Predicting groundborne sound and vibration from HS2

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HS2

Contents

- Brief overview of the project
- HS2s commitments relating to GBSV
- Developing the ES model for GBSV
- Developing our understanding of track roughness
- Detailed predictions of GBSV
- Conclusions and ongoing work

Bringing Britain closer together

HS2 is now being built, it will form the spine of our rail system.

Key facts

- 345 miles of brand new high speed track will connect Birmingham, Manchester, Leeds and London.
- HS2 trains will also run on the existing network, serving towns and cities in the North West, North East and Scotland.
- HS2 will connect 30 million people and 8 of our largest cities, with 25 stops from Scotland to the South East.

Full network statistics

553 KM OF **TRACK**	**73** KM IN **TUNNEL**	**60** KM OF **VIADUCTS**	**192** KM OF **CUTTINGS**	**194** KM OF **EMBANKMENT**
1.9m TONNES OF **STEEL**	**19.7m** TONNES OF **CONCRETE**	**9** MAJOR **RIVERS** DIVERTED	**1,740** **BUILDING DEMOLITIONS** REQUIRED	**96m** CUBIC METRES OF **EXCAVATED MATERIAL**

Information paper E21 - Objectives

3.1. The nominated undertaker will design the temporary and permanent railways such that the level of ground-borne noise and vibration predicted in all reasonably foreseeable circumstances does not exceed the significant observed adverse effect levels given in Table 1 in Appendix B.

3.2. The nominated undertaker will take all reasonably practicable steps to construct, operate and maintain the temporary and permanent railways so that the design objective stated in paragraph 3.1 is fulfilled.

3.3. In addition, the nominated undertaker will take all reasonable steps to design, construct, operate and maintain the temporary and permanent railways such that, in all reasonably foreseeable circumstances, ground-borne noise and vibration does not exceed the lowest observed adverse effect levels given in Table 1 in Appendix B.

3.4. The nominated undertaker will reduce ground-borne noise and vibration from the temporary and permanent railways as far as is reasonably practicable.

Avoid significant adverse effects

Minimise adverse effects

HIGH SPEED TWO PHASE ONE INFORMATION PAPER

E21: CONTROL OF GROUND-BORNE NOISE AND VIBRATION FROM THE OPERATION OF TEMPORARY AND PERMANENT RAILWAYS

Information paper E21 – Effect levels

Table 1 - Ground-borne noise and vibration effect levels for permanent residential buildings

Ground-borne noise	Lowest Observed Adverse Effect Level	L_{pASMax} [dB]	35
	Significant Observed Adverse Effect Level	L_{pASMax} [dB]	45
Vibration	Lowest Observed Adverse Effect Level	VDVday[$m/s^{1.75}$]	0.2
		VDVnight[$m/s^{1.75}$]	0.1
	Significant Observed Adverse Effect Level	VDVday[$m/s^{1.75}$]	0.8
		VDVnight[$m/s^{1.75}$]	0.4

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Information paper E21 – Effect levels

Table 2 - Ground-borne noise impact levels for non-residential buildings

Examples	L_{pASMax} [dB]
Large auditoria; and concert halls	25
Sound recording & broadcast studios; theatres, and small auditoria	30
Places of meeting for religious worship; courts; cinemas; lecture theatres; museums; and small auditoria or halls	35
Offices; schools; colleges, hospitals; hotels; and libraries	40

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Information paper E21 – Effect levels

Table 3 - Ground-borne vibration impact levels for non-residential buildings

Examples	VDVday[m/s$^{1.75}$]	VDVnight[m/s$^{1.75}$]
Hotels; hospital wards; and education dormitories	0.2	0.1
Offices; Schools; and Places of Worship	0.4	n/a
Workshops	0.8	n/a
Vibration sensitive research and manufacturing (e.g. computer chip manufacture); hospitals with vibration sensitive equipment / operations; universities with vibration sensitive research equipment / operations	Risk assessment will be undertaken based on the information currently available for the relevant equipment / process, or where information provided by the building owner or equipment manufacturer.	

Information paper E21 – Control Measures

4.1. The likely ground-borne noise and vibration impact of the temporary and permanent railways has been assessed and the findings reported in the Environmental Statement.

4.2. Ground-borne noise and vibration from the temporary and permanent railways will be controlled by the design and maintenance of the train and track.

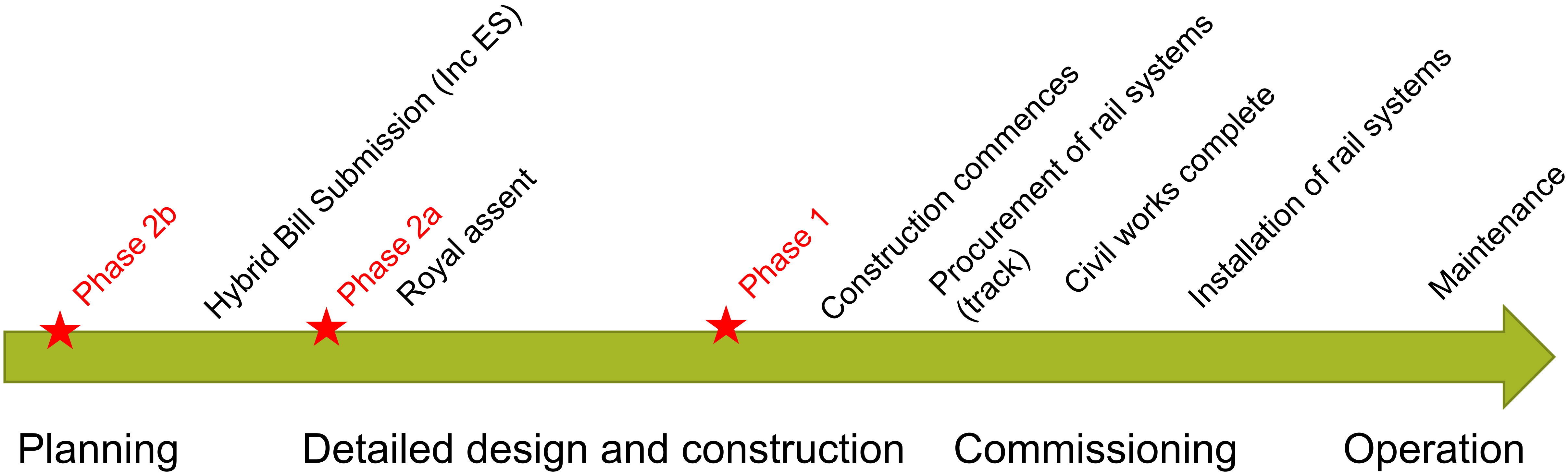
GBSV to be controlled through design of train and track

4.3. To control ground-borne noise and vibration from the temporary and permanent railways, the nominated undertaker will be required to do the following in relation to the track systems:

- at design stage, predict, through the use of appropriate modelling, the engineering requirements of the track system that will fulfil the objectives;
- design a standard track form with the objective of meeting as many of those engineering requirements identified in the previous bullet as can reasonably be achieved by such a standard track system;
- design an enhanced track form for locations where it is predicted that the standard track system will not meet the engineering requirements or to discharge other project commitments and undertakings;
- translate the engineering requirements into contract specifications for the track systems; and
- procure, install and maintain the track systems to meet the contract specifications established above.

