Improved emissions mapping across the GB rail network

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Abstract

Air quality has long been recognised as a significant public health issue, with transport a major contributor to emissions of air quality pollutants. A key step in tackling poor air quality is to estimate the geographical spread (or 'map') of emissions so that policies and interventions can be targeted most appropriately. In the road transport sector, road emissions are typically mapped on a link-level basis (i.e. street by street). Traditionally in the GB rail sector, emissions have been mapped at a lower resolution with emissions averaged over much larger distances, for example, over entire routes such as London to Bristol. This approach provided very limited data on local variations of emissions and therefore where localised air quality issues might occur.

Mapping rail emissions is challenging as it requires a combination of robust emission factors for various train classes along with up to date activity data showing where, and how often the various train types operate around the network. At the time this research was commissioned, emission factors were between 10 and 20 years out of date and the latest rail emissions maps included in the UK National Atmospheric Emissions Inventory (NAEI) were based on rail activity from around 2011. This meant a complete review and update of rail emission factors and a new summary of rail activity data was required to provide a better representation of the geographical spread of emissions from the GB rail fleet. An interactive online GIS-based tool was developed to allow users to study the various insights provided by the refined approach to mapping rail emissions. This paper describes, at a high level, the methodology used to develop the mapping tool and describes some of the new insights that can be gained from the improved emissions estimates.

Keywords: emissions, air quality, particulate, NOx, GIS

1. Introduction

Air pollution is a major public health risk, ranking alongside cancer, heart disease and obesity, and poses the single greatest environmental risk to human health (Defra, 2019). The Department of Health and Social Care's advisory Committee on the Medical Effects of Air Pollutants (COMEAP) estimated that long-term exposure to air pollution shortens lifespans and is equivalent to an additional 28,000 to 36,000 deaths a year (COMEAP, 2018)

Individuals such as the elderly, infants, pregnant women and their unborn children may be more vulnerable to the health effects of air pollution. As a result, some locations such as schools and hospitals tend to be more sensitive to poor air quality. Significant evidence links exposure to certain pollutants such as nitrogen oxides and particulate matter to adverse impacts on health. These two pollutants are commonly associated with diesel engine emissions. Diesel engines are in widespread use in the rail sector meaning exposure to such pollutants may be high in certain rail locations such as enclosed stations.

1.1 Nitrogen Oxides (NOx)

NOx is mostly emitted from the combustion of fossil fuels, with the biggest source in transport being diesel engines. The majority of NOx emitted from fossil fuel combustion is in the form of nitric oxide (NO). When NO reacts with other gases present in the air, it will form nitrogen dioxide (NO_2), which is more harmful to health. NO_2 can cause inflammation of the airways and exacerbate symptoms of those suffering from heart or lung conditions. NO_2 is a precursor to the atmospheric formation of ozone gas, which also causes inflammation of the airways.

In the UK, the National Atmospheric Emissions Inventory (NAEI) shows the transport sector as the single biggest contributor to NOx emissions, contributing to 47% of the total (NAEI, 2019). Other major UK sources of NOx include the energy industries which contribute 17.5% and the manufacturing and construction industries which contribute 18%. Road transport contributes 33% of national NOx emissions, although in roadside locations this can be up to 80% illustrating the magnitude of local impacts. Within the transport sector itself, land-based NOx emissions are dominated by cars, light goods vehicles (LGVs) and heavy goods vehicles (HGVs)

1.2 Particulate Matter (PM)

PM is a mixture of solid and liquid particles suspended in the air that are derived from natural and man-made sources. Natural sources include pollen, spray from the sea, and dust from deserts. Man-made sources of PM include smoke from domestic fires, cooking, soot from vehicle exhausts, and abrasive sources such as tyres and brake wear.

PM is a generic term and more specifically is classified further by its aerodynamic diameter: most commonly PM_{10} (particles smaller than 10 µm in diameter) and $PM_{2.5}$ (particles smaller than 2.5 µm in diameter). PM_{10} particles are approximately 5 times smaller than the width of a human hair whereas $PM_{2.5}$ particles are roughly 20 times smaller. $PM_{2.5}$ particles can travel deep into human lungs and even enter the bloodstream, where they can be deposited in internal organs, increasing the risk of cancer and brain diseases. The single biggest source of $PM_{2.5}$ in the UK (24%) is domestic wood burning (NAEI, 2019).

1.3 Air Quality Management Areas

Since December 1997, UK local authorities have been obliged to continually review and assess air quality as part of their ongoing responsibilities for health and the environment. This involves measuring air pollution and predicting future changes. The aim is to ensure that national air quality objectives—which are broadly in line with EU Directive 2008/50/ EC—will be achieved throughout the UK by the specified deadlines.

Figure 1: AQMAs for NO_2 in London and Edinburgh (Defra, 2022)

If a local authority identifies areas where the objectives are not likely to be achieved, it must declare an Air Quality Management Area (AQMA). This area can be one or two streets or borough wide; Figure 1 provides an example of AQMAs for NO_2 in London and Edinburgh.

1.4 Clean Air Zones

In the last 30 years, stricter European standards have delivered reductions in engine and exhaust emissions in the road sector. This has resulted in an approximate 80% reduction in NOx emissions. Further significant improvements are forecast for larger towns and cities—due to the introduction of Clean Air Zones (CAZs). A CAZ defines an area where targeted action is being taken to deliver immediate improvements to air quality. These can range from charging drivers of more polluting vehicles to enter the zone to banning certain diesel vehicles from city centres. Vehicle types covered by the zone can vary from city to city depending on their specific emissions problems and transport infrastructure which are categorised into four classes, A to D. Class A zones cover buses, coaches, taxis and private hire vehicles (PHVs) whereas a Class D zone covers the same vehicle categories as Class A but with the addition of PHVs, HGVs, LGVs and cars.

