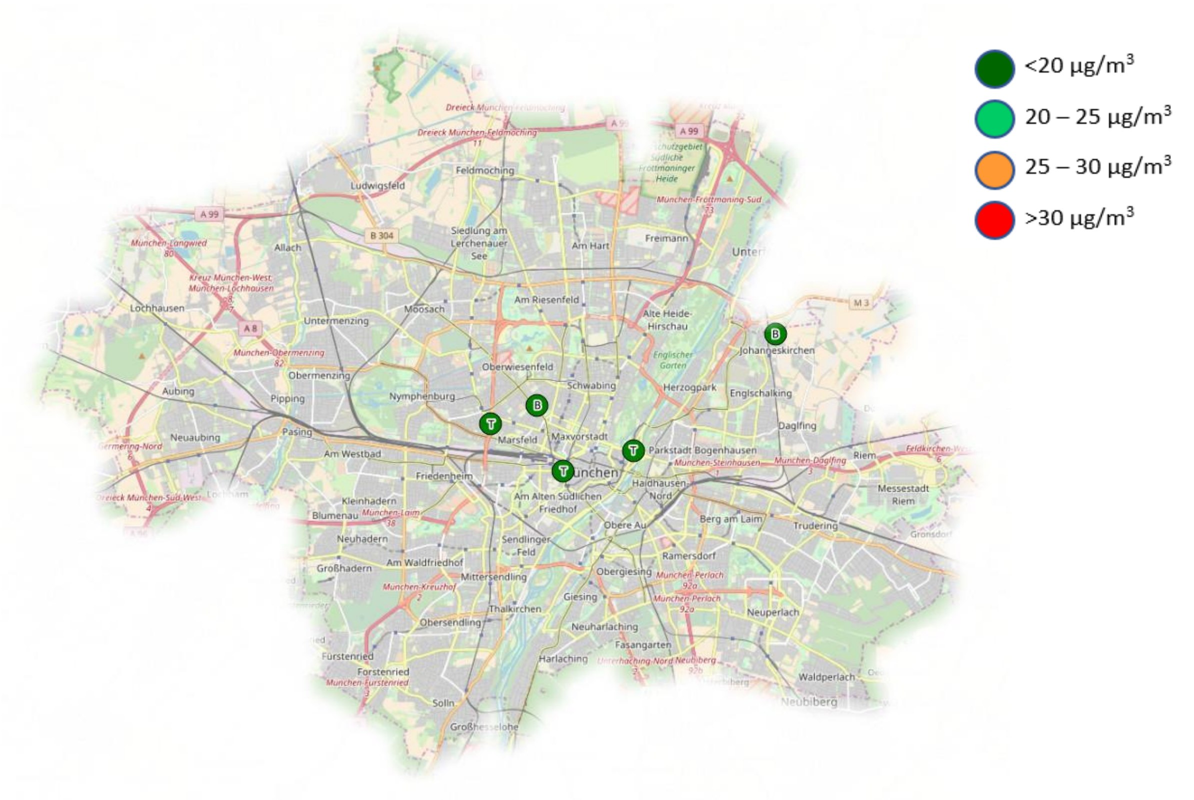
APPENDIX E: DATA AND RESULTS - MUNICH

Munich has been chosen as a representative example of a European city to illustrate general trends

MUNICH NO_2 STATIONS – COMPLIANCE AND LOCATION – UAQ BASE CASE – 2020



MUNICH $PM_{2.5}$ STATIONS – COMPLIANCE AND LOCATION – UAQ BASE CASE – 2020



NO_2 COMPLIANCE AT AIR QUALITY STATIONS IN MUNICH – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 40µg/m^3 annual mean air quality limit value

