RSSB

A Better, Safer Railway

CLEAR: Fleet-Wide Assessment of Rail Emissions Factors

Emission Scenarios Report

RESEARCH AND DEVELOPMENT

Copyright

Written by:

Georgina Mansell, Assistant Consultant, Aether Ltd.

Rosie Brook, Senior Consultant, Aether Ltd.

Neil Grennan-Heaven, Director, Carrickarory Consulting Ltd.

Mark Gibbs, Principal Consultant, Aether Ltd.

Published:

June 2020

Executive Summary

The main report[1] produced under the RSSB T1187 project, *CLEAR: Fleet-wide assessment of rail emission factors,* provided the background, methodology and justification for utilising a new approach for estimating rail emissions by undertaking the calculations using emission factors as a function of notch (engine operating condition). By considering emissions as a function of useful energy delivered in different engine operating conditions, total emissions for specific routes can be calculated according to the operation of the train by using on-train monitoring recorder (OTMR) data and train loading data. Using this methodology, emission factors by notch have been developed for diesel electrical, diesel hydraulic and diesel mechanical transmission operations.

This report uses the emission factors for four major GB locomotive and train classes (66, 158, 170, 220/221) as a function of notch to demonstrate the impacts of different journey scenarios on emissions of NO_x, particulate matter (PM) and CO_2. These include the impacts of reducing idling in stations, the effect of reducing the number of stops in a journey, the effect of maintaining a more constant speed during the journey, and the effect of different freight loadings.

This report is aimed at help environmental, engineering and finance staff in organisations throughout the GB rail industry. It is intended to help stakeholders understand the effectiveness of different approaches to reducing rail emissions.

Key findings of the project were:

- Stop-start systems (different technologies and installation on different rolling stock types) can act to automatically switch off engines after they have been idling for more than 15 minutes. However, analysis of the OTMR data showed that in some instances, stop-start is not always used and can be over-ridden by drivers as its use is not always appropriate. Operator driver training can help reinforce appropriate shut down behaviours.
- In the freight OTMR data, the sampled locomotives spent between 1 and 15 hours (with an average of 6.8 hours) in yards before and after their journey. They spend the majority of this time stationary but travel small distances, often in several small increments interspersed over the period (for example joining or splitting trains that are longer than the loading or unloading sidings).
- The amount of emissions generated while a freight locomotive is idle with the engine still operating will depend on its emission standard. However, in all cases emissions of CO_2, NO_x and PM will continue to increase linearly with time. PM emissions were shown to increase at the steepest rate.

[1] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.

- Long layovers within or between scheduled passenger services offer the opportunity to reduce idling if a train engine can be effectively shut down while maintaining auxiliary loads.
- Delays in the approach to stations result in significantly higher emissions of NO_x, PM and CO_2. This highlights the importance of the emissions produced when accelerating from low speeds, such as in urban or station environments.
- Heavier freight trips have lower emissions per tonne-mile for all three pollutants. There is strong evidence that heavier freight loadings are more fuel and emissions efficient.
- Running two diesel multiple units (DMUs) on a service instead of a single DMU does not result in double the emissions. For journeys with three or five stops, total emissions of NO_x, PM and CO_2 were on average 48% greater for units running in multiple compared to individual units. For journeys with a stopping pattern of six stops the emissions were on average only between a fifth and a quarter higher for units running in multiple compared to individual units.

Examples of the level of granularity available from case studies include:

- A period of approximately 16 minutes stationary idling during a total journey time of 2 hours and 45 minutes undertaken by a Class 158 was found to increase total CO_2, NO_x and PM emissions by 1.5%, 1.1% and 3.3% respectively.
- For a 12.5-mile segment of a Class 66 journey, being able to maintain a constant speed throughout compared to slowing to a stop and accelerating back to speed reduced NO_x, PM, and CO_2 emissions by 0.62 kg, 0.025 kg, and 38.3 kg respectively. This represents savings of 0.72% (NO_x), 0.97% (PM) and 0.69% CO_2 of emissions for the total 229-mile journey.
- When the number of stops was increased for a Class 158 and 170 train from two to six over the same 40-mile journey, it was found that NO_x emissions increased by between 26% and 60%, PM emissions by 50% and CO_2 emissions by between 40%.

The approach presented in this report can be applied to further specific scenarios provided relevant OTMR data is available. It can also be used to develop detailed spatial distributions of rail emissions, as well as evaluating specific mitigation solutions and supporting rolling stock and infrastructure investment cases.

List of abbreviations

ABB	ASEA Brown Boveri
BREL	British Rail Engineering Limited
C-DAS	Connected Driver Advisory System
CLEAR	Clean Air Research Programme
CO	Carbon monoxide
CO_2	Carbon dioxide
DfT	Department for Transport
DMU	Diesel multiple unit
EMD	Electro-Motive Diesel
ETCS	European Train Control System
FOC	Freight operating company
GPS	Global Positioning System
NO_X	Nitrogen oxides
NRMM	Non-road mobile machinery
OTDR	On-train data recorder
OTMR	On-train monitoring recorder
PM	Particulate matter
TOC	Train operating company
SS	Stop-start (engine shut-down system)
TMS	Traffic Management Systems
TOPS	Total Operations Processing System
TRUST	Train Running Under System TOPS
UIC	International Union of Railways

Table of contents

Tables

Figures

1 Introduction

RSSB has established an Air Quality Steering Group comprising members from across the rail industry who oversaw development of an Air Quality Strategic Framework[2] which was published in June 2020. The framework is underpinned by the RSSB Clean Air Research Programme (CLEAR) which incorporates robust research to measure air quality on the rail network and gain a better understanding of rail's contribution to local pollution levels. As well as informing the development and refinement of the Air Quality Strategic Framework, this research will also support the rail industry in establishing a 'baseline' from which potential improvement measures can be evaluated against.

This particular report covers analysis of the impacts of operational requirements on rail emissions carried out for Work Package 3 of the RSSB T1187 project, *CLEAR: Fleet-wide assessment of rail emission factors,* one of several CLEAR projects. An associated main project report[3] provides the background, methodology and justification for utilising a new approach for estimating rail emissions by undertaking the calculations using emission factors as a function of notch (engine operating condition).

Themes identified in the main report include the relative importance of emissions in idle compared to other notches, that emissions are not necessarily linearly related to fuel consumption, and that emissions of air quality pollutants vary according to the engine operating condition (how the fuel is combusted). All these issues underline the need to understand how rail emissions are generated and can vary at a local scale. Generation of emissions in idle or while accelerating at low speeds is important, particularly in enclosed stations where there is potentially high exposure to air quality pollutants for both staff and public.

This report describes a methodology that uses emission factors by notch and on-train monitoring recorder (OTMR) data to quantify the specific effects of changes in engine power outputs and hence changes in emissions from trains having to decelerate, stop and idle, accelerate and/or run at different speeds. This approach allows assessment of the impact of operational requirements, infrastructure limitations, and line speed features on train emissions. Although localised studies of rail emissions have been carried out in the US (e.g. of key freight yards and corridors[4, 5, 6]) where emission factors by notch are widely available, limited studies of such detail, particularly of passenger train emissions, have been carried out so far in Europe.

---

[2] GB Rail Industry (2020). *Air Quality Strategic Framework*. RSSB.
[3] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.
[4] Lindhjem, C. (2008). 'Intermodal yard activity and emissions evaluations', *17th International Emission Inventory Conference*, Portland, Oregon.
[5] Sangkapichai, M., J.-D. Saphores, S. Ritchie, S. You and G. Lee (2009). 'Estimating PM and NO_x train emissions in the Alameda Corridor, California', *Proceedings of the 88th meeting of the Transportation Research Board*, Washington D.C.
[6] Gould, G. M. (2010). *A spatially detailed locomotive emission model and goods movement data constraints on public policy and planning*. University of California, Davis, Institute of Transportation Studies, Research Report UCD-ITS-RR-10-50.

Section 2 of this report covers the emission scenarios and the train classes considered in this study. Emission factors by notch and how they can be combined with OTMR data to calculate temporally granular emissions estimates are discussed in Section 3. Section 4 describes how the OTMR data for each train class was processed and analysed, and a range of specific case studies addressing different emission scenarios are presented in Section 5. Key learnings and conclusions are given in Section 6.

2 Goals of this study

2.1 Emission scenarios considered

This report describes the use of the emissions factors as a function of engine notch (derived during this project) to demonstrate the sensitivity of NO_x, PM and fuel consumption/CO_2 to various operational factors. These include:

- idling reduction in stations
- engine idling in freight loops and at signals
- effect of reducing the number of stops in a journey
- effect of maintaining a more constant speed during a journey
- smooth entry into terminus stations
- effect of increased loading (freight and passenger).

These factors can be grouped into three categories of scenarios:

- What is the cost of stopping (regaining speed, remaining in prolonged idle)?
- What is the impact of infrastructure restrictions (e.g. a reduced junction speed)?
- Variations in loadings (number of units in a train, amount of cargo hauled).

Specific case studies are presented here which evaluate one or more of these emission scenarios. They are based on specific real-world situations identified in the OTMR or else relevant counterfactual scenarios to determine emissions costs of events such as stops caused by network congestion. The results of the case studies can be used to evaluate the effectiveness of various emissions mitigation measures and strategies.

2.2 Train classes considered

Four major GB locomotive and train classes (66, 158, 170, 220/221) were considered. These classes are all used extensively on a wide range of routes and types of services by multiple operators. Collectively, they represent 32% of 2018 diesel passenger services and 83% of 2018 diesel freight services (by fuel usage). Furthermore, these classes are broadly representative of other similar classes to which learnings can also be applied, e.g. Classes 150-156, 159, 165-166, 168, 171 and 222 which combined with Classes 158, 170 and 220/221 then cover 55% of 2018 diesel passenger services by fuel usage.

The Class 66 locomotive is the mainstay of GB diesel freight traction, with around 400 in active service with five freight operating companies (FOC). It was manufactured by Electro-Motive Diesel (EMD) in several batches between 1998 and 2016. The 12N710G3B-EC engine was supplied in three main emission variants, complying with the UIC1, UIC2, Euro IIIA emission standards (which are discussed further in the main project report[7]). The Class 66 has electrical transmission. Based on extensive testing of the same engine family in the US, emissions by notch for the Class 66 are very well understood, and many aspects can be applied to other GB freight locomotives such as Classes 59, 60, 67, 68 and 70.

The Class 158 diesel multiple unit (DMU) is used on many regional passenger services, with 180 units currently in service with multiple train operating companies (TOC). It was initially manufactured by British Rail Engineering Limited (BREL) and later ASEA Brown Boveri (ABB) between 1989 and 1992. Installed engines are the Cummins NTA855R1 (350 hp) and NTA855R3 (400 hp) and the Perkins 2006-TWH (350 hp), which were not subject to any emission standards at the time of manufacture. Transmission is diesel hydraulic. Aspects of how emissions from this class are produced and quantified also apply to Classes 150-156, 159, 165 and 166.

The Class 170 is a more recent DMU, with 180 units (including the virtually identical Class 168 and 171) generally used on higher-speed regional passenger services by many TOCs. It was manufactured by Bombardier Transportation (previously ADtranz till 2000) between 1998 and 2005. The MTU 6R183TD13 engine is installed which is complaint with the prevailing UIC1 or UIC2 emission standard at the time of manufacture. Transmission is diesel hydraulic. Aspects of how emissions from this class are produced and quantified also apply to Classes 168 and 171.

The Voyager (Class 220/221) is currently used by two TOCs on high speed passenger services. 78 units were manufactured by Bombardier Transportation between 2000 and 2002. The Cummins QSK19 engine is installed. Although not subject to a compulsory rail emission standard at the time of manufacture, this engine does meet the non-road mobile machinery (NRMM) Euro II emission standard. Transmission is electrical and though often referred to as 'continuously variable', there are in fact three idle settings and 17 discrete power settings. The Class 221 was built with a tilting mechanism which is currently disabled by one of the two operators. The Class 220 does not have this feature and consequently has lighter bogies: the total weight saving by not having tilt fitted is just over 10 tonnes per vehicle. Aspects of emissions from these classes also apply to the Class 222 (Meridian).

[7] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.

3 Calculating Emissions

3.1 Emission factors by notch

Emissions of most air quality pollutants are not directly proportional to engine power and fuel consumption; if this were the case then all the bars in Figure 1 would be the same height (on g/kWh basis). Production of air quality pollutant emissions is heavily dependent on how fuel is combusted, and the specific drivers of these variations are described in the main report for this project. Rail emissions will therefore vary substantially depending on the particular (real world) drive cycle. For instance, NO_x and PM both have the highest intensity of generation (mass of emissions produced per unit power output) in idle compared to other notches (for example see Figure 1). The resulting concentrations of NO_x from idling trains in key areas such as enclosed stations can be above legal limits, while measured PM concentrations tend not be above legal limits in such locations. As such NO_x is the main GB rail emissions challenge but many of the issues are also applicable to PM.

While the intensity of NO_x (or PM) generation as a function of power output is highest at lower engine power outputs (as shown in Figure 1), the total NO_x produced is highest at higher power outputs as shown below in Figure 2 (with the NO_x emission rates in kg/hr).

Figure 1 **EMD emissions certification test data for NO_x emissions in g/kWh for the 710 V12 Euro IIIA specification engine (as used in the last 29 Class 66 locomotives ordered by GBRf)**

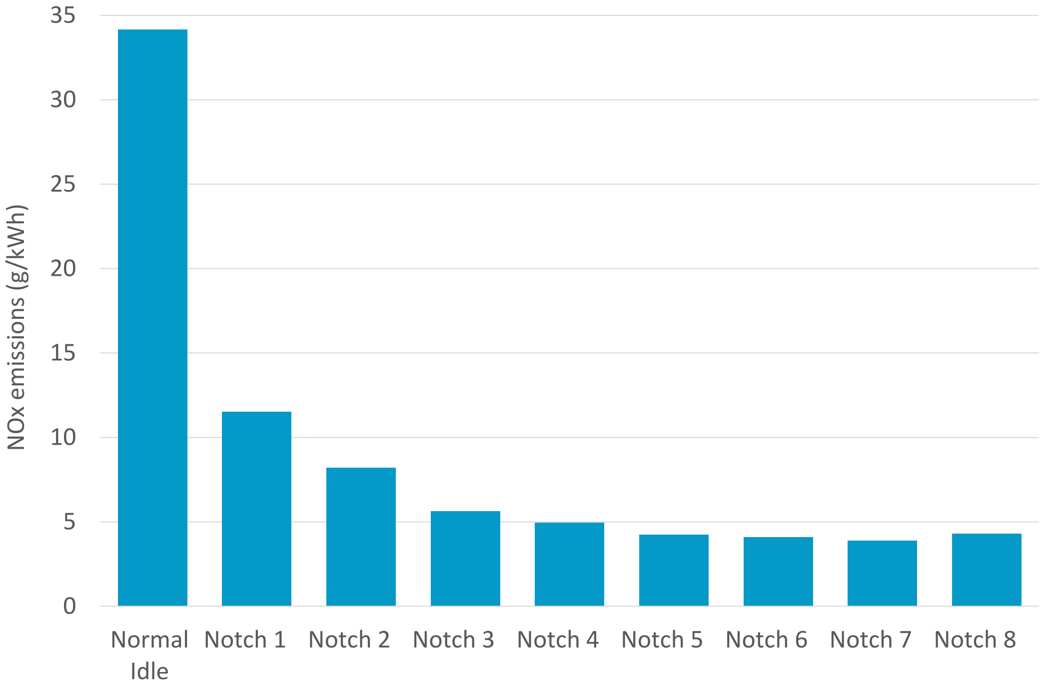
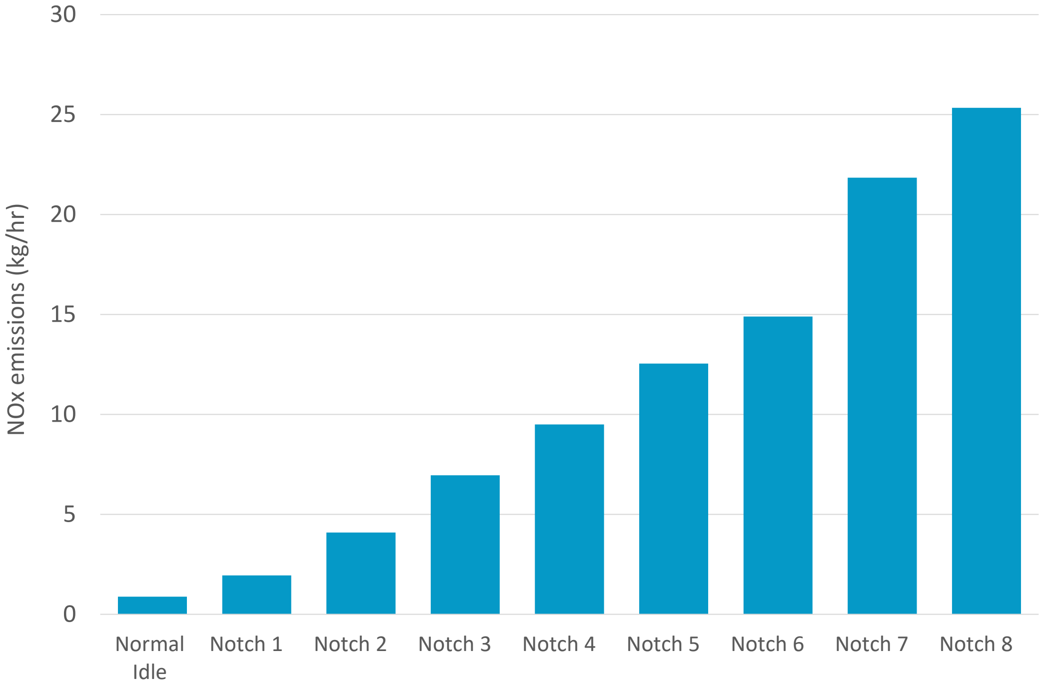


Figure 2 **NO_x emissions in kg/hour for the EMD 710 V12 Euro IIIA specification engine**



Factors in g/kWh relate emissions to the usable energy produced by the engine under certain conditions. Internationally, across multiple sectors, internal combustion engine emission testing and emissions standards are set in units of g/kWh and based on a given drive cycle. For rail diesel engines, the power generated is usually measured in kW. Most rail diesel applications have fixed pre-set throttle levels that correspond to fixed power outputs or fuel injection rates, thus power/notch factors (measured in g/kWh, emissions per unit power) are based on the physical operation of the engine and notches are well-known and used extensively in the rail sector outside of the UK. In addition, this unit of measure is well understood in terms of diesel or petrol engines across different transport sectors.

Emission factors in units of g/kWh offer an improved method to characterise and evaluate measures to reduce diesel engine emissions compared to more simplistic emission factors (e.g., in units of grams per kilometre distance travelled). They can be used to understand energy usage and emissions generated in all parts of a drive cycle, which in turn can vary significantly for the type of service and loadings. Essentially, EFs in g/kWh can incorporate sufficient granularity to reflect real world conditions and variability and therefore allow accurate modelling of rail emissions.

Emission factors by notch can be created by combining:

- high accuracy static testbed emissions testing (needed for engine certification)
- engine and rolling stock technical data
- OTMR data (to understand transmission efficiencies in different notches and at different speeds).

Notch-based emission factors for fuel, CO_2, NO_x and PM were developed as part of the main project work stream and are discussed in detail in the main project report. These emission factors also include auxiliary loads, for example in all cases powering air compressors to supply the braking system and in the case of passenger rolling stock providing electric power for heating ventilation and air conditioning (if fitted), the latter is often referred to as the 'hotel load'.

In the case of electric transmission rolling stock, the notch-based emission factors also include losses in the transmission system as these are far less speed dependant (typically an order of magnitude less variation) than for hydraulic or mechanical transmission. For hydraulic or mechanical transmission DMUs the transmission losses can be handled separately to the emission factors depending on the level of detail required and their calculation based on the proportion of time spent in each notch is discussed further in Section 4.2.3.

3.2 OTMR data

An on-train monitoring recorder (OTMR), also known as an on-train data recorder (OTDR), is a device that records data about the operation of train controls and train performance in response to those controls and other train control systems, primarily for the purposes of incident investigation. It is similar to the flight data recorder ('black box') found on aircraft. All trains operating on Network Rail-controlled infrastructure are required to be fitted with an event recorder, although the standard with which it complies will depend on the date of build of the rolling stock.

The exact format and contents of OTMR data varies by train class, but the method for calculating emissions is largely similar. OTMR data is typically structured as a series of entries, recorded in rows. Each row has a time stamp and a number of other fields recording the status of the vehicle at that point in time, such as the speed of travel, distance travelled and throttle setting, and in some cases Global Positioning System (GPS) location or door interlock status.

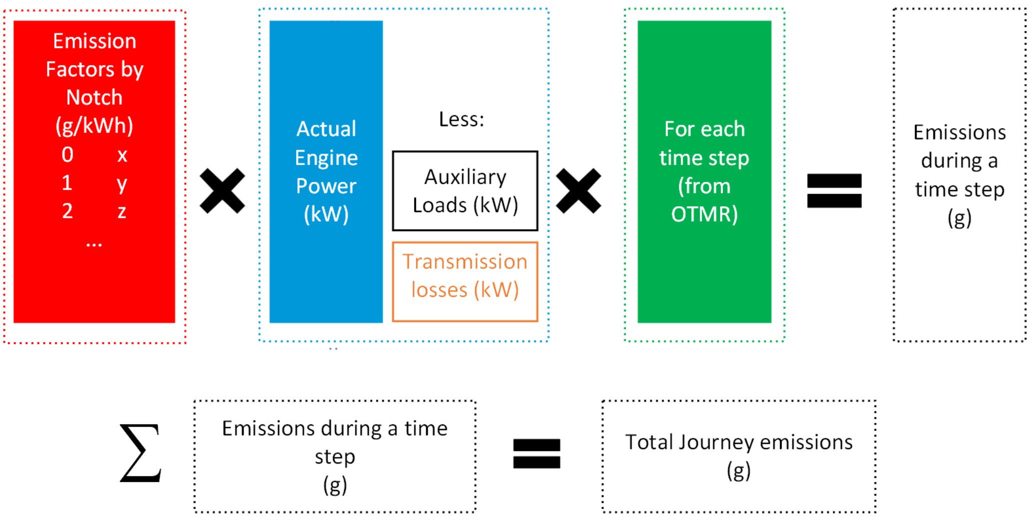
For this project OTMR data for the different locomotive and train classes studied were provided by multiple TOCs and FOCs. This data included multiple journeys over many days, allowing evaluation of many different operational issues based on actual stopping patterns, delays and variable train loadings.

3.3 Deriving emissions estimates

Emission factors by notch in g/kWh can be combined with route-specific OTMR data on engine output to calculate emissions for individual timesteps and then integrated to obtain a complete picture of emissions across a specific train journey.

To analyse OTMR data, a vehicle is assumed to remain in the same state until the next entry. The time difference between an entry (row i) and the next entry (row i+1) is the timestep, for which the train travelled at the speed and throttle setting as recorded in row i. The energy used in each timestep (kWh) can then be calculated by multiplying the typical nominal power usage at the engine (kW) for the train type and throttle setting by the duration of the timestep (h). The energy used in this timestep is then multiplied by emission factors (g/kWh) to determine the emissions (g) of the relevant pollutant (CO_2, NO_x or PM) produced in that timestep. These factors include auxiliary loads (such as hotel loads for passenger trains) and for electric transmission the transmission losses. Depending on the level of output detail required, these factors can also include average transmission losses for hydraulic or mechanical transmissions in the less detailed case. Since the emissions are calculated at such a fine level, with timesteps typically in seconds, the effect of different vehicle behaviours on a journey's total emissions can be discerned. A summary of this methodology is shown in Figure 3.

Figure 3 **Schematic summary of methodology for calculating emissions using emission factors by notch and OTMR data**



The exact format and content of OTMR data, and therefore the analysis undertaken, varied for Class 66, Class 158/170 and Class 220/221 since this depends on the specific technology and model of recording equipment installed. Explanations of the methods applied for each dataset are provided in Section 4.

4 Data analysed

4.1 Freight

4.1.1 Overview of available data

Fifteen OTMR data files for freight locomotives were gathered during the course of this project. These are large comma-separated text files containing real-time recorded information for a single freight locomotive over a number of days. Each file covered multiple trips, with each trip containing both time in yard and time on the journey between specific known locations. The OTMR contains information on the headcode (a four-character code manually typed in by the driver to identify the service), speed, time, distance travelled, notch, and a number of other fields.

Of the individual trips in the OTMR files, 47 had accompanying TRUST[8] and CONSIST[9] data available. This meant that the type of locomotive (from the locomotive number), train weight, and arrival and departure times were known.

Summary-level data for a further 10 trips was available. These data were processed in a previous FOC internal study, whereby the time in yard was trimmed and a drive cycle for each trip was calculated. The drive cycle, weight, and route of each trip were provided, but the raw OTMR data were not available. From the drive cycle, each trip's total emissions could be calculated.

In the total 57 trips, there were six different types of locomotives:

- 10 x 66-UIC1-75mph
- 6 x 66-UIC1-SS-65mph
- 25 x 66-UIC1-SS-75mph
- 9 x 66-UIC2-SS-75mph
- 1 x 59-None
- 6 x 70-EuroIIIa

The first part of the code refers to the locomotive class (e.g. Class 66), the second to the locomotive emission standard (e.g. UIC1), the SS indicates if the locomotive has stop-start fitted, and the final part indicates the maximum speed of the locomotive. The 10 trips with 66-UIC1-75mph locomotives are those with just summary-level data.

[8] TRUST is a Network Rail system used for monitoring the progress of all train movements and tracking delays on the rail network.
[9] CONSIST is a data system used by FOCs to identify the identity, order in train, gross and tare weight, and length of all wagons in a train; it enables determination of the length and the gross and net weight of a train.

4.1.2 Data processing

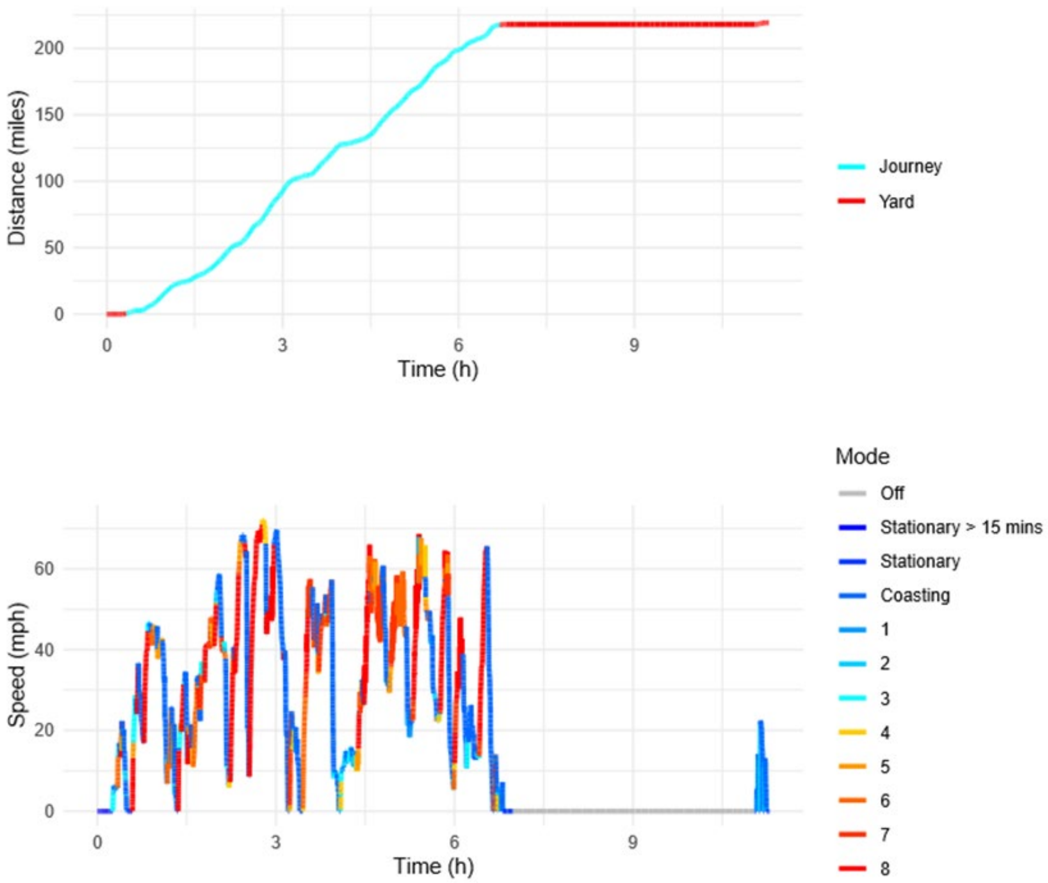
The OTMR data was separated into the 47 individual trips using the headcode information entered by drivers. The trips were matched to the corresponding information from TRUST and CONSIST using the time, date, locomotive number and headcode, before being allocated an anonymous ID (such as A1 or H5).