Likewise, the Scottish Government has committed to introducing low emission zones (LEZs) into Scotland's four biggest cities: Glasgow, Edinburgh, Aberdeen and Dundee.

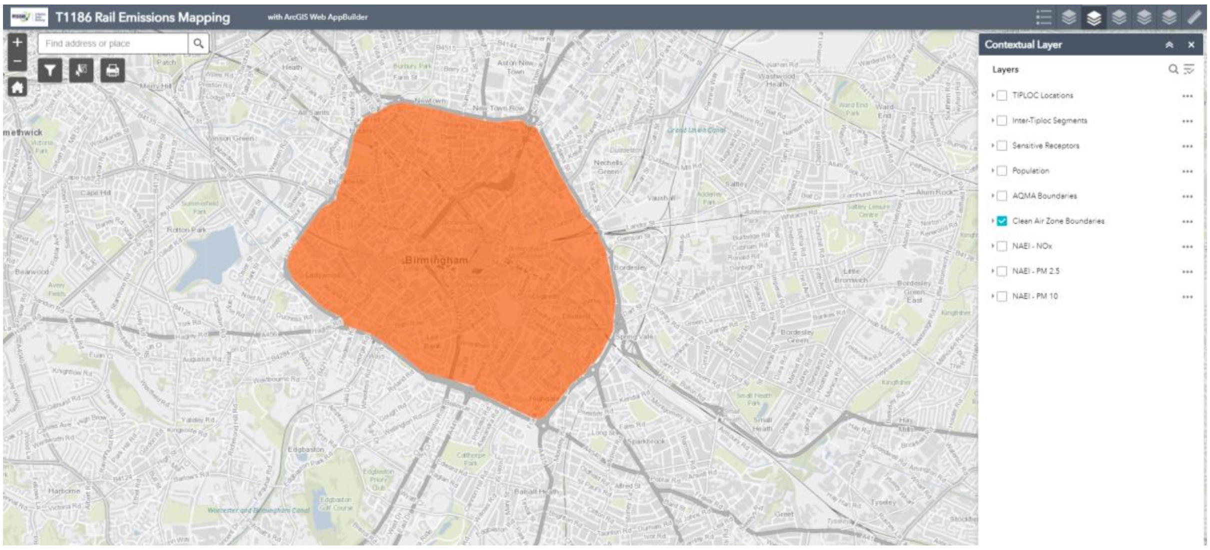


Figure 2: Birmingham Clean Air Zone

1.5 Emissions in Rail

As previously explained, the majority of transport-derived NOx emissions are produced by diesel engines which are in widespread use in the GB rail industry. The majority of GB passenger rolling stock is electrically powered but around 25% is still fully diesel powered on a vehicle basis (RDG, 2018) and 648 million litres of diesel were used to run the rail network in 2019-20 (ORR, 2021) before services were disrupted due to COVID. These emissions occur across a wide range of locations from rural areas to heavily populated urban areas and stations where they may affect staff, passengers, and the public. Understanding the spatial distribution of emissions across the network is therefore a key step prior to developing policy and determining where to focus mitigation measures. For example, the mapping capability has already been used to help determine a list of 105 stations to be included in a national rail air quality monitoring network.

In the rail freight sector, about 90% of traction is diesel powered. Freight trains need to run across the entire rail network—only 38% of which is currently electrified (ORR, 2021) on a route kilometre basis. Electric locomotives can only operate on routes which are electrified from beginning to end, including the depots. Other than electric traction, diesel is currently the only fuel which has the energy density needed to pull loaded freight trains, which can weigh up to 4,000 tonnes. It is estimated that approximately 35-40% of all diesel engines used for traction on the GB railway did not have an applicable emissions standard at the time of manufacture.

2. Methodology

2.1 Emission factors

The first step in developing an accurate map of emissions is to ensure a set of emission factors exists which is up to date, based on best possible data sources, and representative of as much of GB rail's diesel fleet as possible. Emissions estimates are usually calculated by applying an average emission factor to an appropriate activity statistic. That is:

Emissions = Emission Factor x Activity

Previously, rail emission factors (such as those utilised in the UK NAEI) related emissions to distance travelled i.e. g/km. When estimating emissions using this type of factor, a constant rate of emissions is assumed per distance travelled, regardless of the operating condition of the train and how the diesel engine powering the train is running. Therefore, no account is taken of how emissions might vary if the train is idling, accelerating, decelerating or travelling at constant speed. Concerns were raised about the data quality, traceability and assumptions originally used to develop these factors (RSSB, 2020). Some new rolling stock had since been introduced with proxy factors used that were not based on emissions testing data. In some cases, rolling stock such as the Class 43 HSTs had been re-engined from pre-emissions standard Paxman Valenta engines to newer MTU UIC 2 compliant engines but the factors had not been updated accordingly.

Data quality and emissions calculation methods for other transport modes has improved significantly in recent years and the corresponding rail emissions data and methods needed to be updated to ensure more robust comparisons. Furthermore, a more accurate baseline of current emissions allows more robust decision making, identification of improvements, and more effective evidence-based policy decisions to be made.

Therefore, in 2019 RSSB commissioned a project to update the emission factors for GB rail. Full details of the methodology for diesel electric, hydraulic and mechanical transmission are given in the full report.

