Refining rail emission factors to enable a Tier 3 approach

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Background – rail air quality

- Recent key studies of station air quality:
  - Birmingham New Street – Hickman et al. (2018)
  - Edinburgh Waverley and London Kings Cross – RSSB T1122 project
- RSSB has recently deployed an Air Quality Monitoring Network across the GB rail network
- Highest observed concentration values are in:
  - enclosed stations
  - with a high volume of diesel traffic
  - that terminates/lays over for prolonged periods
  - and with contributions from external sources

Why improve rail emission factors?

- Emission factors previously used to estimate GB rail emissions were out of date
  - Original derivation not clear in some cases
- They provided a poor representation of how emissions vary according to engine operating condition
- In some cases, the emission factors have been proven to be overly pessimistic and overestimate emissions from certain rolling stock
- They cannot be easily used for intermodal comparisons
- Need to understand how rail emissions could impact local air quality issues
  - How do rail emissions vary spatially?
- Major focus in the United Kingdom is on combustion emissions given the relatively low level of electrification

Table 5 (continued) Regional passenger train emission factors (g/vehicle-km) used for the 2017 NAEI

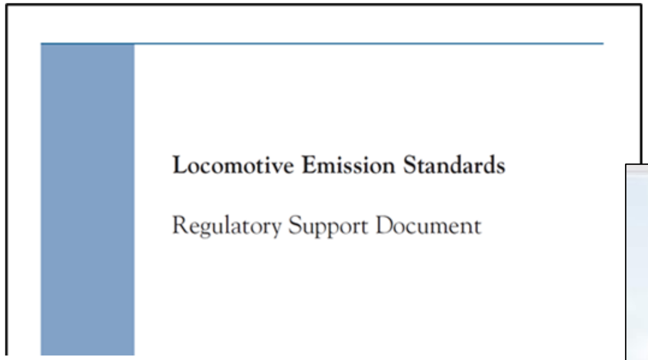
Train class:	158	159	165	166	168	170	171	175	185	
Train type:	Express Sprinter		Turbo		Turbostar			Coradia	Desiro	New trains
CO	2.1	2.2	7.9	7.8	5.0	5.5	6.2	5.4	1.6	6.6
NO_x	17.3	18.3	20.3	20.0	14.7	16.2	18.2	15.8	13.5	3.7
HC	1.1	1.1	1.0	1.0	0.2	0.2	0.2	0.2	0.4	0.4
NMVOC	1.0	1.1	0.9	0.9	0.2	0.2	0.2	0.2	0.4	0.3
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Benzene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1,3-butadiene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PM_{10}	1.4	1.4	0.8	0.8	0.3	0.3	0.4	0.3	0.3	0.0

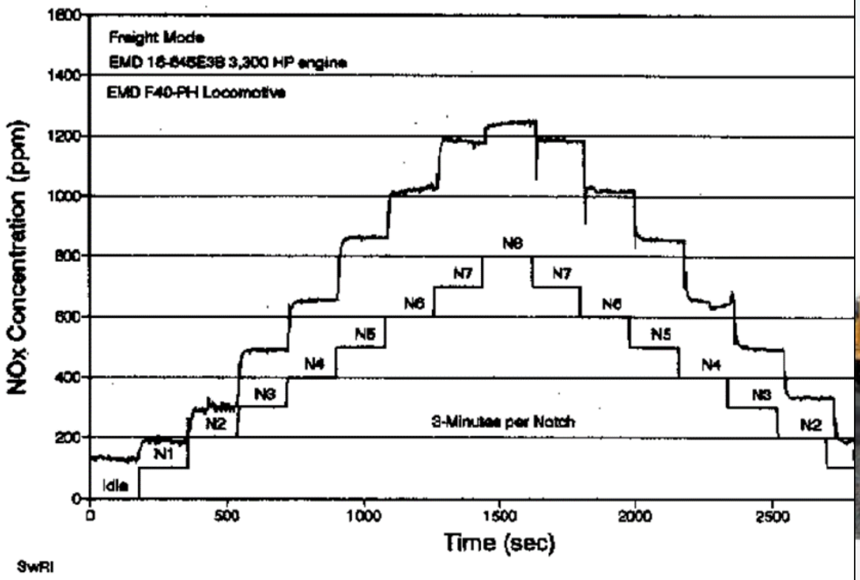
LRC 1998 calculation methodology based on BR Research[52] and EWS testing data.
LRC calculation based on Technical University of Denmark work[53]. Calculations partially based on BR Research data[54] as one of the data sources.
Bombardier 2001 data and calculations used to replicate LRC calculation methodology.
AEAT 2001 calculation[55] replicating LRC methodology using Siemens data at rolling stock design stage.
AEAT 2001 calculation[56] using Alstom data to replicate LRC calculation methodology. Only one calculation was done to cover both Classes 175 & 180 despite them having different engines, transmissions and maximum speeds.
EMEP/EEA assessments[57, 58, 59] replacing original LRC data. One of the underlying data sources is the LRC work.
EWS supplied data.
AEAT 2001 calculations[60] based on maximum allowable emissions under a then future emission standard (was draft UIC3 at the time, later became rail Euro IIIA).

