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Sensitivity of Input Parameter on CNOSSOS-EU Rail Emission Levels

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ABSTRACT

The UK's Department for Environment, Food and Rural Affairs (Defra) commissioned a series of studies investigating the sensitivity of the CNOSSOS-EU noise assessment method. CNOSSOS-EU presents challenges in terms of data accuracy and availability. These studies were commissioned to support data governance and to quantify potential uncertainty in Defra's national noise model. The quality framework in Directive 2015/996 requires that uncertainty in rail emission source levels is limited to ±2 dBA. Due to the CNOSSOS-EU railway emission model being of multivariate complexity, and the multitude of possible parameter combinations, the study took a scenario and parametric-based approach. Railway emissions calculated for each parameter for a set of rail vehicle speeds and rail infrastructure scenarios, were used to indicate which input parameters the emissions are most sensitive to. It was found that emissions are most sensitive to changes in the number of axles on the vehicle (i.e., wheel / rail interaction), the density of track joints (impact noise), the curvature of the track (squeal noise), and the construction of bridges (structural resonances). However, the choice of rail roughness, vehicle transfer function, and track transfer function (except in the case of direct fastenings) were found to have a limited impact on railway emission levels.

1. INTRODUCTION

Large-scale adoption of the CNOSSOS-EU rail noise source emission model presents challenges in terms of the availability and accuracy requirements of input data. Adopters of the CNOSSOS-EU method are often unlikely to have access to precise and comprehensive data on rail vehicle and infrastructure characteristics within a model area. Models covering large areas, such as cities, states, or countries, may have to use incomplete data, modelled estimates, or make assumptions. Furthermore, the CNOSSOS-EU database default values [1, 2] may not be representative for all use cases, e.g. [3].

This study presents a parametric sensitivity analysis of the CNOSSOS-EU railway source model

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input terms, with the aim of quantifying the uncertainty in overall source emission levels due to variations in these parameters. This paper sets out to identify which input parameters have the greatest influence on CNOSSOS-EU railway noise emissions and to quantify the potential uncertainties at the point of emission. The findings can be used to support the drafting of data collection guidelines and could be used by stakeholders to prioritise future data collection campaigns.

2. METHOD

A Python script was developed to calculate CNOSSOS-EU railway source emissions, and to prepare and run the sensitivity analyses. The script implements the methodology within Directive 2015/996 [1] as amended by the 2020 Delegated Directive [2]. It was validated against the CNOSSOS-EU source model C++ code developed by DGMR [4] in 2015. The DGMR source code was not updated to reflect the changes of the 2020 Delegated Directive, so there is no immediate reference code available for validating these changes.

Due to the multitude of possible combinations of all input parameters within the model and the resulting complexity, the range of values for each parameter has been limited to avoid looking at parameters that would not typically vary across the rail network, or those which have negligible impact on emissions. The values studied have been primarily limited to UK rail vehicle and track options from the Rail Equivalence Note (REN) for CRN [5]. The spectrum values used are the most recent of those from Directive 2015/996 or the 2020 Delegated Directive, as applicable.

For each parameter sweep curve, all parameters remain constant except for the one under investigation. The default values kept constant for the study (when not under investigation) are shown in Table 1, along with the values considered for each of the parameters studied. The total sound power level of a rail traffic flow is represented by the energetic sum of the two equivalent line sources [1] and presented as the A-weighted sound power level per metre length, $L_{W'}$.

Table 1: CNOSSOS-EU rail source model input parameters

Input parameter	**Default value**	**Modelled parameter ranges [start, stop, step] / (list)**
Parameters studied		
Hourly rail traffic flow, $\boldsymbol{Q}$	1	$[1,\ 400, 0.1]$
Vehicle speed, $\boldsymbol{v}$ [km/h]	100 km/h	$[0,\ 360, 0.1]$ km/h
Number of axles, $\boldsymbol{Na}$	4	(2, 4, 6, 8)
Wheel roughness spectrum	disc brakes	(cast iron, composite, disc) brakes [1]
Vehicle transfer function spectrum	920 mm diameter wheel, no measure	(680, 840, 920, 1200) mm diameter wheel, no measure [1]
Rail roughness spectrum	CRN equivalent [5]	(EN ISO 3095:2013, Dutch average, CRN equivalent) [2, 5]
Joint density, $\boldsymbol{n}$	0	(1, 4, 10) joints per 100 m
Impact roughness spectrum	No impact	(none, single, CRN jointed) [2, 5]
Curve / turnout radius, $\boldsymbol{R}$ [m]	1000 m	(300, 500, 1000) m
Track transfer function spectrum	concrete sleepers on ballast (M/M)	(M/M, wooden sleepers, direct fastenings) [2]
Bridge correction transfer function	+0 dB	(+0, +10, +15) dBA [2]