In summary, new emission factors were developed by first compiling engine test data, usually presented in units of grams of pollutant per kWh for each power setting or 'notch' of the engine. This data was complemented with auxiliary electrical load data, such as for cooling fans, so that emissions estimates could be adjusted to account for the additional load on the engine in real world operation. On-train monitoring recorder (OTMR) data was used to provide accurate data for this purpose. OTMR data also provided an accurate picture of how much time was spent in each engine notch during typical journeys so that the data could be aggregated into journey average figures in g/km.

Table 1 shows the relative change in g/km emission factors for key items of rolling stock brought about by this work when comparing new factors to old. As can be seen, in most cases rail emissions had been largely overestimated due to the out of date assumptions used. For example, updating the Class 43 PM_{10} emission factor to account for the newer engine, as well as other improved assumptions resulted in a 92% reduction in estimated PM emissions.

	% Change in g/km Factor	
Train Class	NOx	PM_{10}
150	-87	-60
158	-77	-63
43	-21	-92
220	-9.7	41
68 (passenger)	597	1120
Class 66 UIC1	7.2	-47
Class 66 Euro IIIA	-69.9	-78.4

Table 1: Relative change in g/km emission factors for key items of GB rolling stock

The suite of new factors was used in the 2019 NAEI, resulting in an overall drop in estimated rail NOx emissions in the UK of nearly 40% and a 64% reduction for PM_{10}. This resulted in new estimates of rail's total contribution to national emissions of around 1.77% for NO_2 and around 0.3% for PM_{10}.

<table>
<tr><td colspan="2"></td><td colspan="2"><u>Total Emissions (kT/year)</u></td><td colspan="2"><u>% of National Emissions</u></td></tr>
<tr><td colspan="2"></td><td>NO_2</td><td>PM_{10}</td><td>NO_2</td><td>PM_{10}</td></tr>
<tr><td rowspan="2">NAEI Year</td><td>2017</td><td>24.54</td><td>1.25</td><td>2.81</td><td>0.70</td></tr>
<tr><td>2019 – including updated emission factors</td><td>14.84</td><td>0.45</td><td>1.77</td><td>0.30</td></tr>
</table>

Table 2: Impact of improved g/km emissions on total national estimated in the NAEI

2.2 Notch-Based Emission factors

As well as being a key step in developing more accurate average g/km based factors, emission factors by notch provide various benefits in their own right. As previously explained, using g/km factors oversimplifies the variation of emissions according to engine operation and does not allow the evaluation of local impacts, particularly of idling trains. Table 3 shows the emissions for a Class 158 DMU by engine notch in units of g/kWh. Plotting this data illustrates that emissions of NOx and PM are not linear according to engine power output (Figure 3) or fuel consumption i.e. CO_2 emissions (Figure 4). Emissions of NOx and PM tend to be significantly higher on a 'per unit power' basis at lower engine powers associated with engine idling. Therefore, using emission factors by engine notch allows a much more detailed prediction of emissions for individual segments of a journey. Engine idling is important to understand as this is the condition that rail engines spend the majority of their time in, especially in sensitive locations such as stations. This is an issue recently identified as of key importance in enclosed stations on the GB rail network (RSSB 2019). Further explanation of the drivers and causes behind emissions formation are given in the full report.

Engine Notch	Engine Power (Inc. Auxiliary Loads) (kW)	NOx (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
0	26	17.06	5.29	726
1	47	10.45	1.6	648.21
2	64	9.39	0.92	635.9
3	107	8.87	0.46	496.18
4	146	7.74	0.36	496.41
5	177	6.36	0.31	481.32
6	214	5.14	0.26	473.69
7	261	3.11	0.22	586.14