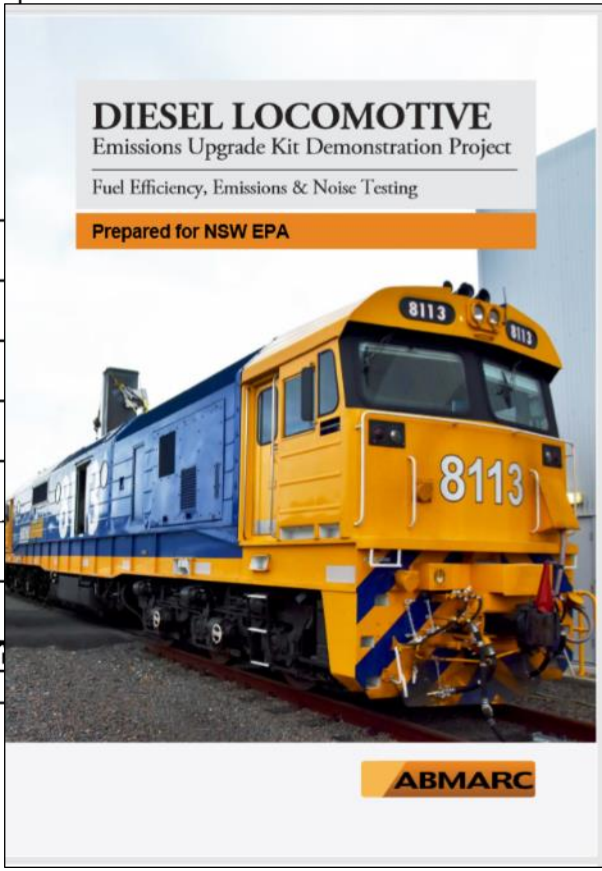
Emissions testing by notch

- Engine notch refers to set power outputs that allow different rolling stock to work in multiple

- Extensive experience of testing by notch in US and Australia



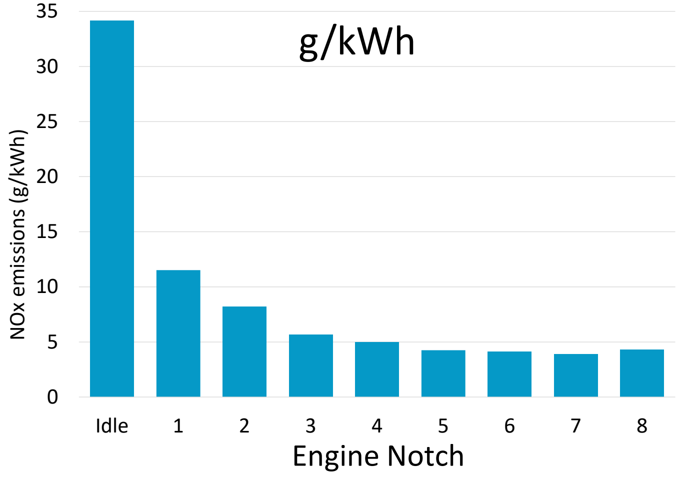


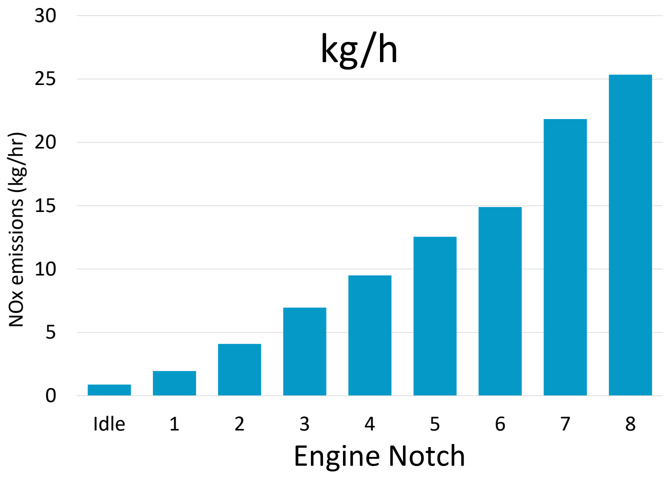


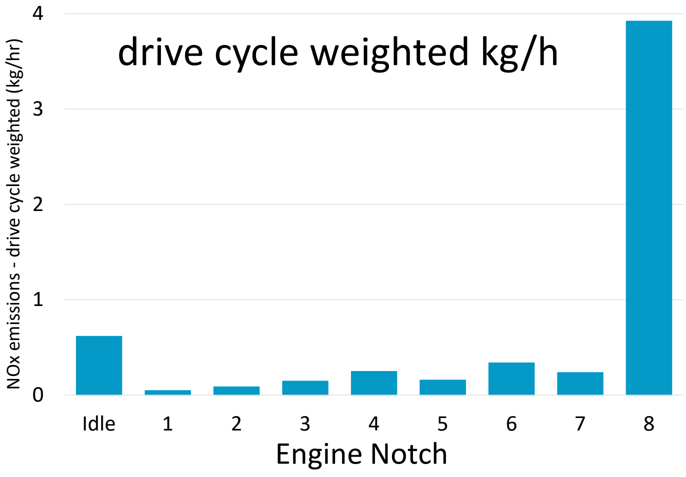
Not all rail emissions are created equal…

- Testing shows non-CO_2 emissions are not proportional to engine power:

NOx emissions by engine notch

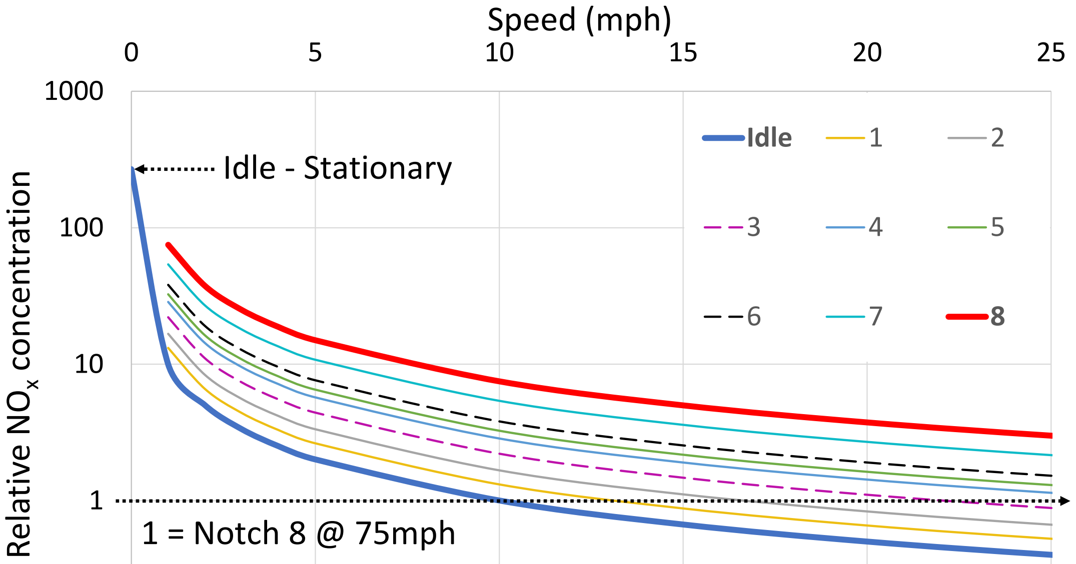






- Highest local concentrations where trains are stationary or accelerating at low speeds:

  - Comparison of relative NOx concentrations at a fixed location versus speed and notch for EMD 710 engine (Class 66)



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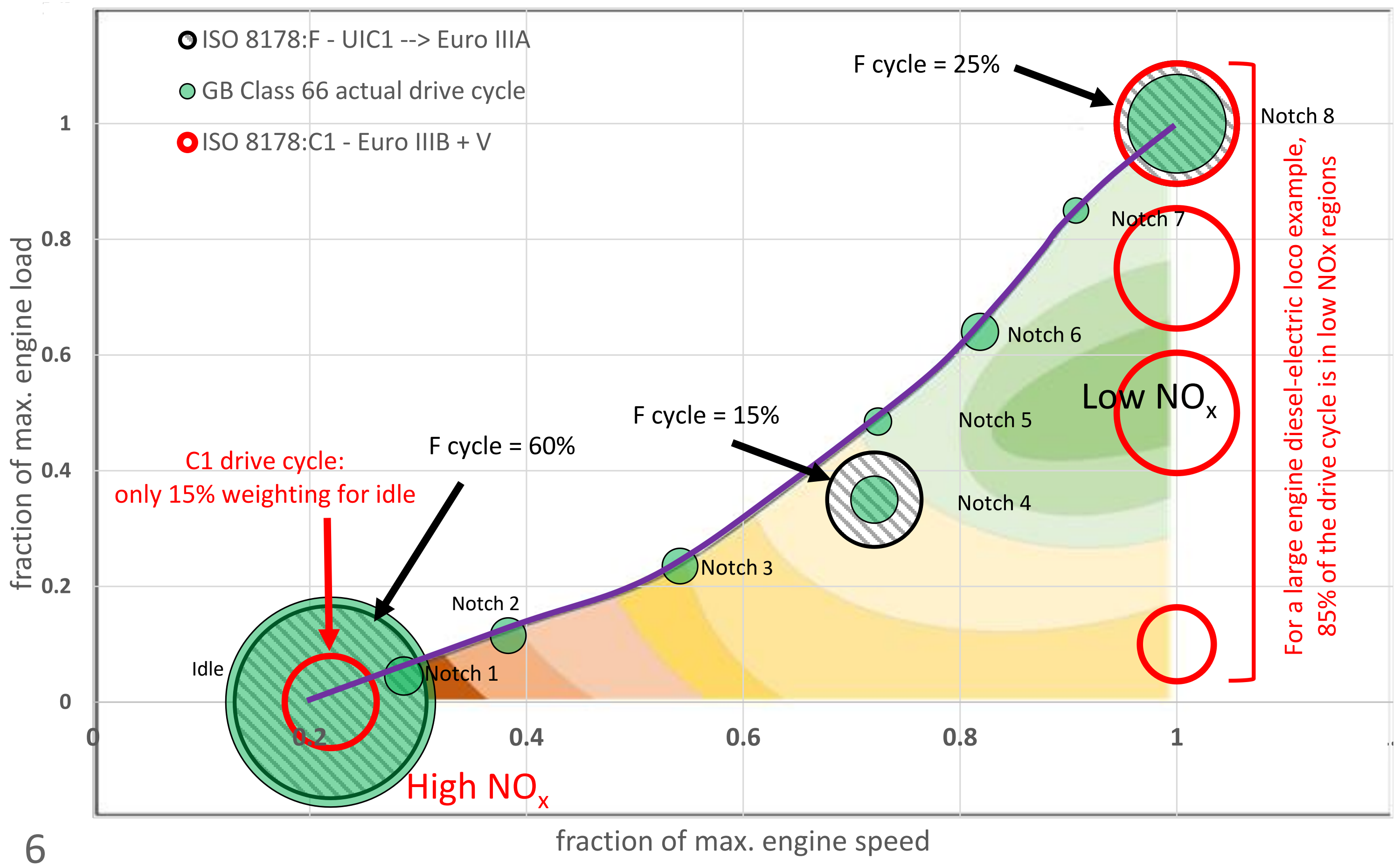
Rail drive cycles – the importance of idling emissions

- Engine operating conditions along with real freight, ISO 1878:F and ISO 8178:C1 drive cycles:

Real –vs – Regulatory Drive Cycles Example



- All GB diesel rolling stock spends substantial time in idle (~55-75%)
  - Includes coasting/braking as well as stationary
- The non-road mobile machinery (NRMM) Euro Stage IIIB drive cycle vastly underrepresents the amount of time in idle
- Compliance with latest emissions standards may not address rail air quality issues
- Air quality solutions will need to meaningfully address emissions at idle, and not just at higher engine speeds (where abatement measures tend to be more effective)

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Example emission factors by notch