	UAQ Base Case			Ricardo Median			Ricardo Mean		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	2	1	4	2	1	4	2	1	4
2011	2	1	4	2	1	4	2	1	4
2012	2	1	4	2	1	4	2	1	4
2013	3	1	3	3	1	3	3	1	3
2014	3	1	3	3	1	3	3	1	3
2015	3	2	2	3	2	2	3	2	2
2016	3	2	2	3	2	2	3	2	2
2017	4	1	2	4	1	2	4	1	2
2018	4	1	2	4	1	2	4	1	2
2019	4	1	2	4	2	1	4	2	1
2020	4	2	1	5	1	1	5	1	1
2021	5	1	1	5	1	1	5	1	1
2022	5	1	1	5	1	1	5	1	1
2023	5	1	1	5	1	1	5	1	1
2024	5	1	1	5	1	1	5	1	1
2025	5	1	1	5	2	0	5	2	0
2026	5	1	1	5	2	0	5	2	0
2027	5	2	0	5	2	0	5	2	0
2028	5	2	0	5	2	0	5	2	0
2029	5	2	0	6	1	0	6	1	0
2030	5	2	0	6	1	0	6	1	0

	Ricardo E6DMax			Ricardo E6DEarly			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	2	1	4	2	1	4	2	1	4
2011	2	1	4	2	1	4	2	1	4
2012	2	1	4	2	1	4	2	1	4
2013	3	1	3	3	1	3	3	1	3
2014	3	1	3	3	1	3	3	1	3
2015	3	2	2	3	2	2	3	2	2
2016	3	2	2	3	2	2	3	2	2
2017	4	1	2	4	1	2	4	1	2
2018	4	1	2	4	1	2	4	1	2
2019	4	2	1	4	2	1	4	2	1
2020	5	1	1	5	1	1	5	1	1
2021	5	1	1	5	1	1	5	1	1
2022	5	1	1	5	1	1	5	1	1
2023	5	1	1	5	1	1	5	1	1
2024	5	1	1	5	1	1	5	1	1
2025	5	2	0	5	2	0	5	2	0
2026	5	2	0	5	2	0	5	2	0
2027	5	2	0	5	2	0	5	2	0
2028	5	2	0	5	2	0	6	1	0
2029	6	1	0	6	1	0	6	1	0
2030	6	1	0	6	1	0	6	1	0

$PM_{2.5}$ COMPLIANCE AT AIR QUALITY STATIONS IN MUNICH – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 25µg/m^3 annual mean air quality limit value

	UAQ Base Case			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	4	1	0	4	1	0
2011	4	1	0	4	1	0
2012	4	1	0	4	1	0
2013	5	0	0	5	0	0
2014	5	0	0	5	0	0
2015	5	0	0	5	0	0
2016	5	0	0	5	0	0
2017	5	0	0	5	0	0
2018	5	0	0	5	0	0
2019	5	0	0	5	0	0
2020	5	0	0	5	0	0
2021	5	0	0	5	0	0
2022	5	0	0	5	0	0
2023	5	0	0	5	0	0
2024	5	0	0	5	0	0
2025	5	0	0	5	0	0
2026	5	0	0	5	0	0
2027	5	0	0	5	0	0
2028	5	0	0	5	0	0
2029	5	0	0	5	0	0
2030	5	0	0	5	0	0

PM_{10} COMPLIANCE AT AIR QUALITY STATIONS IN GERMANY – TOTALS OF ALL STATIONS BY SCENARIO

Compliance with the 40µg/m³ annual mean air quality limit value

	UAQ Base Case			ZEV Scenario		
Year	**Compliant**	**Uncertain**	**Non-Compliant**	**Compliant**	**Uncertain**	**Non-Compliant**
2010	4	1	0	4	1	0
2011	4	1	0	4	1	0
2012	4	1	0	4	1	0
2013	5	0	0	5	0	0
2014	5	0	0	5	0	0
2015	5	0	0	5	0	0
2016	5	0	0	5	0	0
2017	5	0	0	5	0	0
2018	5	0	0	5	0	0
2019	5	0	0	5	0	0
2020	5	0	0	5	0	0
2021	5	0	0	5	0	0
2022	5	0	0	5	0	0
2023	5	0	0	5	0	0
2024	5	0	0	5	0	0
2025	5	0	0	5	0	0
2026	5	0	0	5	0	0
2027	5	0	0	5	0	0
2028	5	0	0	5	0	0
2029	5	0	0	5	0	0
2030	5	0	0	5	0	0