Design, specify, install and maintain track to achieve objectives

E21 delivery timeline



PART 2

Developing the ES Model

HS1 Method

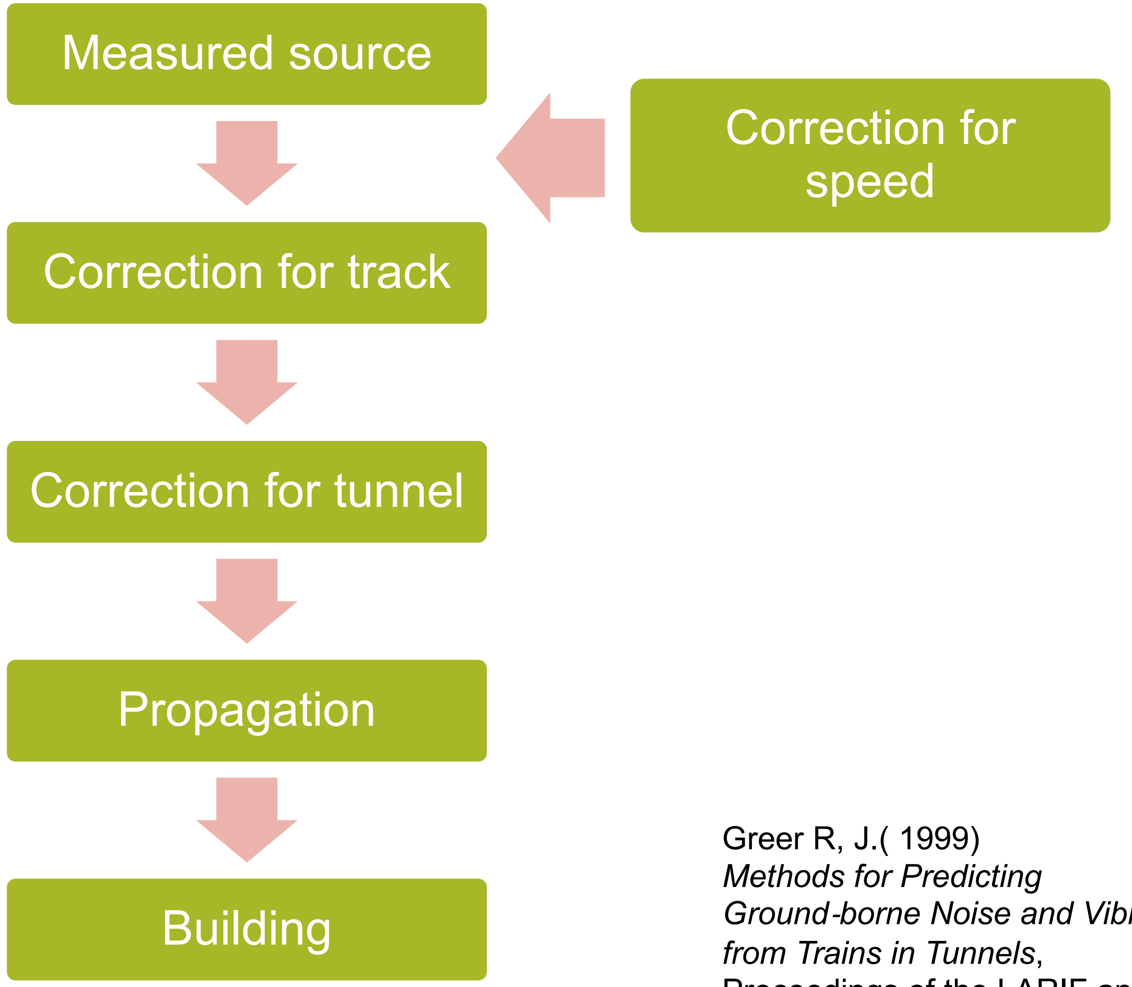
- Empirical method developed in the 1990s
- Developed and validated with 1000s measurements
- Intended for use up to 300km/h

Challenge:

- Ensuring the model is accurate at high speeds (up to 360km/h)

Solution:

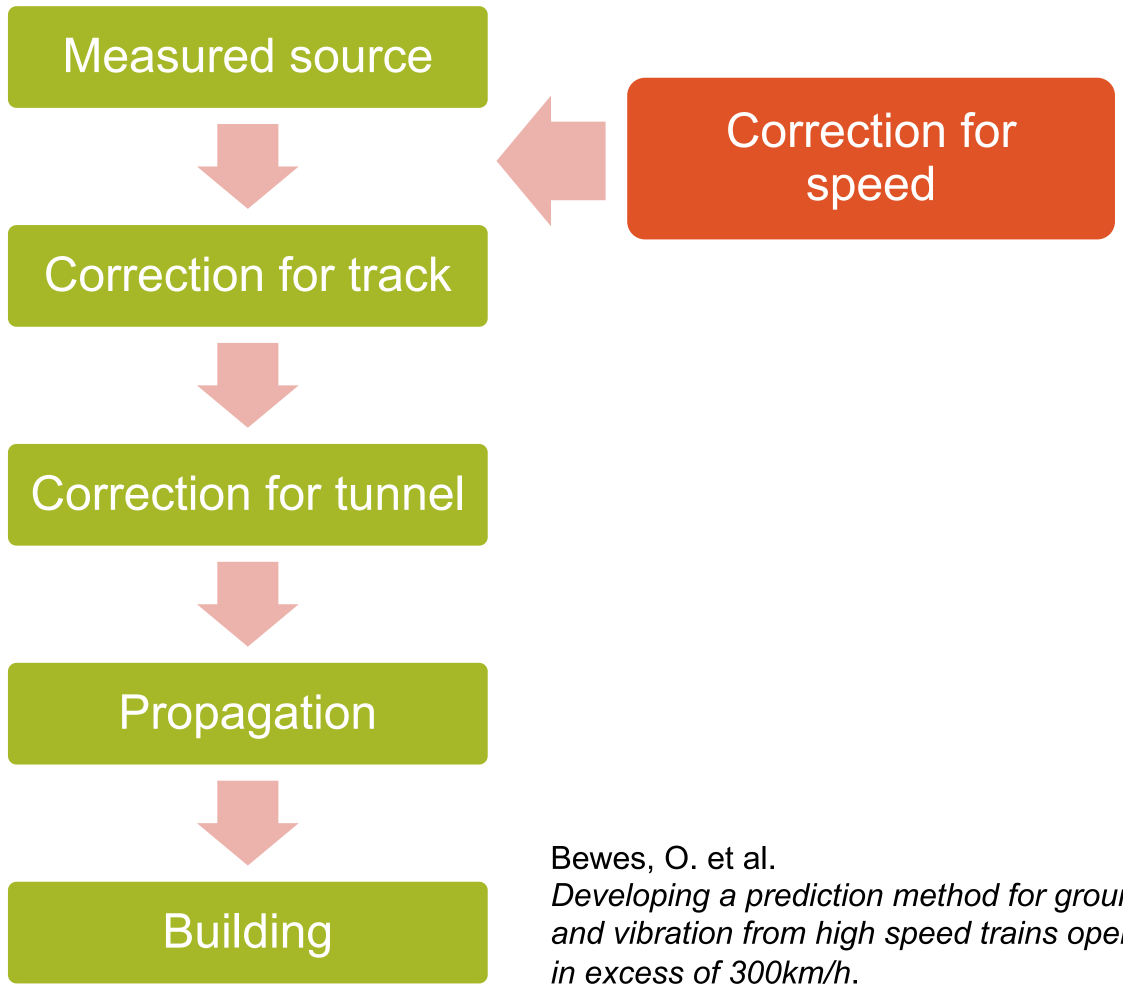
- Ensure mechanisms that generate ground-borne vibration are appropriate for speed range
- Maximise the goodness of fit with available vibration data



Greer R, J.(1999)
Methods for Predicting Ground-borne Noise and Vibration from Trains in Tunnels,
Proceedings of the LARIF and IoA Conference

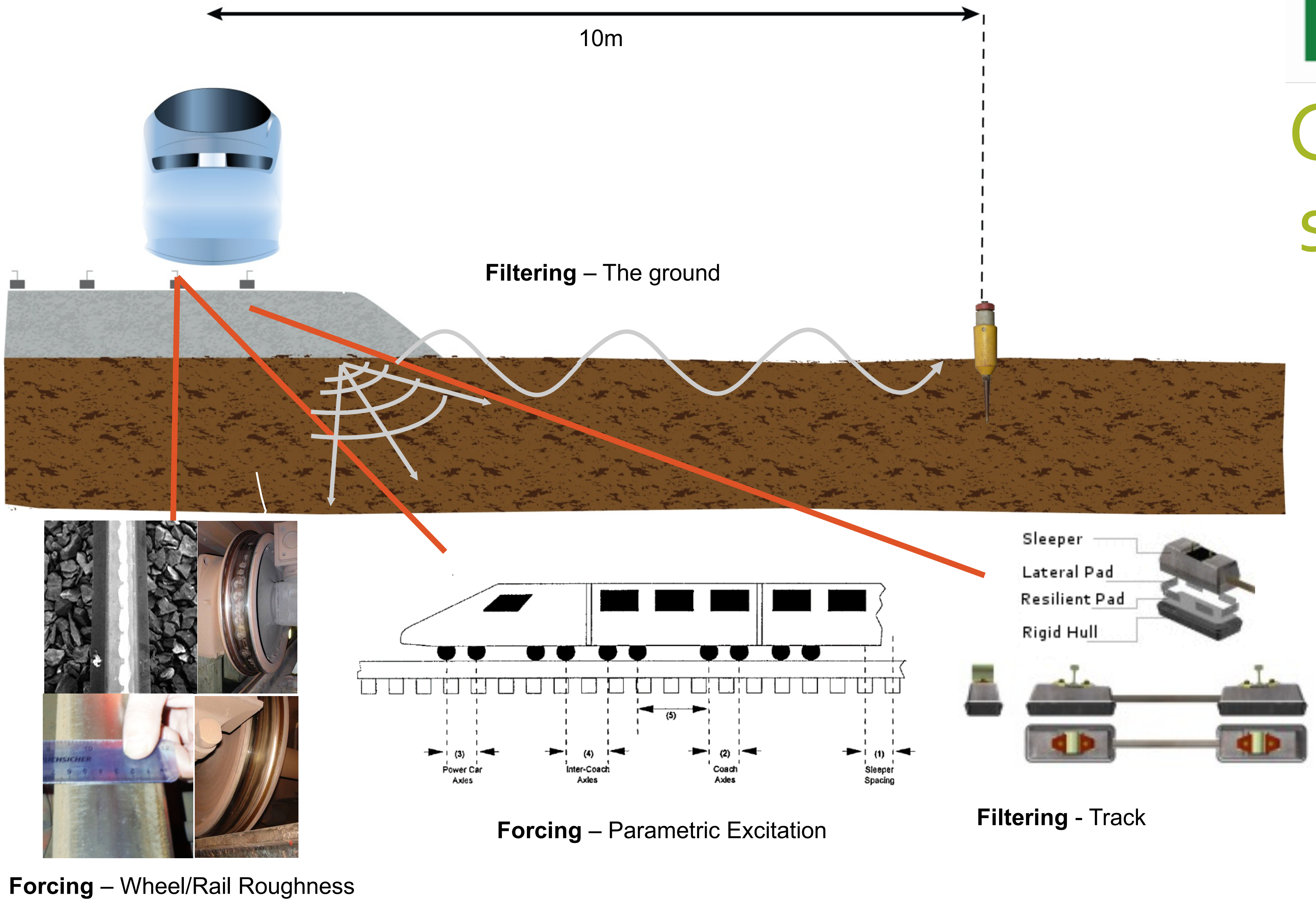
HS2 method

- HS1 model updated for HS2 ES
- Updates focussed on the speed correction
- ANC Transportation Noise Control Award 2014