The OTMR recordings often included time spent in yards before or after the main journey, and so timesteps were allocated into 'Journey' and 'Yard' sections using the arrival and departure times from the TRUST data. An example of this allocation is shown in the upper panel of Figure 4.

The locomotive's mode at each timestep was determined using the speed, engine rpm, and throttle fields of the OTMR. This approach allows differentiation of what the locomotive is doing when the engine is idling, An example of the mode determination is shown in the lower panel of Figure 4, where the following logic was used:

- If the engine rpm was 0, the mode was 'Off'.
- If the speed was 0, the mode was 'Stationary' (S).
- If the throttle was 0 (the engine was at idle) but the speed greater than 0, the mode was 'Coasting' (C). (This includes both movement while braking as well as true coasting.)
- Otherwise, the mode was set to the recorded throttle notch - a value from 1 to 8.
- If the locomotive is stationary for more than 15 minutes, the mode was 'Stationary >15 mins' (S15+).

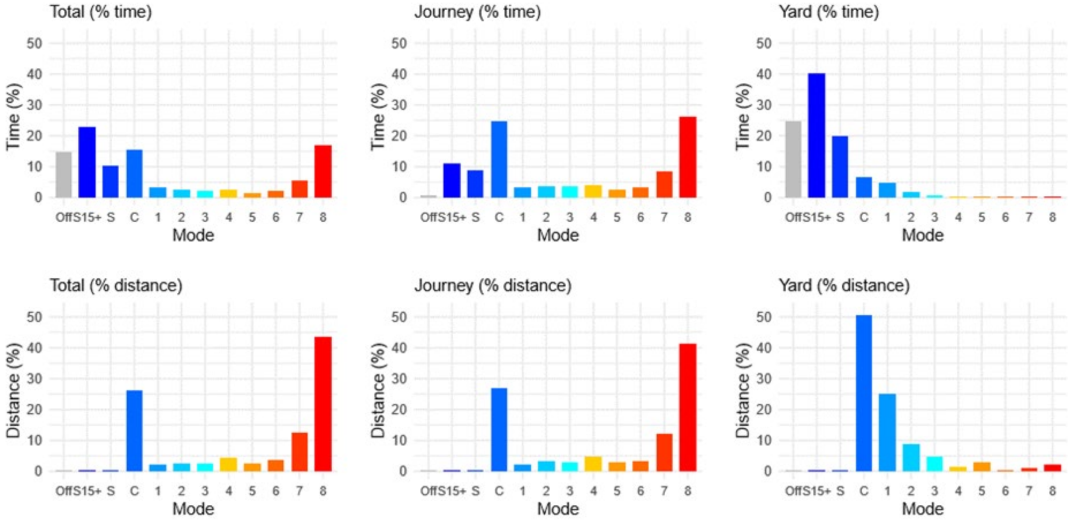
Figure 4 **Overview of Trip C1 showing (i) cumulative distance by time and (ii) speed and mode by time**



For each trip, a drive cycle could be calculated, which is the proportion of time the locomotive spent in each mode. From the OTMR data, different types of drive cycle could be constructed by considering the total trip recording, the Journey component, or the Yard component, on either a time or distance basis. Figure 5 shows each type of drive cycle as averages of the 47 OTMR trips.

Rail engines naturally have high amounts of time in idle with all locomotive electric transmissions permitting coasting due to the lower rolling resistance that is inherent to the physics of rail, but not road (or off-road), wheel movement. This allows a train to continue moving for many miles with the engine(s) effectively being disconnected from the wheels and the engine(s) just supporting auxiliary loads in idle – equivalent to a road vehicle being in neutral. For freight trains the range of time spent coasting or braking (the engine is in idle) during a journey ranges from 15-34% depending on load and route factors. Between 8%-40% of the distance covered in freight train journeys involves coasting or braking.

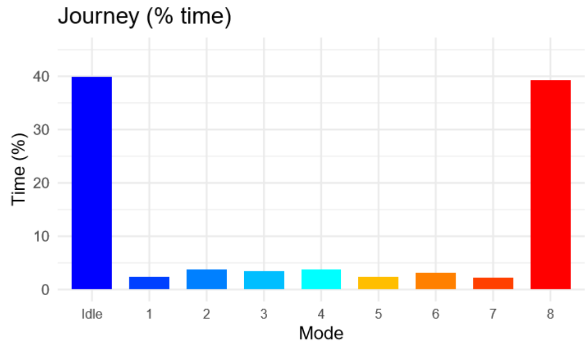
Figure 5 **Average drive cycles for freight trips with OTMR data**



The results are as expected. In the Journey drive cycle, most of the time spent and distance travelled is in Notch 8 or coasting. In the Yard drive cycle, most of the time is spent in the Off, Stationary, or Stationary >15mins modes, and the limited distance covered is in lower notches. Unsurprisingly, no distance is covered when the mode is Off or Stationary.

For the 10 trips with only summary data available, an average drive cycle was calculated and is shown in Figure 6. As the yard component was already removed from these data, the drive cycle is comparable to the 'Journey (% time)' panel of Figure 5.

Figure 6 **Average drive cycle for freight trips with summary data**



4.1.3 Freight emissions

For the 47 trips with OTMR data, NO_x, PM and CO_2 emissions were calculated for each timestep using emission factors by notch in units of g/kWh, as described in Section 3. Emission factors for Class 59, Class 66-UIC1, Class 66-UIC2 and Class 70 locomotives were derived during the course of this project[10] and examples are shown in Table 1 and Table 2. Emissions were then summed across the trip to obtain the total emissions but

[10] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.

these could also be investigated at a finer resolution when evaluating particular scenarios (see Section 5).

Table 1 Class 66 UIC1 emission factors by engine notch

Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
0	46	19.23	2.253	1040.7
1	188	10.38	0.160	775.2
2	314	13.02	0.398	822.6
3	581	11.98	0.391	784.6
4	856	11.10	0.288	726.6
5	1117	11.23	0.289	735.7
6	1372	10.86	0.285	711.1
7	2014	10.84	0.292	709.9
8	2460	10.30	0.283	704.9

Table 2 Class 66 UIC2 emission factors by engine notch

Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
0	46	17.90	1.623	1040.7
1	188	8.58	0.255	775.2
2	314	7.70	0.188	822.6
3	581	5.99	0.188	784.6
4	856	5.94	0.174	726.6
5	1117	5.55	0.134	735.7
6	1372	5.98	0.121	711.1
7	2014	6.40	0.107	709.9
8	2460	6.62	0.121	704.9

Although there are no 66-Euro IIIA locomotives in the freight data used in this project, the relevant emission factors are shown in Table 3. These are used in later comparisons of emissions from the three Class 66 emission variants (UIC1, UIC2 and Euro IIIA).

Table 3 Class 66 Euro IIIA emission factors by engine notch

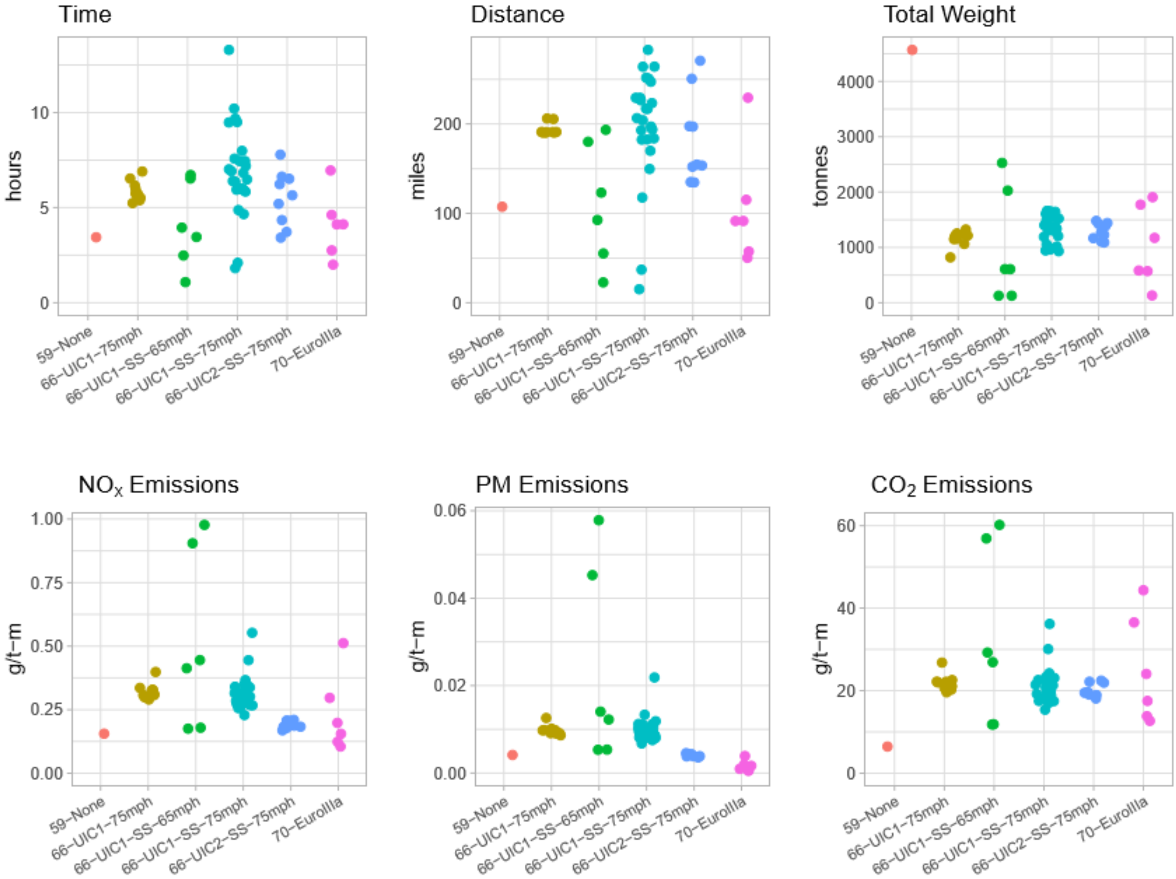
Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
0	46	15.51	0.603	1659.1
1	188	9.21	0.134	915.1
2	314	8.21	0.134	826.5
3	581	5.96	0.094	776.9
4	856	5.12	0.080	752.9
5	1117	5.12	0.080	755.0
6	1372	4.70	0.080	723.9
7	2014	4.06	0.080	712.3
8	2460	4.61	0.080	710.0

For the 10 trips with summary data available, which were all UIC1 locomotives, NO_x, PM and CO_2 emissions were calculated using the same engine power values and emission factors shown in Table 1. However, these were calculated for the total time in each notch rather than by timestep.

4.1.4 Summary of freight trips

In the freight data there are 57 trips each with a Journey component. The total time, distance, weight, and emissions from each of the 57 freight journeys is shown in Figure 7. The data have been split into six columns to show the different locomotive types, and a point is plotted for each journey. This means the range and distribution of data can be easily seen. Emissions are shown in grams emitted per tonne-mile (g/t-m), so that journeys of different weights and distances can compared.

Figure 7 **Summaries of 57 freight journeys**



The vast majority of freight services fall in five distinct groupings:

- Intermodal trains (max 75 mph, generally travelling over 200 miles)
- Laden bulk trains (max 60 mph, generally loads over 2000 tonnes, except where there are siding or freight loop length limitations)
- Empty bulk trains (generally 60 mph max but occasionally 75 mph, weight 450-700 tonnes)
- 'Light' locomotive-only movements (to reposition locomotives for refuelling, maintenance or to infrequently served locations)
- Works trains for Network Rail (for both maintenance and infrastructure projects with a wide variety of lengths and weights).

The sample freight OTMR data used in this study covers the first four categories of freight services.

In this data, the journeys with 66-UIC1-SS-65mph locomotives (in green in Figure 7) cover the second, third and fourth categories, and these have the greatest variation in weight and emissions per tonne-mile. Note that the two journeys that appear to have very high emissions are light locomotive moves; the total weight of the locomotive is only 127 tonnes, giving much higher values for emissions in grams per tonne-mile.

However, when considering the impact of train weight on emissions (Section 5.4), the light locomotive data is useful in assessing trends over a wider range of train weights, especially with a moderately sized data set.

Conversely, the journeys with 66-UIC1-75mph locomotives (in yellow in Figure 7) all have very similar times, distances, weights and emissions, as they were largely running the same routes. The single Class 59 locomotive journey has been included in this study as an example of a journey with a very high weight (4570 tonnes).

The 57 freight Journeys, on average: **take 5.9 hours, travel 174 miles, weigh 1283 tonnes, and emit 0.31 g NO_x, 0.009 g PM, and 22.4 g CO_2 per tonne-mile.**

These are average values and cover an underlying range of different freight train service types and loadings between full and empty (discussed further in Section 5.4), as well as three light locomotive moves (discussed further in Section 4.1.5).

A full summary of the freight data is shown in Table 4 and Table 5 below. In these tables, the data shown is for the total trips (both Journey and Yard time).

Table 4 Summary of 47 freight trips with OTMR (total recording)

Trip ID	Locomotive	Weight (tonnes)	Time (h)	Distance (miles)	NO_x (kg)	PM (kg)	CO_2 (kg)
A1	66-UIC1-SS-75mph	931	4.9	118	40.2	1.30	2656
A2	66-UIC1-SS-75mph	1205	7.6	251	96.0	2.87	6475
A3	66-UIC1-SS-75mph	1016	9.5	252	82.3	2.62	5421
A4	66-UIC1-SS-75mph	1643	5.8	184	81.2	2.38	5479
A5	66-UIC1-SS-75mph	1365	5.9	150	53.5	1.72	3579
B1	66-UIC1-SS-75mph	944	7.5	227	95.2	2.85	6436
B2	66-UIC1-SS-75mph	1375	6.9	247	102.2	2.99	6905
B3	66-UIC1-SS-75mph	1539	7.2	223	78.8	2.33	5292
B4	66-UIC1-SS-75mph	1511	6.5	229	93.7	2.75	6353
B5	66-UIC1-SS-75mph	1463	6.8	229	86.0	2.53	5709
C1	66-UIC1-SS-75mph	1303	6.4	217	74.2	2.19	4945
C2	66-UIC1-SS-75mph	1056	8.0	194	69.7	2.28	4623
C3	66-UIC1-SS-75mph	1302	6.1	193	79.2	2.30	5209
C4	66-UIC1-SS-75mph	1607	6.0	207	92.7	2.67	6268
D1	66-UIC1-SS-75mph	1191	5.9	183	75.8	2.25	5077
D2	66-UIC1-SS-75mph	1413	4.7	183	77.8	2.21	5264
D3	66-UIC1-SS-75mph	1307	7.4	204	84.5	2.58	5678
D4	66-UIC1-SS-75mph	983	7.0	170	58.2	1.88	3857
E1	66-UIC1-SS-75mph	1522	9.7	264	109.8	3.22	7335
E2	66-UIC1-SS-75mph	1540	6.4	197	89.4	2.61	6001

Trip ID	Locomotive	Weight (tonnes)	Time (h)	Distance (miles)	NO_x (kg)	PM (kg)	CO_2 (kg)
E3	66-UIC1-SS-75mph	1660	13.3	217	107.8	3.52	7219
E4	66-UIC1-SS-75mph	961	1.8	15	8.0	0.32	526
F2	66-UIC1-SS-75mph	1401	2.1	37	17.5	0.58	1170
F3	66-UIC1-SS-75mph	1654	10.2	264	116.7	3.56	7899
F7	66-UIC1-SS-75mph	1336	9.5	283	107.7	3.29	7264
G3	66-UIC2-SS-75mph	1385	4.3	135	38.4	0.81	4091
G2	66-UIC2-SS-75mph	1421	6.5	152	39.0	0.92	4121
G4	66-UIC2-SS-75mph	1089	7.8	271	61.9	1.34	6618
G5	66-UIC2-SS-75mph	1104	6.6	251	57.4	1.21	6140
H1	66-UIC2-SS-75mph	1267	3.4	135	28.9	0.61	3099
H2	66-UIC2-SS-75mph	1480	6.2	197	52.0	1.11	5525
H3	66-UIC2-SS-75mph	1228	5.2	155	35.5	0.82	3724
H4	66-UIC2-SS-75mph	1440	5.7	198	52.1	1.09	5546
H5	66-UIC2-SS-75mph	1167	3.7	154	32.8	0.69	3511
K3	66-UIC1-SS-65mph	2027	3.9	123	44.7	1.33	2961
K4	66-UIC1-SS-65mph	607	2.5	93	23.2	0.69	1513
K5	66-UIC1-SS-65mph	127	1.1	23	2.6	0.13	165
K6	66-UIC1-SS-65mph	2527	6.7	180	79.8	2.44	5377
K8	66-UIC1-SS-65mph	607	6.5	193	52.3	1.65	3435
L7	66-UIC1-SS-65mph	127	3.5	55	6.8	0.41	421
I1	70-EuroIIIa	1773	7.0	229	42.8	0.21	5160
N1	59-None	4570	3.4	107	76.4	2.03	3174
P1	70-EuroIIIa	571	4.1	115	13.0	0.11	1583
Q1	70-EuroIIIa	131	2.0	57	3.8	0.03	333
R1	70-EuroIIIa	1907	2.8	50	11.9	0.06	1324
S1	70-EuroIIIa	1173	4.6	91	16.6	0.10	1880
S2	70-EuroIIIa	582	4.1	91	15.8	0.10	1945

Table 5 Summary of 10 freight trips with summary level data available

Trip ID	Locomotive	Weight (tonnes)	Time (h)	Distance (miles)	NO_x (kg)	PM (kg)	CO_2 (kg)
M1	66-UIC1-75mph	1062.6	6.5	206	73.6	2.22	4947
M5	66-UIC1-75mph	1252.6	5.4	191	69.4	2.07	4692
M9	66-UIC1-75mph	1215.6	5.2	191	71.4	2.10	4835
M10	66-UIC1-75mph	1219.4	5.7	190	71.4	2.11	4797
M11	66-UIC1-75mph	1149	5.7	191	71.9	2.16	4860
M12	66-UIC1-75mph	820	6.9	206	67.2	2.12	4521

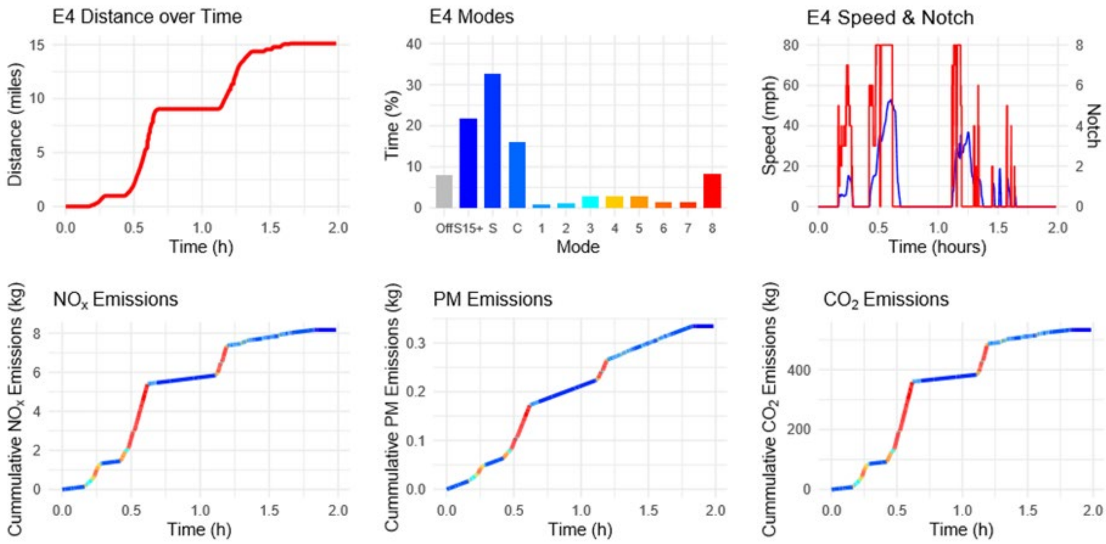
M13	66-UIC1-75mph	1324.4	6.2	191	75.6	2.30	5116
M14	66-UIC1-75mph	1238.6	5.5	190	73.4	2.18	4971
M15	66-UIC1-75mph	1155	5.8	191	72.2	2.16	4885
M16	66-UIC1-75mph	1198	6.0	191	74.6	2.23	5039

4.1.5 Outlier trips and their emissions

There are two clear outliers for NO_x, PM and CO_2 g/t-m emissions in Figure 7, due to low weights: these are two 127-tonne Class 66 light locomotive moves. Interestingly, a 131-tonne Class 70 light locomotive move does not appear as an outlier, as this locomotive latter has much lower emissions as it is compliant with a newer emission standard and has a more efficient transmission and better auxiliary load management. A third outlier journey, one of the 66-UIC1-SS-65mph locomotives (in blue in Figure 7), also has high g/t-m emissions. This is journey E4, which travels 15 miles in 2 hours, and was stationary for half an hour in the middle of the journey with the engine left running.

Graphs of trip E4 are shown in Figure 8, including its drive cycle (top centre, dominated by the Stationary >15 mins, S15+) and its emissions profiles (bottom row).

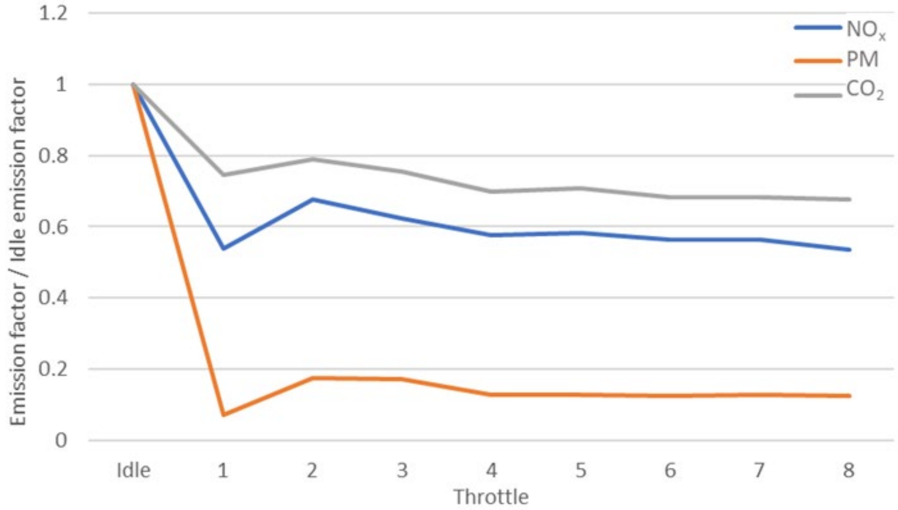
Figure 8 **Summary plots of journey E4**



All emissions of this journey are significantly affected by the stationary period, but emissions of the three pollutants are not equally affected. PM continues to be emitted at a very high rate while the train is idling, while NO_x and CO_2 continue to be emitted but at a lower rate. This is due to the large difference in idling and powered emission factors.

To illustrate this, Figure 9 shows the Class 66-UIC1 emission factors by notch, for each of the three pollutants, normalised to the respective idle emission factor.

Figure 9 **Class 66-UIC1 emission factors by notch normalised to the respective Idle emission factor**



The difference between the Notch 1-8 and Idle emission factors is greatest for PM, where Notch 1 is around 90% less polluting per unit of energy consumed than while idling. While there is also a decline in the NO_x and CO_2 g/kWh emission factors between Idle and Notch 1-8, this decline is much smaller than for PM as discussed in the main report for this project[11]. This is in line with how the different pollutants are formed, since CO_2 emissions depend almost entirely on the carbon content of the fuel consumed, whereas PM and NO_x emissions depend on operating conditions and how these affect combustion, such as time above critical temperature in the engine cylinder.

4.2 Class 158 and Class 170

4.2.1 Overview of available data

On-train monitoring recorder (OTMR) data from a TOC for both Class 158 and Class 170 trains was provided for a large number of three-day periods throughout 2019. The analysis presented here considered all of the trips within one particular three-day period which provided approximately 85,000 miles of Class 158 and 170 OTMR data.

The Class 158 and 170 OTMR data included unit number, vehicle number, timestamp, speed, throttle setting, GPS coordinates, and general location. Information on when individual services began and ended, and on whether units were single or running in multiple was not available in the raw OTMR data.

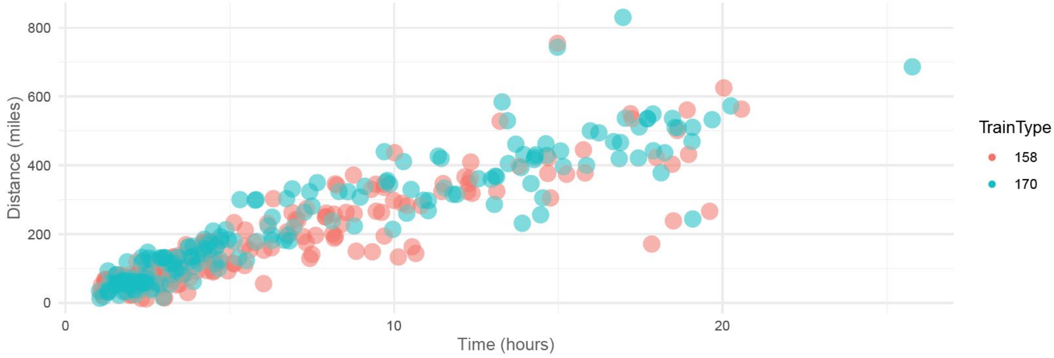
The recordings were split into trips that were separated by periods where units were stationary for more than 1 hour. Trips can have multiple stops, where stops are counted as each time a train slows to 0 mph both within and outside of stations (e.g. held at a signal). The trips had a range of times and distances up to approximately 20 hours and

[11] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.

800 miles, respectively. Some trips corresponded to one or two scheduled services, whereas others corresponded to a full day's diagram. An overview of the data analysed for Class 158 and 170 trains is presented in Figure 10 below.

Each trip could be segmented into smaller journeys for detailed analysis. A journey was defined as a portion of a trip when a train moves between two specifically identified stations or signal locations. Various journeys were selected for the analysis undertaken for the case studies presented in Section 5.