Table 3: Class 158 emission factors by engine notch

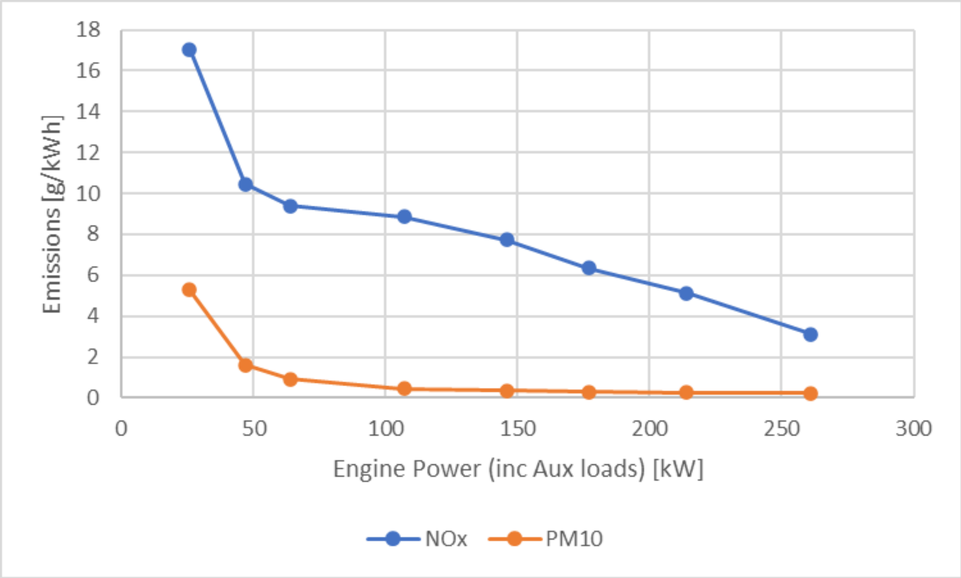


Figure 3: NOx and PM emissions vs engine power

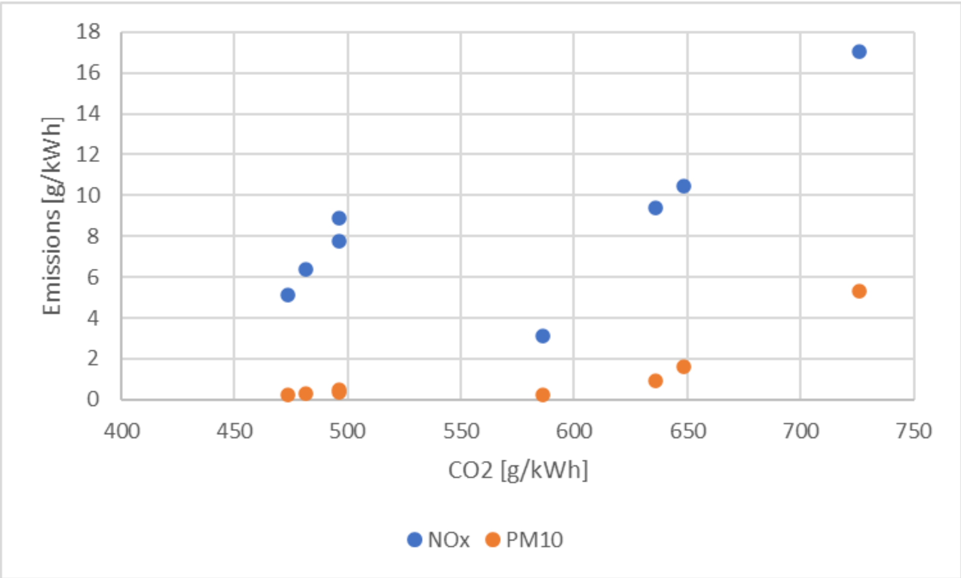


Figure 4: NOx and PM emissions vs CO_2 emissions

Emission factors by notch were developed for the following train classes which are the most common locomotive and rolling stock types covering ~91% of current passenger diesel mileage and ~97% of freight diesel mileage in 2018:

- Sprinters (Classes 150, 153, 155, 156)
- Express Sprinters (Classes 158, 159)
- Network Turbos (Classes 165, 166)
- Turbostars - Hydraulic transmission (Classes 168, 170, 171)
- Turbostars - Mechanical transmission (Class 172)
- Cordia (Class 180)
- Desiro (Class 185)

- Civity (Class 195)
- Voyager/Meridian (Classes 220, 221, 222)
- IET (Classes 800, 802)
- HST (Class 43)
- Locomotive Classes 57, 59, 60, 66, 67, 68, 70.

2.3 Activity Data

As explained previously, emissions estimates require both emission factors but also up to date activity data. Rail emissions spatial distributions in the NAEI were based on rail activity data from 2011 meaning a full update was required to ensure estimates were as up to date and robust as possible. The approach required assembling a wide range of rail datasets available from open sources and from the rail industry. A number of detailed sources were combined describing network activity at the individual train level which was then aggregated to represent annual average activity on the rail network. The network was divided up into around 7,500 defined segments of the network between specific timing point locations (TIPLOCs). TIPLOCs are locations on the network that have an arrive, depart or pass time in the working timetable which means that train movement data can be logged to provide a basic level of detail required to characterise emissions or other attributes such as noise. All stations have a TIPLOC as do junctions, depot entry/exit points and crossovers etc. Train running information was collected for the 2019 calendar year through Network Rail's Open Data platform, making use of the Train Movement (TRUST), Train Describer and SCHEDULE feeds. The train power type (i.e. diesel or electric) and passenger or freight classification of the services was primarily based on the activity data from the Open Data platform.

Activity data were processed to provide the annual aggregated train km between each TIPLOC. Diesel multiple unit (DMU) trains usually have a diesel engine under each carriage or vehicle so additional data was processed from the Network Rail Track Access Billing System (TABS) to determine an annual average number of carriages per train. Emissions could then be calculated for each inter-TIPLOC segment on the rail network individually.

2.3 Geospatial Mapping

The key end requirement of the project was to display rail emissions data in a granular and accurate manner within the mapping tool. To achieve this, it was necessary to create a geospatially accurate view of the rail network that was sufficiently simplified to enable emissions statistics to be processed and then presented in a clear and user-friendly manner. The following figures show the TIPLOCs and inter-TIPLOC segments mapped using Birmingham as an example area:

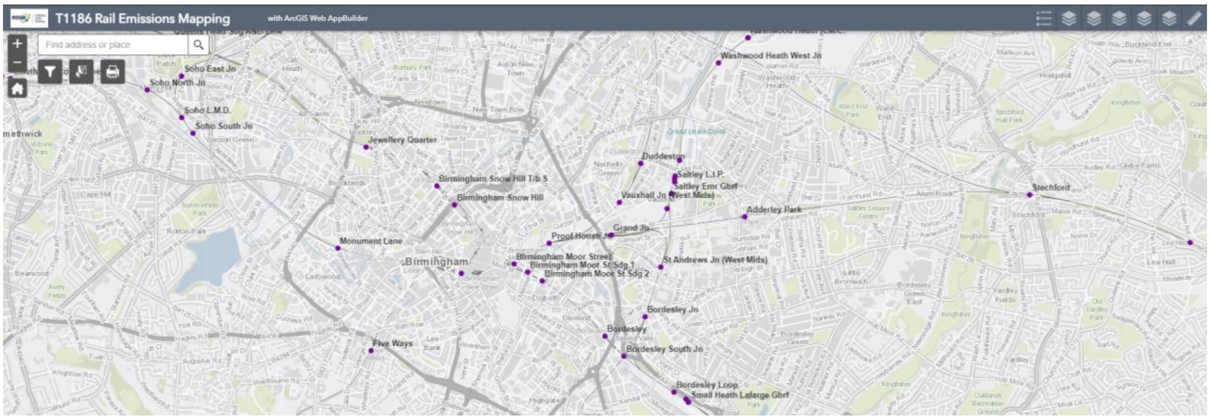


Figure 5: TIPLOCS in the Birmingham area

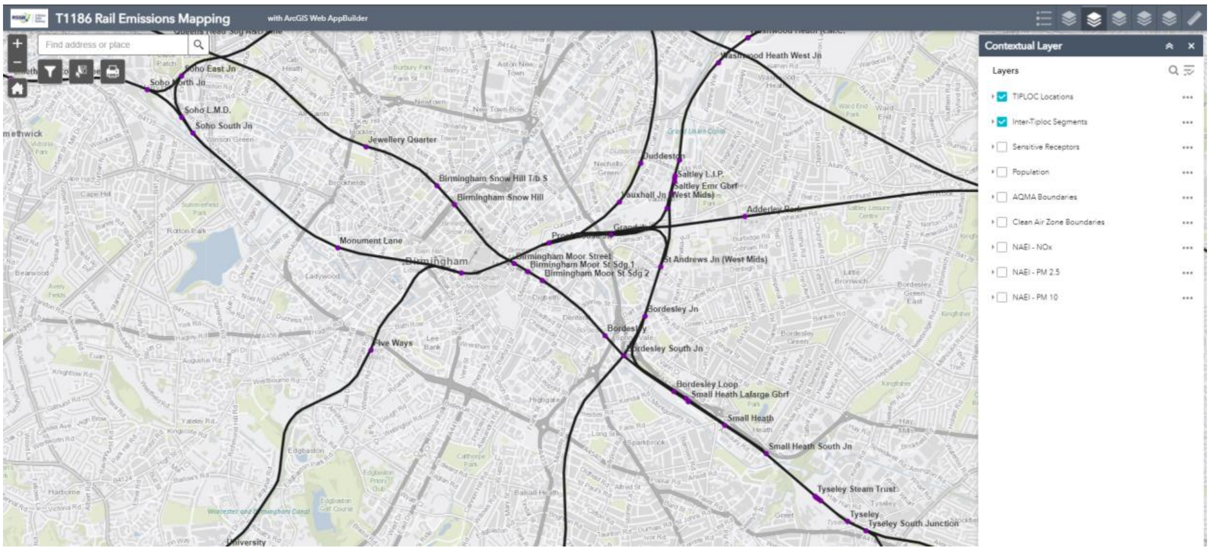


Figure 6: Rail network in the Birmingham area with TIPLOCs overlaid

2.4 Online Mapping Tool

An online mapping tool was developed using the ArcGIS Online platform which can be accessed using most internet browsers. The tool is able to display the following information in a range of layers selectable by the user:

- Inter-TIPLOC segments for which the emissions predictions are carried out
- Population density information
- Air Quality Management Area (AQMA) boundaries and
- Clean Air Zone (CAZ) boundaries
- Previous NAEI rail emissions estimates (total NOx, PM_{10} and $PM_{2.5}$ emissions per km^2 grid increment)
- Total and detailed rail emissions per inter-TIPLOC segment for NOx, PM_{10} and $PM_{2.5}$ for:
  - The entire network based on updated g/km distance-based emission factors
  - 10 selected areas using notch-based emission factors to derive higher resolution predictions
- A viewable attribute table showing details of rolling stock in operation, train operator and a breakdown of emissions for each type of rolling stock for each inter-TIPLOC segment.