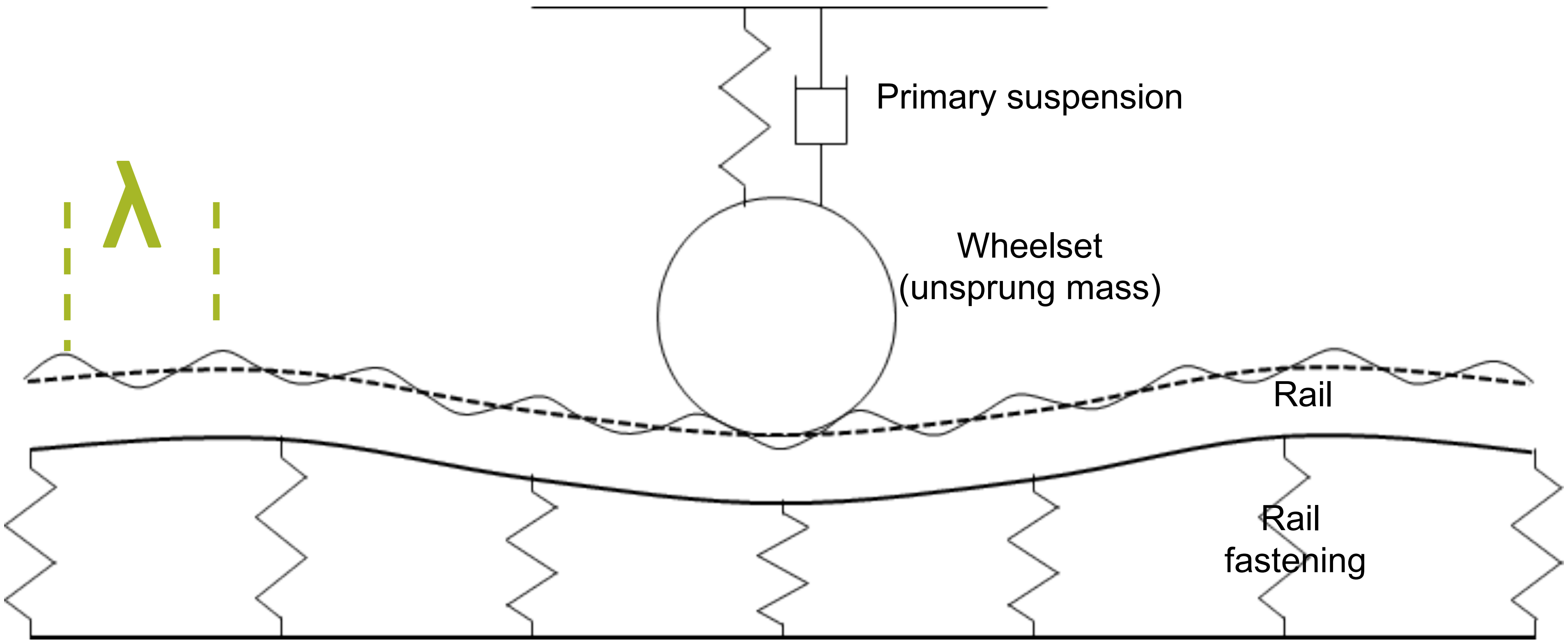
Bewes, O. et al.
Developing a prediction method for ground-borne sound and vibration from high speed trains operating at speeds in excess of 300km/h.
Proceedings of the 21st International Congress on Sound and Vibration, 13th – 17th July 2014, Beijing, China