- Class 66 UIC1 (from RSSB T1187 project)

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

- T1187 Class 158 (from RSSB T1187 project)

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

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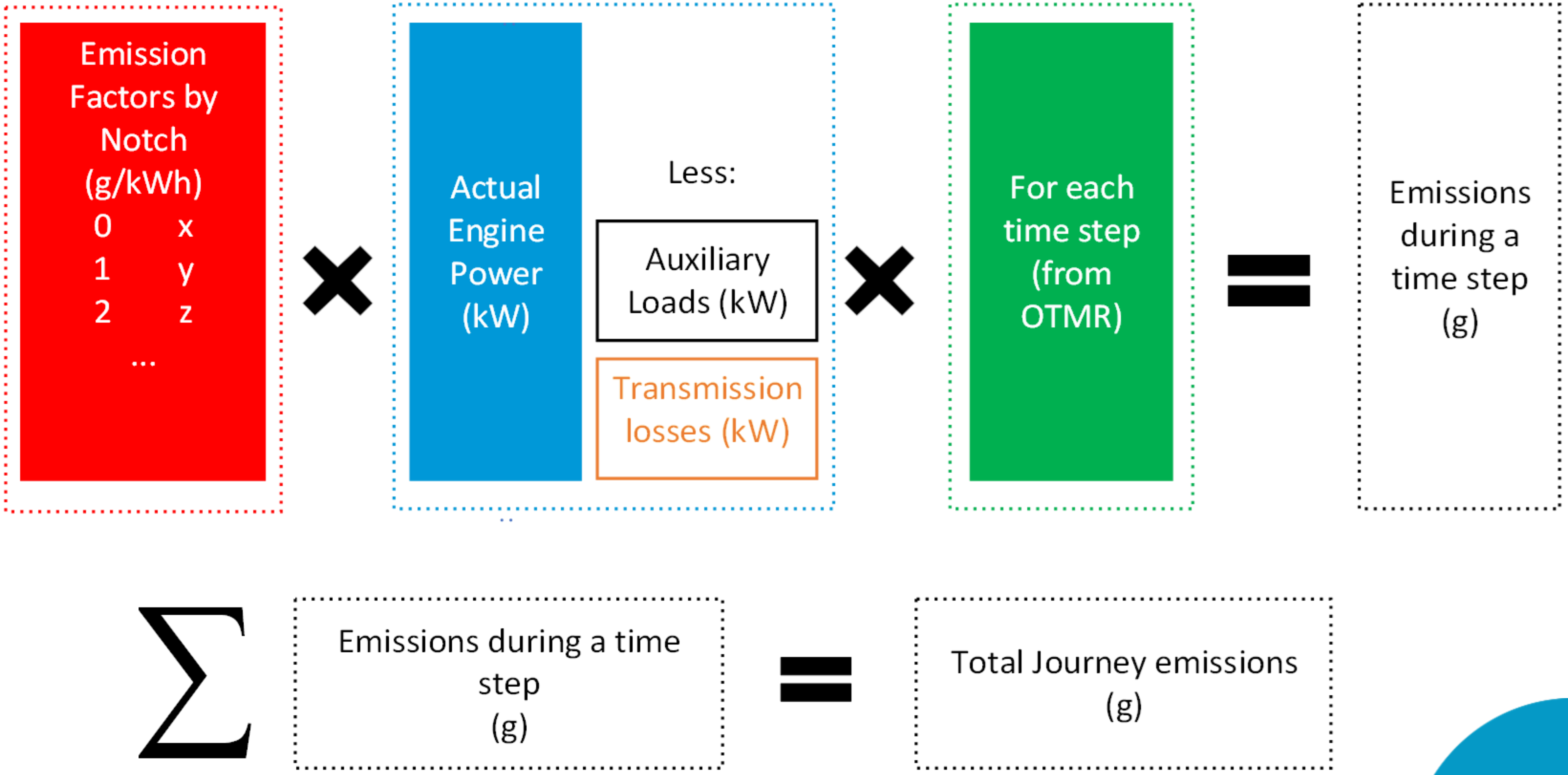
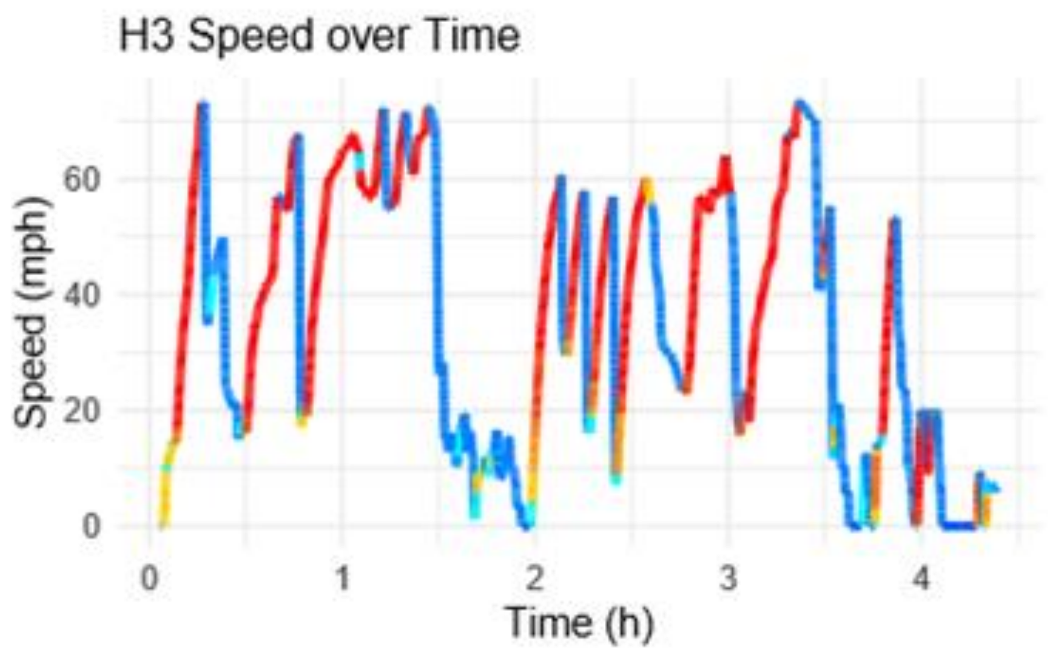
Using emission factors by notch