Figure 10 **Overview of the identified trips for Class 158 and 170 trains, demonstrated by the spread of distance travelled (miles) over time (hours)**

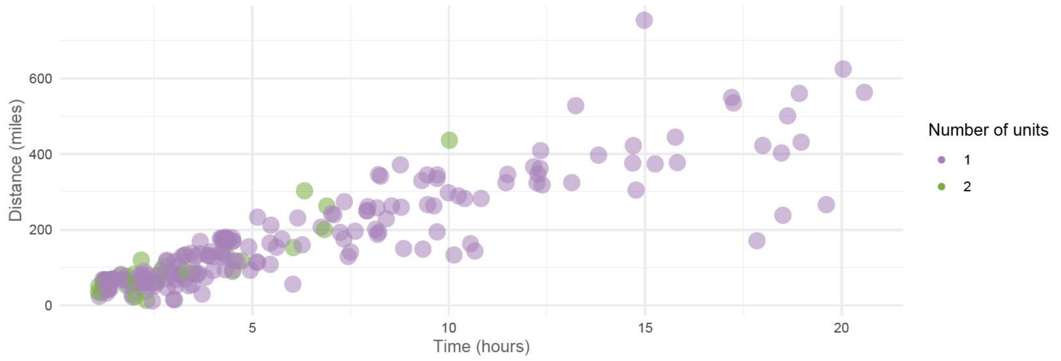


The data in Figure 10 can be split out by train class and by number of units, as shown in Figure 11. Approximately 200 trips for both Class 158 and 170 trains were recorded, with only 26 and 7 running in multiple trips, respectively.

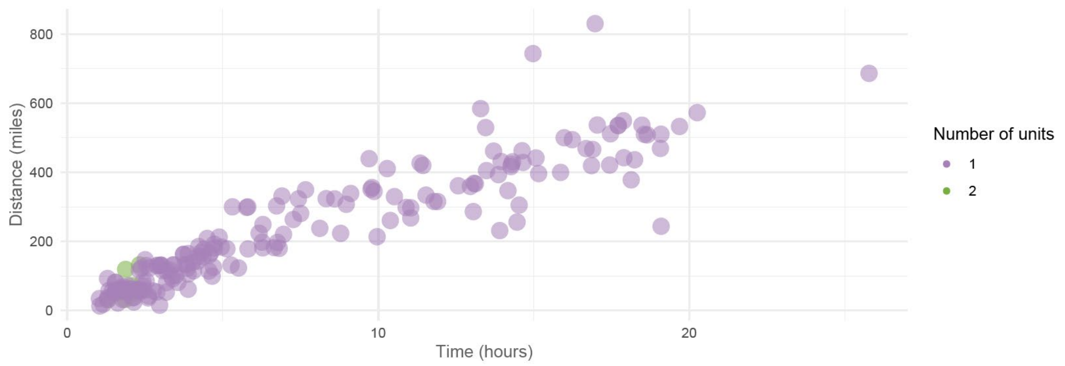
While units of both train classes run along the same routes in many of the cases, the services operated by the different classes vary in terms of the number of stops. Whether units are operated singly or doubled up varies significantly: for example the 2-vehicle Class 158 units are much more likely to be doubled up to be operated as 4-vehicle units than the Class 170 units are to be doubled up to operate as 6-vehicle units (which tends to happen at just peak times).

Figure 11 **Overview of the identified single-unit and running in multiple (two units) trips for a) Class 158 and b) 170 trains, demonstrated by the spread of distance travelled (miles) over time (hours).**

a) Class 158



b) Class 170



4.2.2 Data processing

The raw OTMR data was split by unit number. The difference between timestamps was then calculated to generate a timestep between each OTMR data entry. Given the small increments between timestamps (generally <100th of a second) assuming that the trains are travelling a straight line between each data entry was considered reasonable. The distance travelled was calculated using the GPS coordinates which was verified using the calculated distance based on the time and speed. There was generally good agreement between the distance calculated using the GPS compared to the time and speed data. However, this did highlight some erroneous GPS coordinates within the data which were subsequently removed from the dataset.

The OTMR data included entries for each vehicle associated with a unit enabling the number of component vehicles of a unit to be determined. In order to identify whether units ran as single or joined, records of all units of the same train class were compared to find other units in the same location at the same time using the GPS and timestamp data. Where units were found to stop at the same time and location at two consecutive stops and could be identified together at the same locations while moving between the stops, they were assumed to be joined (running in multiple). Joined units were combined into one dataset for the analysis and assigned a new unit ID. Where matches were not identified, the units were analysed as single units. The number of units and vehicles was used together with the emission factors to calculate emissions for each timestep (see Section 3).

The OTMR data did not always distinguish between when a train was stationary and idling versus stationary and the engine off. Based on extensive analysis, it was determined that when the timestep between data entries was greater than 20 minutes a reasonable assumption was that the engine was off and therefore no emissions were being generated. Where the timestep was less than 20 minutes, it was assumed that the train was stationary and in idle (mode referred to as 'S'). Where the train was stationary and remained in idle for more than 15 minutes the mode 'S15+' was assigned. In cases when the train is in Notch 0 but is moving, it was assumed that the train is coasting (mode referred to as 'C', which can include movement while braking as well as pure coasting). Table 6 provides the full logic applied to assign modes based on the throttle and speed data included in the OTMR recordings.

Table 6 Logic table for assigning modes based on the throttle setting and speed included in OTMR data for Class 158 and 170 trains

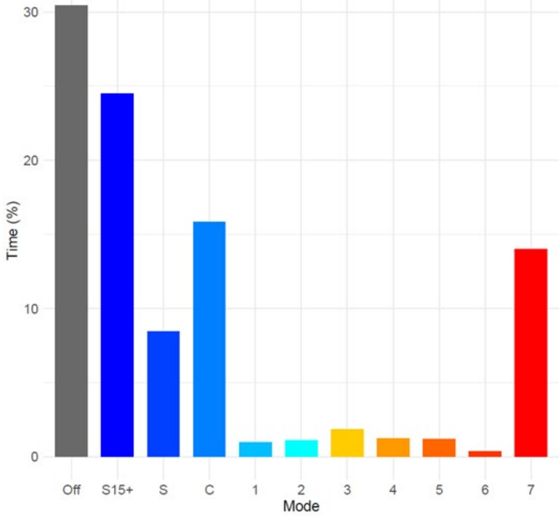
Throttle	Notch	Mode	Logic for determining mode
000	0	Off	Timestep >20 minutes
000	0	S15+	Time in S is ≥15 minutes
000	0	S	Speed = 0
000	0	C	Speed >0
100	1	1	Same as notch
010	2	2	Same as notch
110	3	3	Same as notch
001	4	4	Same as notch
101	5	5	Same as notch
011	6	6	Same as notch
111	7	7	Same as notch

An example of a typical drive cycle for a Class 170 unit over the three-day period compared to one trip is shown in Figure 12. Over the three-day period the unit travels approximately 1,200 miles compared to a typical individual trip which could cover 80 miles in as little as 90 minutes. A more detailed overview of this individual trip is shown in Figure 13.

For almost a day of the 3-day period the engine is switched off. The train is stationary for greater than 15 minutes in Idle for over 18 hours, stationary for less than 15 minutes at idle for ~8 hours, and coasting or braking for ~12 hours, with just 10 hours when the train is using power from the engine. In contrast, for the individual journey ~45% of the time is spent in Notch 7 and ~35% in Idle (28% of the total journey time is coasting or braking). The emissions for this trip are presented in Section 4.2.3.

Figure 12 **Typical drive cycle for a single Class 170 unit over a) three days and b) one trip**

a)



b)

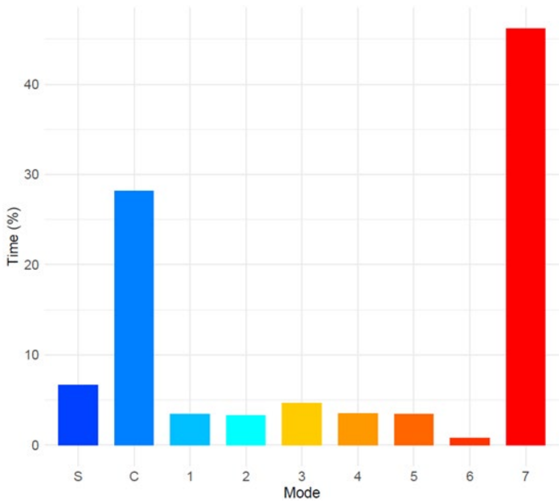
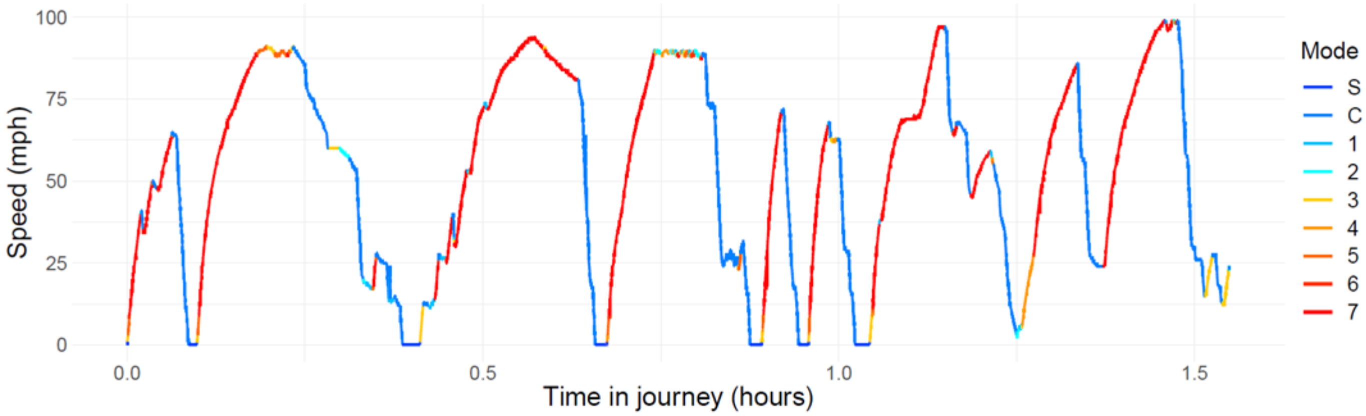
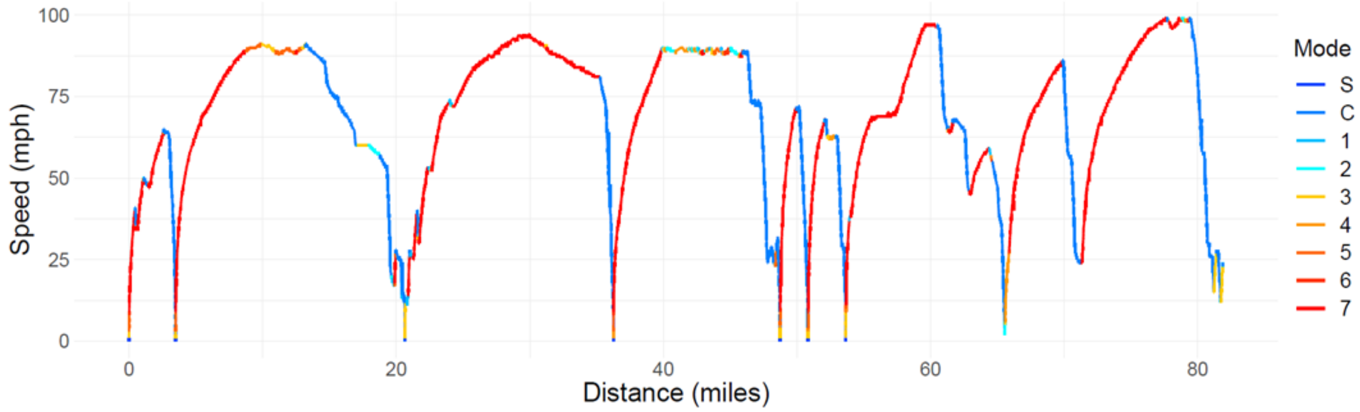


Figure 13 **Overview of an example Class 170 trip**

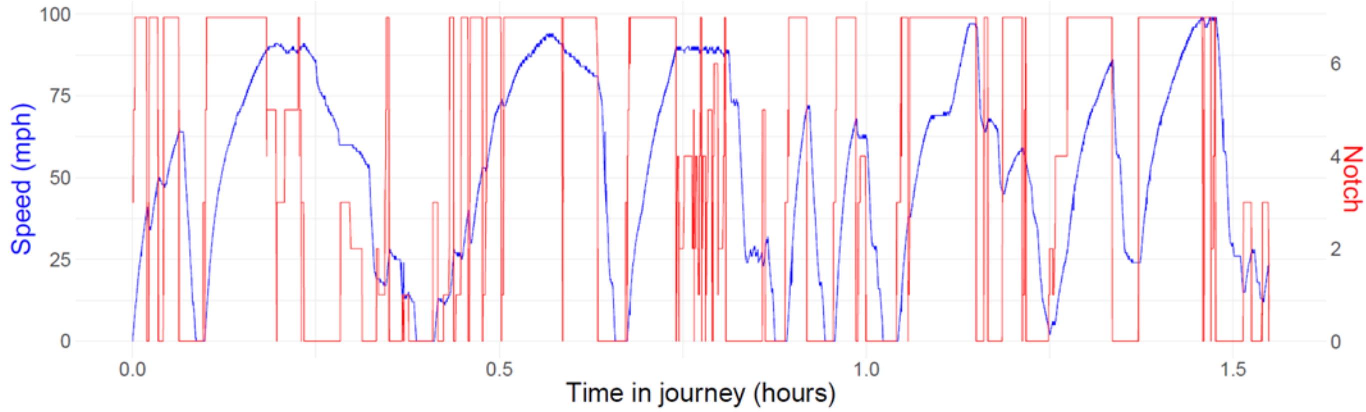
a) Speed over time



b) Speed over distance



c) Speed and notch over time



4.2.3 Class 158 and 170 emissions

For all the Class 158 and 170 trips identified within the OTMR data, NO_x, PM and CO_2 emissions were calculated for each timestep using OTMR data, emission factors by notch in units of g/kWh, including auxiliary loads, as described in Section 3.

Emission factors for Class 158 and 170 derived during this project[12] are presented in Table 7 and Table 8, respectively.

Table 7 Class 158 emission factors by engine notch

Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
0	26	17.06	5.29	726.00
1	47	10.45	1.60	648.21
2	64	9.39	0.92	635.90
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

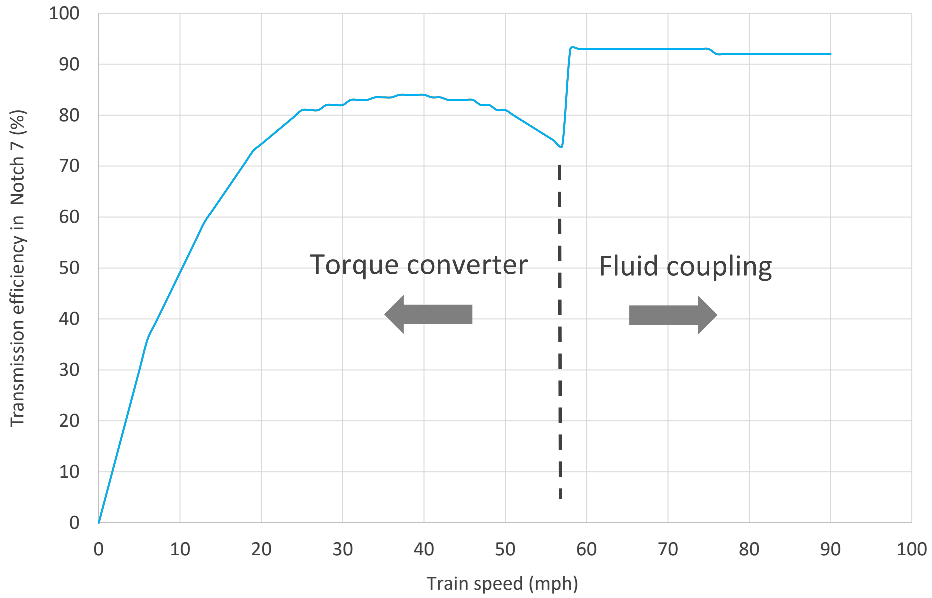
Table 8 Class 170 emission factors by engine notch

Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
0	26	15.40	0.24	1206.00
1	54	13.05	0.15	941.00
2	94	9.27	0.12	658.05
3	135	9.00	0.09	625.13
4	179	6.91	0.09	638.91
5	230	4.89	0.08	621.33
6	271	3.29	0.08	653.05
7	315	2.73	0.07	671.52

The transmission efficiency of hydraulic drive systems varies substantially with train speed and engine notch, hence detailed analysis is needed to assess transmission losses if the greatest level of accuracy is desired, for example in the Class 158 and 170 case studies discussed in this report. The very variable efficiency of the overall transmission with notch and train speed can be seen in Figure 14 below. Curves for other notches are similar shapes but with the transition speed lower and with lower efficiencies when the torque converter is operational.

[12] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.

Figure 14 **Transmission efficiency versus train speed for Class 158 with Cummins 400 hp engine in Notch 7**

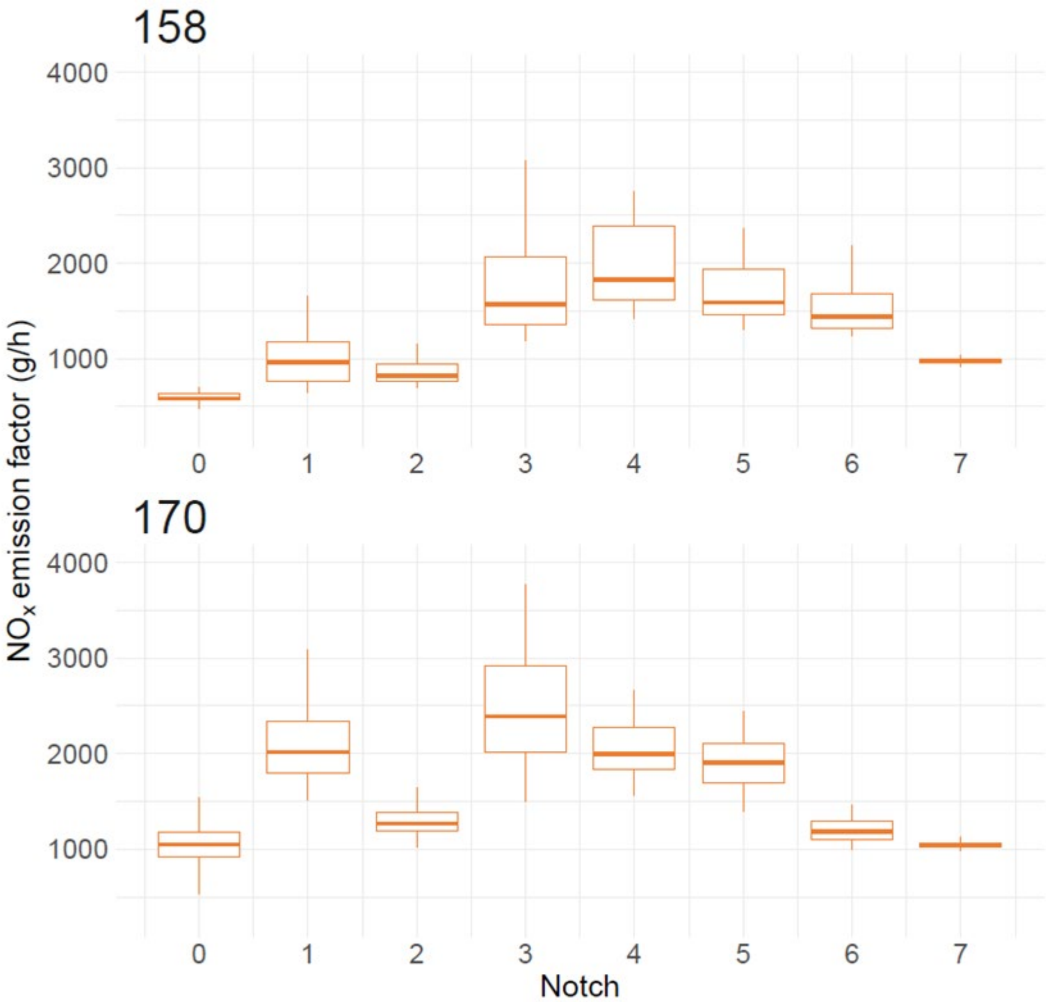


The variation in transmission efficiency with speed for trains with diesel hydraulic and diesel mechanical transmissions creates a significantly wider range of total possible emissions for Notches 1-7. The variation in emissions by engine notch (in units of g/hr) for Class 158 and 170 based on a large dataset of actual OTMR data can be seen in the boxplots[13] in Figure 15.

While there is significant variation in emissions at some notches (mainly intermediate notches, especially those used to pull away from stationary) there is very little variation in Notch 7 and in Idle (which includes stationary, coasting and braking). These notches account for the majority of the drive cycle for a hydraulic transmission DMU.

[13] A boxplot is a standard way of displaying the distribution of a set of point: the bold line in the middle is the median, the box represents the central 50% of the points (i.e. the bottom and top of the box are at the first and third quartiles), and the vertical lines extend to the maximum and minimum values (excluding any extreme outliers). A thin box indicates there is low variability in the data.

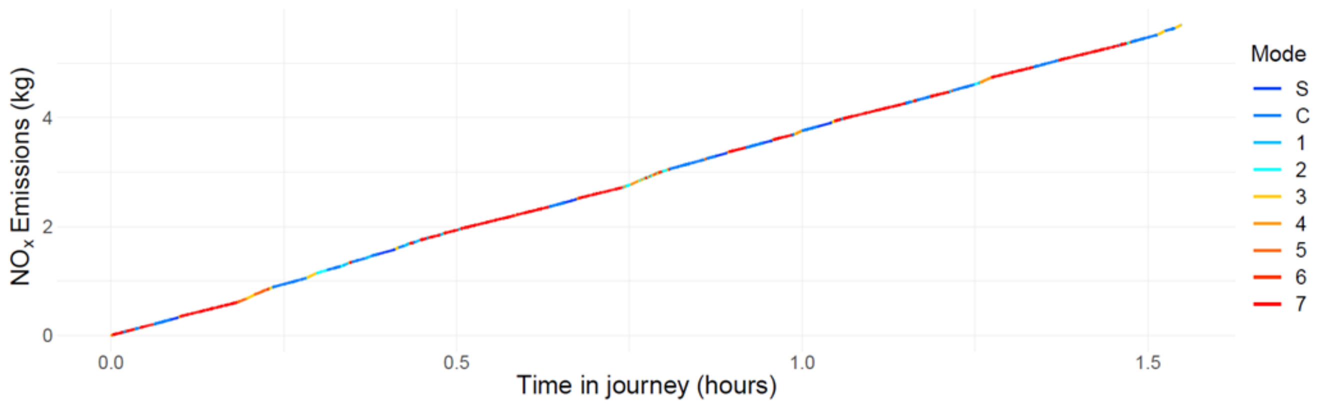
Figure 15 **Class 158 and 170 emissions by engine notch (in g/hr) showing the effect of speed-dependent transmission efficiency variation on total emissions**



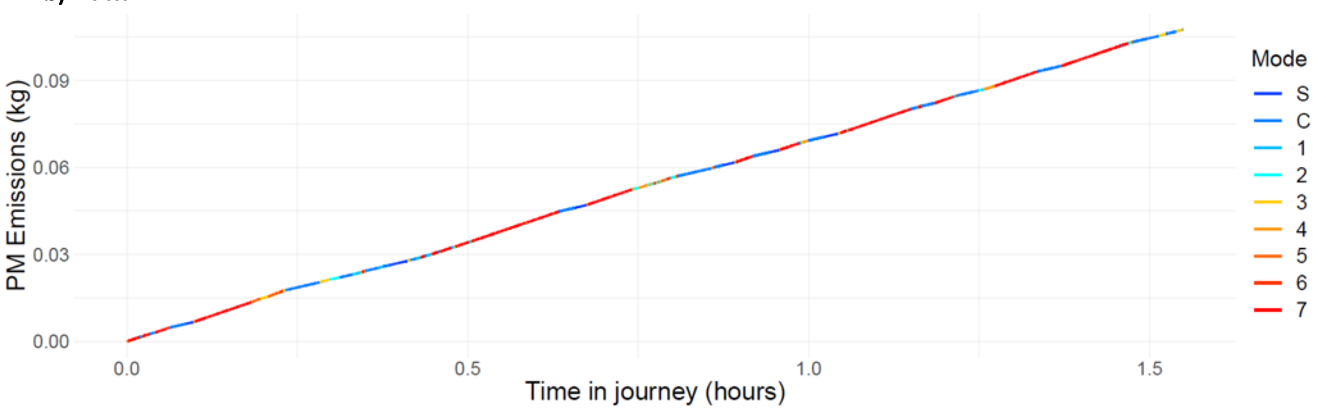
The emission factors by notch were combined with the relevant transmission efficiency by speed and notch to calculate emissions on a time basis in units of g/h per vehicle for each timestep. Emissions of each pollutant were then summed across the trip and multiplied by the number of vehicles per train to obtain the total trip emissions. However, emissions could also be investigated at a finer resolution when evaluating particular scenarios (see Section 5). The emissions generated in the Class 170 example introduced in Section 4.2.2 are presented in Figure 16 below.

Figure 16 **Overview of cumulative emissions (in kg) generated by an example Class 170 trip over time**

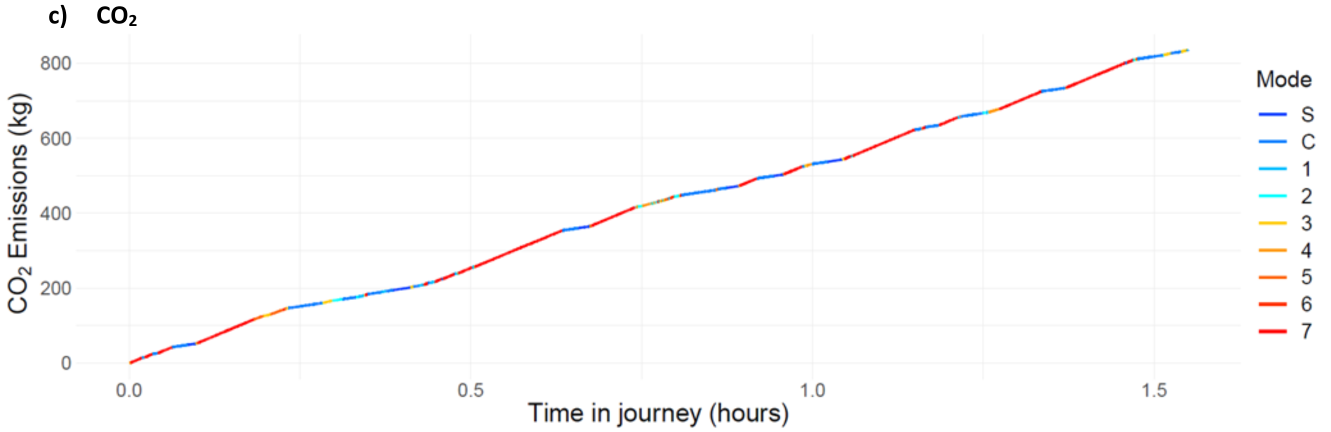
a) NO_x



b) PM



c) CO_2



4.2.4 Example trips and their emissions

Examples of two typical trips in the dataset are shown below. The examples selected are for Class 158 units for trips of approximately 100 miles over 2h40. Figure 17 is for a single unit and Figure 18 is for two units running in multiple. These journeys were on different routes with similar linespeed characteristics; however, the gradient profiles of these routes are substantially different.

The first trip in Figure 17 is on a largely flat route with the linespeed closely matching the maximum speed of the Class 158, but operating a stopping service with the need to keep to tight timings to avoid delaying fast services also operating on the same line. The total emissions for the trip were 2.2 kg NO_x, 0.3 kg PM and 531.4 kg CO_2.