Correcting a source term



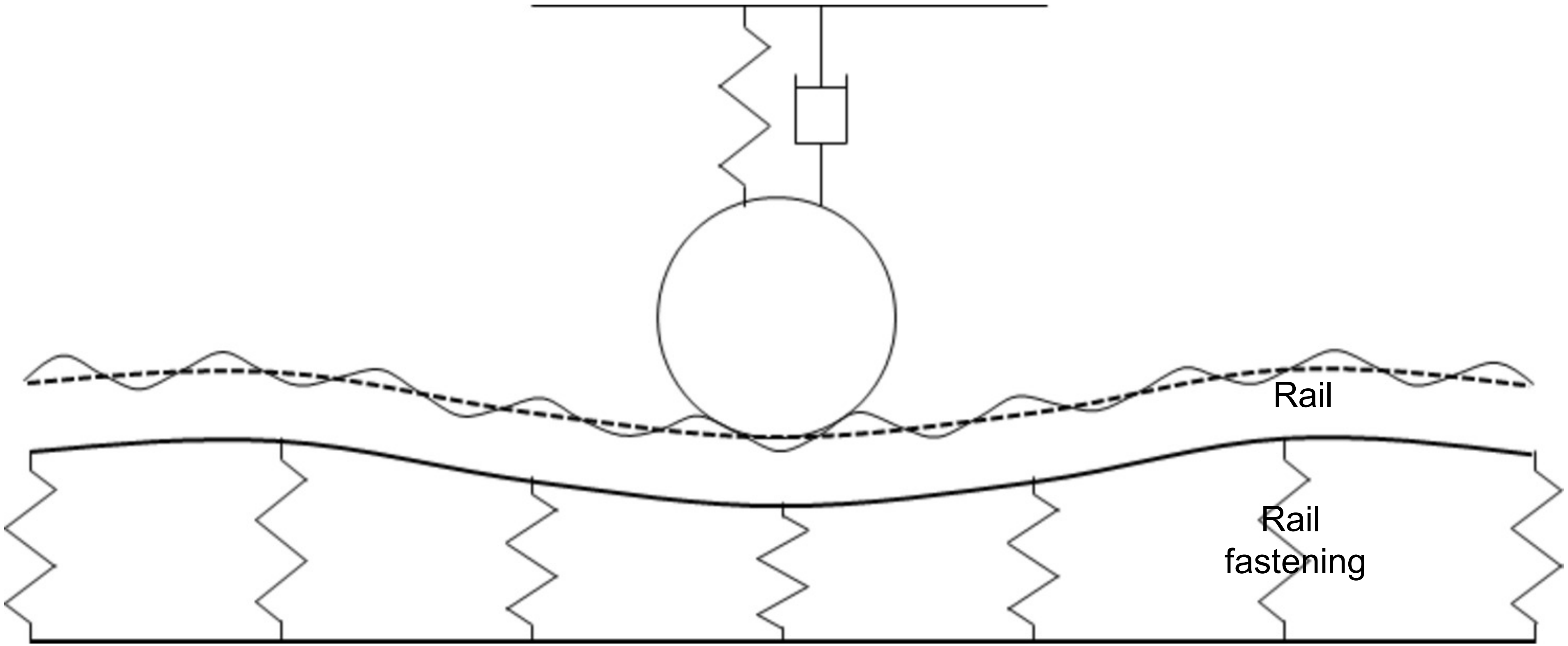
10-12 November 2020

Roughness



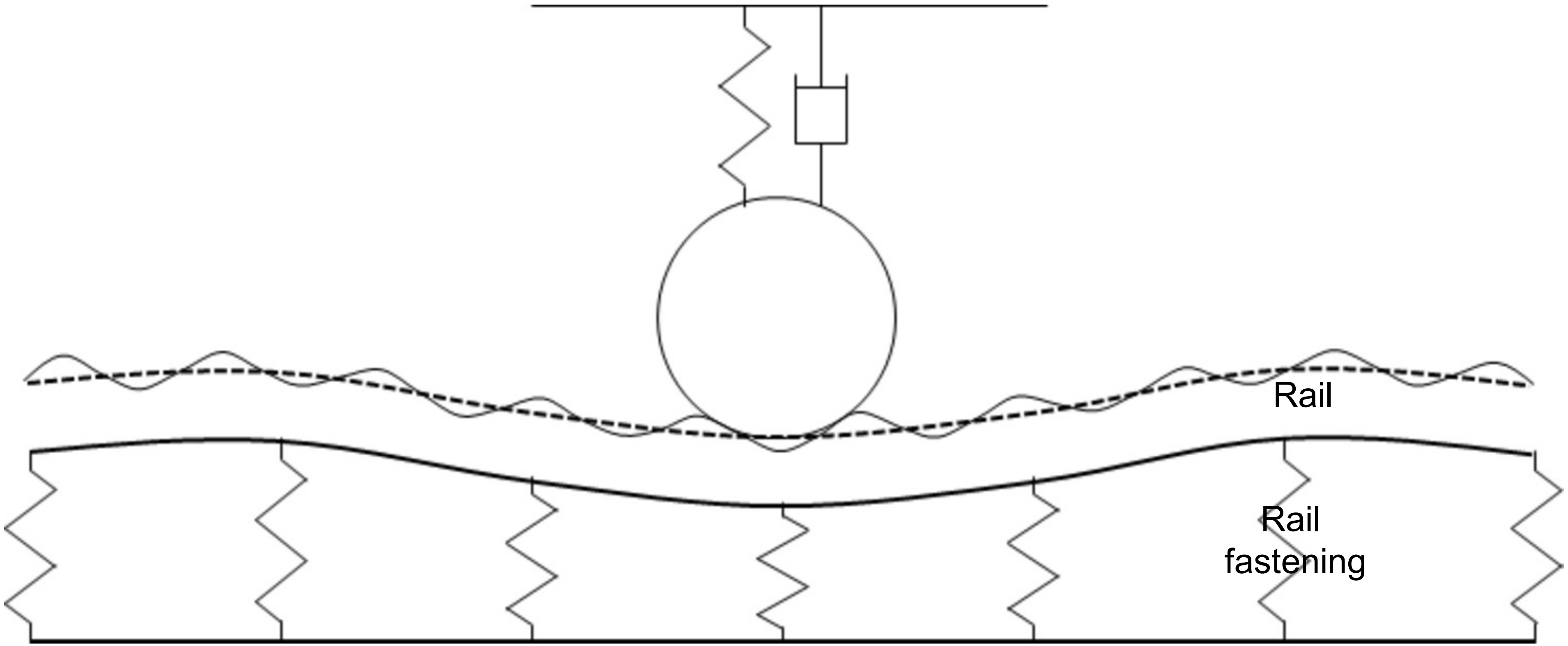
λ = roughness wavelength (m)

Roughness



At a train speed *c* (m/s) the roughness excites the system at a frequency *f* (Hz) according to $f = c / \lambda$

Roughness



If the train speed doubles so does the frequency of excitation

Which wavelengths?

	Roughness wavelength in m for a given train speed			
Frequency in Hz	40 km/h (11.11m/s)	80 km/h (22.22m/s)	160 km/h (44.44m/s)	315 km/h (87.5m/s)
1	11,11	22,22	44,44	87,50
2	5,56	11,11	22,22	43,75
4	2,78	5,56	11,11	21,88
8	1,39	2,78	5,56	10,94
16	0,69	1,39	2,78	5,47
31,5	0,35	0,71	1,41	2,78
63	0,18	0,35	0,71	1,39
125	0,09	0,18	0,36	0,70
250	0,04	0,09	0,18	0,35

Long wavelength measurement

Short wavelength measurement

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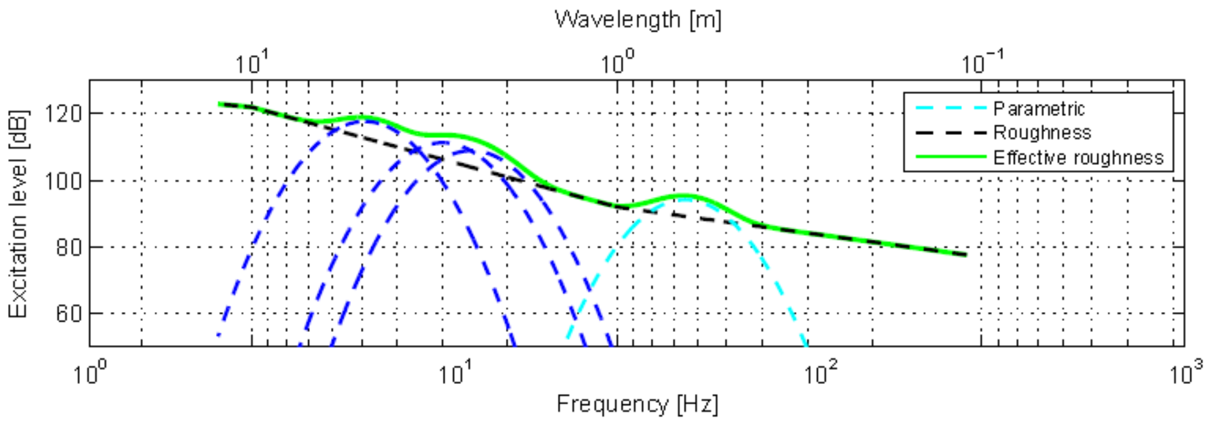
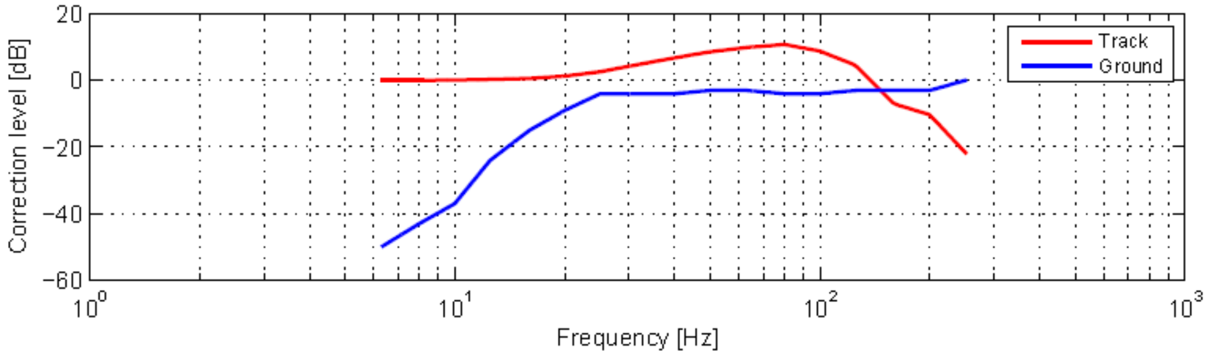
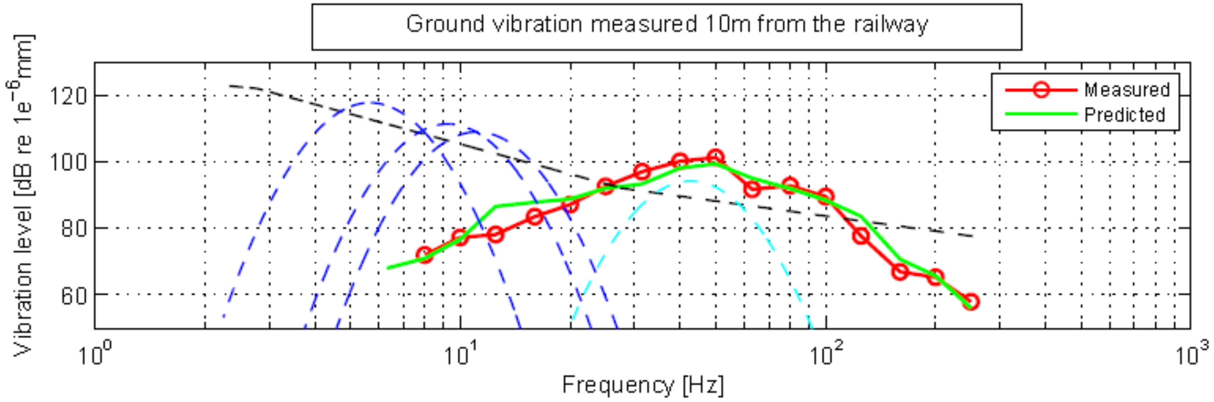
100km/h