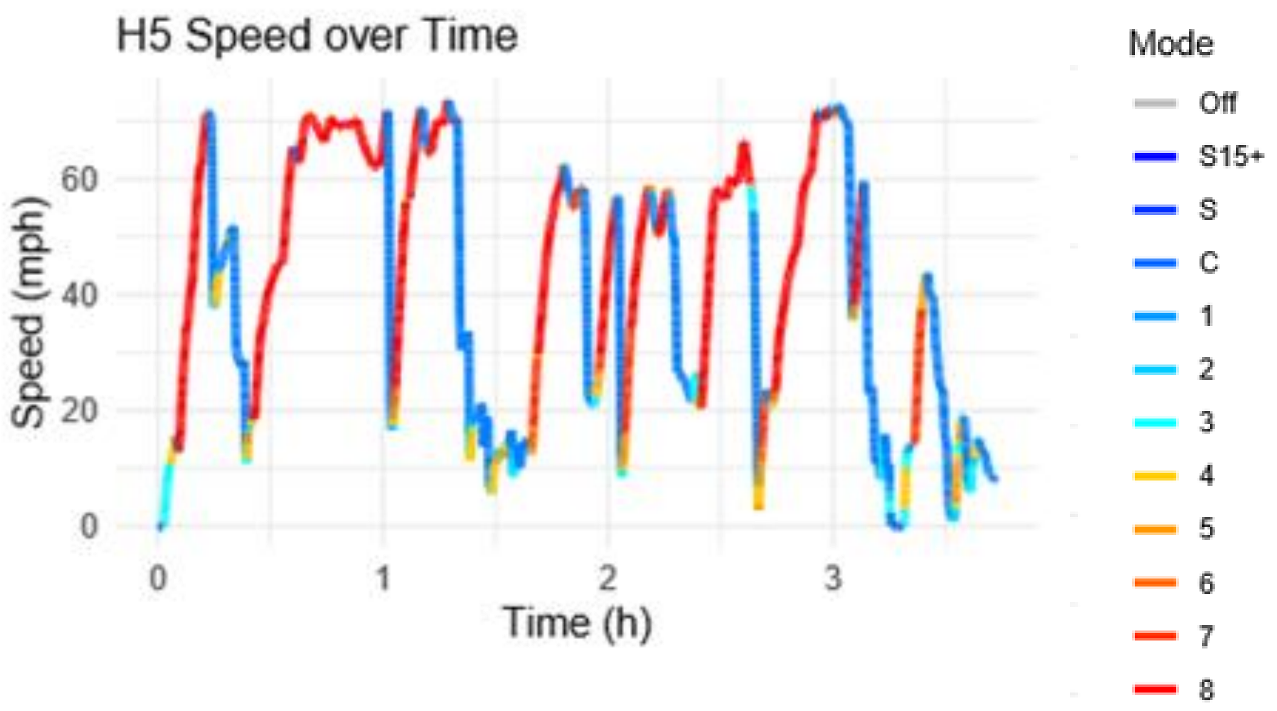
- Combining with on-train monitoring recorder (OTMR) data to derive total journey emissions:



Example application: Impact of delays

- Same locomotive, same wagons, same loading, same route, consecutive days
- Journey H3 (which experienced more delays) emits 1.13 kg NOx, 0.045 kg PM, and 108 kg CO_2 more than journey H5 over same route.
- These differences are **12%**, **16%** and 3.5%, respectively, of total journey NOx, PM and CO_2 emissions





Detailed emissions modelling for different routes

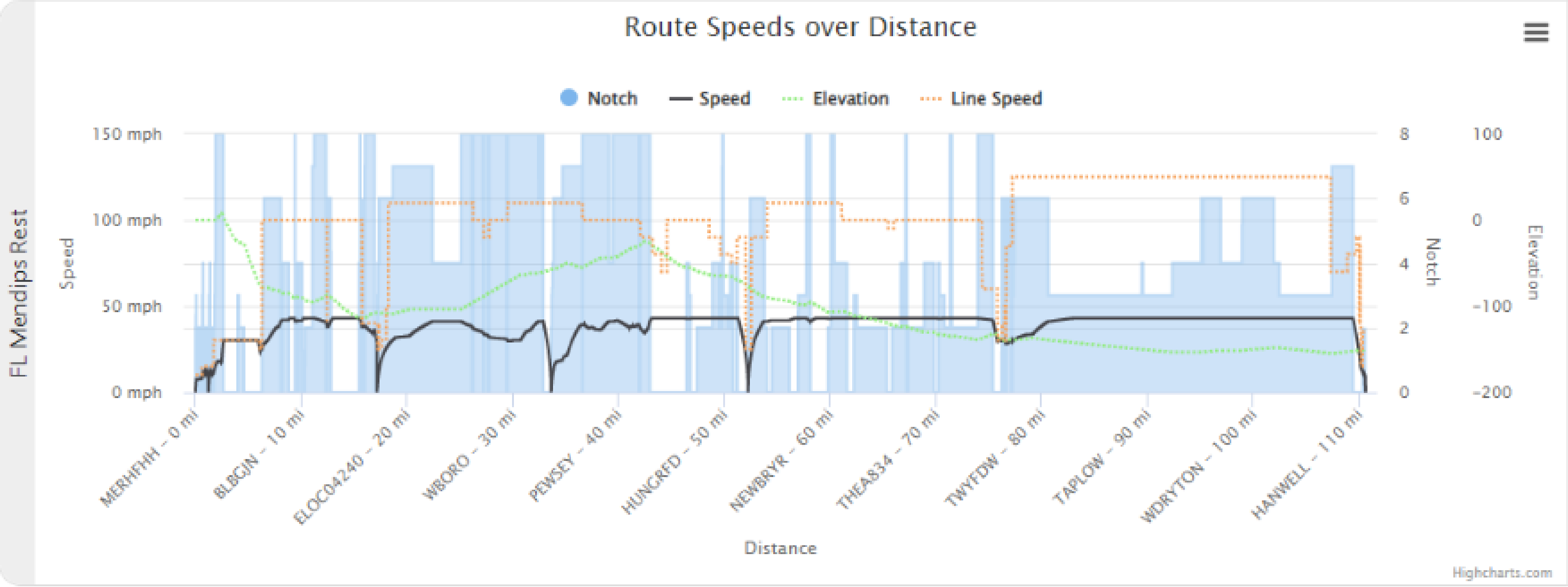
- To replicate different loads on particular routes can use a version of the Davis force-balance equation and then determine which notch is required and what the associated emissions would be using the g/kWh factors