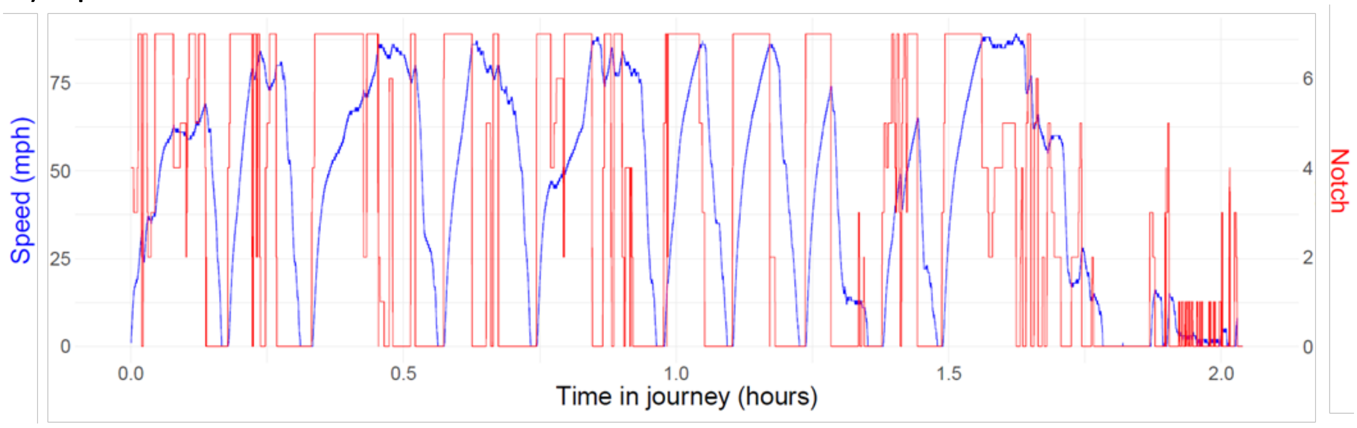
The second trip in Figure 18 includes two substantial waits at stations with passing loops while the train waits to enter the single-track section ahead. This journey also contains three substantial climbs from stations where the speed of the unit is limited for extended periods by starting from a standing start and the relatively limited power available results in higher emissions. In these three cases the unit is never able to attain more than two thirds of the linespeed during the extended climbs despite the use of Notch 7. The total emissions for the trip are 4.3 kg NO_x, 0.5 kg PM and 1,100.6 kg CO_2.

While the two trips have very different characteristics, the emissions per unit are very similar (and above average) but for different reasons. The former has more stops on a mixed-use line and in later has extensive climbs and a much longer journey time.

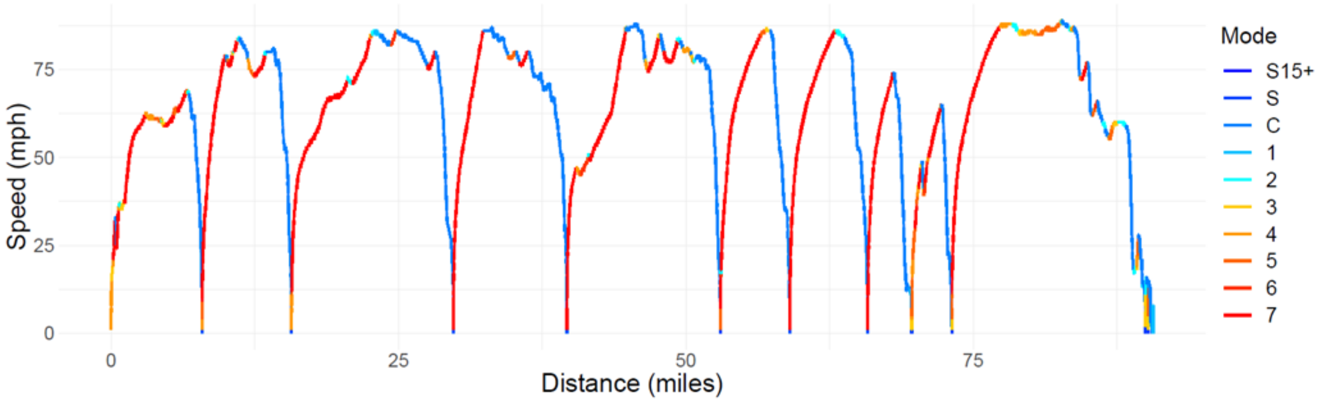
The journeys selected for the analysis undertaken for the specific case studies presented in Section 5 typically considered a portion of the available trips depending on the scenario being evaluated. The trip presented in Figure 18 is used in the reducing idling case study (Section 5.1). A combination of journeys extracted from the other available trips were used in the minimising delays and reducing number of stops on a journey and train loadings case studies (see Section 5).

Figure 17 **Example of a single-unit Class 158 trip**

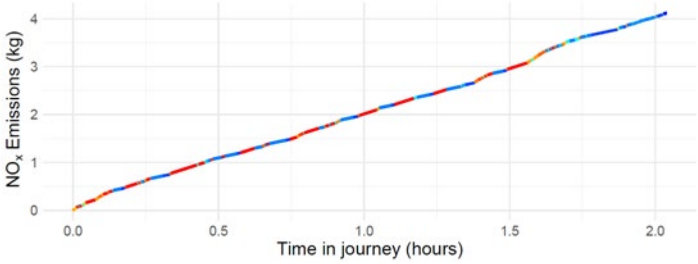
a) Speed and notch over time



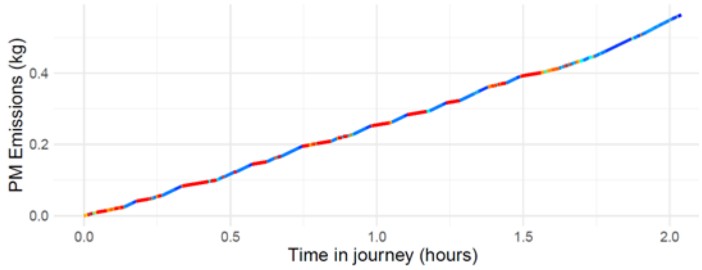
b) Speed over distance (coloured by mode)



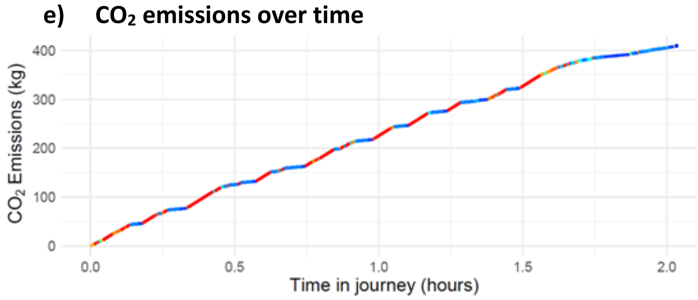
c) NO_x emissions over time



d) PM emissions over time



e) CO_2 emissions over time



f) Drive cycle

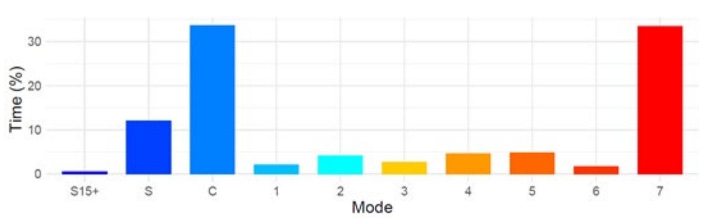
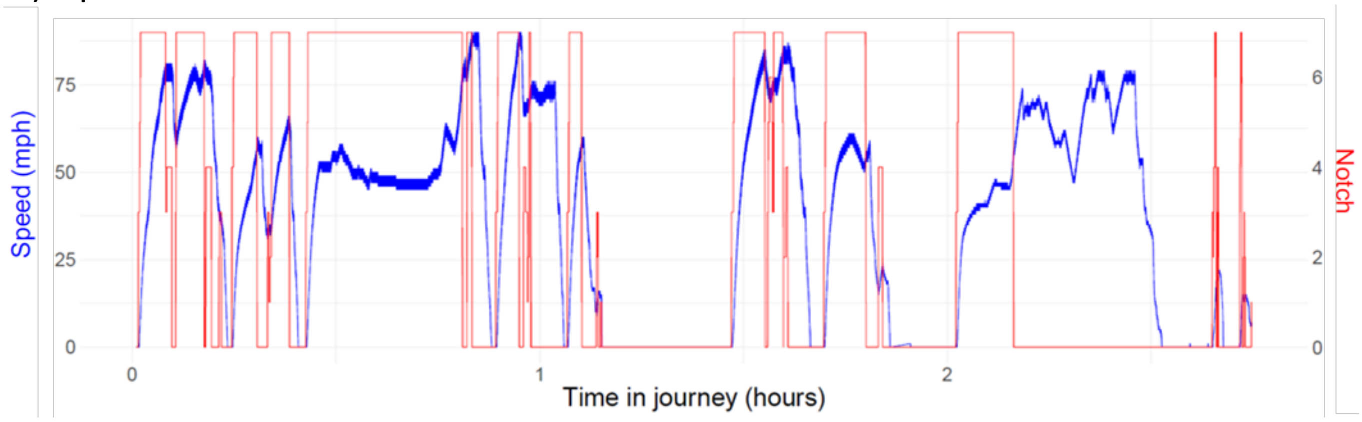
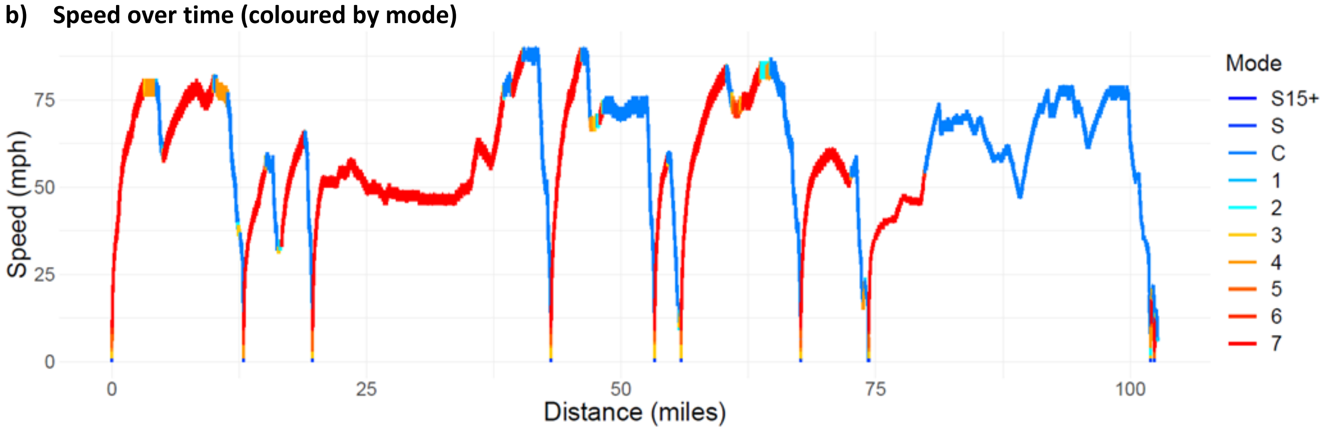


Figure 18 **Example of a Class 158 trip running in multiple**

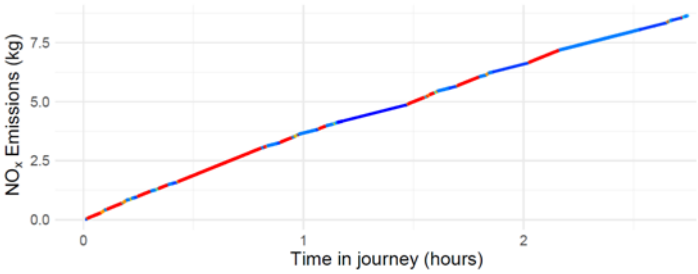
a) Speed and notch over time



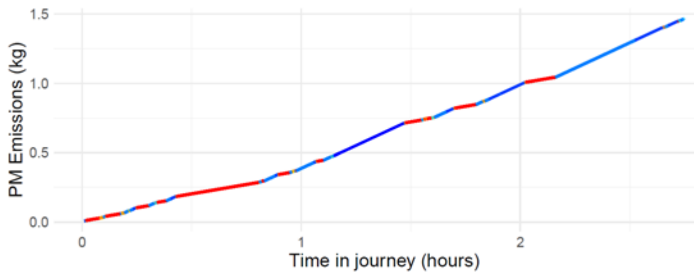
b) Speed over time (coloured by mode)



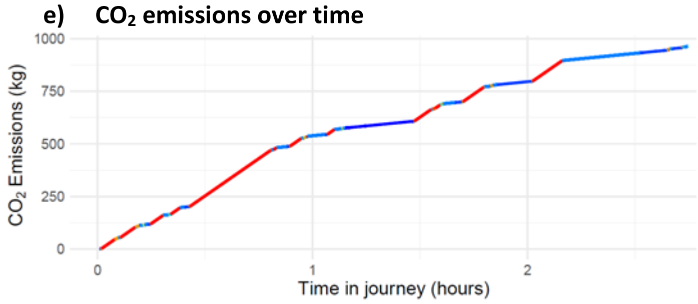
c) NO_x emissions over time



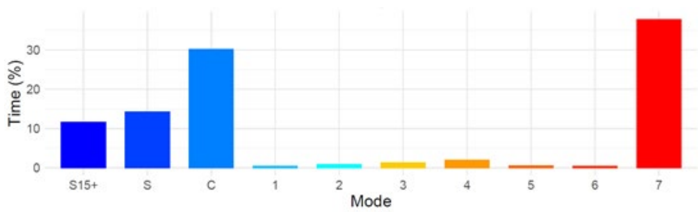
d) PM emissions over time



e) CO_2 emissions over time



f) Drive cycle

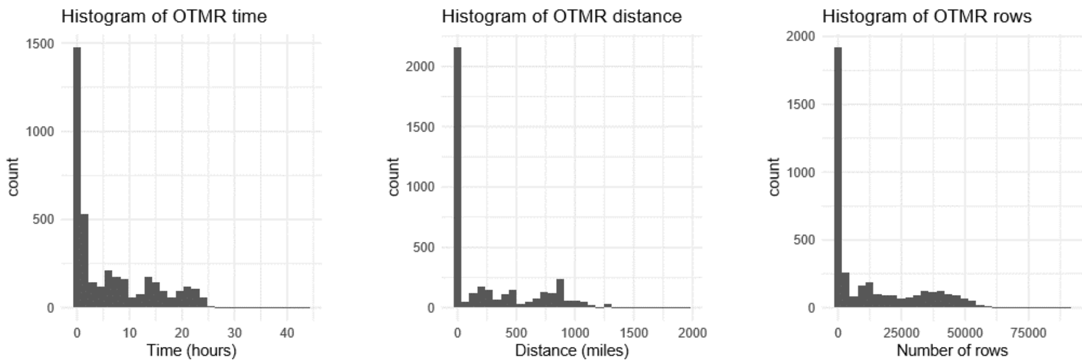


4.3 Class 220/221 (Voyager)

4.3.1 Overview of available data

For the Voyager data, 4222 separate OTMR files covering a three-month period were acquired. A large proportion of the files contain very little data, while a few files contain recordings over 1800 miles. A distribution of the data available is shown in Figure 19, which excludes 375 files that contained less than 100 rows. A large number of files representing short time periods and short distances are primarily out of service moments within or to and from maintenance depots, or else the unit has been briefly turned on to charge up the air compressors and prepare the unit without it actually moving.

Figure 19 **Distribution of data in 3846 Voyager OTMR files**



4.3.2 Data processing

Two numerical fields (Speed, Traction Power or Brake Level), and six binary fields (Traction, Brake, Forward, Neutral, Reverse, Emergency Brake), are recorded in the OTMR. These fields can be used in combination to determine the vehicle's status. The Traction/Brake field (values 10-90) was first converted to Notch (values 0-16) using the lookup in Table 9. The 'continuously variable' transmission of the Voyagers is actually based on well-defined throttle settings. Detailed analysis of the recorded throttle settings shows that Traction/Brake settings fall into well-defined peaks in each range (e.g. 10 for Power 0, 15 for Power 1, 20 for Power 2, etc.), so the ranges either side of these peaks in Table 9 (typically covering transients when changing setting) are used to ensure all recorded values are allocated to a particular notch value.

Table 9 Notch lookup table for Class 220/221 OTMR

Traction/Brake	Notch value
10 – 12	Power 0
13 – 17	Power 1
18 – 22	Power 2
23 – 27	Power 3
28 – 32	Power 4
33 – 37	Power 5
38 – 43	Power 6
43 – 47	Power 7
48 – 52	Power 8
53 – 57	Power 9
58 – 62	Power 10
63 – 67	Power 11
68 – 72	Power 12
73 – 77	Power 13
78 – 82	Power 14
83 – 85	Power 15
86 – 90	Power 16

The ‘Stationary’ and ‘Coasting’ modes are allocated using the Speed and Notch fields. As above for the Class 66, if the speed and notch are 0 then the train’s mode is Stationary, and if the notch is 0 but the speed greater than 0, the mode is Coasting.

Combinations of the six binary OTMR fields were used to refine the Stationary and Coasting modes. After excluding a small number of instances of combinations of these six fields that were deemed logically impossible, such as forward and reverse both being TRUE, 32 combinations of these binary fields are used to define the following categories:

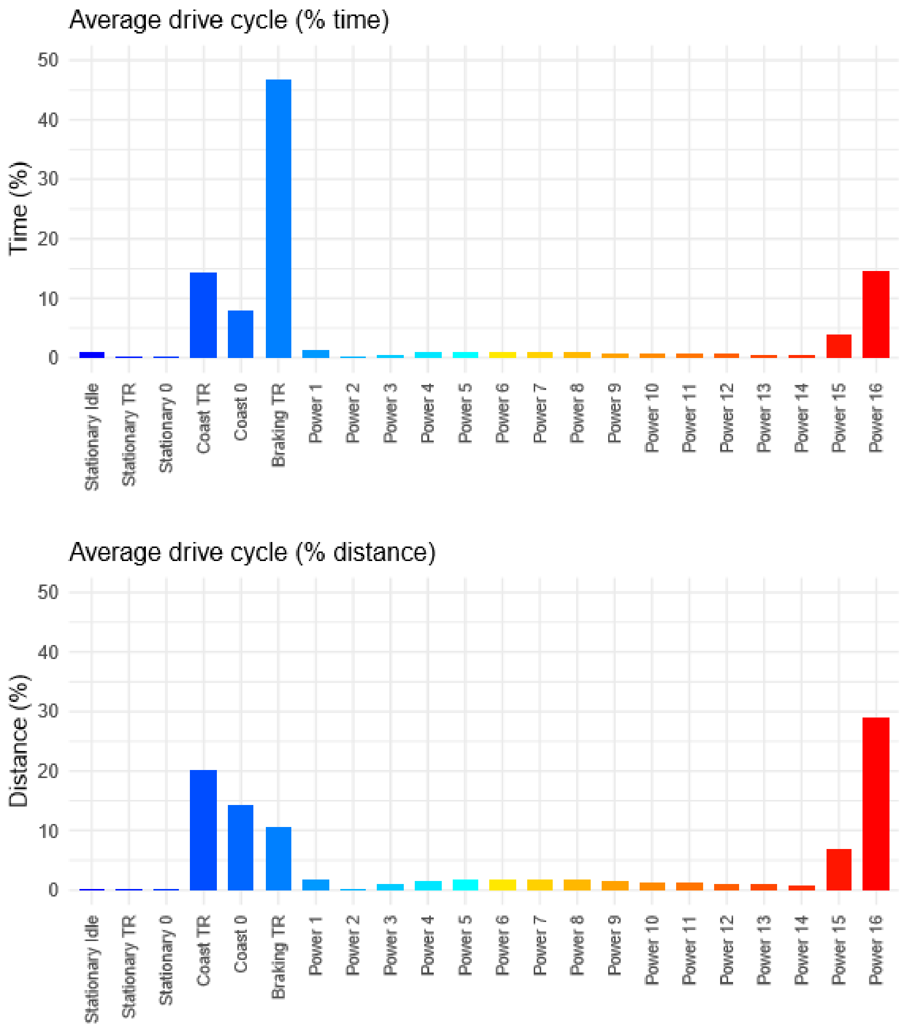
- ‘Coasting in Notch 0’ (Coast 0) – engine at 1800 rpm
- ‘Coasting Traction Ready’ (Coast TR) – engine at 1150 rpm
- ‘Stationary in Notch 0’ (Stationary 0) – engine at 1800 rpm
- ‘Stationary Traction Ready’ (Stationary TR) – engine at 1150 rpm
- ‘Stationary Idle’ – engine at 900 rpm
- ‘Braking Traction Ready’ (Braking TR) – engine at 1150 rpm.

Additionally, some rows at the beginning of the files contained missing values or timestamps for 01/01/1990 (effectively a missing date) and were removed. When the timesteps are calculated, any time that would have been allocated to these removed rows is now allocated to the preceding row, and no time was unaccounted for.

Due to the large number of small files, the data were further filtered for later analyses to only include files with more than 5 miles of recording. This excluded train moves within depots or to and from depots and stabling locations, leaving 1819 OTMR files.

The drive cycle of each of these files was aggregated, and the average drive cycle is shown in Figure 20. The largest amount of time is spent in coasting and braking, followed by substantial time in Notches 15 and 16. Time in all other modes is relatively limited. As would be expected, no distance is covered in the stationary modes. However, a substantial amount of distance is covered when coasting.

Figure 20 **Average trip drive cycle (by % time and % distance) from Class 220/221 OTMR data**



Unfortunately, in the Class 220/221 OTMR data no location information is available. Using the binary door interlock field, when the train reaches a station and the doors are opened can be identified. It is possible to use this information to manually match the train stopping patterns to known routes to identify particular services and diagrams.

However, noise in the data (such as varying standard stopping patterns or missing stops and so distances differing from standard route stopping patterns) has meant this could not be automated during this project.

Class 220/221 trains can run as single or multiple units depending on the route. Each unit is made up of four or five vehicles, where the first and last vehicle of each unit have OTMR recordings. Therefore, the large number of the Voyager OTMR recordings needed to be grouped to find recordings from the same unit, and from units running in multiple.

Since the OTMR does not contain any route or location identifiers, the files could be matched using only the date and time and the distance travelled. Vehicles in the same unit can additionally be identified as their vehicle IDs have a known relationship. The recordings are compared to ensure they have matching journey profiles.

For example, if two recordings starting at 10:30 am on the same day and both record for 7.4 hours covering 170 miles of travel (within a reasonable margin of error), the recordings were assumed to be from vehicles running together.

For 1164 out of the 1819 processed OTMR files, the corresponding vehicle in the unit could be identified. For 12 of these files, a second unit running in multiple could be clearly identified (3 journeys, 6 units). An example of each case is shown in Section 4.3.4.

4.3.3 Calculating emissions

Emissions are calculated for each OTMR recording on a timestep basis as described in Section 3. Emission factors for Class 220/221 passenger trains in g/kWh by notch are shown in Table 10, with separate emission factors for 'Idle' and 'Traction Ready' modes.

Since there are two vehicle recordings for each unit of four or five vehicles, the emissions for the unit are calculated for the leading vehicle only and multiplied by the number of vehicles in the unit. For units running in multiple, the emissions are calculated for each unit and added together.

Table 10 Emission factors for Class 220/221 passenger trains

Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
Idle	45	11.1	0.85	862.2
TR	45	11.1	0.85	958.0
Notch 0	45	2.5	0.43	965.8
Notch 1	80	2.5	0.41	944.2
Notch 2	110	2.5	0.38	925.6

Engine notch	Engine power (including auxiliary loads) (kW)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)
Notch 3	141	2.5	0.36	907.0
Notch 4	171	2.8	0.33	888.4
Notch 5	201	3.0	0.31	869.8
Notch 6	231	3.3	0.28	851.2
Notch 7	261	3.6	0.26	832.6
Notch 8	292	3.9	0.24	814.0
Notch 9	322	4.1	0.21	795.4
Notch 10	352	4.4	0.19	776.8
Notch 11	382	4.7	0.16	758.2
Notch 12	412	5.0	0.14	739.6
Notch 13	443	5.2	0.12	721.0
Notch 14	473	5.5	0.09	702.4
Notch 15	503	5.8	0.07	683.8
Notch 16	521	6.0	0.05	672.7

4.3.4 Example journeys and their emissions

Three example journeys were identified where two units were running in multiple (as described in Section 4.3.2). Three similar examples were found where only a single unit was running. An example of a single-unit journey, J3, is shown in Figure 21, and an example of a multiple unit journey, J1, is shown in Figure 22. The examples are matched approximately for total time and total distance and appear to have a similar journey profile. Each vehicle's speed is plotted over time, coloured by mode, and shown in a separate subfigure.