Force



Filters



Response

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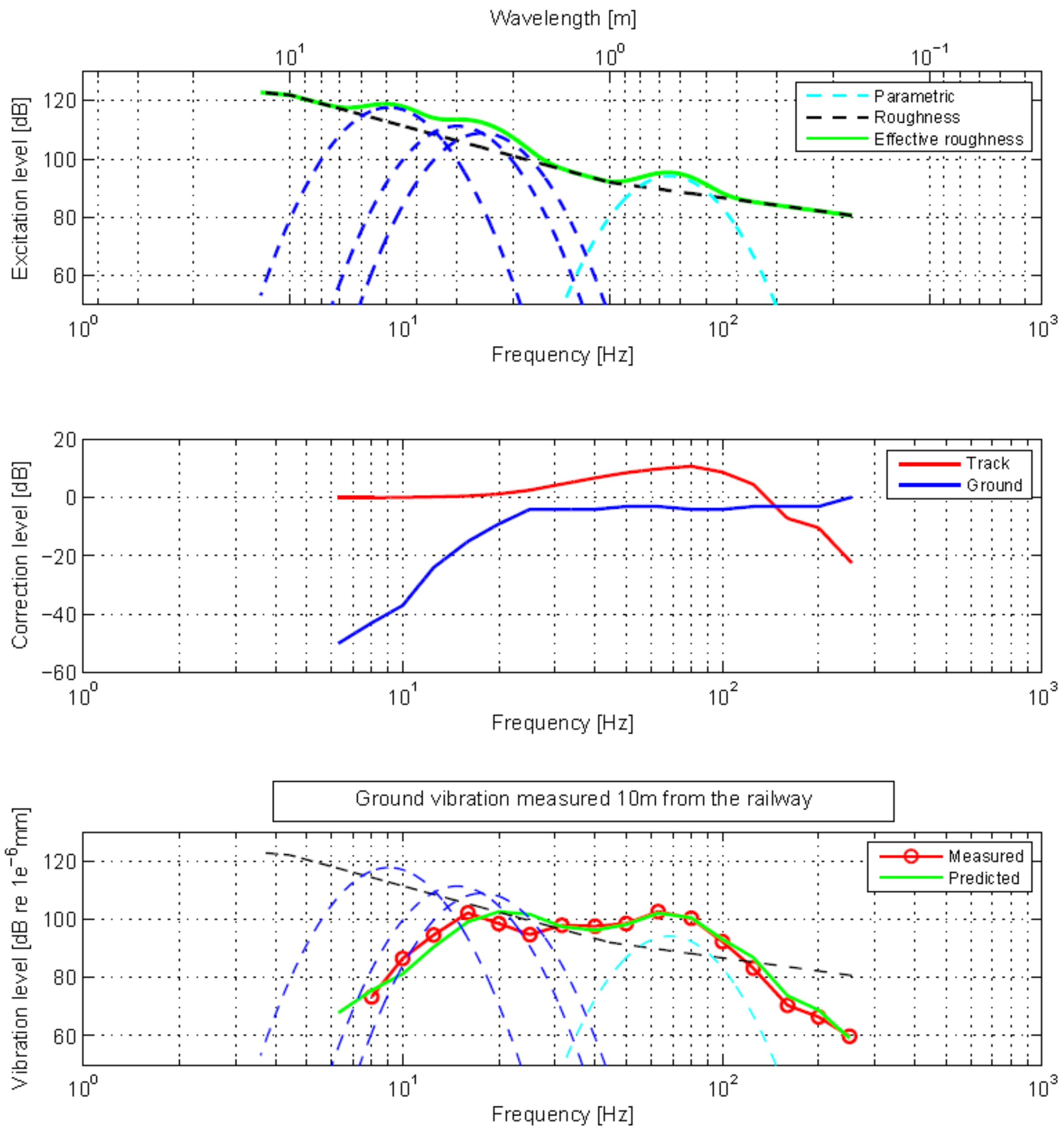
160km/h



Force

Filters

Response

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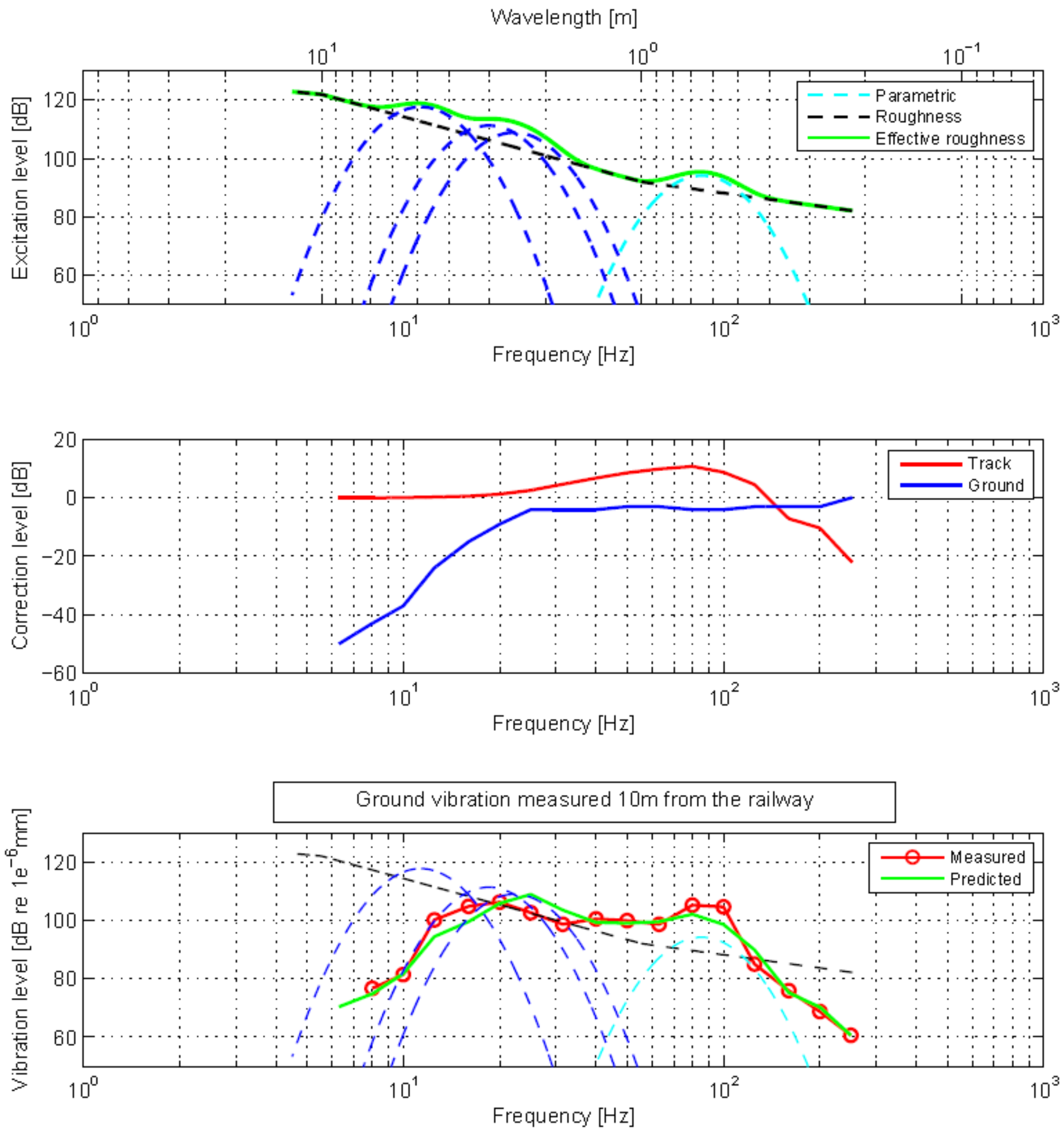
200km/h