APPENDIX F: UNCERTAINTY AND VALIDITY

Even the most simple of predictions are subject to a degree of uncertainty and it is important not to misrepresent the certainty of any forecast. In this study, uncertainty is represented by an allowance either side of the predicted value that reflects the likelihood that the actual value will appear somewhere within that range. We refer to this as an "uncertainty bound". These uncertainty bounds reflect unavoidable uncertainties in input data, modelling techniques and future meteorological conditions.

Validity checking within the AQUIReS+ model is performed using a series of back-casting techniques applied to every modelled point for which a corresponding measurement exists. This provides a station specific uncertainty which enables us to state, that for a given station in a given year, an average error in predicted concentration. The RMS error within the AQUIReS+ model domain for each pollutant, comparing modelled data with the previous ten years of measured data is shown in **Table 9**.

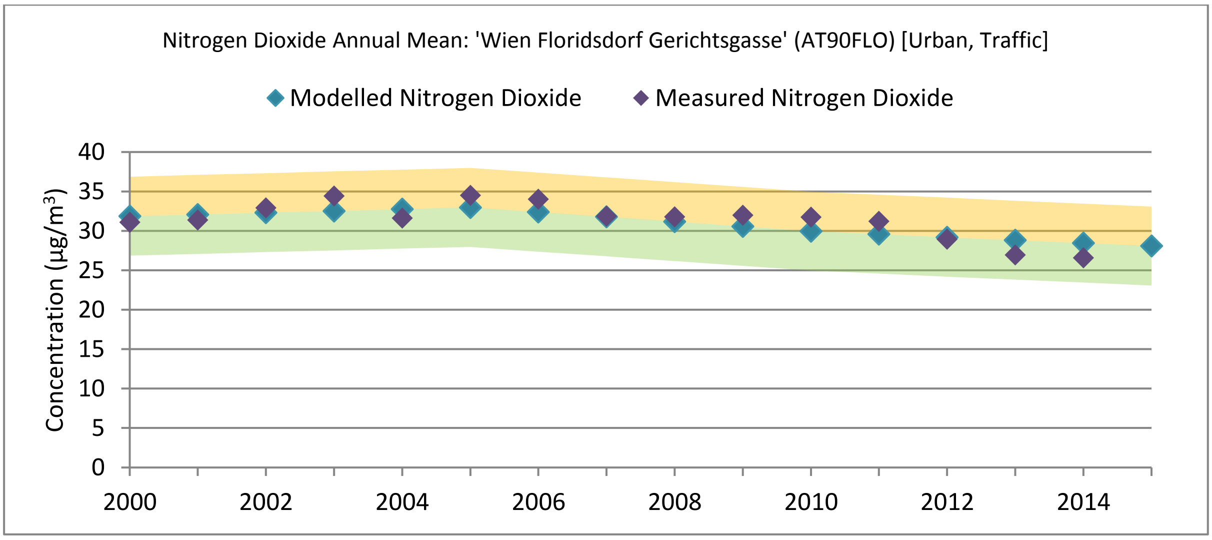
Table 9 AQUIReS+ mean RMS error for each pollutant

	NO_2	$PM_{2.5}$	PM_{10}
Mean RMS Error (µg/m³)	3.7	0.9	1.7

The Ambient Air Quality Directive (2008/50/EC) specifies that the uncertainty of fixed measurements of NO_X and NO_2 should be no greater that 15%, and for $PM_{2.5}$ and PM_{10} no greater than 25%. This means that the maximum permissible level of uncertainty for actual measurements at the relevant air quality limit values are all slightly greater than ±5µg/m³. Given the above, and in common with other published work[28] a 5µg/m³ allowance either side of the modelled value has been chosen. This uncertainty then reflects both the accuracy of the model and uncertainties in input data whilst allowing direct comparison with other data sources.