Figure 21 **Example single-unit journey J3 – speed plotted over time and coloured by mode for both cabs**

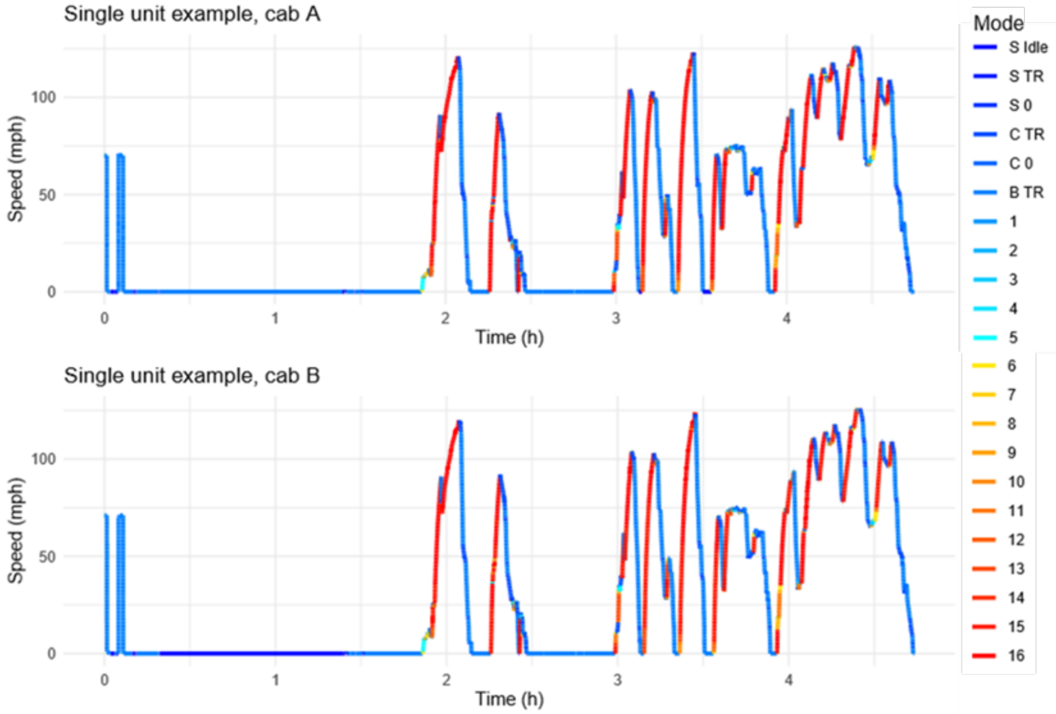
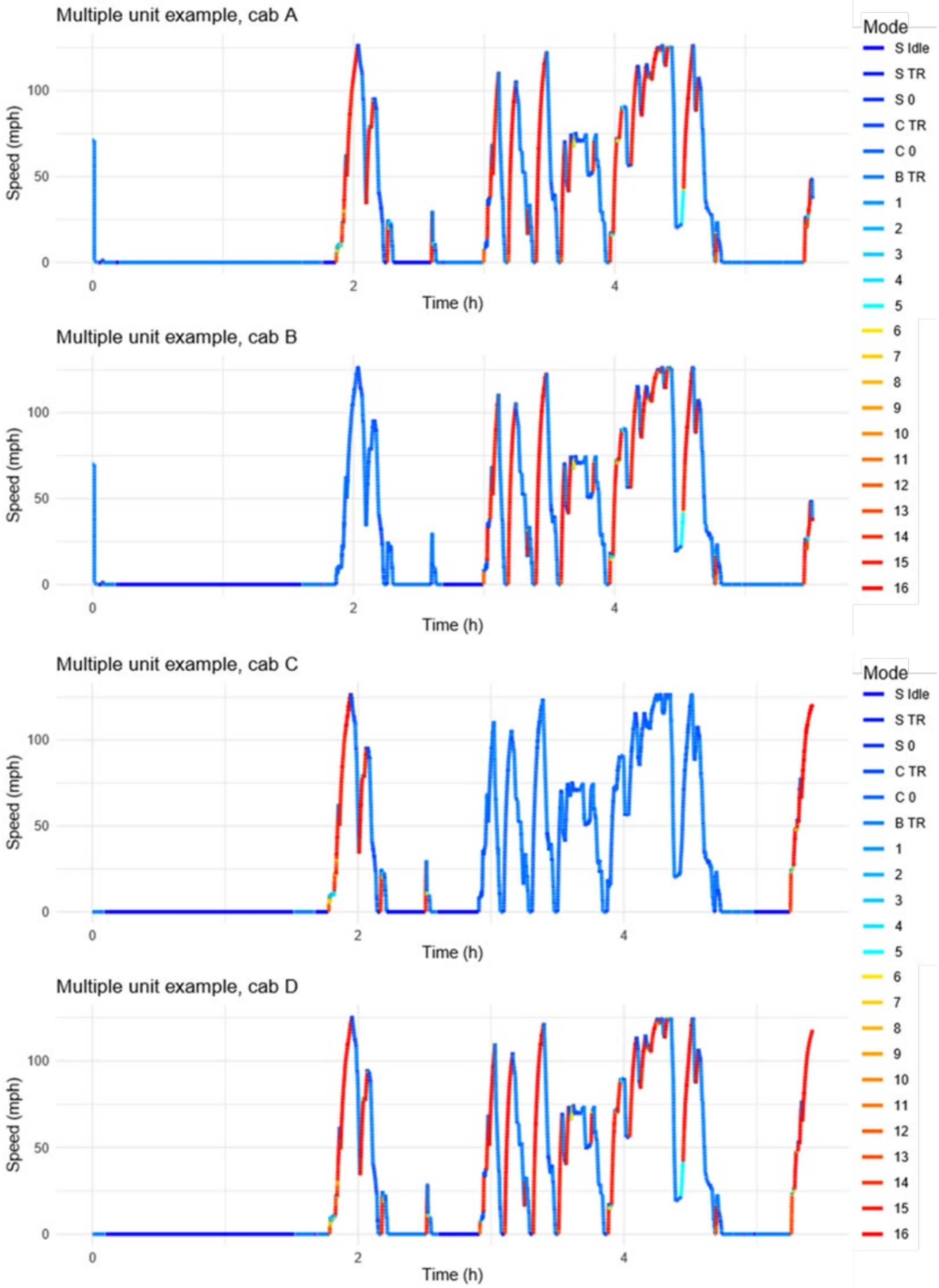


Figure 22 **Example multiple unit journey J1 – speed plotted over time and coloured by mode for all four cabs**



Interestingly, in the example running in multiple (Figure 22), one of the engines (cab B) was isolated for the early part of the journey before being restarted.

5 Specific case studies

A series of case studies, based on actual OMTR data, are presented in this section to illustrate the impact on emissions of different scenarios.

5.1 Reducing idling

5.1.1 Freight yards

Freight locomotives idling in yards is known to contribute to emissions. Stop-start systems are installed to combat this by automatically switching off the engine after it has been idling for more than 15 minutes. However, stop-start can be over-ridden by drivers, which is the norm on any mid-journey stops when the route may become available at short notice.

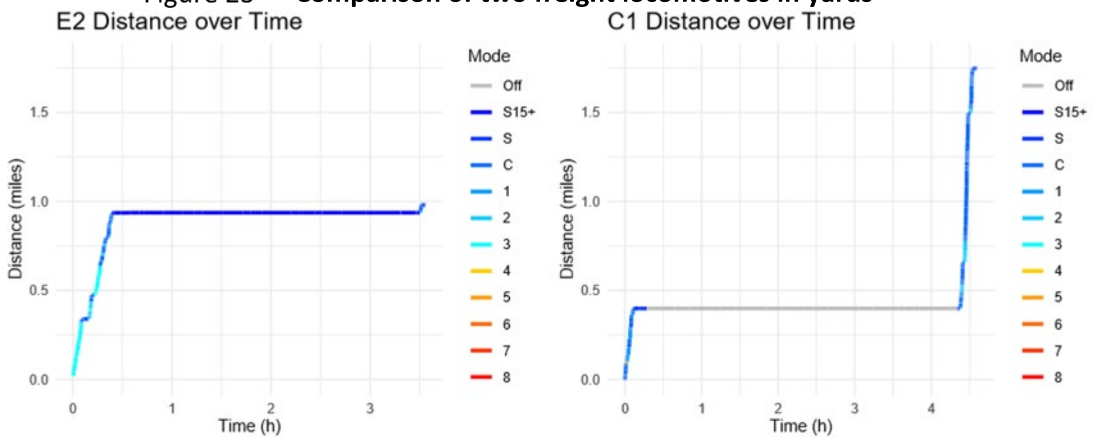
In the freight OTMR data, the sampled locomotives spent between 1 and 15 hours (with an average of 6.8 hours) in yards before or after their journey. Although they spent the majority of this time stationary, the locomotives travelled small distances (4.77 miles on average), often in several small increments interspersed over the period (for example joining or splitting trains that are longer than the loading or unloading sidings).

Case Study: Class 66– Idling in yard

- Compare two examples where locomotives were stationary over three hours
- Estimate emissions produced while idling
- Apply emission factors for different emission standards

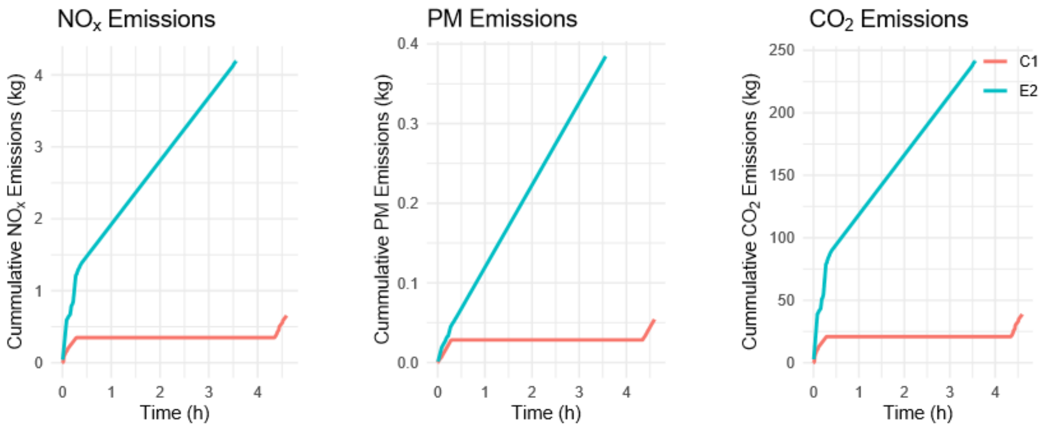
Two examples were found in the OTMR data where the locomotives were stationary in yards for over three hours. In one of the examples (C1), the engine was switched off, but in the other (E2), the engine remained on the whole time. A side-by side comparison of these two examples' cumulative distance over time coloured by mode is shown in Figure 23.

Figure 23 **Comparison of two freight locomotives in yards**



Other than the engine shutdown, the examples are similar (same locomotive type, 238 tonnes difference in train weight). However, their emissions differ significantly. The cumulative emissions of the three pollutants during these two examples are shown in Figure 24.

Figure 24 **Cumulative emissions of two freight locomotives in yards**



While the engine is left on, the emissions of all three pollutants continues to increase linearly, whereas the emissions flatline if the engine is switched off. As discussed in Section 4.1.5, PM emissions increase at the steepest proportionate rate while idling compared to NO_x and CO_2.

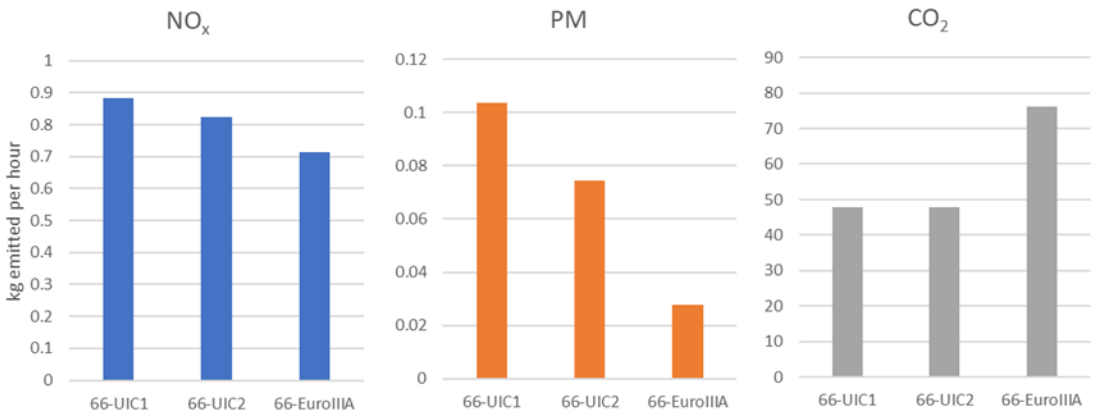
The yard emissions for these two examples are shown, in kg per hour, in Table 11. Both of these examples are UIC1 locomotives, and the amount of emissions in idle depends on their emissions standard.

Table 11 Kg per hour emissions for two freight locomotives in yards

Example	**NO_x (kg/h)**	**PM (kg/h)**	**CO_2 (kg/h)**
E2	1.18	0.108	67.9
C1	0.14	0.012	8.4

The effects of three emissions standards (UIC1, UIC2, and Euro-IIIA) be compared by simulating the emissions resulting from 1 hour of idling, since the average engine power for Notch 0 is known. The results are shown in Figure 25. Idling NO_x and PM emissions decrease with each emissions standard, but CO_2 emissions are highest in the Euro-IIIA locomotives, a consequence of fuel injection changes to minimise NO_x emissions.

Figure 25 **Simulating one hour of idling in three different Class 66 emissions variants**



While a Class 66-UIC1 locomotive is idling, it emits 0.88 kg NO_x, 0.104 kg PM and 47.8 kg CO_2 per hour.

A Class 66-UIC2 locomotive emits 0.82 kg NO_x, 0.075 kg PM and 47.8 kg CO_2 per hour, and a Class 66-EuroIIIA locomotive emits 0.71 kg NO_x, 0.028 kg PM and 76.2 kg CO_2 per hour.

On average, for 40 freight trips with full OTMR data for associated yard activity, yard emissions make up 7% of NO_x, 16% of PM and 6% of CO_2 overall emissions.

5.1.2 Extended station stops

Long layovers within or between scheduled passenger services offer the opportunity to reduce idling if a train engine can be effectively shut down while maintaining auxiliary (hotel) loads, as well as ensuring sufficient brake pressure is available when the train is ready to move.

Case Study: Class 158 – Idling at a station

- Total trip distance: 103 miles
- Total trip time: 2h45
- Maximum time in idle at station: 15m50s (occurred at 1h09 into the trip)

In the example journey shown in Figure 26, the highlighted period of approximately 16 minutes of idling that takes place after about an hour into the journey can be examined in more detail (Figure 27).

Passenger train idling at stations is known to contribute to emissions where there is relevant exposure of passengers and staff[14, 15]. Stop-start systems and reminders are installed to address this automatically or by recommending switching off the engine

[14] Hickman, A., C. Baker, X. Cai, J. Delgado-Saborit, and J. Thornes (2018). 'Evaluation of air quality at the Birmingham New Street railway station. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232(6): 1864-1878.
[15] Green, D.C., A. Font, A. Tremper, M. Priestman, D. Marsh, S. Lim, B. Barratt, M. Heal, C. Lin, J. Saunders and D. Pocock (2019). *Research into air quality in enclosed railway stations*. RSSB.

after it has been idling for a certain duration. However, these systems can often be over-ridden by drivers.

An example of a trip where a Class 158 train idles at a station for more than 15 minutes and how emissions from this interval contributes to the total trip emissions was assessed. A summary of the trip is shown in Figure 26 (see also Figure 18), the trip lasts for 2h45 and covers 100 miles. At 1h09 into the trip the train stops at a station and is in idle for 15 minutes and 50 seconds while awaiting the single-track section ahead to become clear. This period of idle in the trip was isolated to calculate the emissions generated.

Figure 26 **Example Class 158 trip with over 15 minutes spent in idle (shaded in grey)**

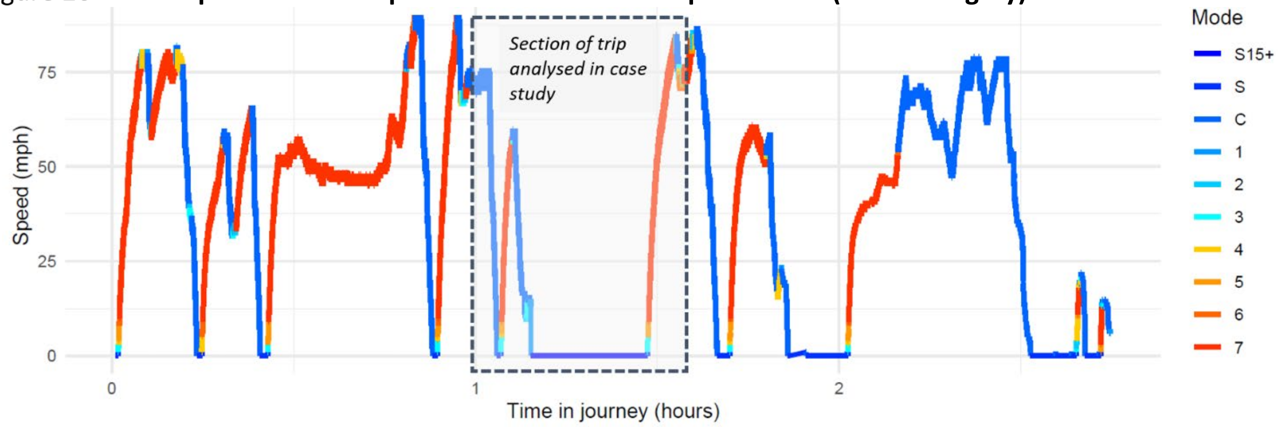


Figure 27 shows the highlighted section of the trip from Figure 26 in more detail. Between 1h00 and 1h30 into the trip the train stops at a station and idles for more than 15 minutes (Figure 27a). Table 12 presents an overview of the emissions generated over the entire 100-mile trip and during the period spent in continuous idle for over 15 minutes. For every 15 minutes spent in idle, approximately 60 g of NO_x, 20 g of PM and 27 kg of CO_2 are generated.

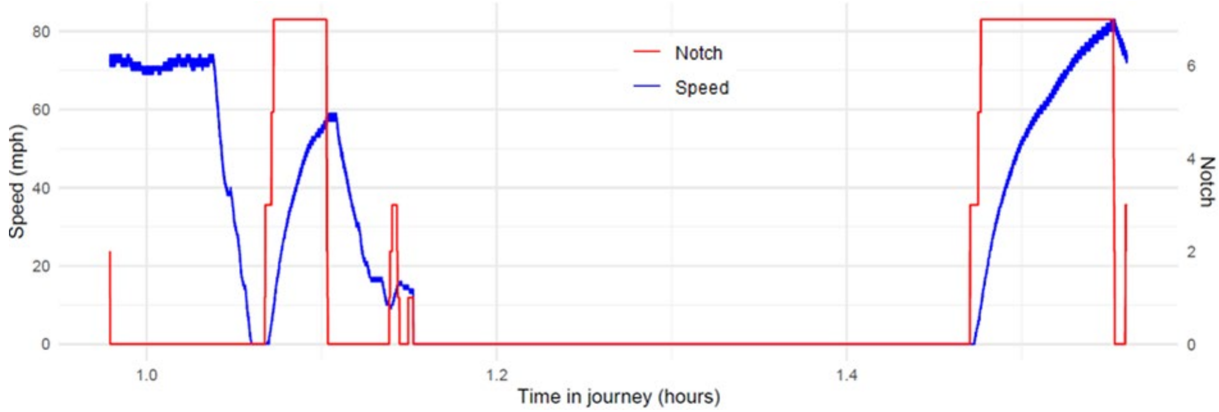
While the emissions of the extended stop in the example are a small part of the overall total, they occur in an urban area and as the train is stationary, the emissions are not widely dispersed under most circumstances and highlight that some features of emissions are endemic due to features and characteristics of the current network. Once a delay occurs with an earlier train travelling in the opposite direction then several periods of extended waiting in successive passing loops occur.

Table 12 Comparison of emissions from total trip (100 miles) with time spent in idle for over 15 minutes

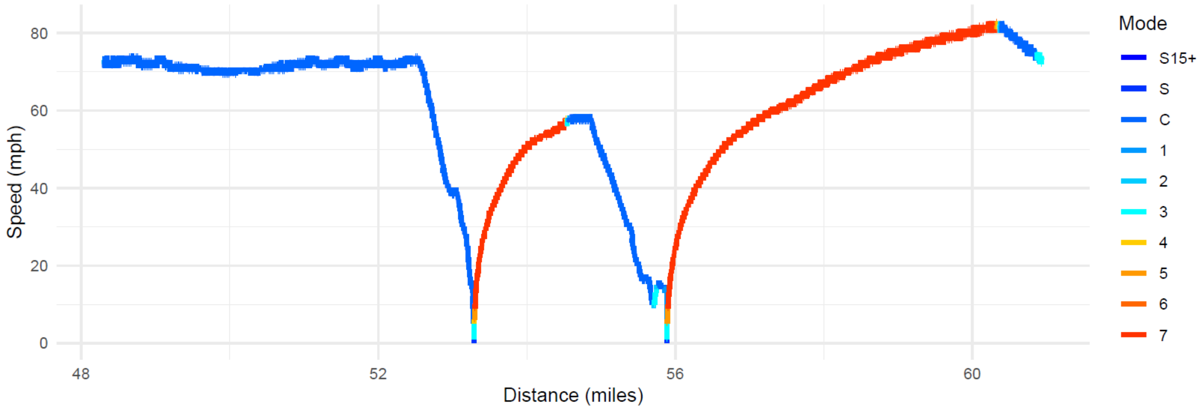
Pollutant	Emissions from total trip (kg)	Emissions from time in Idle 15+ (kg)	Contribution of S15+ to total trip
NO_x	8.6	0.63	7%
PM	1.5	0.19	13%
CO_2	963.4	27.2	2.8%

Figure 27 **Example Class 158 idling for approximately 16 minutes**

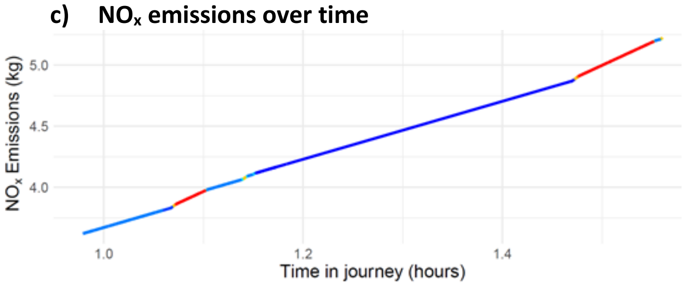
a) Speed and notch over time



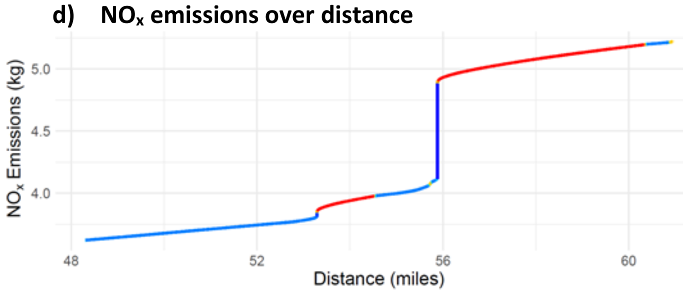
b) Speed over distance



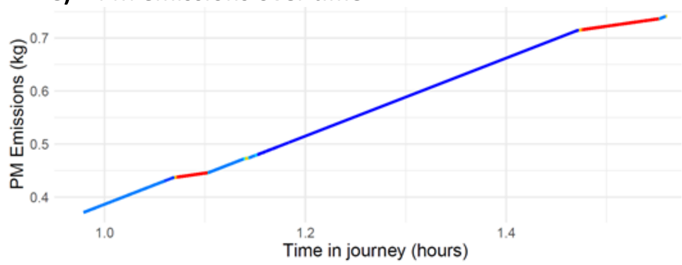
c) NO_x emissions over time



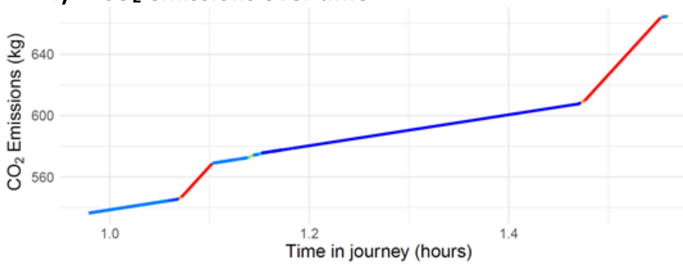
d) NO_x emissions over distance



e) PM emissions over time



f) CO_2 emissions over time



Case Study: Class 220/221 – Emissions from a long-layover

- 30 minutes of idling emissions compared to a typical long-distance journey

A long layover at a large railway station in the north of Britain was identified in the OTMR data for a Voyager journey. The engine was left on throughout the 30-minute stop, generating NO_x, PM and CO_2 emissions of 1.26 kg, 0.096 kg and 109.6 kg of CO_2. These amounts are 2.9%, 8.1% and 2.1%, respectively of the total start to stop emissions of a typical long-distance Voyager journey. While a relatively small component of the full journey emissions, it is important to note that these emissions were generated in one place (an enclosed station), whereas the journey emissions would have been dispersed along the length of the greater than 400-mile journey.

5.2 Minimising delays

Delays to services arising from operational issues and network congestion see trains having to slow or stop and then accelerate again resulting in higher overall emissions. This is due to a combination of both the engine running for longer and more power being needed to complete the journey than during a no-delay situation. While reducing delays is the best solution in this case, better information supplied to drivers than is currently available, for example Connected Driver Advisory System (C-DAS), European Train Control System (ETCS) Level 2 with in-cab functionality, and Traffic Management Systems (TMS), could help reduce the emissions impact of delays by providing more data to allow drivers to approach in a smoother way in many cases.

5.2.1 The cost of a stop

Case Study: Class 66 – Compare emissions from a freight stop to a simulated no-stop scenario

- Total journey segment: 12.5 miles
- Train slows to a stop and regains original speed after 20 minutes
- Compared to 'counterfactual' where train maintained cruising speed

A section of OTMR from trip B5 was identified where the train was cruising at constant speed in Notch 7 but then slowed to a stop before returning to the same speed in Notch 7. The relatively smooth deceleration and acceleration curves indicate the cause was signal regulation on a stretch of line where full linespeed could have been maintained throughout. This section of the journey was also simulated as if the train did not stop, and stayed at Notch 7 for the total distance covered by the train in the actual case, from the time it started to decelerate to the time it returned to the original speed (Figure 28). Comparisons of the emissions produced for this segment of the journey for the two scenarios are shown in Figure 29 and Table 13.

Figure 28 **Simulating a no-stop scenario for a section of journey B5**

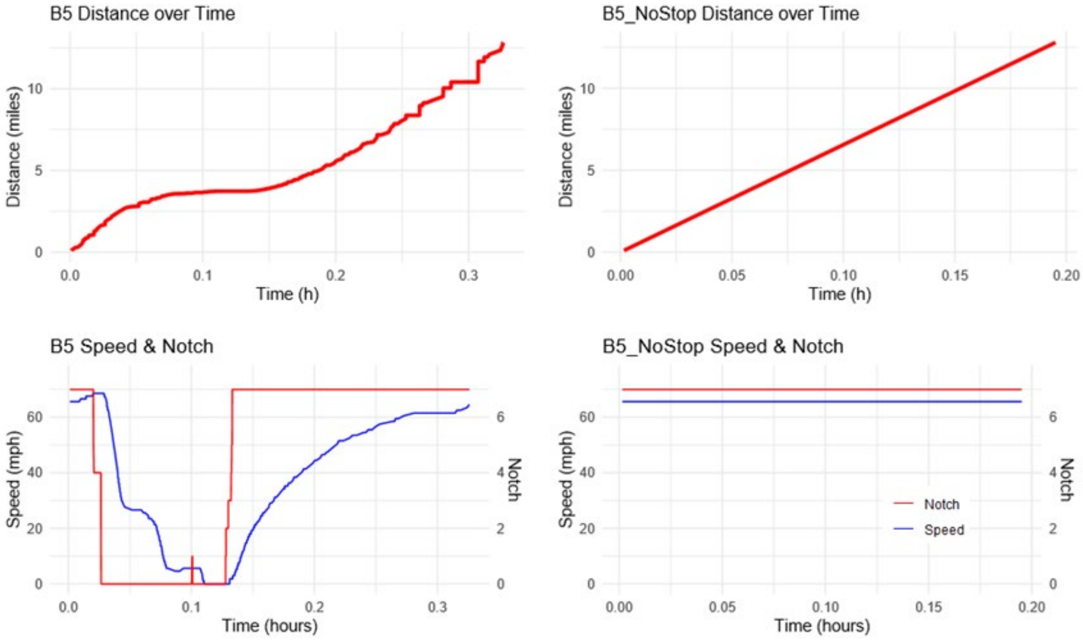


Figure 29 **Comparing emissions for a section of journey B5 to a no-stop scenario**

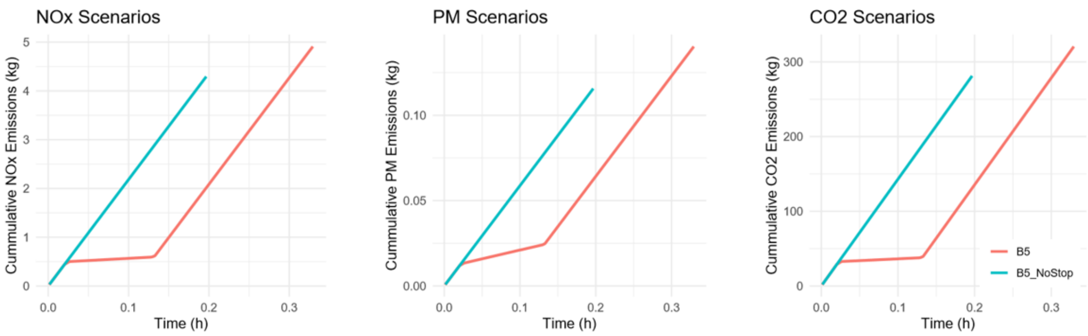


Table 13 Emissions cost of an example stop in journey B5

Scenario	**NO_x (kg)**	**PM (kg)**	**CO_2 (kg)**
Stop	4.91	0.140	321
No-Stop	4.29	0.116	281

The emissions savings from this no stop scenario are: 0.62 kg NO_x, 0.025 kg PM and 38.3 kg CO_2, equivalent to 0.72%, 0.97% and 0.69%, respectively, of the total journey emissions. These percentages are small, but note that this case study covers only 20 minutes (or 4.9%) of a 6.8 hour journey: the impacts for just the assessed segment of the journey (from where the train had to start to decelerate to where it returned to its original speed) are equivalent to 14.5%, 20.6% and 14.2% of the NO_x, PM and CO_2 emissions, respectively .