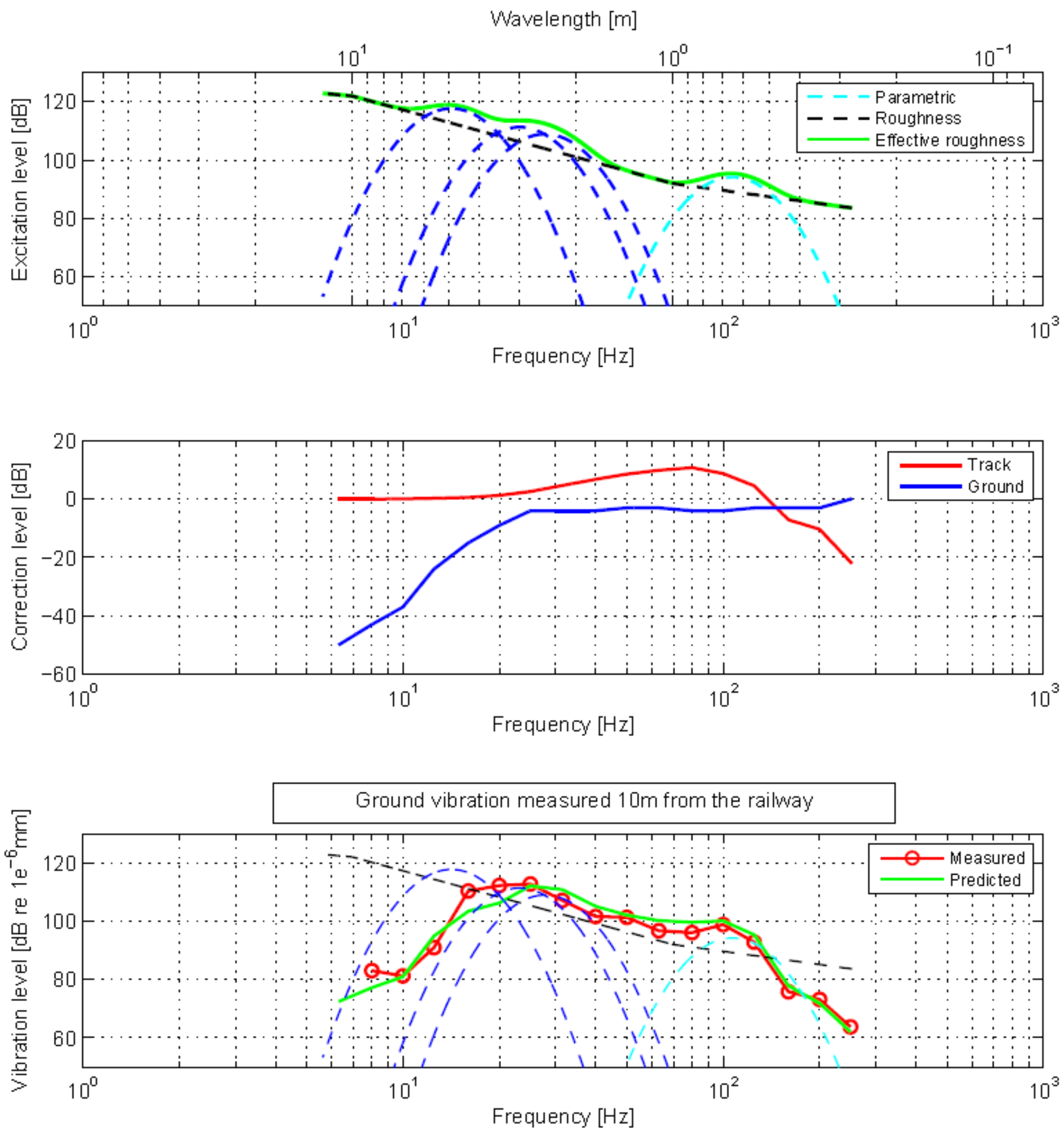
Force

Filters

Response

10-12 November 2020

250km/h



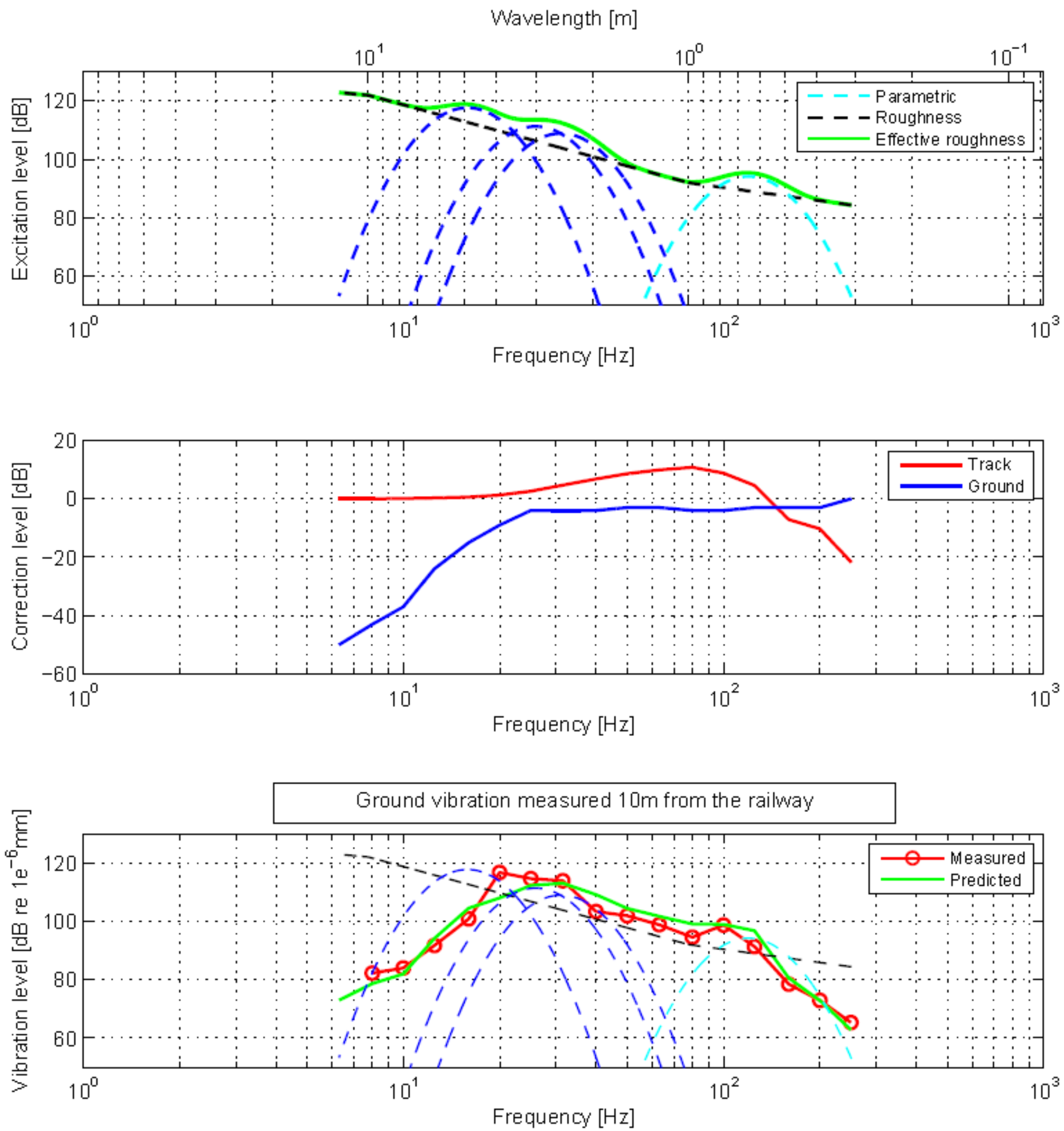
Force

Filters

Response

10-12 November 2020

280km/h



Force

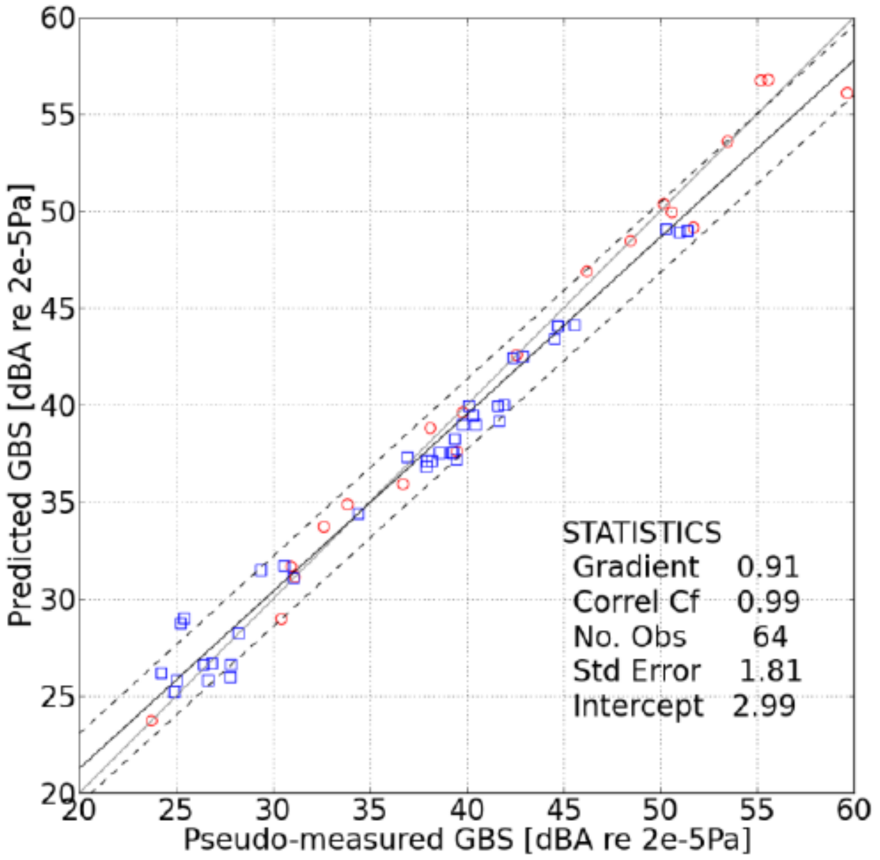
Filters

Response

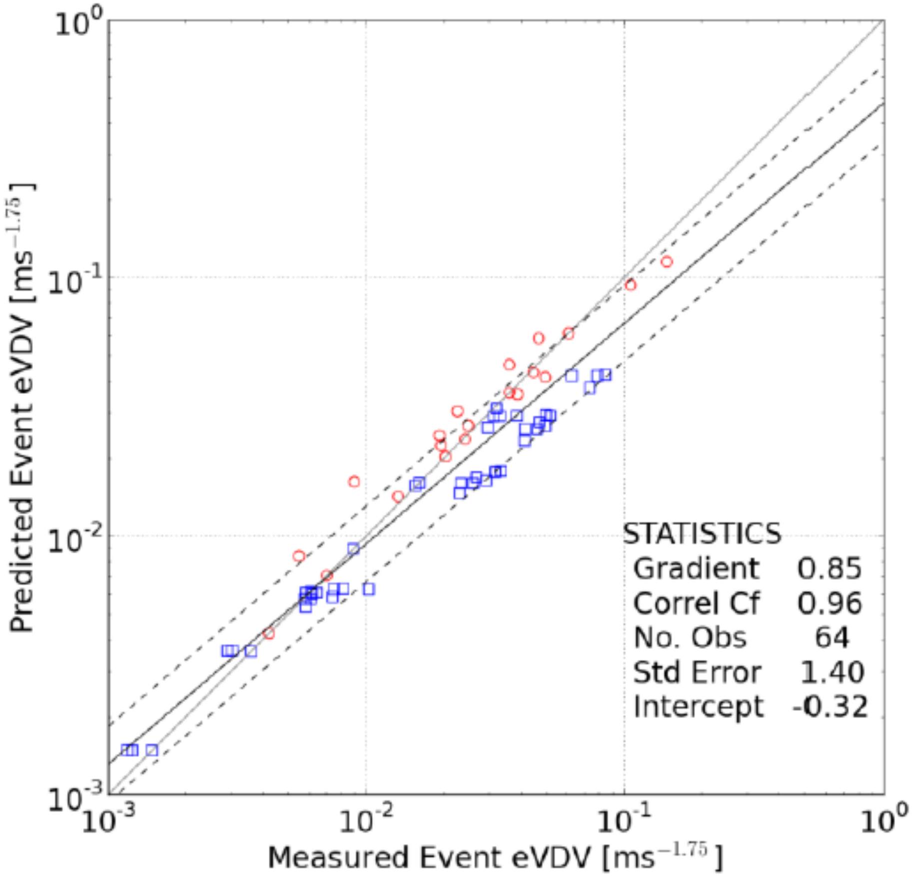
10-12 November 2020

Accuracy of speed correction