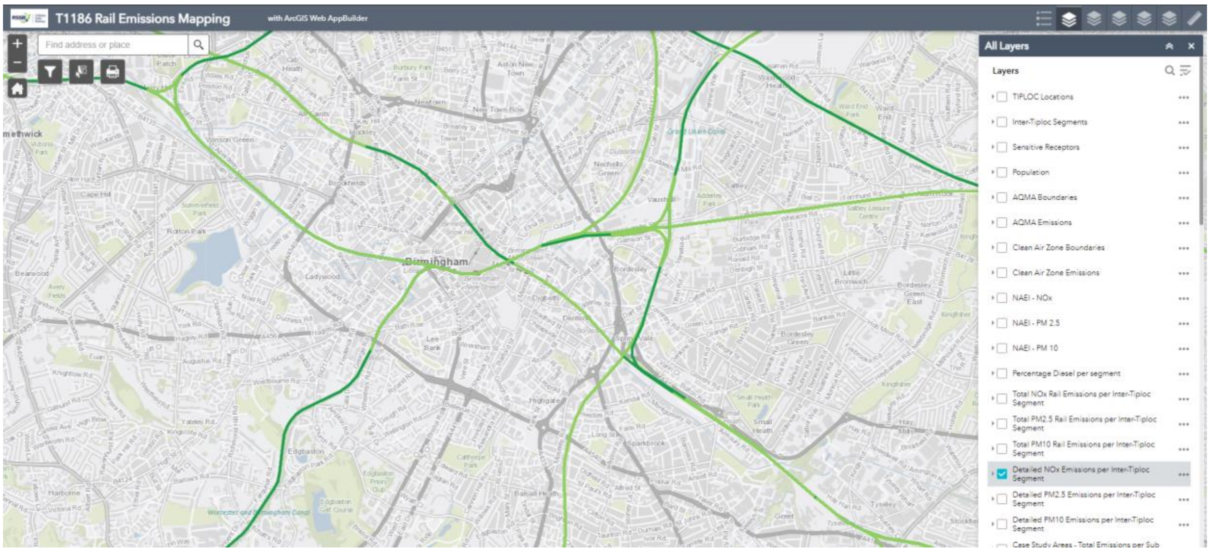


Figure 7: Mapped emissions in the Birmingham area using g/km emission factors

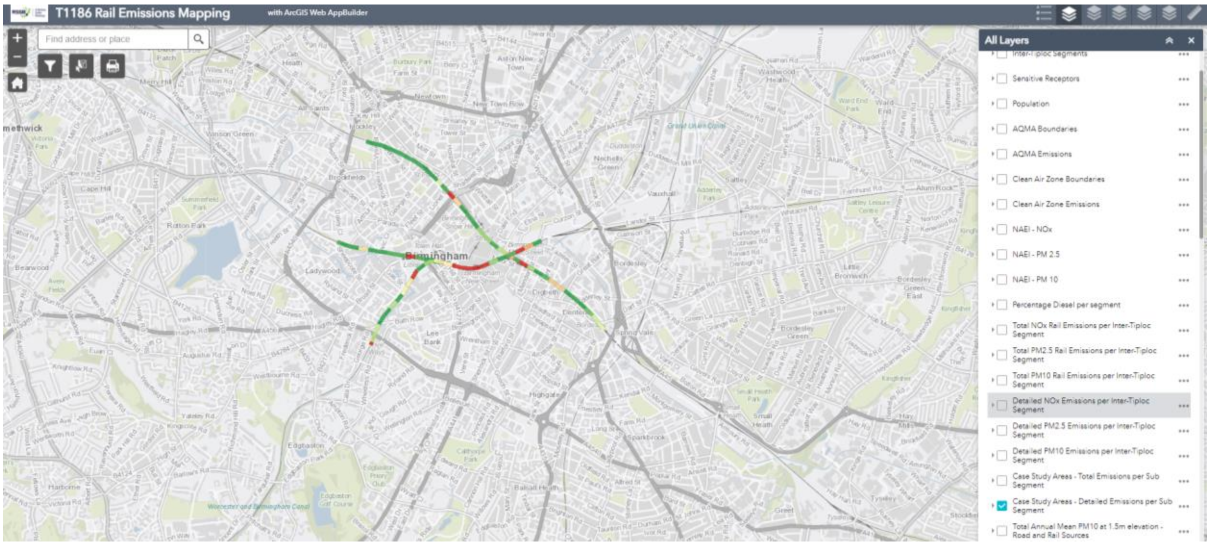


Figure 8: Emissions predictions in the central Birmingham area using notch-based emission factors

3. Insights

As previously discussed and shown in Figure 9, rail emissions estimates in the NAEI provided limited insights on localised variations of emissions by presenting rail emissions in 1 km^2 grid square increments with rail emissions averaged over long distances. Furthermore, these emissions estimates provided no detailed breakdown of the types of rolling stock operating in an area and what contribution such rolling stock had to total rail emissions in that area. The information contained in the new mapping tool allows many new insights to be developed regarding rail emissions and some of these are described here.

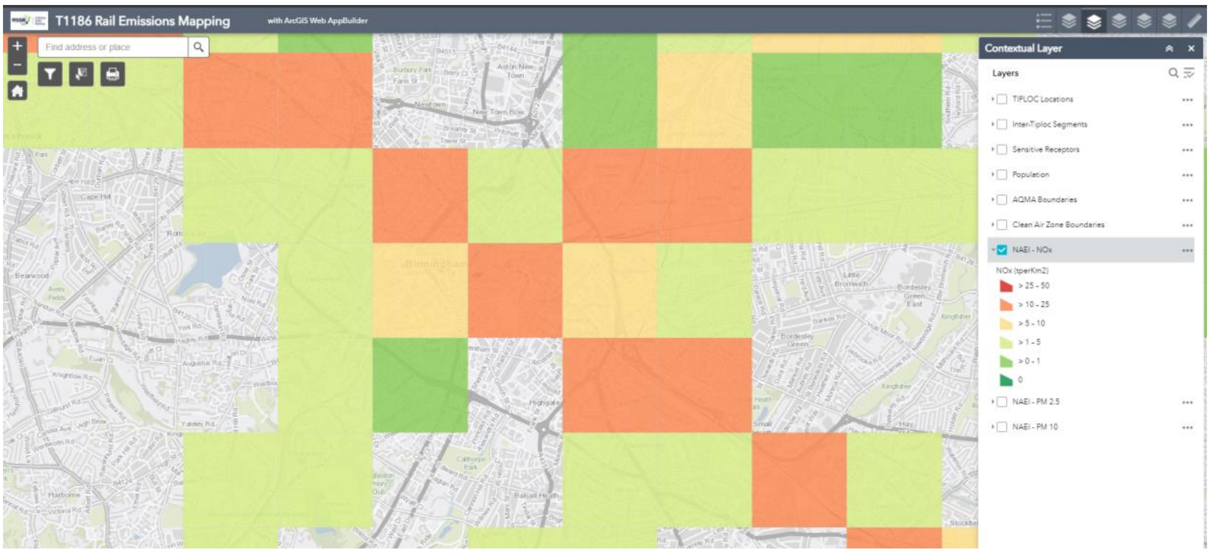
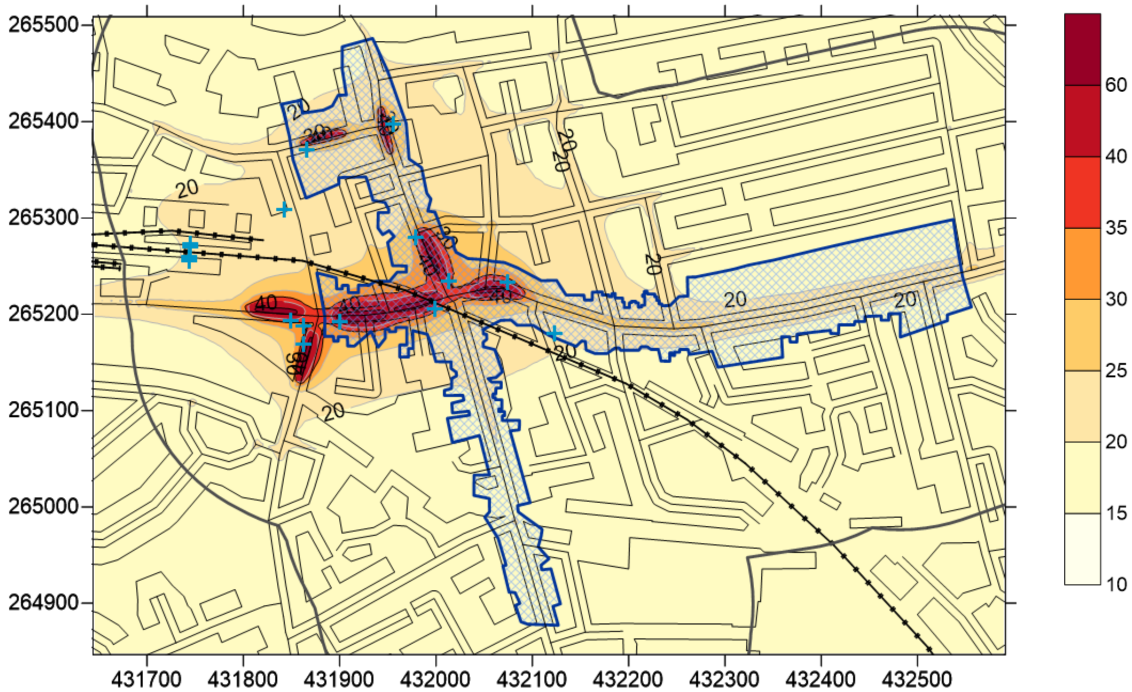