In this example, the actual emissions are 0.62 kg NO_x, 0.025 kg PM and 38.3 kg CO_2 higher than the simulated counterfactual where the locomotive did not have to stop. These amounts are equivalent to increases in NO_x, PM and CO_2 emissions of 14.5%, 20.6% and 14.2%, respectively, for the assessed segment of the journey due to the train having to stop.

However, these emissions savings are conservative, as a locomotive would not maintain a constant speed while at a high notch for this length of time. In reality the locomotive is likely to switch between higher and lower notches to maintain speed, and so the resulting counterfactual emissions would be lower than calculated here. Thus the increase in emissions from having to stop would be greater than that calculated above.

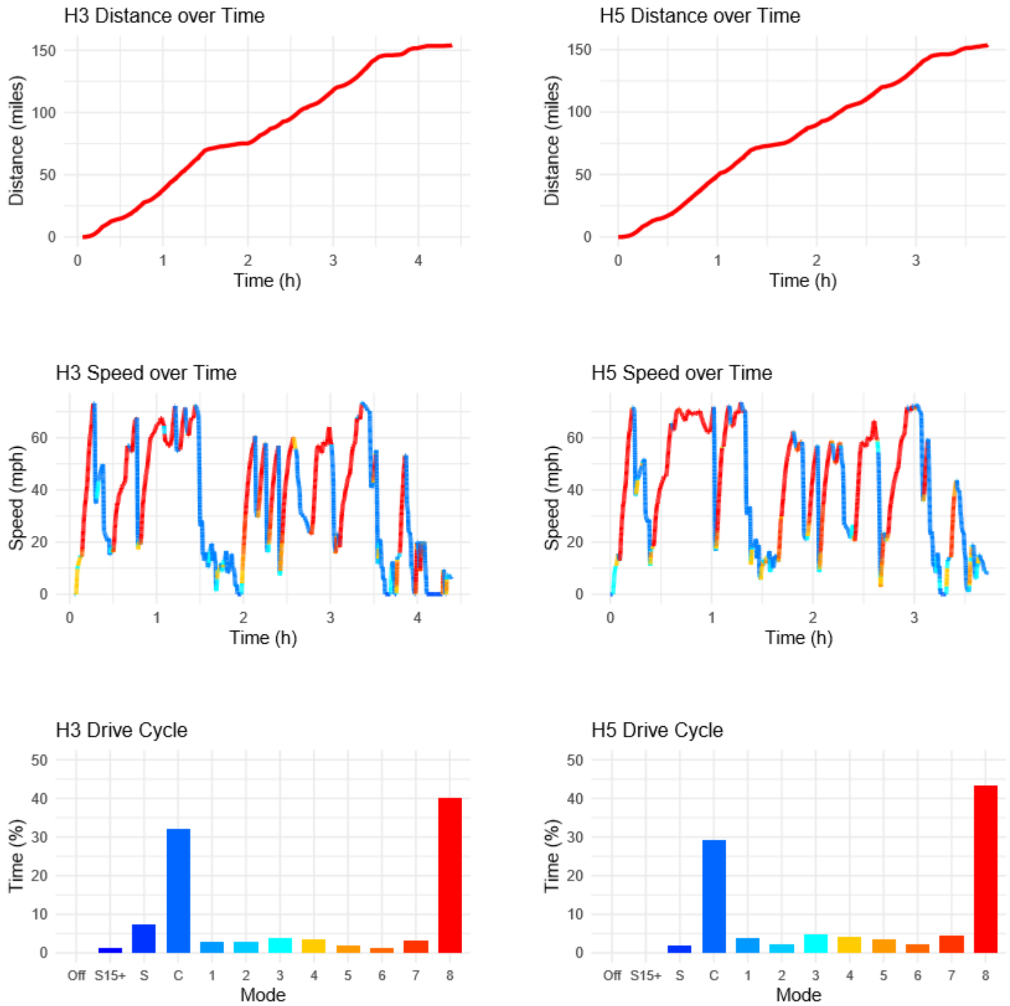
Case Study: Class 66 – Compare emissions from two freight journeys on the same route on different occasions

- Total journey: 154 miles
- Average journey time: 4.05 hours

Two journeys on the same route on different occasions can have different emissions depending on the specific driving conditions, such as increased stops at signals. A summary of two freight journeys on the same route on different occasions is shown in Figure 30.

The top panels show cumulative distance over time, the central panels show speed over time coloured by mode, and the bottom panels show the journey drive cycles. The journeys are matched for route and locomotive type, while the weights are within 60 tonnes (H3 being heavier).

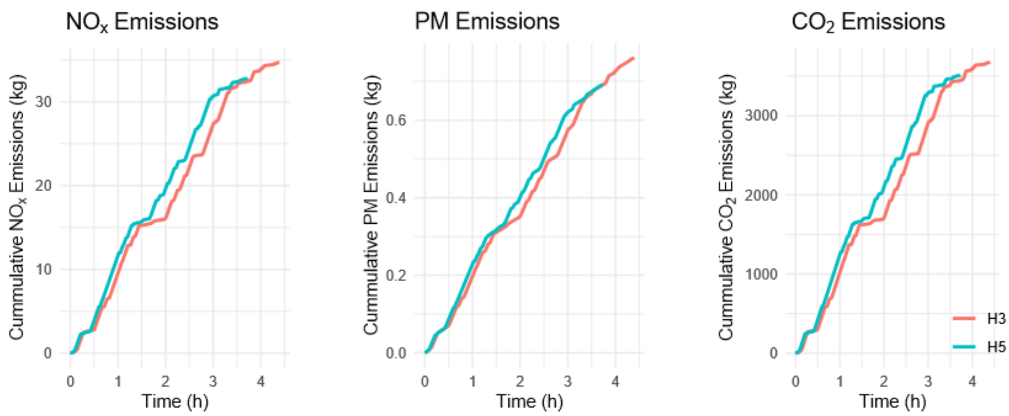
Figure 30 **Summary figures for two freight journeys on the same route on different occasions**



Though the journeys may appear similar, journey H5 on the right has a smoother profile and fewer stops than journey H3 on the left. The drive cycles show that H3 spends more time in stationary modes, whereas H5 spends more time in Notch 7 and 8. H3 also takes an additional 41 minutes to arrive at the destination.

Figure 31 shows the cumulative emissions over the course of the two journeys. The emissions follow similar patterns due to the route, though the emissions from H3 continue to increase for an additional 41 minutes as this journey takes longer.

Figure 31 **Cumulative emissions of two freight journeys on the same route on different occasions**



There is a section of the journey around 1.5 hours where H3 has to slow and come to a complete stop, whereas H5 slows but not for as long and does not come to a stop. This section appears to account for the majority of the differences in emissions. This particular location, where the freight train has to cross a busy mainline on the flat, is prone to congestion.

Overall, journey H3 (which experienced more delays) emits 1.13 kg NO_x, 0.045 kg PM, and 108 kg CO_2 more than journey H5 over the same route. These differences are 12%, 16% and 3.5%, respectively, of total journey NOx, PM and CO_2 emissions.

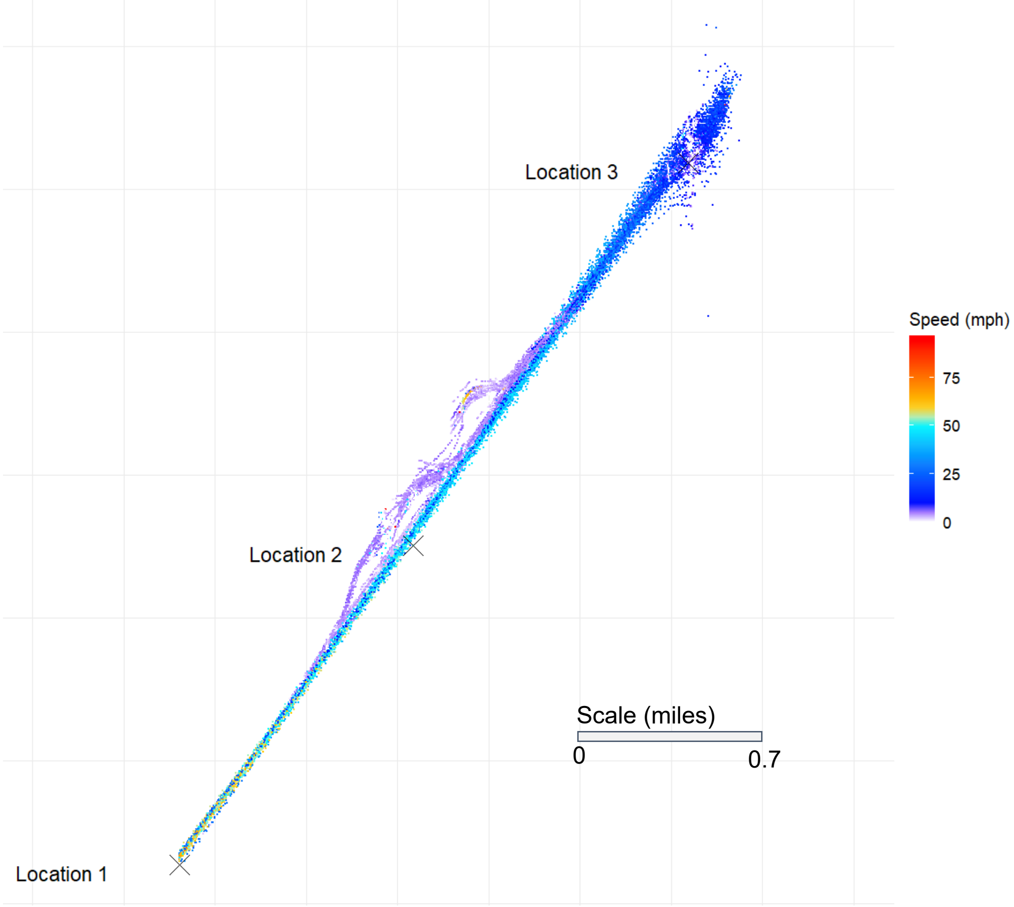
5.2.2 Smooth approach to stations

Case Study: Class 158 and 170 – Smooth approach to a station

- Journey distance: 1.2 miles
- Average journey time: range from 0h02 – 0h06
- Number of stops: range from 1 – 3
- Number of journeys: 61

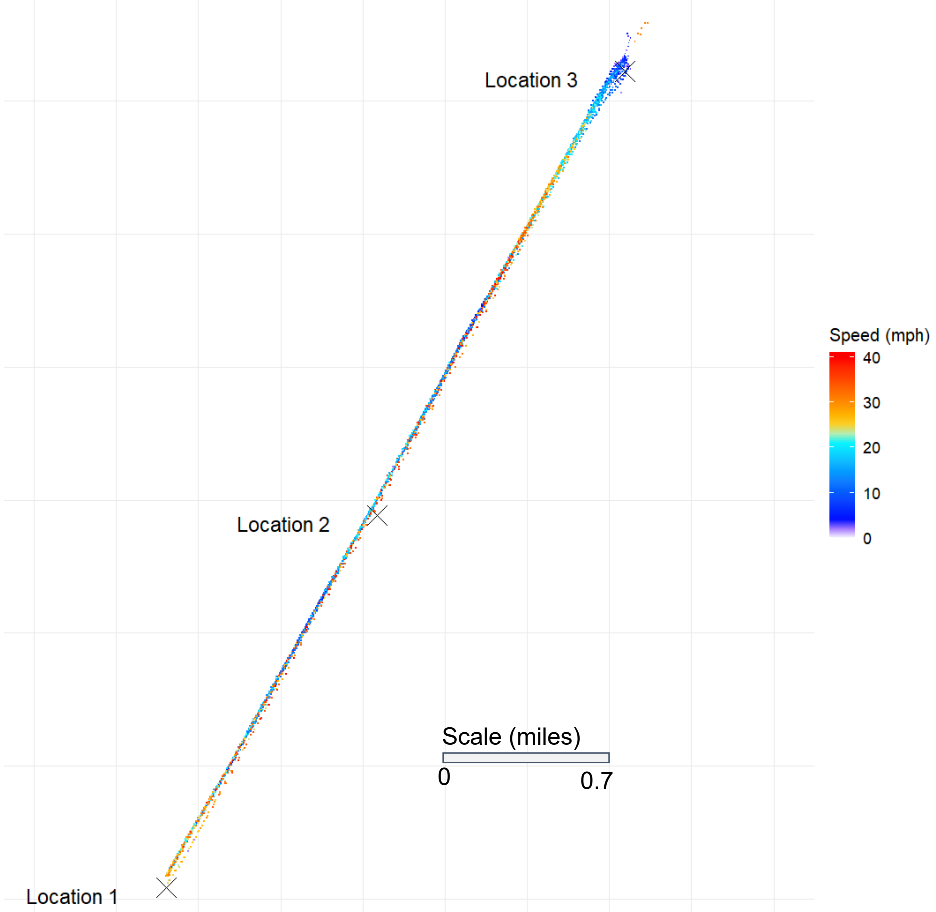
The example used in this case study is an area (Figure 32) frequently subject to congestion, where trains can be held at two junctions (Locations 1 and 2) during the approach to a major station (Location 3). Although a maintenance depot is located next to Location 2, only traffic in passenger service, i.e. passing through both Locations 1 and 2 before arriving at the station (Location 3) was considered in this analysis as shown in Figure 33. The analysis covered up to arrival at the station, i.e. any idling within the station was not included. This was done to improve the comparability of the emissions generated upon approach to the station. The erroneous GPS coordinates shown in Figure 32 around Location 3 were removed once the journeys which pass through all three locations were extracted from the dataset.

Figure 32 **Location map for smooth approach to station case study**



Speeds of the trains considered in this analysis are displayed in Figure 33. Most trains pass through at less than 40 mph. The impact of signalling delays, resulting in trains having to stop outside the station, idling and then having to accelerate away from a stop to finally reach the station, can be expected to result in higher emissions than for trains that are able to coast smoothly into the station. The latter represents the current lowest possible emissions scenario without the introduction of new technology such as battery hybrids with programmed swapping from diesel to battery power on approaches to stations in situations like these.

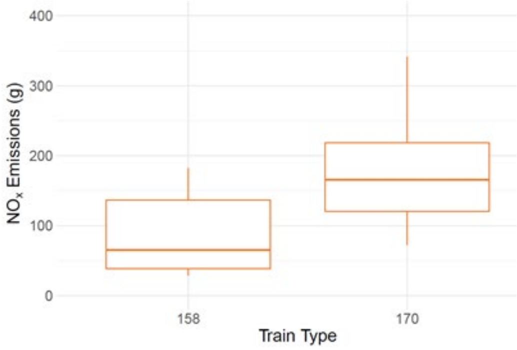
Figure 33 **Range of train speeds for all journeys in smooth approach to station case study**



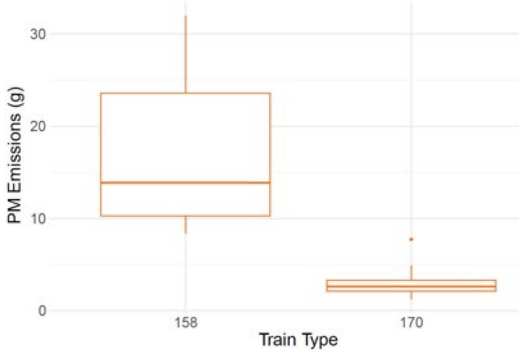
There are a number of factors that impact the emissions that are generated as a train enters a station. Here, the emissions generated during the final mile of a journey during the approach to a major station were assessed. All journeys considered were for individual Class 158 or Class 170 trains. The various factors considered include the proportion of time spent in idle (both along the journey and upon arrival at Location 3), the number of stops and the average speed. These various factors resulted in a wide range of emissions being generated by the different journeys in this small study area (Figure 34).

Figure 34 **Boxplot of emissions by train class generated by the journeys in the smooth approach to station case study**

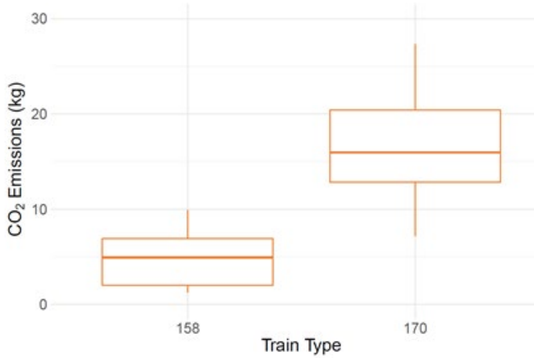
a) NO_x (g)



b) PM (g)



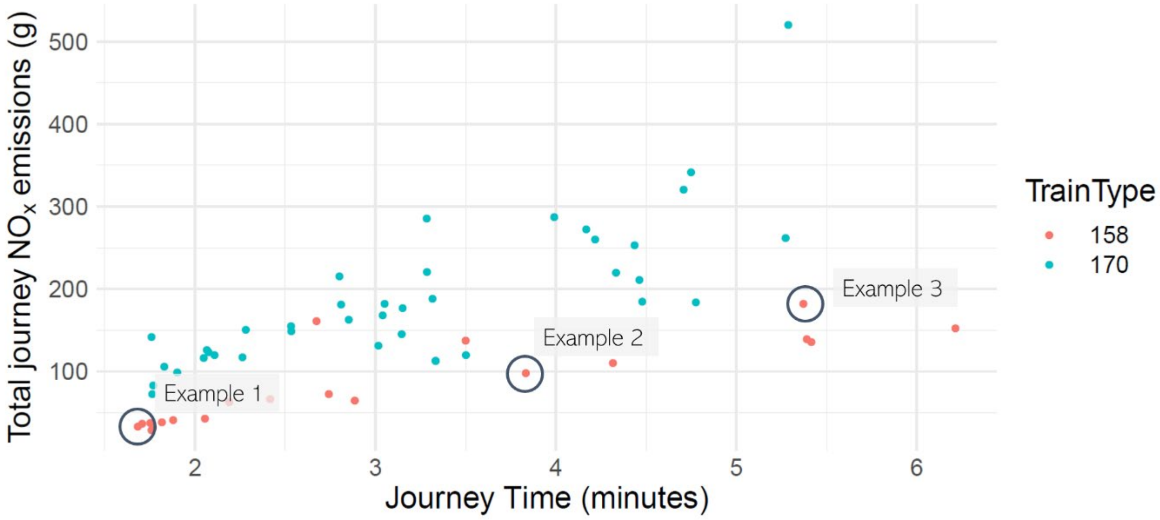
c) CO_2 (kg)



The variation in emissions generated could not be described in terms of one single cause; instead, three Class 158 examples are presented to provide a range of examples of different operational situations. These examples were selected for detailed analysis to demonstrate a range of total NO_x emissions and delays (represented by journey time and the number of stops). The examples (shown in Figure 35) were:

1) No stopping, lowest NO_x emissions (34 g) and the shortest journey (1 minute 14 seconds) – the current lowest possible emissions scenario
2) One delay (train slows to around 10 mph before speeding back up to 30 mph), mid-range NO_x emissions (98 g) and journey time (3 minutes 50 seconds)
3) Two stops before arrival at the station, highest NO_x emissions (182 g) of Class 158 trains and long journey time (5 minutes 22 seconds)

Figure 35 **Total journey NO_x emissions against the total journey time for individual Class 158 and 170 trains on example approach to a major station**



The cumulative NO_x emissions generated for the journeys of the three examples are presented in Figure 35. The emissions generated for PM and CO_2 follow the same trend as the journey emissions for NO_x. The total journey emissions for each example is presented in Table 14.

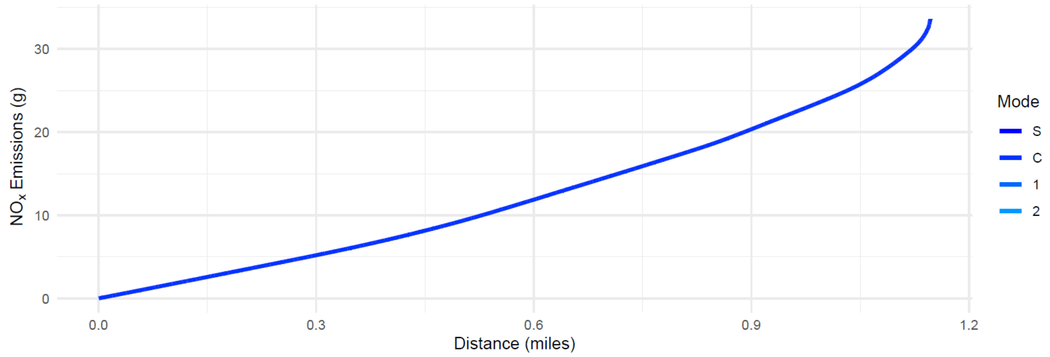
In example 1, there are no delays, the train is able to coast from Location 1 through to Location 3. Example 2 demonstrates a case of one delay between Locations 2 and 3, the train gradually slows to around 12 mph before accelerating in Notch 5 to reach 30 mph, before slowing into Location 3. This acceleration generates the majority of the journey's NO_x emissions and represents 10% of the drive cycle for the journey in the case study area. The greatest NO_x emissions occur in Example 3 which has two delays over the journey. The first delay causes the train to come to a complete stop at Location 2, which is followed by a period of acceleration in Notch 4. The train then maintains its speed for a short time before the second delay between Locations 2 and 3 causes the train to halve its speed. The train then accelerates in notch 6 before coasting into Location 3.

Table 14 Journey emissions for three Class 158 examples of approaches to a station

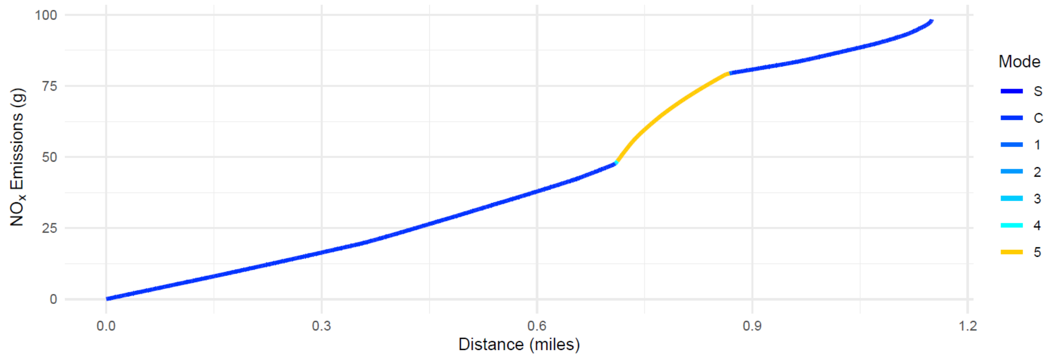
Example	NO_x emissions (g)	PM emissions (g)	CO_2 emissions (g)
1	34	10	1,429
2	98	22	5,233
3	182	32	9,888

Figure 36 **Cumulative NO_x emissions over distance for three Class 158 station approach examples (note the different y-axis scales)**

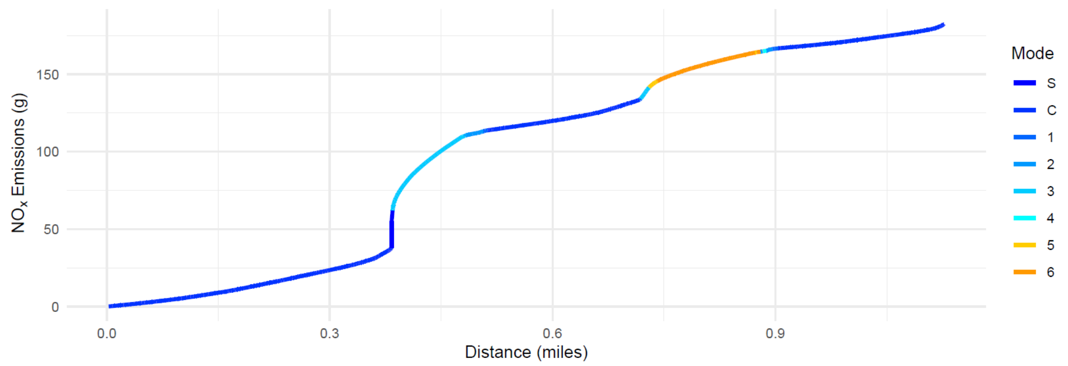
Example 1: No stopping, coasting through from Location 1 to 3 – lowest emissions



Example 2: One period of delay



Example 3: Two periods of delay – highest emissions



The NO_x emissions generated in Examples 2 and 3 (the delayed approaches) were approximately three and five times greater than Example 1 (the smooth approach), respectively.

Delays in the approach to stations result in much higher emissions for NO_x, PM and CO_2.

Although this scenario considered approaches to a major station and the impact of congestion (through causing stops) on emissions, it also highlights a broader issue which is the importance of emissions produced when accelerating at low speeds (from a stop) in a station area or in urban locations more generally. The combination of a high total amount of emissions with limited dispersion (since the train is not moving quickly) can lead to locally high concentrations of air quality pollutants.

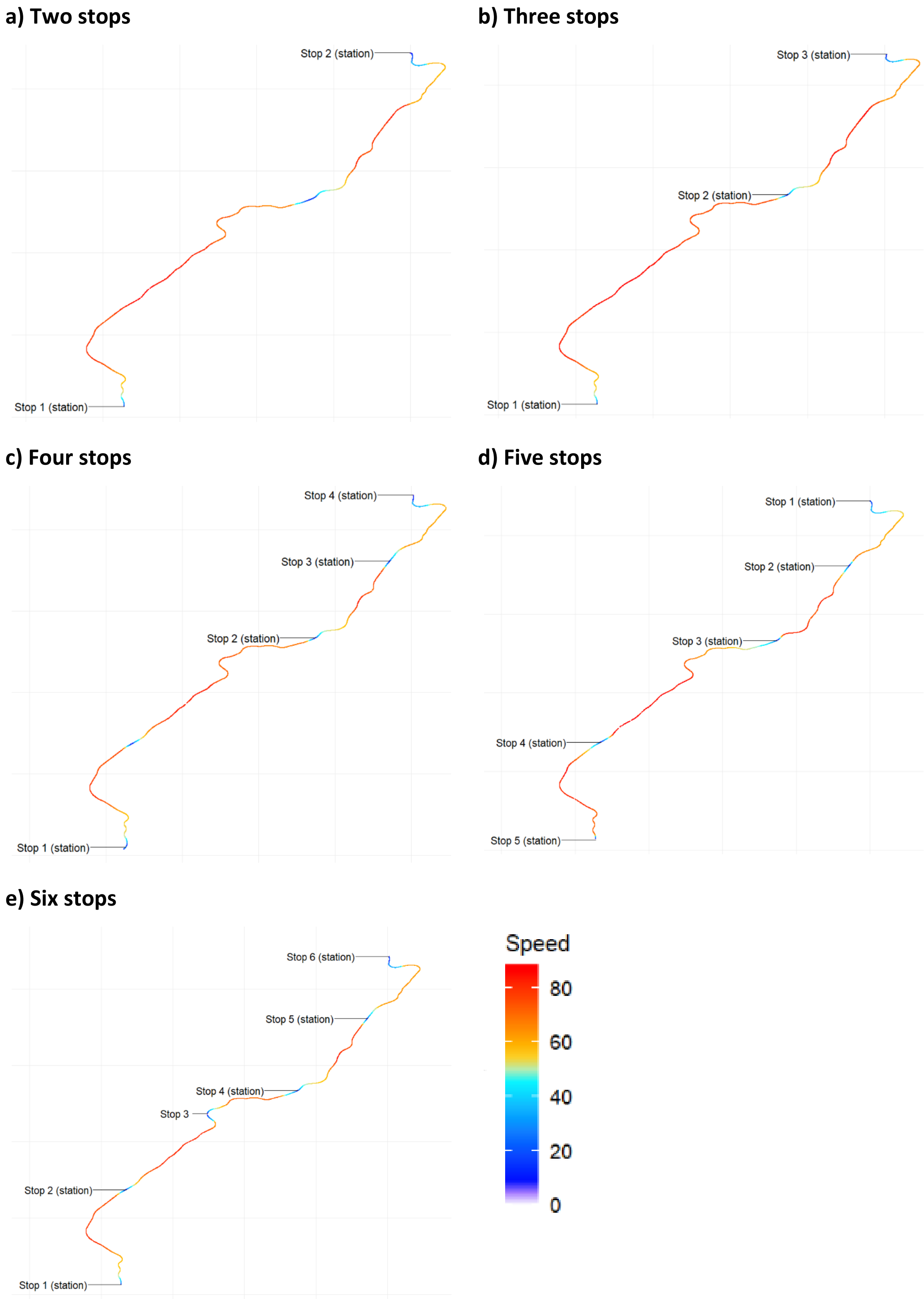
5.3 Reducing number of stops on a journey

Case Study: Class 158 and 170 – How the number of stops impacts emissions

- Journey distance: 40 miles
- Average journey time: 1h15
- Number of stops: range from 2 - 6
- Number of journeys: 96

Journeys made between two stations (Station A and Station B) by individual Class 158 and Class 170 trains with varying stopping patterns were compared to assess how reducing the number of stops in a journey impacts NO_x, PM and CO_2 emissions. Example journey location maps for each of the different stopping patters are presented in Figure 37. The minimum number of stops was two i.e. the train stops at Stations A and B only, the maximum number of stops was six. The majority of stops are at stations, but signal stops were also identified on some journeys. All journeys with six stops included five station stops and one signal stop. Journeys in both directions of travel between Station A and Station B were used in the analysis.