$L_{Amax,S}$



VDV



PART 3

Improving our understanding of roughness

How do we present roughness?

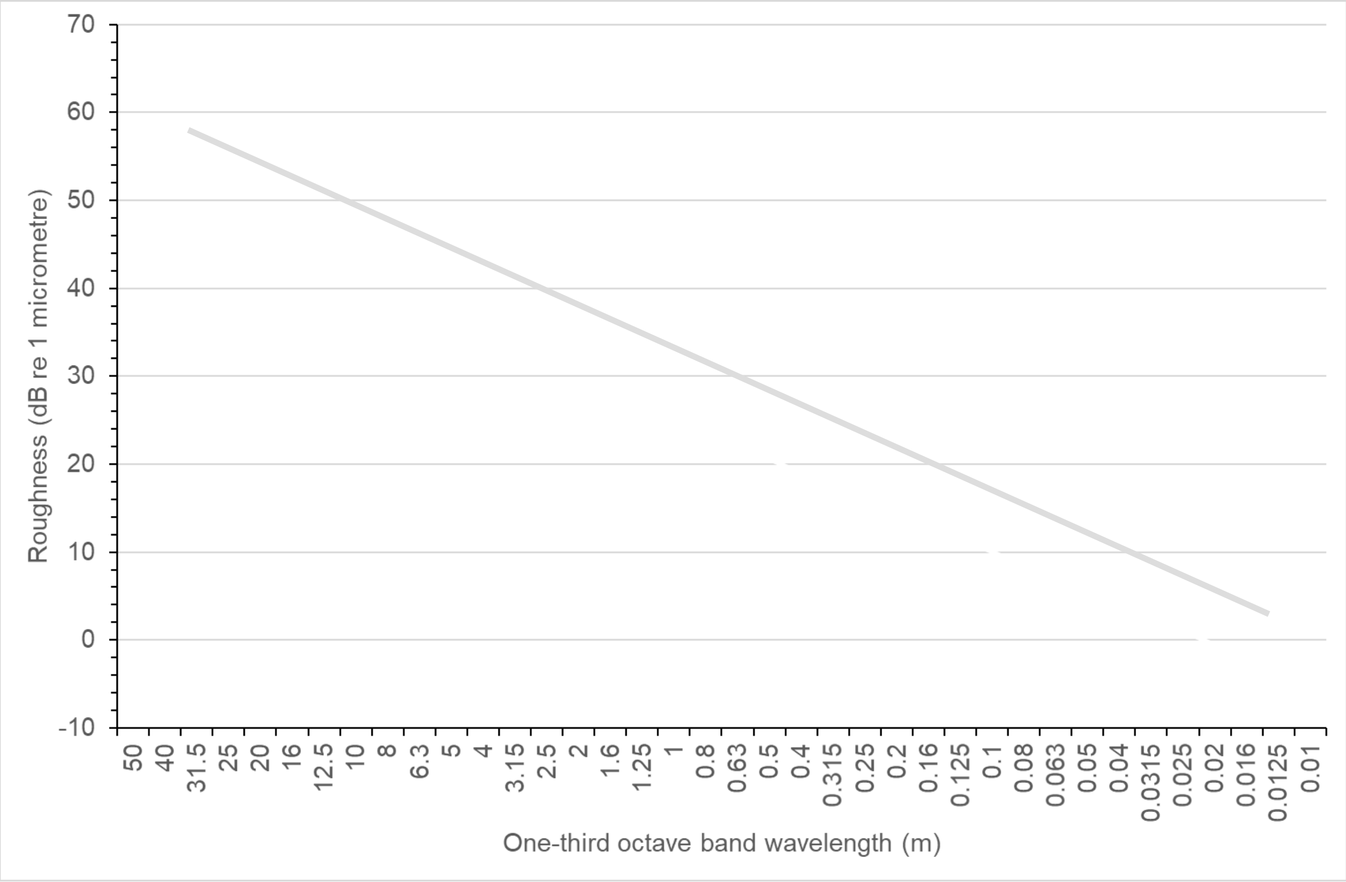
Roughness typically presented as a one-third octave band spectrum

Wavelength in m on *x*-axis

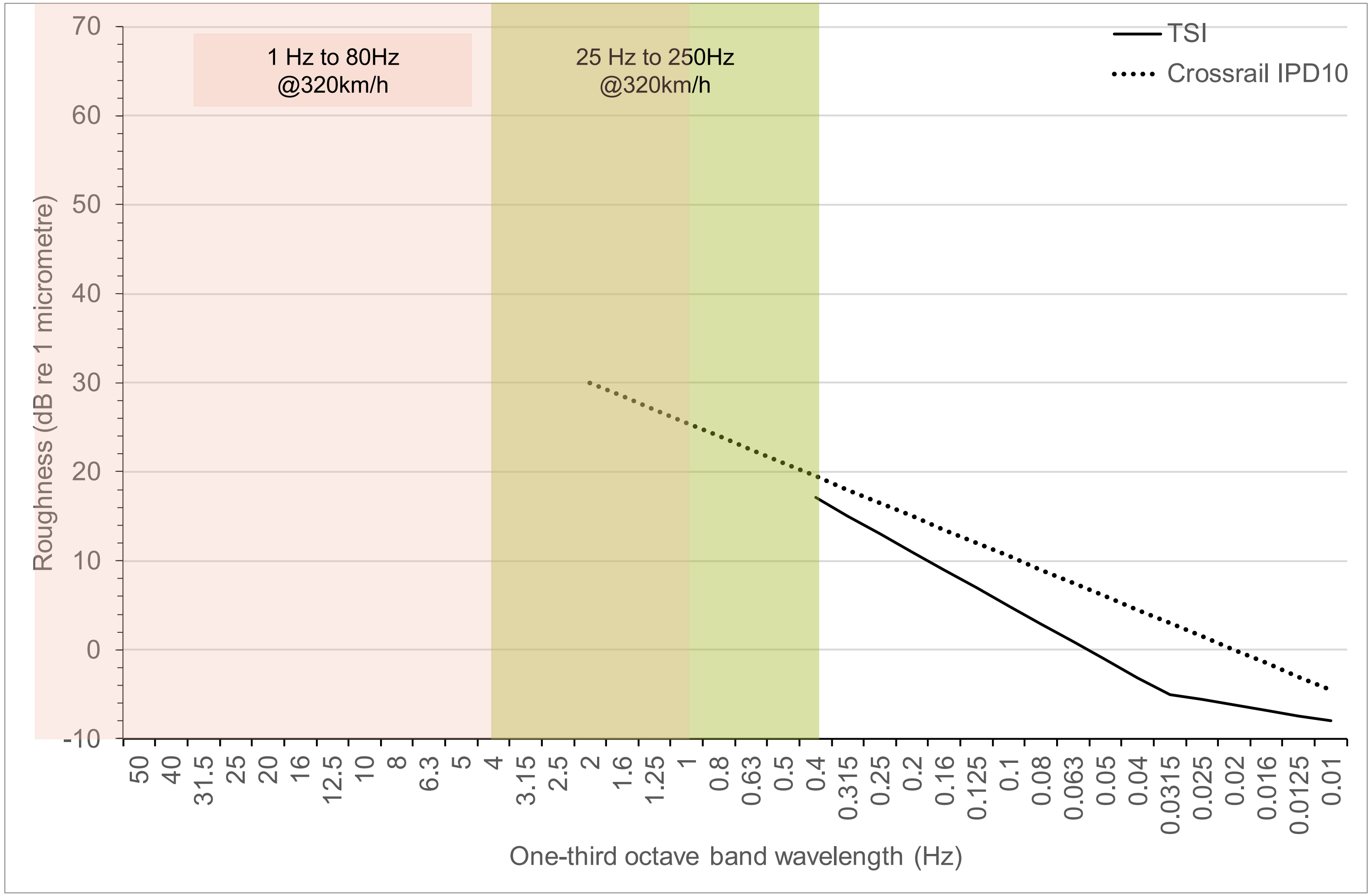
A reversed *x*-axis because frequency is inversely proportional to roughness wavelength