Parameters not studied	
Traction source spectrum	Electric multiple unit [1]
Contact filter, A_3	Axle load 100 kN; 920 mm wheel diameter [1]
Superstructure transfer function	EU standard (no correction) [1]
Idling time, T_{idle}	0 hours
Track length, L	100 m
Source horizontal / vertical angle	30° / 60° [4]

[5] provides for concrete and wooden sleepers, however, the choice between wooden or concrete sleepers (mono-block sleeper on medium stiffness pad) is not observed to have a significant effect. Therefore, unless otherwise stated, only results for concrete sleepers are presented here as they represent the majority of the rail network in the UK.

Traffic flow and vehicle speed can be analysed as numeric variables, with variations in vehicle parameters represented by different vehicle categories. Ten rail vehicle categories are specified within [5], several of which were found to give the same emission results. Four groups have been selected: Categories 2a/2b (light rail): Manchester Metrolink / Yorkshire Supertram

- Categories 2/5/6: Class 165 DMU / Merry Go Round Coal Hopper / Freightliner
- Category 7: Class 60 Diesel Locomotive
- Categories 1/3/4/ES: Class 422 EMU / 2- / 4-axle tank wagons / Eurostar Class 373 Power Car

The remaining parameters are analysed as categorical variables. Vehicle speed and wheel roughness were seen to have a significant effect on the results. Therefore, the analysis is presented for a range of speeds: (50, 100, 150, 250, 350) km/h; as well as wheel roughness spectra for 'cast iron tread', 'k-block composite', and 'passenger disc brake'. Unless otherwise stated, the assumptions set out in Table 1 apply. The absolute emission level for each parameter has been normalised to present the change in emission relative to a benchmark value.

3. RESULTS

3.1 Rail Traffic Flows

Emission levels and rail traffic flow volume have a simple logarithmic relationship for all vehicle categories, as in Figure 1 (left). For every doubling / halving in the traffic flow, emissions change by ±3 dBA. While relative changes in flow result in a consistent change in emission level, emissions are more sensitive to absolute changes in traffic flow where the flow is low, and less sensitive when the flow is high.

3.2 Rail Vehicle Speed

The curves in Figure 1 (right) exhibit a ripple effect as speed increases, resulting from the interpolation function which calculates the 1/3 octave frequency spectra, f, from the rolling source roughness wavelength spectra, λ, using $f = \lambda/v$. Speeds used in the calculation of rolling noise have a threshold of 50 km/h (for heavy rail, or 30 km/h for light rail) [1], while speed used to calculate the vehicle flow emission [1, eq. (2.3.2)] is not restricted. Emissions increase exponentially as v decreases towards 0 km/h, suggesting that modelling should be avoided at low speeds. Figure 1 (right) shows a discontinuity in sound level which occurs at 200 km/h where the aerodynamic source component is introduced, causing a step-up in emissions for all vehicle categories. Otherwise, emissions for different vehicle categories increase relatively in parallel with each other in a nearly linear relationship with speed. There is slightly greater sensitivity at speeds below 150 km/h, where the slopes of the curves are steepest. The difference in sensitivities between vehicle categories is not greater than 2 dBA at any speed.