Figure 37 **Example journey location maps for each stopping pattern (coloured by speed) used for the reducing number of stops on a journey case study**



Similar NO_x emissions were generated by the Class 158 and 170 trains over the journey. There is a clear trend of increasing emissions with number of stops (Figure 38). A similar pattern with less variation is reflected in the PM emissions for Class 158 trains compared to little variation for Class 170 trains (Figure 39). There are greater CO_2 emissions for Class 170 trains and a greater variation in emissions with increasing stops. For both Class 158 and 170 trains CO_2 emissions increase with the number of stops (Figure 40).

Figure 38 **Journey NO_x emissions for individual Class 158 (left) and 170 (right) trains by the number of journey stops**

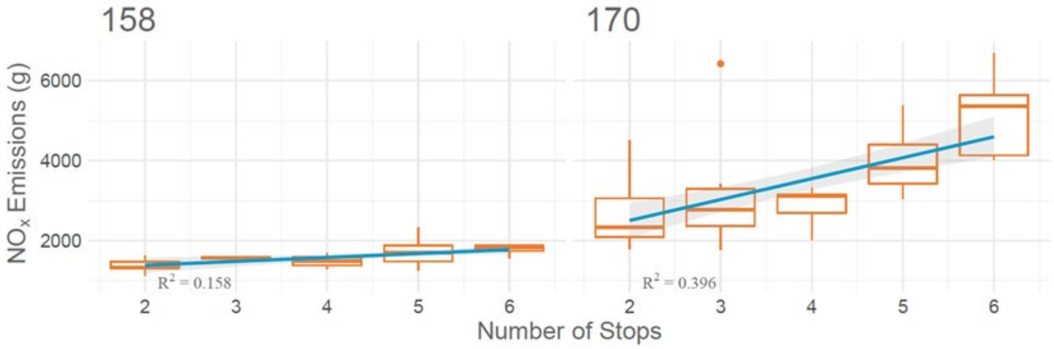


Figure 39 **Journey PM emissions for individual Class 158 (left) and 170 (right) trains by the number of journey stops**

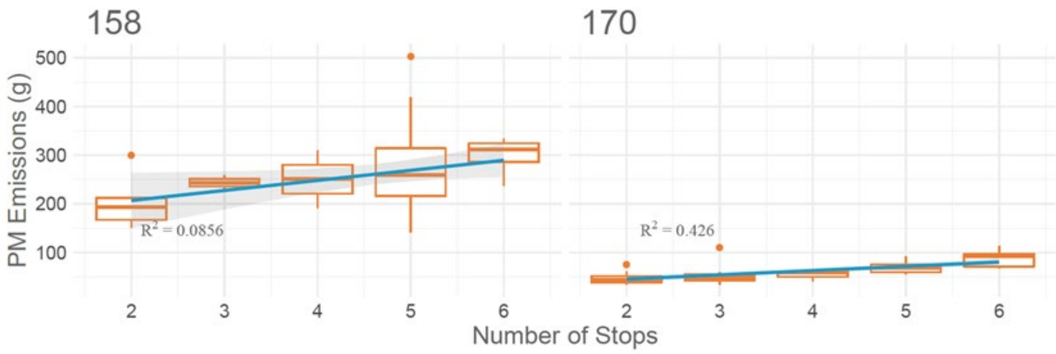
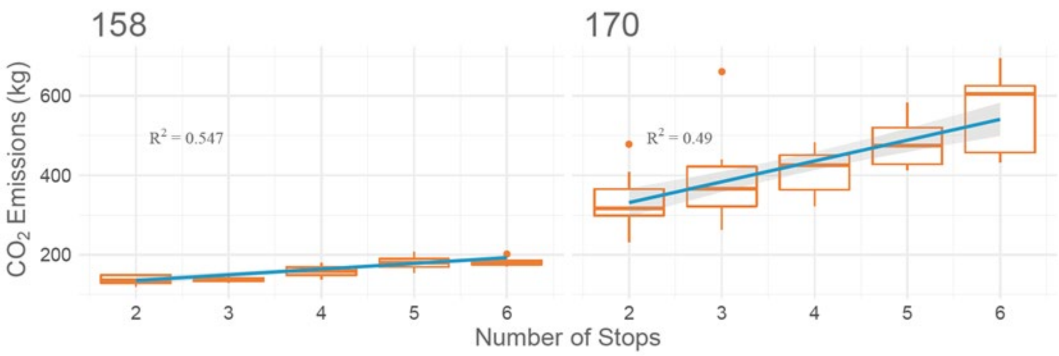


Figure 40 **Journey CO_2 emissions for individual Class 158 (left) and 170 (right) trains by the number of journey stops**



NO_x: On average, six compared to two stops resulted in between 26% and 60% more emissions over the journey.

PM: On average, six compared to two stops resulted in double the emissions over the journey.

CO_2: On average, six compared to two stops resulted in 40% more emissions over the journey.

For Class 158 trains the greatest difference seen is between a 4 and 5-stop pattern, with emissions for all pollutants increasing on average by 13%. In contrast for Class 170 trains the greatest difference seen is between a 2 and 3-stop pattern, with emissions for all pollutants increasing on average by 24%.

The addition of the fifth stop sees a noticeable increase in Class 158 emissions due to the inclusion of a stop with a substantial climb out of the station and the requirement to maintain both the same end-to-end journey time and same intermediate timings along the route due to the nature of this route (single track with passing loops). This is another example where endemic features of particular route can increase emissions above levels that might be seen on other routes. For example, greater double tracking (which has been examined for this route by Network Rail) would likely see reduced emissions.

Case Study: Class 220/221 – How the number of stops impacts emissions

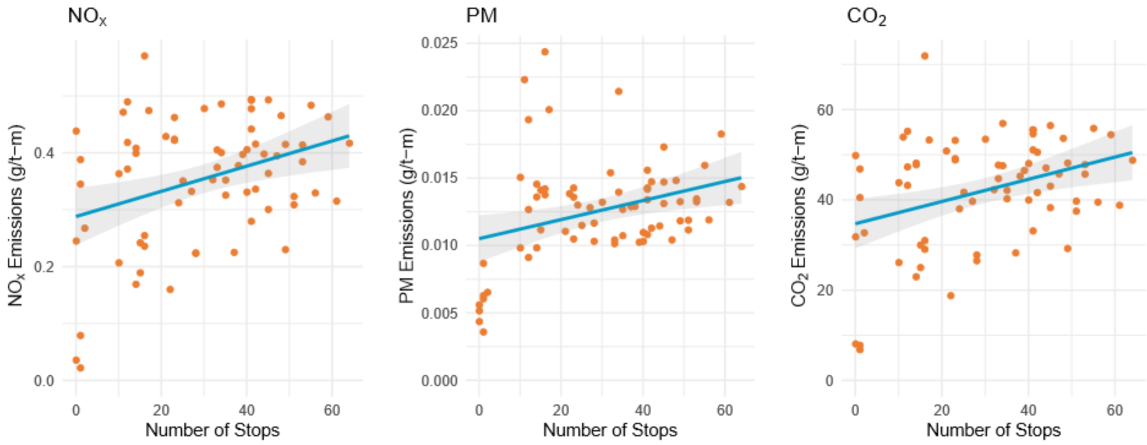
- Number of journeys: 70 Voyager single-unit journeys
- Number of stops: ranged from zero to over 60 per journey

OTMR recordings for the first 100 single-unit journeys were selected from the Class 221 dataset. Each journey has two recordings from different cabs in the unit, and the emissions for the total journey were calculated as described in Section 4.3.3. Of the 100 journeys, 30 were removed which were stationary for significant portions of the recording.

The number of times each journey stopped was determined as the number of times the train speed dropped to 0 mph for more than a minute. This method of counting stops was validated through a comparison to the number of times the times the 'Door Interlock' field in the OTMR data indicated the doors had opened. The two different methods of counting stops had similar results and a correlation of 0.90 for the 70 journeys.

The emissions per mile for each of the three pollutants is plotted against the number of stops in Figure 41. A linear model is fitted to the points shown in blue (the grey shaded region displaying the 95% confidence level interval for the model).

Figure 41 **Class 220/221 Emissions for single-unit journeys against number of stops**



There is an increasing trend in the kg/mile emissions of each pollutant as the number of stops increases. However, the trend is not as clear as in the Class 158 and 170 passenger trains case study above. This could be due the recordings being over a range of different routes. A significant part of the difference in scale of the trend between the Class 158 and 170 and Class 220/221 is likely due to two large factors:

- The electric transmission of the Class 220/221 has less speed-based variation in transmission efficiency, so the emissions cost of a stop is lower.
- High-speed running, which is more energy intensive due to the higher aerodynamic forces, so the energy usage of the Class 220/221 is higher in general and the emissions costs of stops is a lower proportion of the total.

The gradients of the lines in Figure 41 represent an increase in emissions of 0.00221 g/t-m NO_x, 0.0000707 g/t-m PM, and 0.0246 g/t-m CO_2 for each additional stop.

5.4 Train loadings (freight)

Case Study: Class 66 – Acceleration curves by freight loading

- The energy required to haul freight trains varies significantly with the weight of the train
- For passenger trains the passenger ('cargo') weight is <10% of the total
- For fully loaded freight trains the maximum cargo weight is between 62% and 78% of the train weight depending on the type of cargo
- As power available from diesel locomotives is limited by the size of the engine, the acceleration rate of trains decreases as they get heavier (this is less of an issue for electric trains)

Acceleration curves were located in the Class 66 OTMR data by looking for segments with continually increasing speed, from less than 1 mph to more than 40 mph. All the resulting curves are grouped by weight and shown in Figure 42 below. The acceleration curves are not always smooth, reflecting real operating conditions, and a single example for each category is highlighted in blue. The figures show clearly that the heavier the train's loading, the slower its acceleration, thus increasing the journey time which results in higher emissions. However, despite higher total emissions from heavier loads, the emissions on a per unit weight basis decrease as the train weight increases.

Figure 42 **Acceleration curves for freight trips with different loadings**

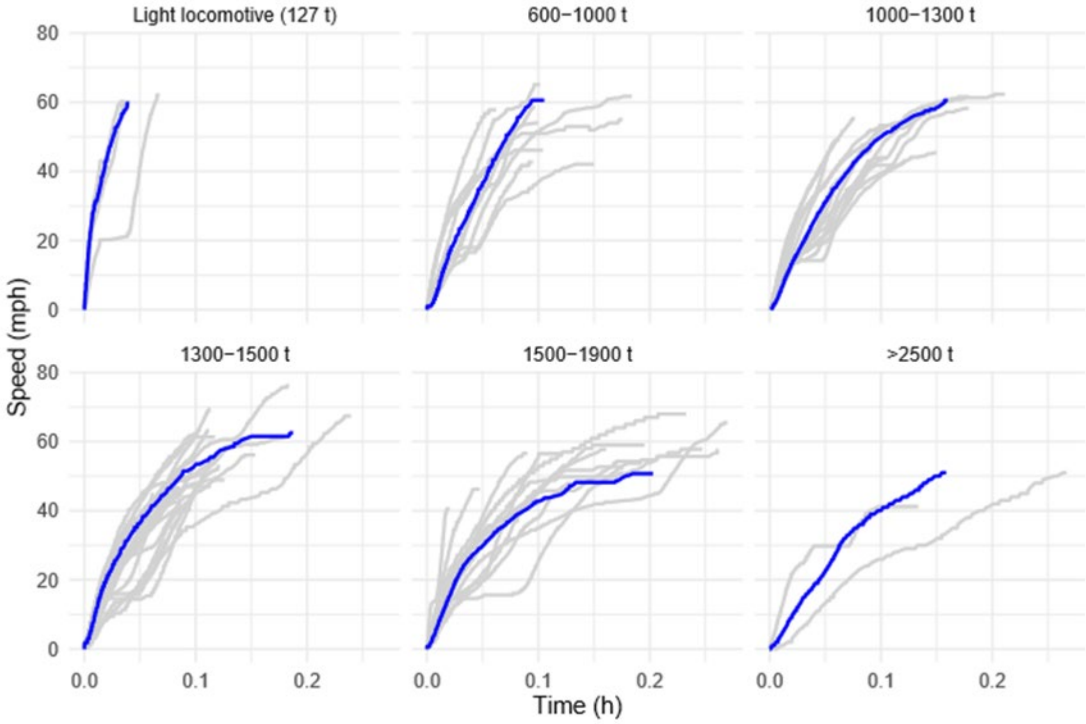
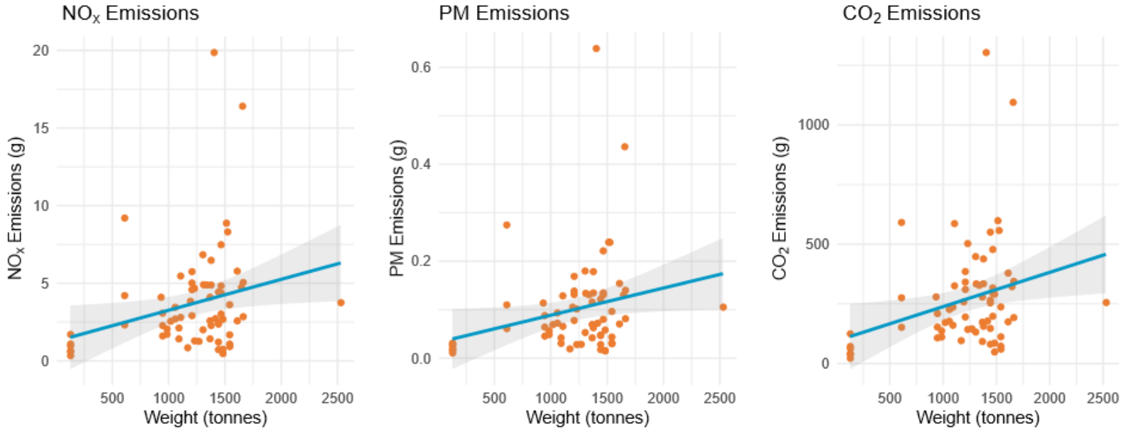


Table 15 Table of the time taken to reach a given speed

Weight	Time taken to reach speed (mins)					
	10 mph	20 mph	30 mph	40 mph	50 mph	60 mph
Light locomotive (127 t)	0.12	0.30	0.53	1.07	1.58	
600-1000 t	0.81	1.54	2.43	3.27	4.27	5.64
1000-1300 t	0.91	1.88	2.91	4.21	6.09	9.42
1300-1500 t	0.59	1.18	2.17	3.56	5.27	8.49
1500-1900 t	0.82	1.58	3.07	5.28	10.78	
>2500 t	1.22	2.63	3.74	5.82	8.89	

The times taken to reach each speed increase as the weight of the example locomotive increases. Some of the examples did not reach 60mph and so these values cannot be displayed.

Figure 43 **Emissions from acceleration curves increase with loading**



Most of the freight data have similar weights, clustered around 1000-1500 tonnes. However, the few examples with more extreme weights show that there is a positive trend: emissions from acceleration increase with train loading. More examples with a wider range of weights would help to clarify the exact nature of this relationship.

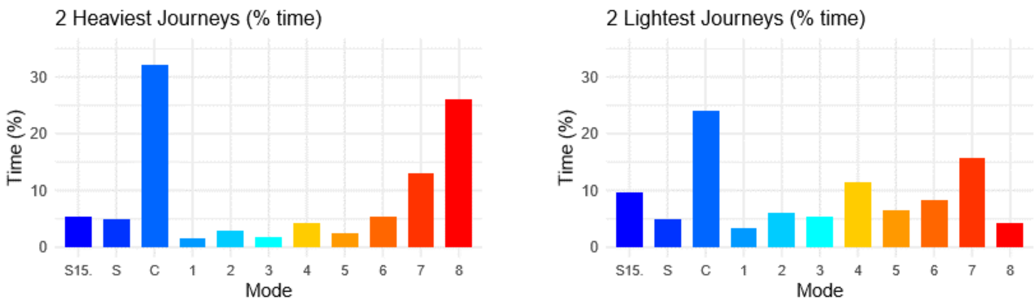
Case Study: Class 66 – Comparing emissions of light and heavy freight journeys

- The power required to haul freight trains increases significantly with the weight of the train as do the emissions
- For fully loaded freight trains the maximum cargo weight is between 62% and 78% of the train weight depending on the type of cargo
- Two extremes are considered: heavy (78% of train weight is cargo) versus light (empty wagons with 0% cargo)

Train loadings have an effect on the journey emissions. From the freight data, two of the heaviest journeys, both weighing more than 2000 tonnes, were compared to two of the lightest journeys, both weighing less than 610 tonnes (but not light locomotive moves).

The average drive cycles for the heavy and light journeys are shown in Figure 44. The lighter trips spend more time in Notches 1 to 7, whereas the heavier trips spend the most time in Notch 8 or coasting.

Figure 44 **Comparing heavy and light trips drive cycles**



The journeys were all had the same locomotive type. The two journey pairs of loaded outward and empty return legs (with the same wagons) were roughly matched by the distance travelled (there were slight routing variations on each leg): one light and one heavy shorter journey (around 110 miles), and one light and one heavy longer journey (around 185 miles).

In Figure 45, the emissions for these four journeys is plotted over time; the heavier journey emissions follow a consistently higher trajectory than those for the lighter two journeys. Table 16 shows a comparison of the average emissions per tonne-mile for the heavy and light journeys.

Figure 45 **Comparing two heavy and two light trip emissions profiles**

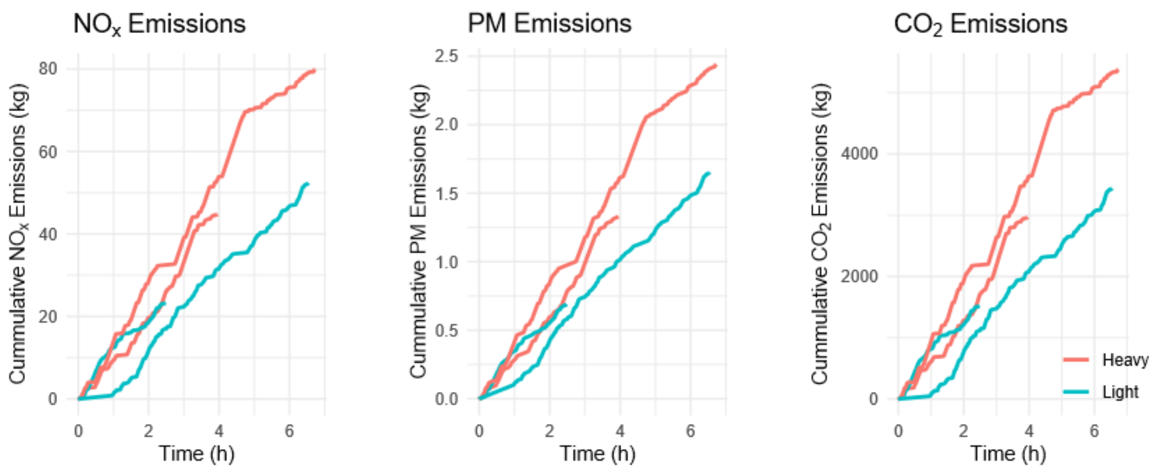


Table 16 Comparing heavy and light trips normalised emissions

Pollutant	Average for heavy trips (g/t-m)	Average for light trips (g/t-m)
NO_x	0.177	0.429
PM	0.005	0.013
CO_2	11.8	28.1

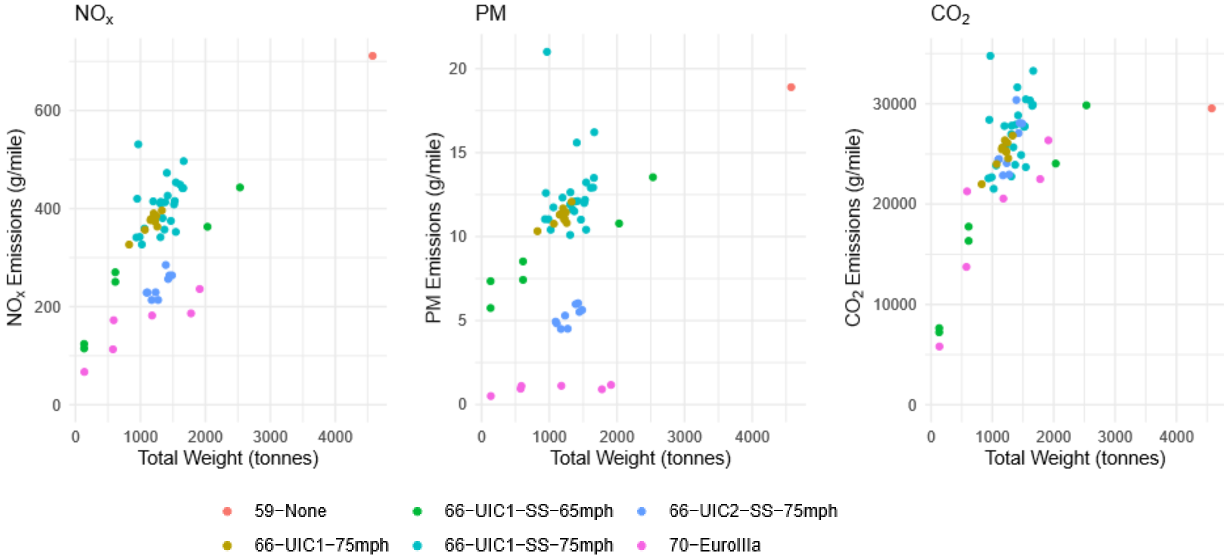
The heavier trips have lower emissions per tonne-mile of all three pollutants. This is strong evidence that **heavier freight loadings are more emissions efficient**.

Case Study: Emissions efficiency curves of freight journeys

- 57 freight journeys with a broad range of train loadings
- Only considered Journey component of trips
- Range of locomotives complaint with different emission standards

To evaluate how emissions vary with loading, emissions in grams per mile were plotted against total locomotive weight. The points in Figure 46 are coloured by locomotive type showing the clear effects of compliance with different emissions standards. For example, the PM emissions of the Class 70-EuroIIIa journeys are significantly lower than for the other locomotive types.

Figure 46 **Emissions per mile plotted against total weight for 57 freight journeys**



From the data shown in Figure 46, it appears that within each class there is an approximate linear relationship between emissions in grams per mile and weight. Importantly, this relationship shows that doubling the weight of the train does not double its emissions (gradient is less than 1). The outlier discussed in Section 4.1.5, journey E4 at 961 tonnes, is a very short and slow journey with a large amount of intermediate stationary time.

There is a limited range in train weights for most of the locomotive classes. However, the 4570 tonne Class 59 journey provides some insight into how emissions from the other train classes may vary with heavier loadings. For example, the Class 59 journey's CO_2 emissions (per mile) are at a similar level to journeys with half its weight. This indicates that emissions per unit distance may increase at a slower (non-linear) rate as weight increases and is consistent with the idea that rolling resistance per tonne decreases as weight increases.

Focussing on the two classes that have a reasonably large spread of weights, Figure 47 shows these journeys with a square root model fit to each set of points ($g/m = A + B\sqrt{weight}$, where A and B are regression parameters)[16].

[16] Lines of best fit were found using least-squares regression in the statistical computing language R.

Figure 47 **Emissions per mile plotted against total weight for two locomotive classes**

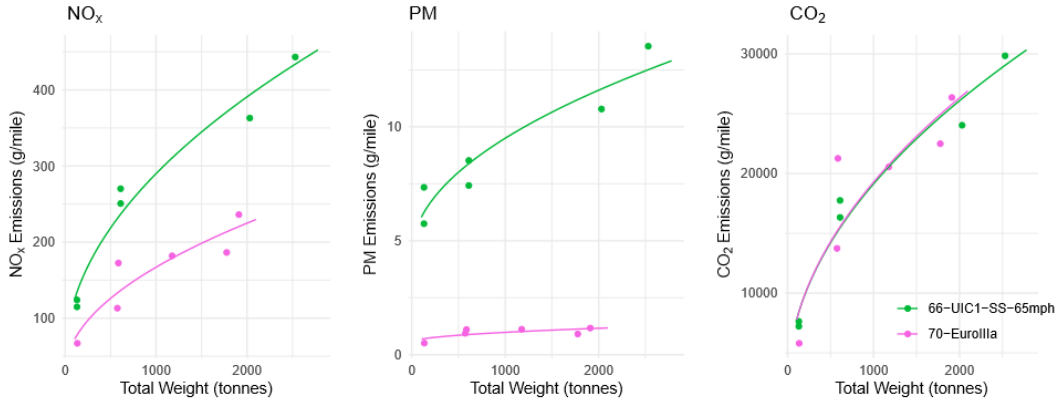
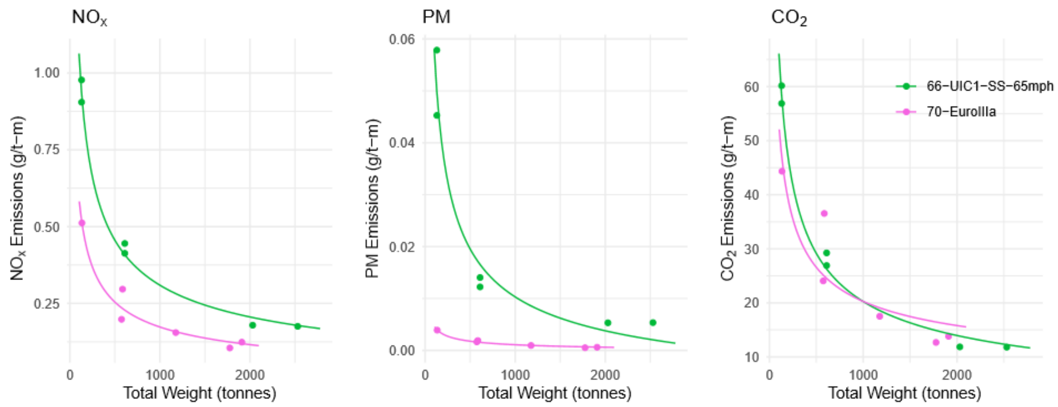


Figure 48 shows the emissions for the same two classes of locomotive plotted as g/t-m against weight. A 1/√x model was fit to each set of points, since there will be the same relationship modelled in Figure 47[17].