Figure 9: NAEI mapped emissions per 1 km^2 grid cell in the Birmingham area

3.1 Dispersion Modelling

Leamington Spa was one of ten areas where detailed emissions mapping was carried out using notch-based emission factors. This allowed a detailed study to be undertaken to assess the impact of rail emissions on the Leamington Spa town-centre AQMA. An elevated railway line runs through the centre of the AQMA and passes the busy junction of High Street and Bath Street. The industry standard ADMS-Roads dispersion model was used to determine the impact of emissions from the railway network on sensitive receptors. The area for the dispersion modelling study was defined using a 200 m buffer around the AQMA. Emissions from the local road network were modelled using standard techniques and combined with the detailed rail emissions estimates for NOx, PM_{10} and $PM_{2.5}$. The impact of the road and rail sources was then combined with background emissions to predict total annual mean concentrations of NO_2, PM_{10} and $PM_{2.5}$. Finally, the predicted concentrations were compared against the relevant annual mean objectives (Defra, 2022), and the contribution of rail emissions sources was assessed in an attempt to determine the significance of its impact on local air quality.



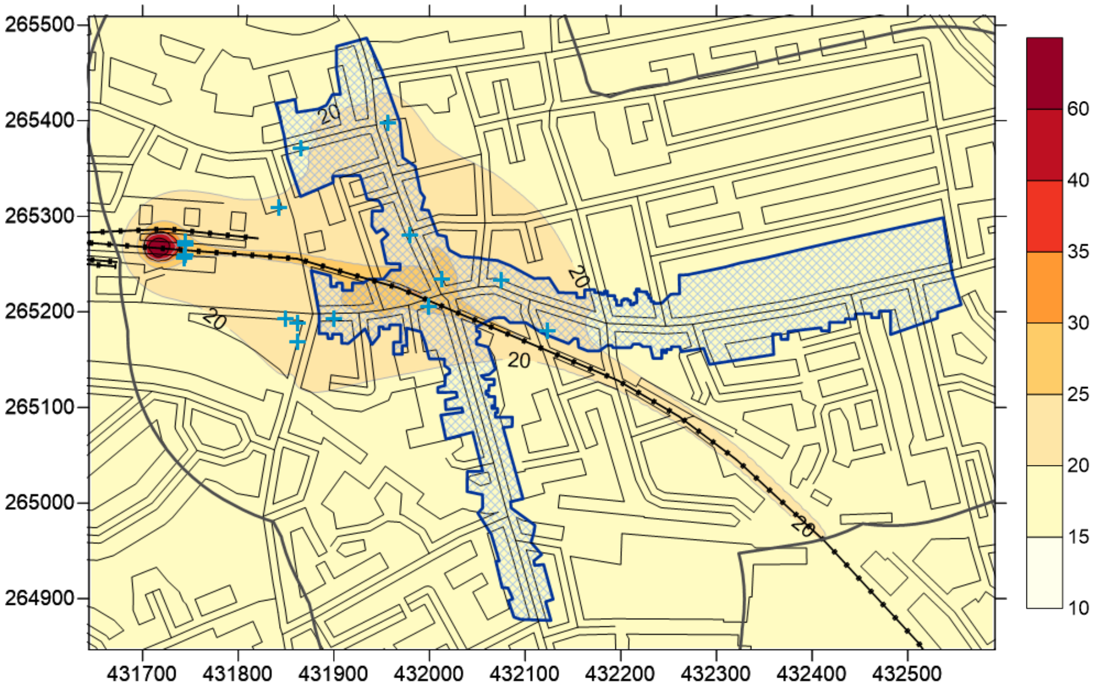


Figure 10: Estimated total annual mean NO_2 concentrations(µg/m3) in 2019 at 1.5 m (top) and 8.5 m (bottom)

The results showed a large variability in annual mean NO_2 concentrations across the study location, with exceedances at busy road junctions. It was estimated that the railway network contributes to between 3 – 30% of the total annual NO_2 concentrations at relevant receptors, compared to a 5 – 63% contribution from road sources. The impact of the railway network was greatest at the railway station platform, where it was estimated to contribute approximately 8 µg/m^3 to the annual mean NO_2 concentrations. The impact of the railway network was much lower compared to the impact of road sources. At the modelled sensitive receptor locations, the railway network was found to contribute up to 11% of the annual mean NO_2 concentrations. However, the total concentrations were relatively low at these locations. In contrast, at the worst-case locations where concentrations are close to the objective level, the road network contributed approximately 50% of the annual mean NO_2 concentrations.