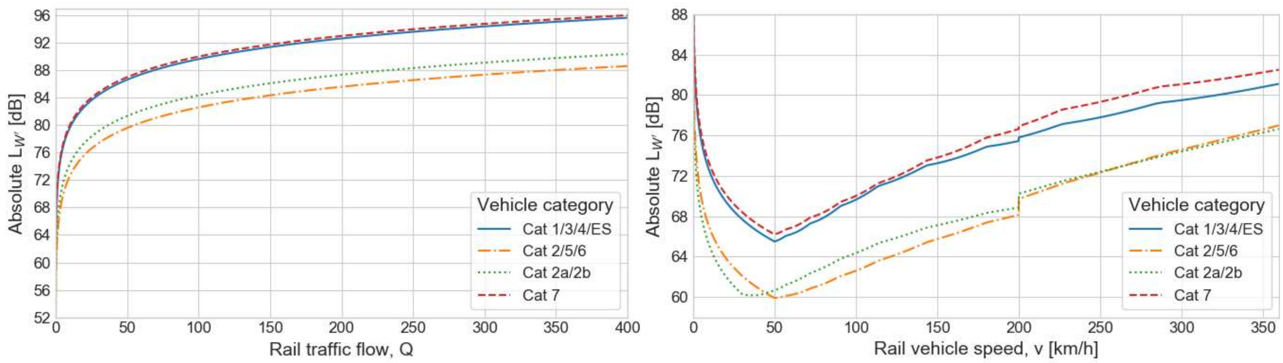

Figure 1: Sensitivity sweeps for (left) rail traffic flow; and (right) vehicle speed.

3.3 Wheel Roughness

The three spectra for wheel roughness (WR) considered were:

- WR1 – standard freight cast iron tread (benchmark)
- WR2 – freight with k-block composite
- WR3 – passenger disc brake

Figure 2 (left) shows that the sensitivity of emissions to WR spectrum increases as the number of axles increases. Changes in WR can result in the emission level changing by up to 8 dBA between passenger disc brakes (WR3) and freight cast iron tread brakes (WR1).

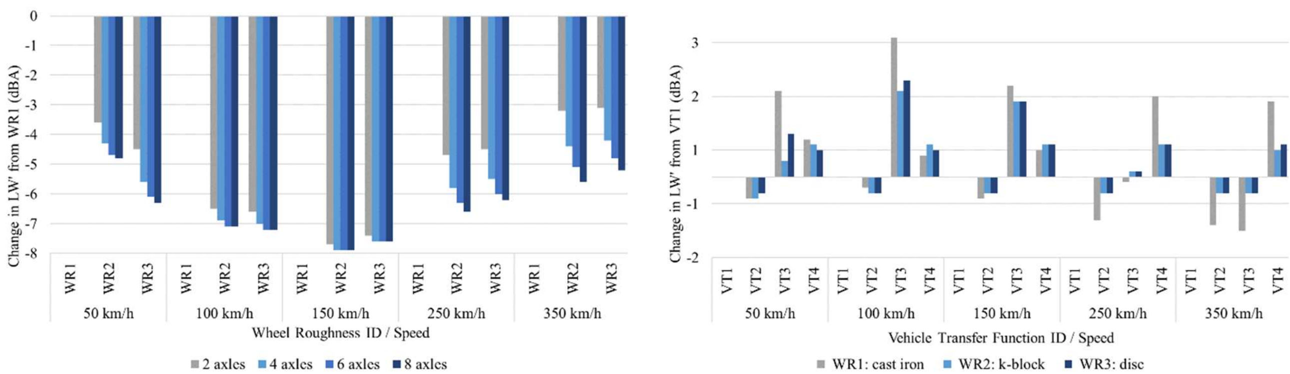

Figure 2: Sensitivity analysis for (left) wheel roughness, and (right) vehicle transfer function

3.4 Vehicle Transfer Function

The four spectra for the vehicle transfer (VT) function considered are listed below and analysed in combination with each of the default WR settings. VT1 is the benchmark.

- VT1 – wheel with diameter 920 mm, no measure
- VT2 – wheel with diameter 840 mm, no measure
- VT3 – wheel with diameter 680 mm, no measure
- VT4 – wheel with diameter 1200 mm, no measure

Speeds below 50 km/h have been excluded from this analysis since light rail (typically 680 mm wheel diameter [5]) are the only vehicle type valid below speeds of 50 km/h [1]. Figure 2 (right) shows the difference to the absolute emission levels for VT1 (920 mm wheels), which represents most heavy rail categories [5].