The AQUIReS+ model performs calculations on individual stations, it is therefore possible to compare the modelled concentration with the measured in a given year and use this data for result validation and error checking. A selection of stations covering urban and suburban regions is shown in **Figure 29** through to **Figure 32** for stations in Austria, Belgium, Germany and Spain respectively. The banding shows the 5µg/m³ uncertainty band discussed above.

Figure 29 Model validation: Station AT90FLO (Austria)



[28] Amann, M. TSAP Report# 11 - The Final Policy Scenarios of the EU Clean Air Policy Package, Feb. 2014 - International Institute for Applied Systems Analysis (IIASA)

Figure 30 Model validation: Station BELSZ02 (Belgium)

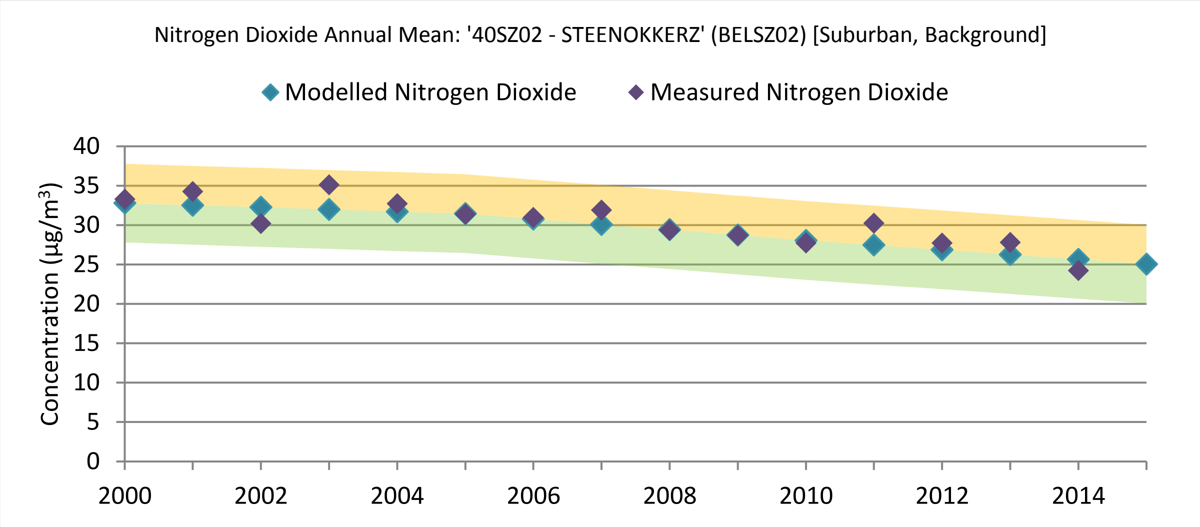


Figure 31 Model validation: Station DERP026 (Germany)