Net Force = Tractive Effort (for each notch) – Resistance – Braking – Body Forces

$$\text{Force} = m\frac{\delta v}{\delta t} = (Dv^4 + Ev^3 + Fv^2 + Hv + I) - (A + Bv + Cv^2) - mg\beta - mg\alpha$$

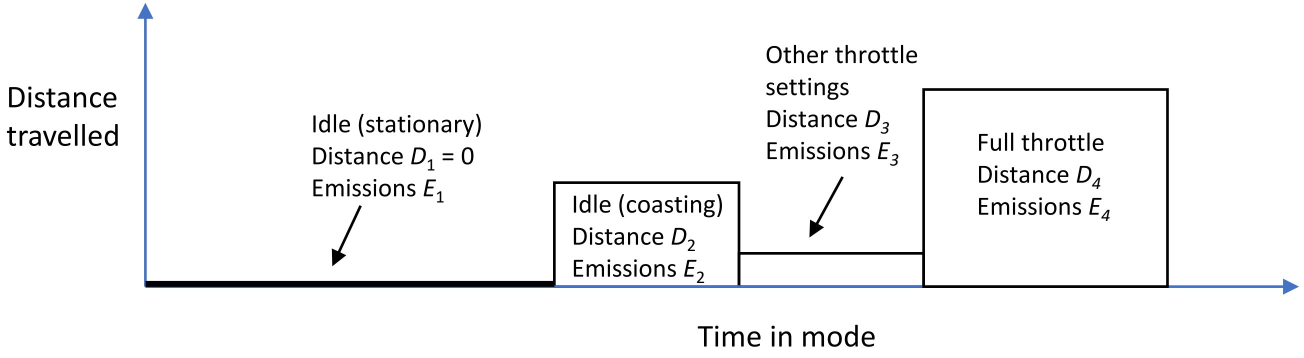
(Only needed for Hydraulic and Mechanical transmission multiple units)

- Railfreight Energy & Emissions Calculator (developed by Aether and the University of Hull) – example aggregates train:



Refining g/km factors

- Sufficiently detailed activity data may not be available to fully utilise g/kWh emission factors
- National network activity data may only be available in terms of train (or vehicle) kilometres travelled
  - This is the level of information available for the UK NAEI timeseries (which goes back to 1970)
- The new g/kWh factors can be used to refine the g/km factors
- From a review of OTMR data the following are obtained:
  - Average distances covered
  - Proportions of time in:
    - Idle – which can be coasting as well as stationary
    - Full throttle
    - Other intermediate settings
  - Using g/kWh factors average emission rate per km for the typical drive cycle is then determined:

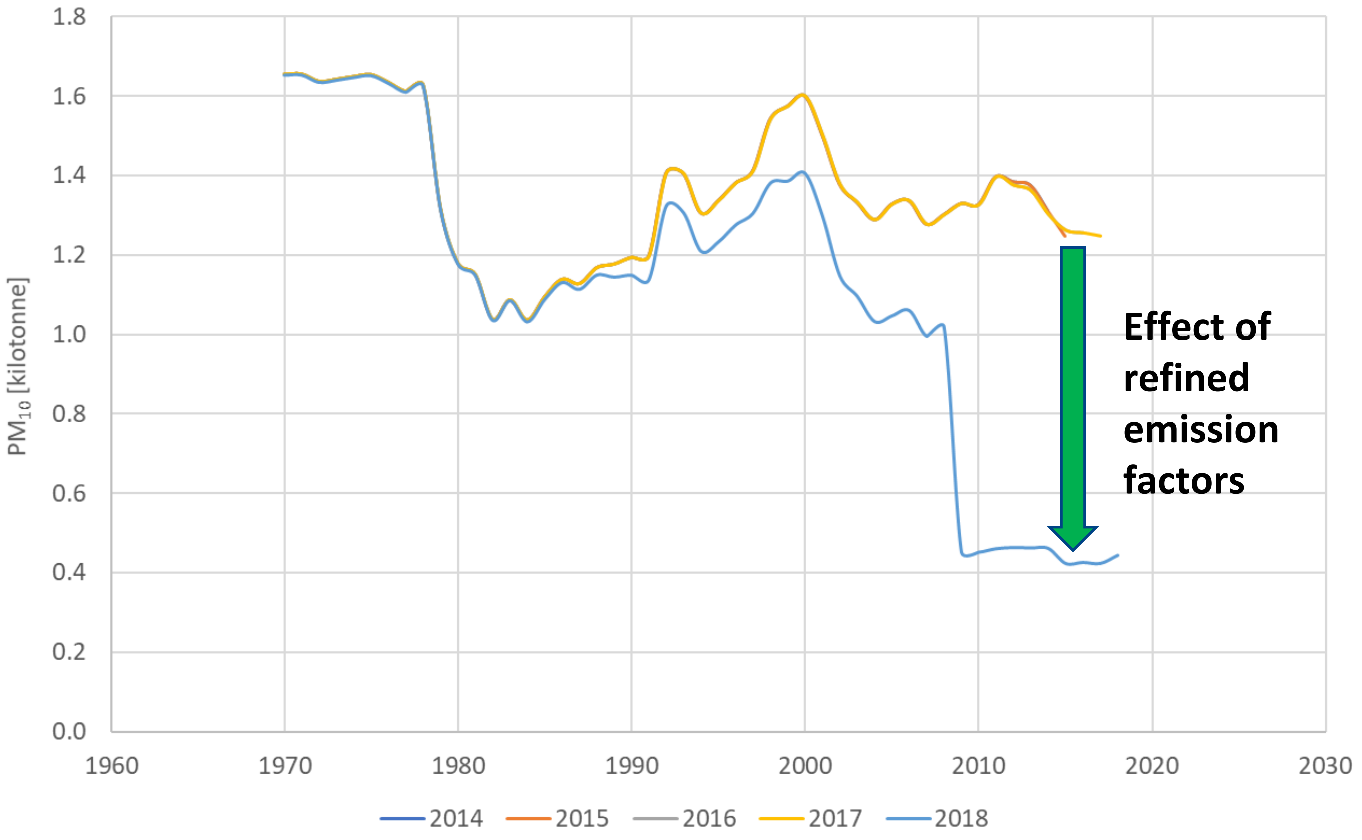


g/km Emission Factor =

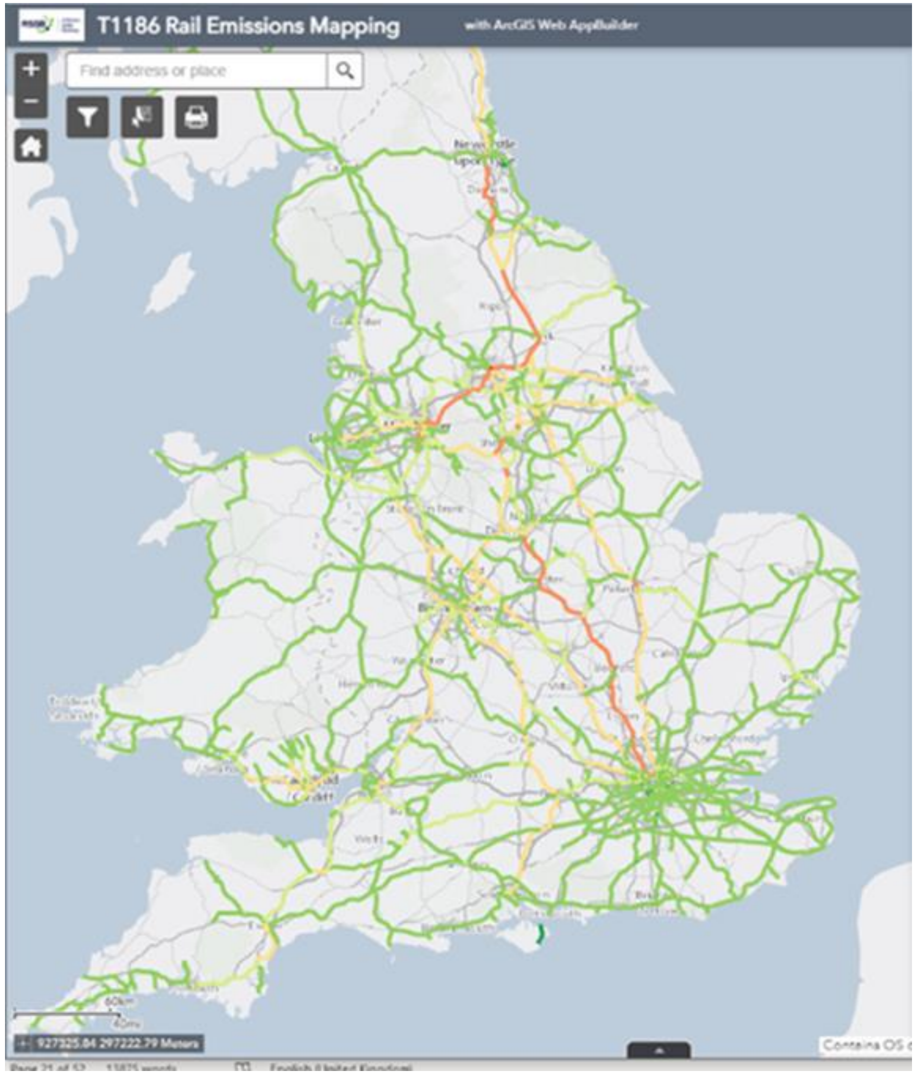
$$\frac{E_1 + E_2 + E_3 + E_4}{D_1 + D_2 + D_3 + D_4}$$

Utilising improved g/km emission factors

- Improvements to the national timeseries
  - PM_{10} example:

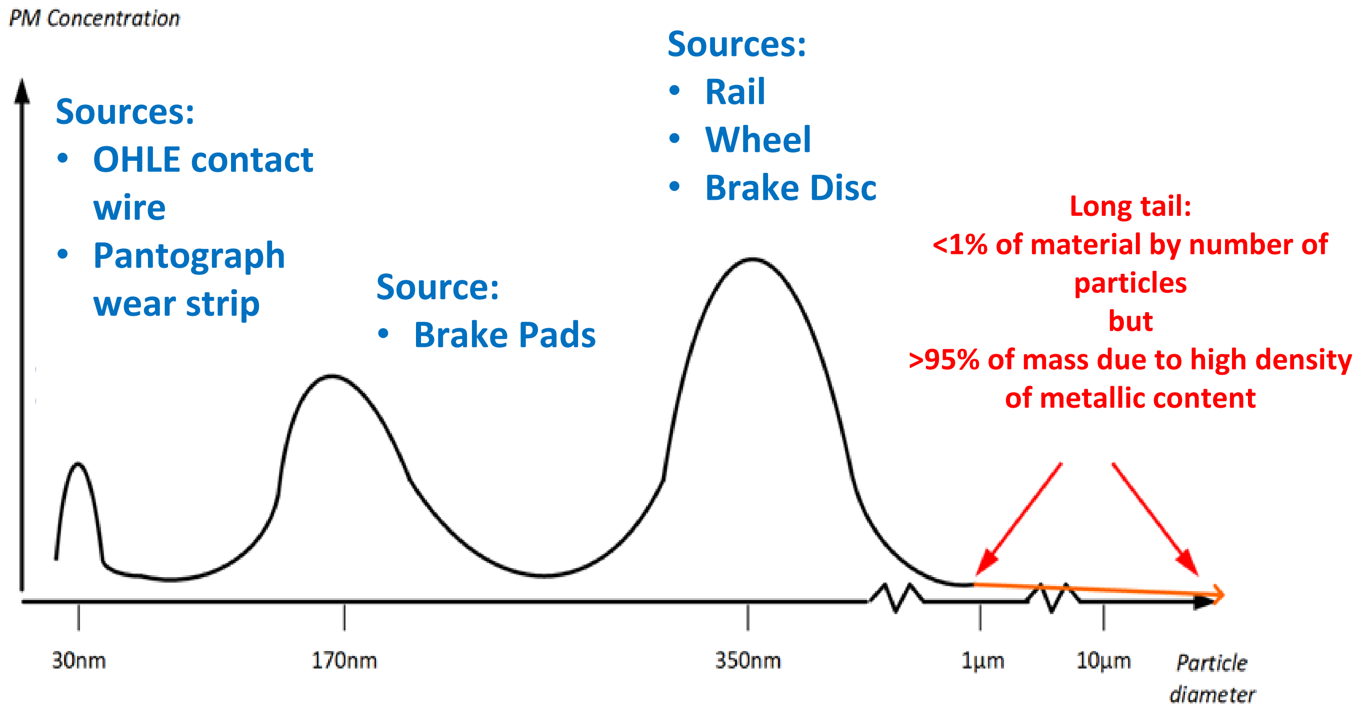


- Improved national mapping:



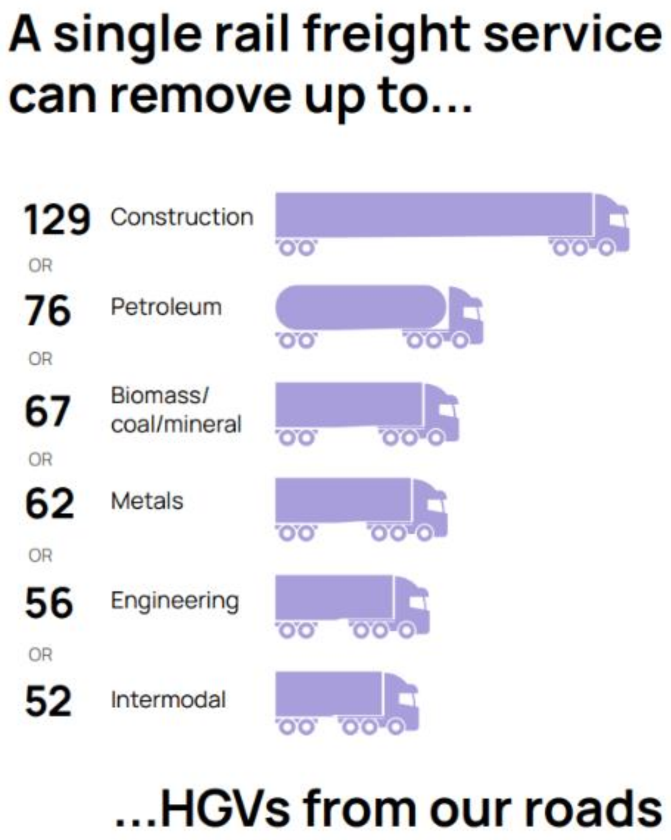
Abrasive PM emissions

- Abrasion emissions from GB rail are less significant than combustion PM
- Abrasion particles are very small (<0.1 µm) but denser than combustion PM, so settle out quickly
- Can be a major issue in metro tunnels with continual re-entrainment
- More are data needed – the quantity of abrasion PM measured in air is a small fraction of total material lost to rail, wheels and brake wear
- German inventory $PM_{2.5}$ factors:
  - Rail, wheel and brake wear: 0.013 g/vehicle-km
  - Pantograph wear: 0.00016 g/vehicle-km



Key messages

- New emission factors by notch (g/kWh):
  - Have improved estimates of rail’s contribution to UK national emissions
  - Can be combined with OTMR data to understand local air quality issues, especially where idle and lows speeds are prevalent
  - Can help with providing quantified support to investment cases
  - Enable more effective intermodal (g/tonne-km) comparisons
- All GB diesel rolling stock spends substantial time in idle (~60-70%)
  - This does not align with the drive cycle for current emission standards
  - Has important implications for the effectiveness of abatement measures such as selective catalytic reduction (SCR)
- Based on g/kWh and g/tonne-km factors for different freight services (Rail Partners, 2023):



Thank you

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