VT does not have a large effect on the emission levels. The largest differences, up to 2.5 dB, can be observed between vehicles with 840 mm wheels and 680 mm wheels, particularly at speeds of 100 km/h and 150 km/h. The choice of WR spectrum has a limited impact sensitivity of emissions to the VT function. However, using standard freight cast iron tread brakes (WR1) typically increases sensitivity to the VT function compared to using other brake types.

3.5 Number of Axles

Results are presented in Figure 3 comparing the use of 2, 4, 6 and 8 axles per vehicle, for each of the default WR and speed values. 4 axles is the benchmark, which is the number of axles, Na, used by the majority of rail vehicle categories [5].

Emission levels change by up to ±3 dBA when Na changes by a factor of 2 (e.g., from 2 to 4, or 4 to 8, and vice versa), which is in line with expectations as the rolling noise level is directly correlated to Na [1]. There is some reduction in sensitivity at certain speeds and WR settings.

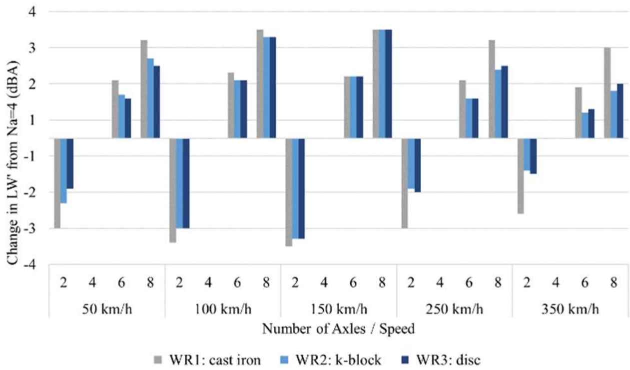

Figure 3: Number of axles sensitivity analysis

3.6 Rail Roughness Spectrum

The three spectra for rail roughness (RR) considered are listed below and analysed in combination with each of the default WR and speed values. RR1 is the benchmark.

- RR1 – EN ISO 3095 2013 with extrapolation
- RR2 – (Dutch) average network with extrapolation (normally maintained smooth)
- RR3 – spectrum to approximate CRN conditions (with a smooth wheel) [5]

Figure 4 shows that the maximum difference in emissions occurs around 150 km/h, which is approximately 1.7 dBA between RR1 and RR3, in line with [5]. The choice of WR has limited impact on the sensitivity here, except where cast iron brakes are used.

3.7 Track Transfer Function

The three values of track transfer (TT) function considered during the testing were those considered within [5] (wood and concrete sleepers) in addition to direct fastenings, added in [2]:

- TT2 – Mono-block on medium stiffness rail pad (concrete sleepers)
- TT7 – Wooden sleepers
- TT8 – Direct fastening on bridges

TT2 is the benchmark. Due to the relationship between TT function and bridges [2], results have also been plotted against variations of the BT function from [2]: BT0 (0 dBA correction), BT1 (+10 dBA), and BT2 (+15 dBA). Since Figure 5 (left) shows the relative change when varying the TT spectrum, the influence of the bridge correction may appear counterintuitive. While the absolute SWL of the source with a given TT function increases with a higher bridge correction, the impact of selecting a different TT function decreases, so the choice of TT spectrum has less influence on the output, because the bridge correction component relatively dominates the emissions.

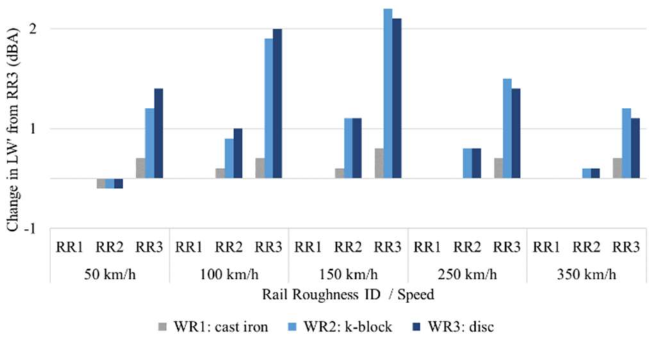

Figure 4: Rail roughness spectrum sensitivity analysis

There is no significant difference on the modelled emission level when changing between concrete (TT2) or wooden (TT7) sleepers. However, tracks on bridges with direct fastenings (TT8), but no bridge correction (BT0), can introduce differences of up to 5.8 dBA, achieved at speeds of 150 km/h and 100 km/h respectively. For track on a bridge which incurs a bridge correction, the sensitivity of emissions to the TT function is reduced as the bridge correction increases.