In contrast to NO_2 concentrations, much lower concentrations of PM_{10} and $PM_{2.5}$ are estimated which are well within the mean objectives. The railway network in this area is estimated to contribute up to a maximum 11% and 2%, respectively, to total PM_{10} and $PM_{2.5}$ concentrations.

3.2 Forecasting Emissions Reductions

The mapping of emissions by inter-TIPLOC segment allows an accurate picture of the contribution to total emissions of the various types of rolling stock operating at a particular part of the network. This means a reasonably accurate picture can be built up for certain stations (which by their nature will always have associated TIPLOCs). For example, Table 4 shows the top contributors to total NOx and $PM_{2.5}$ emissions at Edinburgh Waverley station in 2019:

Operator	NOx Contribution	$PM_{2.5}$ Contribution
ScotRail	39.7%	56.4%
LNER	26.7%	10.7%
CrossCountry	21.2%	23.2%
Caledonian Sleeper	5.4%	1.7%

Avanti West Coast	3.9%	5.1%
TPE	1.8%	1.0%

Table 4: Percentage contribution to total rail emissions by operator at Edinburgh Waverley in 2019

Having this type of insight allows forecasts to be made of the likely improvements in overall emissions in the future through changes in rolling stock and/or electrification programmes, at particular stations, along certain routes, or across the network. GB rail has recently made significant investment in new rolling stock. Therefore, in the near future, newer, cleaner trains will enter into service and replace older more polluting trains. For example, Class 80x bi-mode trains are now in operation on Great Western and Trans Pennine routes and will be introduced to Avanti West Coast and East Midlands Railway. The Stadler Class 755 bi-mode has also been introduced on Greater Anglia routes. Bi-modes significantly reduce the amount of running 'under the wires' where diesel power is used on electrified lines.

A large reduction in emissions is expected in Birmingham New Street and other stations when Avanti replace their current Class 221 Voyagers with Hitachi Class 80x trains. The fleet will comprise 10 7-car electric sets for London, West Midlands and Liverpool routes along with 13 bi-mode sets for use on North Wales routes. Based on RSSB estimates, replacing the Avanti Voyager fleet will result in over 95% emissions reduction in London Euston and over 20% reduction in Birmingham New Street.

Likewise, replacement of East Midlands Railway's diesel stock with Class 80x bi-modes and electric trains is expected to almost eliminate traction exhaust emissions in London St Pancras while cutting emissions in Nottingham and Sheffield by more than half.

4. Conclusions

The work outlined in this paper has significantly advanced the GB rail industry's ability to understand its emissions impact at both a national and local level. Emissions estimates are no longer averaged along entire routes and now provide a clearer picture of local variations. The use of up to date and more granular rail activity data means that the estimates are built upon a much more realistic picture of rolling stock and how this operates across the network. Updated g/km based emission factors based on specific engine test data provides more confidence in the estimates used and more detailed notch-based (g/kWh) factors allow higher resolution estimates to be made to account for real world operating patterns and specifically the impact of engine idling. This paper has outlined some of the insights which are now possible and have already been used in a number of other air quality research projects being undertaken by RSSB.

Acknowledgments

The authors would like to thank Network Rail for provision of the rail GIS and activity data as well as many GB rail organisations including Porterbrook, Angel, MTU, First Group, Scotrail etc. for provision of emissions and drivetrain data for the development of the emission factors.

References

[1] Defra (2019), Clean Air Strategy, https://www.gov.uk/government/publications/clean-air-strategy-2019
[2] COMEAP (2018), Nitrogen dioxide: effects on mortality, https://www.gov.uk/government/publications/nitrogen-dioxide-effects-on-mortality
[3] NAEI (2019), National Atmospheric Emissions Inventory, https://naei.beis.gov.uk/
[4] Defra (2019), Clean Air Strategy, https://www.gov.uk/government/publications/clean-air-strategy-2019
[5] Defra (2022), AQMAs interactive map, https://uk-air.defra.gov.uk/aqma/maps/
[6] RDG (2018), Long Term Passenger Rolling Stock Strategy for the Rail Industry, https://www.raildeliverygroup.com/files/Publications/2018-03_long_term_passenger_rolling_stock_strategy_6th_ed.pdf
[7] ORR (2021), Rail Infrastructure and Assets, https://dataportal.orr.gov.uk/media/2014/rail-infrastructure-assets-2020-21.pdf
[8] RSSB (2020), Fleet wide assessment of rail emission factors (T1187), https://www.rssb.co.uk/en/research-catalogue/CatalogueItem/T1187
[9] RSSB (2019), CLEAR: Research into air quality in enclosed railway stations (T1122), https://www.rssb.co.uk/research-catalogue/CatalogueItem/T1122
[10] Defra (2022), UK Air Quality Limits, https://uk-air.defra.gov.uk/air-pollution/uk-eu-limits