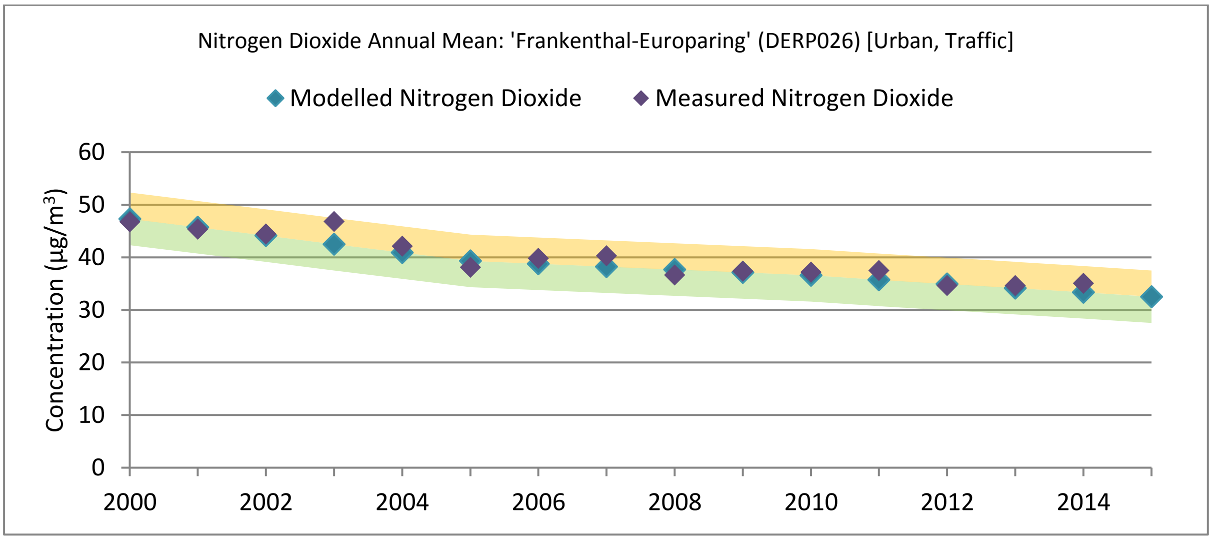
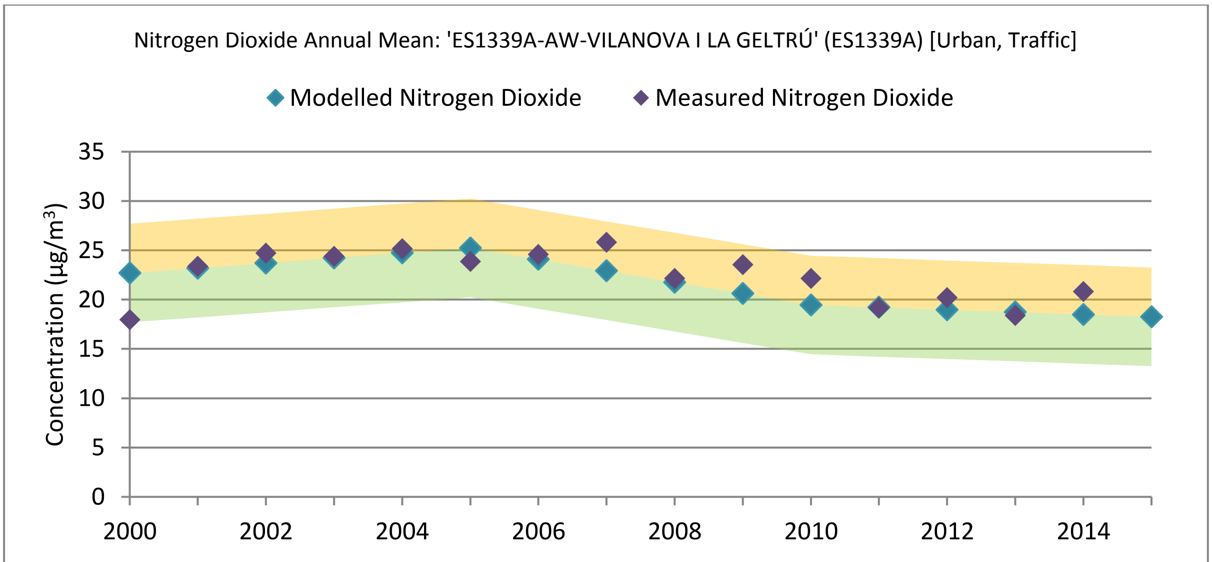


Figure 32 Model validation: Station ES1339A (Spain)



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