These results show that the model is relatively insensitive to change in the TT function, except in the case of direct fastenings on bridges, where it is important to correctly identify bridge constructions with direct fastenings, particularly where they may not also incur a +10 dBA or +15 dBA correction.

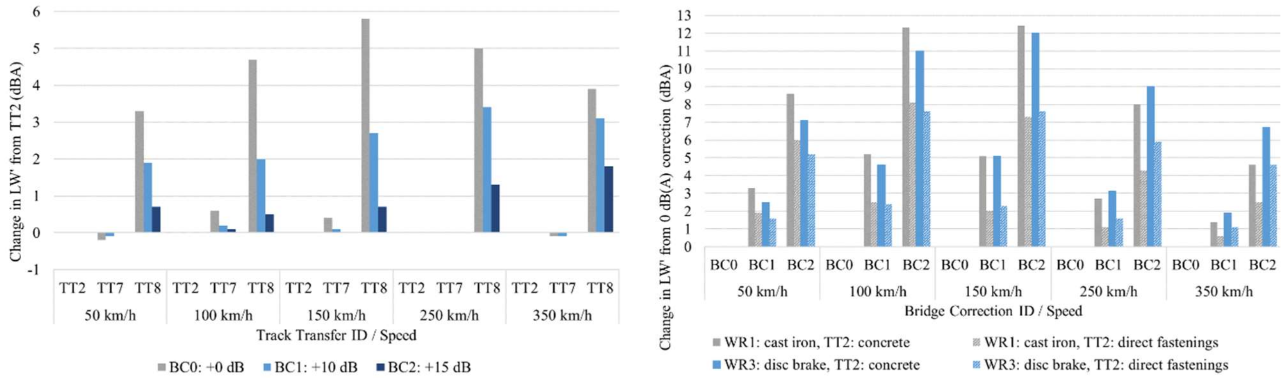

Figure 5: Sensitivity analysis for (left) track transfer function, and (right) bridge transfer function

3.8 Bridge Transfer Function

Figure 5 (right) analyses the sensitivity of the bridge correction for BT0 (0 dBA correction, which is the benchmark), BT1 (+10 dBA), and BT2 (+15 dBA). [2] does not explicitly state which types of bridge each spectrum may apply to, so it is for the user to determine appropriate use of the corrections. The overall effect of the BT function is influenced significantly by both the WR and the TT function. Therefore, the results include variations of WR1, WR3, TT2 and TT8. The choice of BT function has a significant effect, with differences over 12 dBA. The highest differences are observed for speeds of

100 km/h and 150 km/h. Bridges with direct fastenings (TT8) provide a reduction in sensitivity (between 2 and 4 dBA) compared to those with concrete sleepers, at all speeds and WR settings. WR has a small influence on the sensitivity of the BT function at lower speeds, using WR3 (disc brakes) instead of WR1 (cast iron tread) can introduce changes in BT spectrum sensitivity of 2 dBA.

3.9 Impact Roughness Spectrum and Joint Density

The three spectra considered for impact roughness (IR), as given for a single impact, were:

- IR0 – empty spectrum (no impact / continuously welded / silent impacts) (benchmark)
- IR1 – single switch/joint/crossing per 100 m [2]
- IR2 – jointed track at 18.3 m lengths [5]

The number of joints per 100 m, n, is required within the impact noise component of the rolling noise. Therefore, the results have been plotted against various numbers of joints: $n = 1$, 4, and 10.

The IR spectrum has a significant effect, with differences for heavy rail of +22 dBA at 150 km/h with IR2 and +18 dBA with IR1. The sensitivity reduces slightly as speeds increase above 100 km/h. IR2 in [5] is defined as being 7.4 dB greater at all wavelengths than the default IR1 [2]. This difference is reflected in the Figure 6, although the magnitude of this is affected by the speed, v, and number of joints, n. In practice, joints would not be present where rail vehicles travel at any of the higher speeds – these were tested only to demonstrate the effect. These results suggest that correctly identifying the location and density of track joints is important for modelling under CNOSSOS-EU.