Figure 48 **Emissions per tonne-mile plotted against total weight for two locomotive classes**



These plots show that as the trains get heavier, their g/t-m emissions decrease with a non-linear trend and become more emissions efficient. There is a significant difference between the two locomotive classes for NO_x and PM with the new Class 70 having a greater reduction in PM than NO_X as would be expected primarily from changes to emission standards but also due to more efficient electrical systems and handling of auxiliary loads, while the CO_2 emissions are more similar.

Heavier freight trips have lower emissions per tonne-mile for all three pollutants. There is strong evidence that heavier freight loadings are more fuel and emissions efficient. Heavier (longer) freight trains are more emissions efficient which assists cases for potential infrastructure improvements to permit longer freight trains where not limited by available traction power or gradients on routes but by other features such as passing loop length or siding length at origin or destination.

[17] If there is a linear relationship between g/m and weight, there will be a 1/x relationship between g/t-m and weight. If there is a square root relationship between g/m and weight, there will be a 1/√x relationship between g/t-m and weight.

Freight journeys are increasingly emissions efficient as their weight increases; doubling the train weight does not double the emissions.

While there is an approximately linear pattern within a narrow range of weights, over a wide range of weights this trend begins to plateau. However, more data would help elucidate the precise relationship.

Locomotive emissions standards have a clear impact on emission efficiency, but the effect of increasing loading outweighs the effect of emission standards for NO_x and CO_2 emissions.

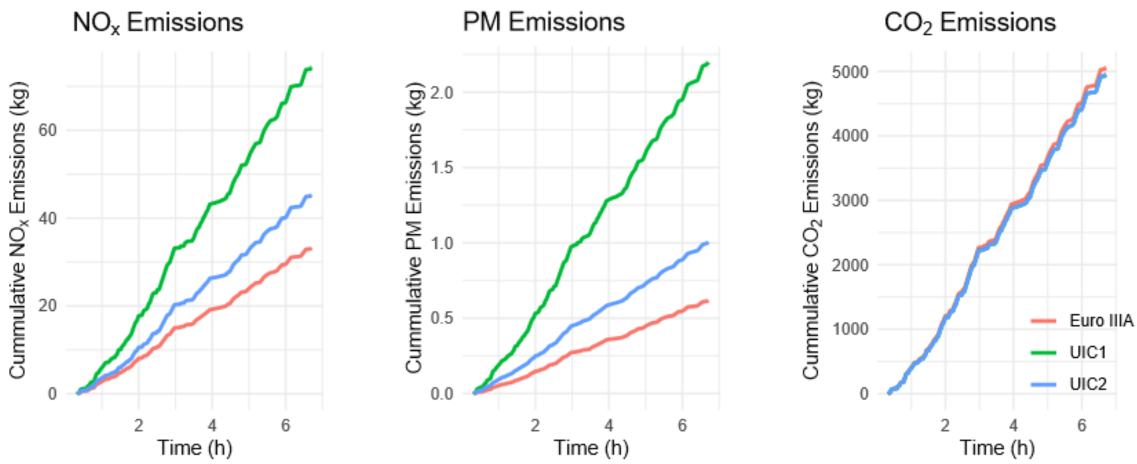
5.5 Impact of different emission standards

Case Study: Class 66 – Simulating one freight journey with different emission standards

- Trip C2 weighed 1056 tonnes and covered 194 miles
- Only considered Journey component of trip
- Emissions calculated for each timestep, using three different sets of emission factors for different Class 66 emissions variants

Emission factors by notch allow evaluation of emissions mitigation scenarios without requiring engine specific testing. Different emission factors for Class 66 locomotives meeting the UIC1, UIC2 and Euro IIIA emission standards were used with the OTMR data for Trip C2 to evaluate the impact of these standards on emissions (Figure 49 and Table 17).

Figure 49 Simulating one freight journey with different emission standards



The NO_x and PM emissions reflect the evolution of the three emission standards, with the largest difference for PM between UIC1 and UIC2[18]. The UIC1 and UIC2 CO_2 emission factors are the same so these lines cannot be differentiated in Figure 49, while the Euro IIIA CO_2 emission factor is slightly higher so trip CO_2 emissions are slightly higher.

Table 17 Total Journey component emissions for Trip C2

Emission standard	NO_x (kg)	PM (kg)	CO_2 (kg)
UIC1	74.2	2.19	4945
UIC2	45.2	1.00	4945
Euro IIIA	33.1	0.615	5056

5.6 Train loadings (passenger)

5.6.1 Units running in multiple

The leading vehicle of a train always has significantly higher aerodynamic loadings (especially above 50 mph) than the following vehicles in the train. Hence in the case of multiple units with all vehicles powered, the average aerodynamic drag per vehicle reduces as the number of vehicles increases. Therefore, longer multiple units have slightly more power available to accelerate the train mass due to lower aerodynamic drag. This often leads to question such as “does doubling the train length mean double the emissions?”

Case Study: Class 158 – does double the passenger capacity (double the train length) mean double the emissions?

- Journey distance: 12 miles
- Average journey time: 0h24
- Number of units: range from 1 – 2
- Number of stops: range from 3 – 6
- Number of journeys: 30 (20 individual and 10 running in multiple)

Journeys made along the same route and starting and ending at the same two stations by individual (1 unit) and running in multiple (2 units) Class 158 trains with varying stopping patterns were compared to assess how increased capacity impacts NO_x, PM and CO_2 emissions. Journeys with 3, 5 and 6 stops along the same route were available for both 1 and 2-unit Class 158 trains. Figure 50 presents example journey location maps for each of the different stopping patterns used in this case study. It should be noted that journeys with four stops were only available for running in multiple Class 158 trains. Where there are gaps in the OTMR recording, it is assumed that the train

[18] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors – Main report*. RSSB.

continues at a constant speed and notch as the previous timestep. The majority of stops are at stations, but signal stops were also identified on some journeys. Journeys in both directions of travel between the two stations were used in the analysis.

Figure 50 **Example trip location maps for each stopping pattern coloured by speed used for the train loadings case study**

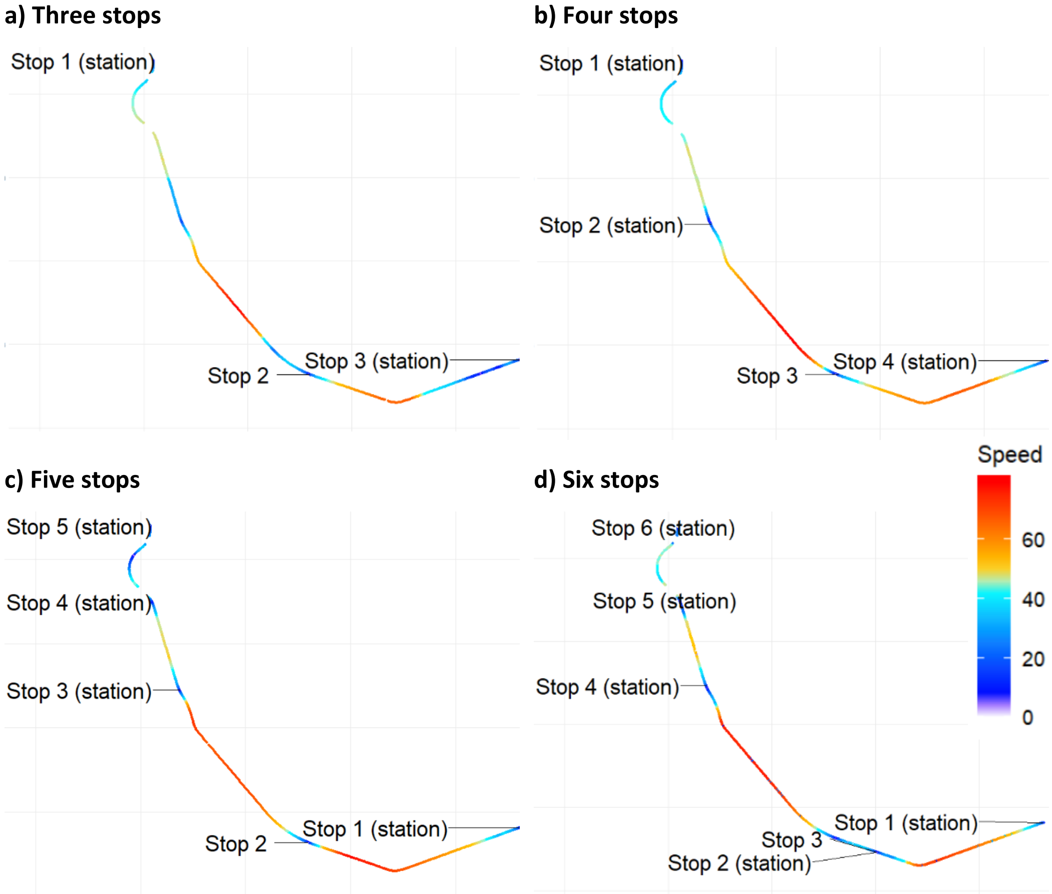


Figure 51 shows a comparison of NO_x emissions per unit. The NO_x emissions for units running in multiple show little variation across the stopping patterns and show lower emissions when normalised for the number of units compared to the single-unit Class 158 trains. For journeys with 6 stops, the NO_x emissions per unit were approximately 60% lower for joined units compared to individual units. Higher emissions were recorded for units running in multiple for journeys with 5 stops compared to 6 stops.

Figure 51 **Journey NO_x emissions per unit for 1-unit Class 158 (left) and 2-unit Class 158 (right) trains by the number of journey stops**

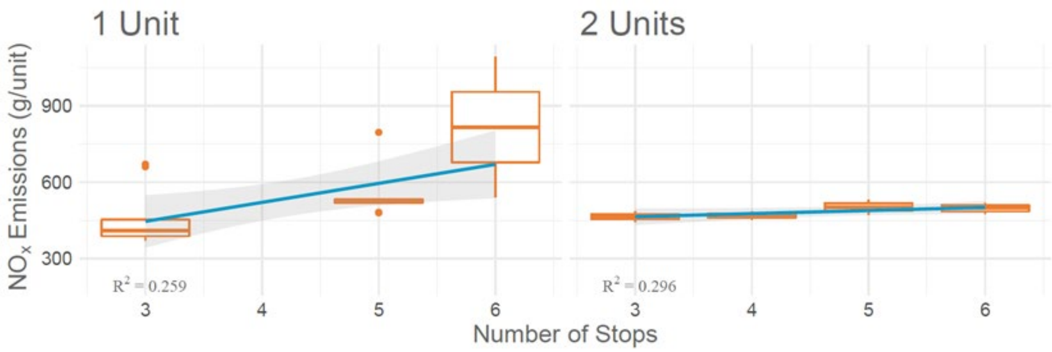


Figure 52 shows the total journey NO_x emissions by number of stops. As expected, emissions for units running in multiple are higher than individual units, however as demonstrated in Figure 51 above the emissions do not double with doubled capacity.

Overall, NO_x emissions from units running in multiple compared to individual units are on average 50, 46 and 18% higher for journeys with 3, 5 and 6 stops, respectively. Similar trends for NO_x are shown for PM (Figure 53) and CO_2 (Figure 54). Emission of PM are approximately 50% higher for trains running in multiple compared to individual units for journeys with 3 or 5 stops, but this is reduced to 22% for journeys with 6 stops. The addition of the six-stop service pattern for a single unit sees a noticeable increase in Class 158 emissions due to pressurised timetabling requiring a far greater use of Notch 7 and more aggressive braking. Less time spent is spent coasting because of the requirement to maintain both the same end-to-end journey time and the same intermediate timings along the route as the other stopping patterns.

CO_2 emissions are approximately 47% higher for trains running in multiple compared to individual units for journeys with 3 or 5 stops, but this is reduced to 26% for journeys with 6 stops. The relative impact of the number of stops and stopping pattern on emissions reduces as the number of vehicles in the train increases (if the average power per vehicle is kept constant) which can be seen in the flatter gradient of the best fit line on the right-hand graphs in the figures below.

The leading vehicle of a train always has significantly higher aerodynamic loading (especially above 50 mph where this loading depends on both the speed and the square of the speed) than the following vehicles in the train. Hence in the case of multiple units with all vehicles powered, the average aerodynamic drag per vehicle reduces as the number of vehicles increases. Therefore, longer multiple units have slightly more power available to accelerate the train mass due to lower aerodynamic drag. In the Class 158 case with comparatively modest power available per vehicle, the extra available power for acceleration per vehicle when operating services with more vehicles can make a significant difference to the overall time taken to accelerate the units, especially as the transmission efficiency is comparatively poor at lower speeds. Consequently, the emissions cost of a stop is lower.

Figure 52 **Journey NO_x emissions (g) for Class 158 trains with 1 unit (left) and 2 units (right) by the number of journey stops**

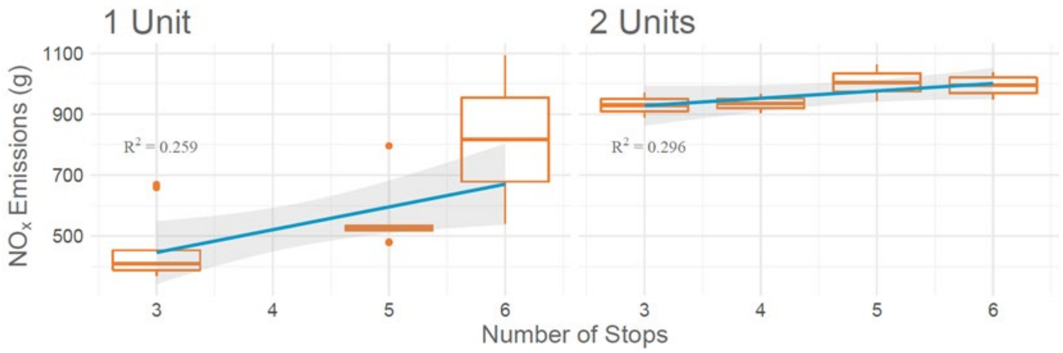


Figure 53 **Journey PM emissions (g) for Class 158 trains with 1 unit (left) and 2 units (right) by the number of journey stops**

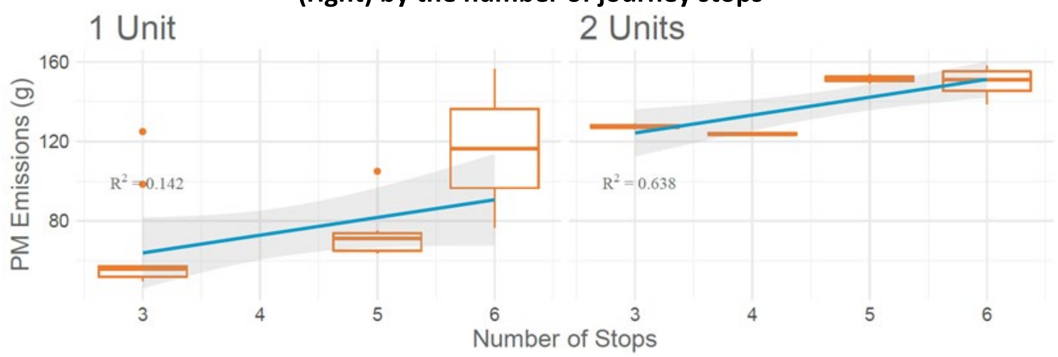
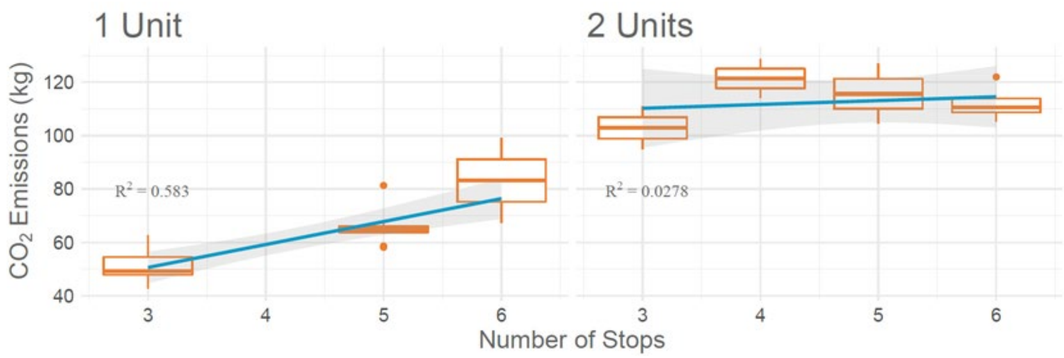


Figure 54 **Journey CO_2 emissions (kg) for Class 158 trains with 1 unit (left) and 2 units (right) by the number of journey stops**



Double the capacity i.e. running two units, did not result in double the emissions. For journeys with three or five stops, total emissions of NO_x, PM and CO_2 were on average 48% greater for units running in multiple compared to individual units.

For journeys with a stopping pattern of six stops the emissions were on average only between a fifth and a quarter higher for units running in multiple compared to individual units.

While the results are route specific and there is some variation based on local geography as to the impact of each individual stop, the overall trend is that increasing the train length does not result in a matched increase in emissions but rather a lesser increase.

This has important implications for increasing capacity on local and regional services in large parts of Great Britain, in that increasing capacity by lengthening trains with more DMU vehicles does not increase emissions by as much as the increase in capacity, i.e. as the number of vehicles is increased the emissions per seat decreases. The emissions cost of adding an extra station stop to longer multiple unit services is much less than for shorter multiple unit services.

Case Study: Class 220/221 – does double the capacity mean double the emissions?

- Number of journeys: 3 individual and 3 running in multiple

Journeys where Voyagers were running as single units or in multiple where identified using the process described in Section 4.3.2. Three pairs of single and multiple journeys with similar duration and distance were selected for consideration (Table 18).

Table 18 Comparison of emissions from a Voyager single-unit journeys to a journey with Voyager units running in multiple

Journey ID	Joined status	Time (hours)	Distance (miles)	NO_x (kg)	PM (kg)	CO_2 (kg)	NO_x (g/t-m)	PM (g/t-m)	CO_2 (g/t-m)
J1	Multiple	5.48	149.1	38.8	1.97	4198	0.43	0.022	46.3
J3	Single	4.74	145.3	21.6	0.90	2385	0.49	0.020	53.8

In the case of the Class 220/221 the single and double units were not always running on the same routes so the comparison is less direct than the earlier Class 158 analysis. Factors other than just train length make it harder to disaggregate the effect of number of units (train length) on emissions. For example, with the Voyager fleet the use of two units versus one unit on a service depends on the passenger loadings. Certain busier routes are much more likely to have services run as two units and some of the busier passenger routes tend to have higher linespeeds and therefore greater high speed running with greater energy use (and so greater expected emissions).

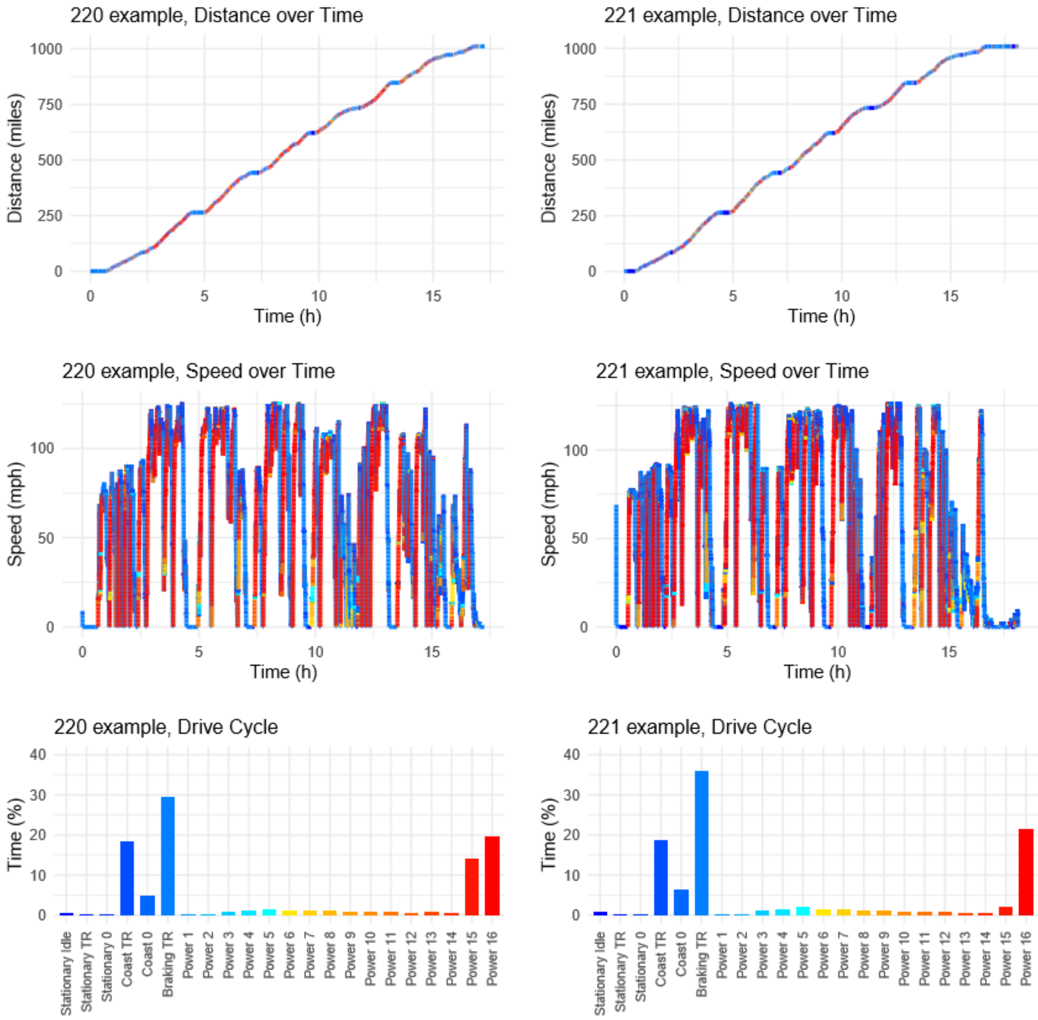
The Voyager routes with higher passenger demand (and hence use of double units) also tends to be on typically busier sections of line requiring more aggressive time keeping and so typically higher energy use. The transmission efficiency of the electrical transmission on the Class 220/221 units also varies far less with speed compared to the hydraulic transmission of the Class 158.

The total emissions for the multiple-unit journey are unsurprisingly higher than the emissions of the single-unit journey. However, the multiple-unit journey has lower NO_x and CO_2 emissions when they are converted to a grams per tonne-mile basis. Unlike with the Class 158 case study, doubling Class 220/221 units appears more complex (based on a small sample size) to with only a small decreases in NO_x and CO_2 emissions on a per vehicle basis and a small increase in PM on a per vehicle basis. CO_2 emissions decrease by 24% below double, NO_x emissions by 20% below double and PM emissions by 18% above double as can be seen in Table 18 above and are far smaller than the variations seen in the previous Class 158 example. Hence further detailed analysis is required of the Class 220/221 case to eliminate other factors so that the impacts of changes in length can be examined on disaggregated basis. This also illustrates the need for accurate data on the services data (e.g. TRUST or GPS) so that the variables in journeys can be understood.

5.6.2 Effect of heavier rolling stock

An example Class 220 trip was identified that was similar in profile to the Class 221 trip, both trips covering around 1010 miles in 18 hours. Summary plots for the two trips are shown in Figure 55.

Figure 55 **Example Class 220 and 221 trips, matched for total time and total distance**



The emissions of the two trips are shown in Table 19, both as a total over the trip and as g/t-m. The Class 221 trip has more vehicles and a tilt system making it heavier overall, and it has greater total emissions of all three pollutants than the lighter Class 220 example. However, when converting the total emissions to a grams per tonne-mile basis, the Class 221 has lower values, and is therefore more emissions efficient.

Table 19 Emissions of example Class 220 and 221 trips

Class	Weight (tonnes)	Number of stops	Total NO_x (kg)	Total PM (kg)	Total CO_2 (kg)	NO_x (g/t-m)	PM (g/t-m)	CO_2 (g/t-m)
220, Non-tilt	210	35	97.9	2.58	11693	0.46	0.012	55.1
221, Tilt	304	42	106.4	3.43	12809	0.35	0.011	41.7

However, it is important to note that these two train types cover different services and so the examples may be on very different routes in terms of linespeeds and exact stopping patterns.

6 Conclusions

This report covers analysis of the impacts of operational requirements on rail emissions carried out as part of Work Package 3 of the RSSB T1187 project *CLEAR: Fleet-wide assessment of rail emission factors*. It describes a methodology that uses emission factors by notch and on-train monitoring recorder (OTMR) data to quantify the specific effects of changes in engine power outputs and hence changes in emissions from trains having to decelerate, stop and idle, accelerate and/or run at different speeds. This granular approach allows assessment of the impact of operational requirements, infrastructure limitations, and linespeed features on train emissions, and can contribute to a better understanding of the GB rail industry's impact on local air quality issues.

The work described here represents an introduction to detailed evaluation of emission scenarios. It is based on a limited sample of journey data, however the emissions estimated here provide an understanding of the magnitude and variation under a wide range of conditions.

Specific case studies evaluated different emission scenarios in order to start answering a simple high-level question:

Which operational changes lead to the biggest savings in NO_x, PM and CO_2 emissions?

Answers to this question, which can inform the development of emissions mitigation measures and strategies and can support TOC, FOC, Network Rail and Department for Transport (DfT) investment cases, are listed below.

- Slowing down services so that journeys take longer is not necessarily very effective for improving air quality; quicker running can reduce overall emissions in some cases as the overall engine running time can be less with consequently less emissions.
- Smoother journeys with less stopping and starting, and minimising overall periods of acceleration, can significantly reduce emissions from both passenger and freight services.
- A low proportion of an individual trip is in idle; however, where that happens is significant as it is often where there is potentially high exposure to the public and staff and is especially relevant to enclosed stations where there is limited dispersion of air quality pollutants. In such cases, where operational requirements permit, simply switching the engine off has the most impact.
- While there is limited scope (without battery hybrid solutions) to reduce passenger train emissions while accelerating at low speeds in and outside of stations (at locations that are normally in urban areas), a smooth coasting approach without signalling delays can substantially reduce emissions when entering stations.
- Grams per tonne-mile factors have been developed for a sample of freight journeys and these are significantly lower than those used in previous intermodal comparisons

(e.g. 40% lower than the factors used in the DfT 2017 freight modal study[19]). This enables an improved understanding of the environmental performance of rail freight compared to other modes. Freight emissions can vary with a number of operational aspects but the sample examined in this study has set out a range and distribution of emission estimates under a variety of conditions.

- Heavier freight trips have lower emissions per tonne-mile for all three pollutants. This is strong evidence that heavier freight loadings are more fuel and emissions efficient. Heavier (longer) freight trains are more emissions efficient which assists cases for potential infrastructure improvements to permit longer freight trains where not limited by available traction power or gradients on routes but by other features such as passing loop length or siding length at origin or destination.

This study has provided an initial examination of operational effects on combustion emissions and has resulted in significant gains in understanding, hence there is the potential to examine further aspects based on the analysis so far. Recommendations for further work in this area include:

- Further analysis of the extensive Class 158 and 170 OTMR data that is already available.
- Collecting and analysing further OMTR data for other freight locomotives (e.g. Class 68) and for more services with both light loads (such as some Network Rail infrastructure trains) and very heavy loads (such as aggregates, steel and fuel traffic). This would enable both better intermodal analysis and emissions estimates for freight services on a greater variety of routes and loadings.
- Additional analysis of freight services to look at a greater range of parameters that might affect emissions.
- Calculating emissions for all services in selected areas would allow development of detailed spatial emissions estimates. This will be particularly relevant for key urban areas where rail may be a significant contributor to local air quality issues.

[19] DfT (2017). *Freight carbon review 2017*.