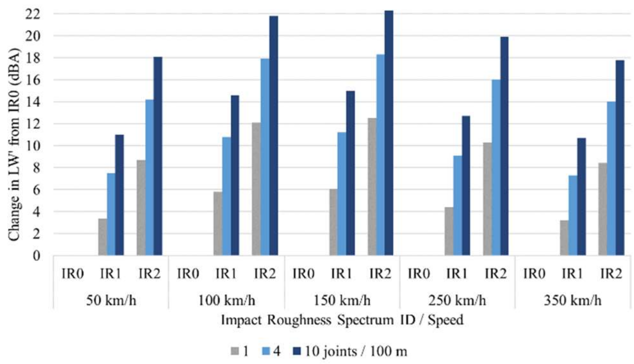

Figure 6: Impact noise source sensitivity analysis

3.10 Curve / Turnout Radius – Squeal Source

Results for curve radius, R, are presented in Figure 7 for curves with 300 m, 500 m, and 1000 m radii (benchmark with no correction), for each of the default WR and speed values. The curve type ('curve' or 'turnout') [2] is not relevant to this analysis since the correction for a 'turnout' only applies to radii ≤ 300 m and is the same as for a 'curve'. Likewise, the 200 m radius correction for Trams is the same as the 300 m correction for Trains [2]. Since the 'curve' type and Train is applied at a greater number of radii this is the setup for which results are presented.

Curve squeal is significant and consistently within 2 dBA of the correction value (+8 dB at 500 m and +5 dB at 300 m), influenced by vehicle speed and WR spectrum. The sensitivity between curve radii is greatest at speeds of 100 km/h and 150 km/h. Below 50 km/h the difference due to WR within a curve radius category can be more than 1.5 dBA. At and above 200 km/h the aerodynamic source component appears to dampen the sensitivity of curve squeal. [2] indicates that the default corrections should be used only if no actual measurements are available and for locations where it is known that squeal occurs. However, the calculation assumes that the correction applies to all days in the annual average model, and not only when there are dry wheels on dry tracks.

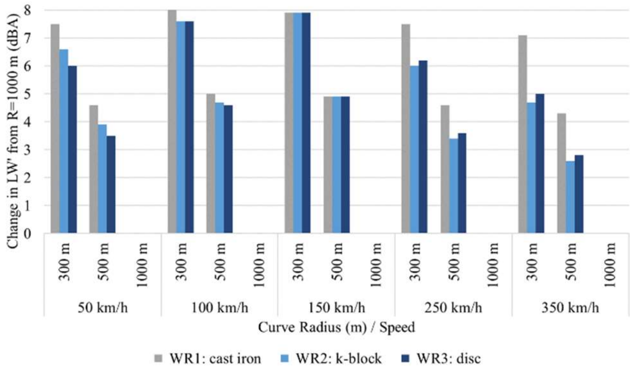

Figure 7: Curve radius sensitivity analysis

4. CONCLUSIONS

Key findings and recommendations are made regarding the sensitivity of the calculated sound power emission level to variance in the input parameters of the CNOSSOS-EU rail emissions calculation model. The results presented for each of the parameters investigated can be used to help inform input data quality requirements for noise modelling, for example in the context of the ±2 dBA accuracy requirement at the point of emission within the CNOSSOS-EU quality framework [1].

In order, the most important data collection considerations are to identify: (1) sections of track with impact sources such as joints, and joint density; (2) the mean speed per vehicle type; (3) bridge types which incur a correction and where track is directly fastened to the bridge; (4) braking systems; (5) curved track, measures against squeal, and curved track known to not squeal, and calculate track curvature; (6) rail flow per vehicle; (7) the number of axles per vehicle; (8) wheel diameter for vehicles with cast iron tread brakes. The sensitivity of emissions to all remaining parameters is less significant and default values may be assumed without introducing a significant level of uncertainty.

The results presented may differ if the rail track incurred a different combination of corrections, although this would typically only decrease sensitivity of emissions to the given parameter.

5. ACKNOWLEDGEMENTS

We would like to thank Defra for commissioning the study.

6. REFERENCES

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