Roughness amplitude in decibels on *y*-axis

BS EN 15610:2019 *Railway applications – Acoustics – Rail and wheel roughness measurement related to noise generation*



Limited data available at hybrid Bill stage



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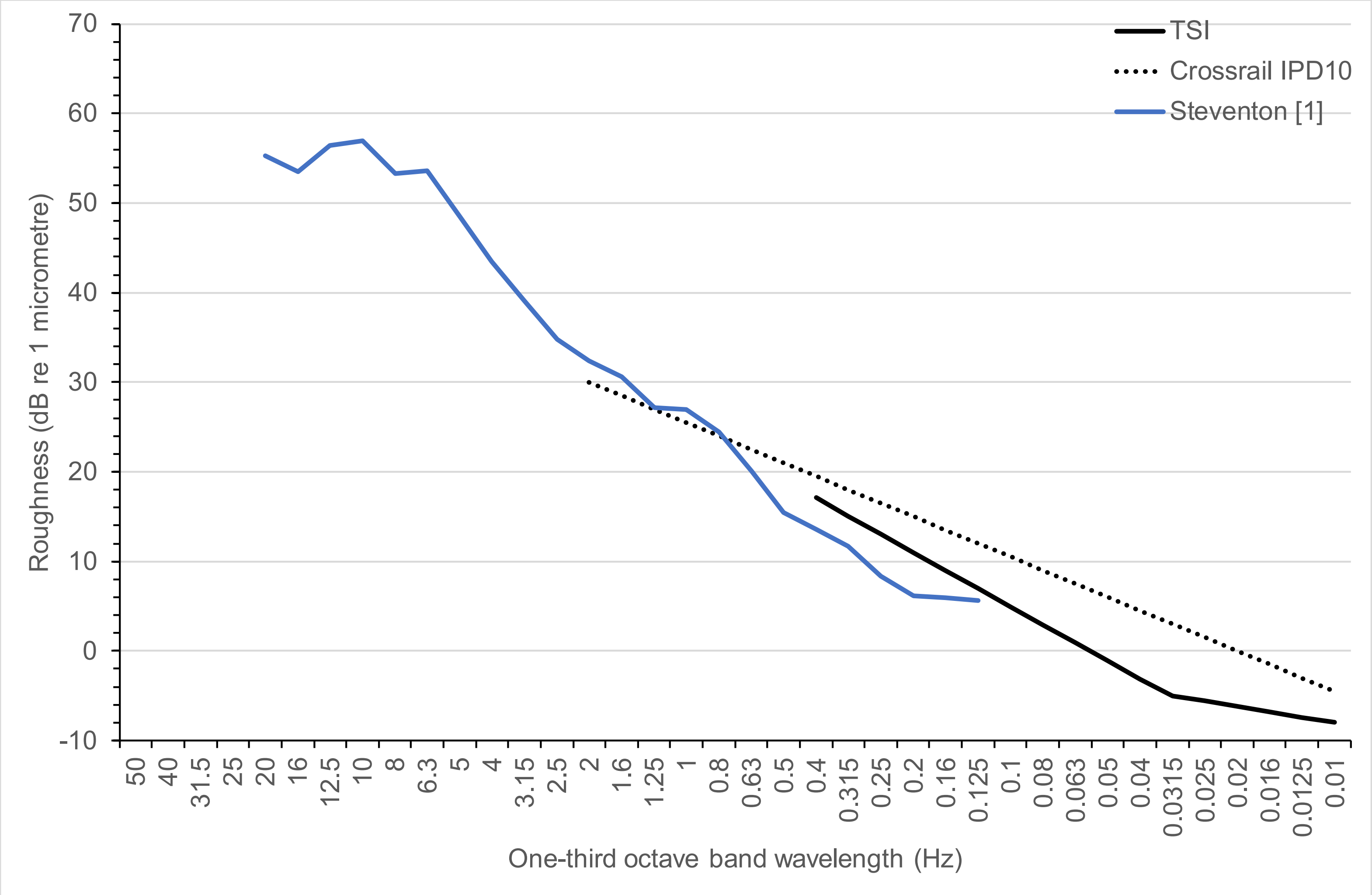
Roughness measurements on UK mainline ballast track



[1] N. Triepaischajonsak et al *Ground vibration from trains: experimental parameter characterization and validation of a numerical model*, Journal of Rail and Rapid Transit, Proceedings of Institution of Mechanical Engineers Part F, 225F, 140-153, 2011

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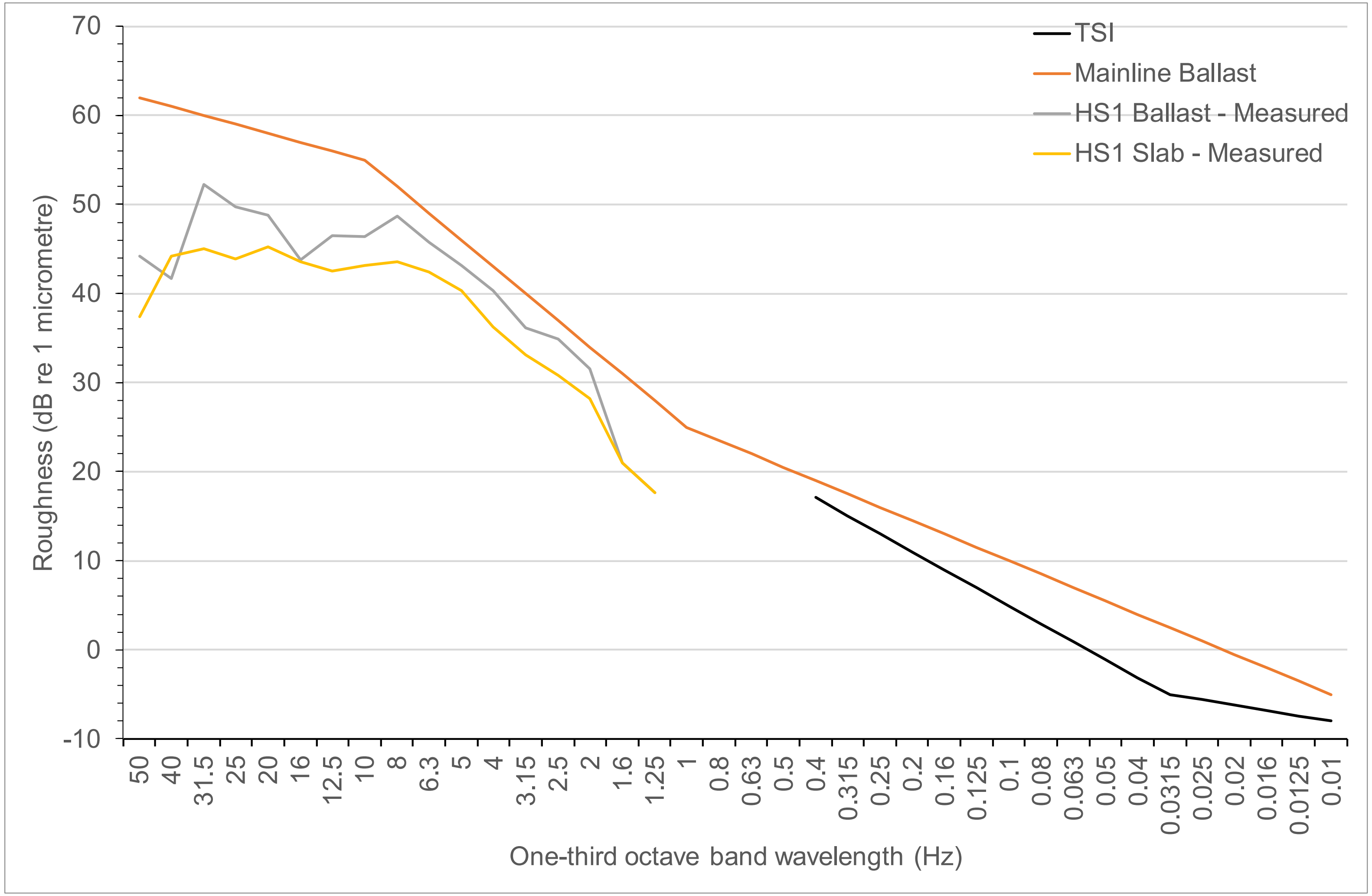
Long wavelength measurements on HS1 ballast and slab



Short wavelength measurements on high speed ballast in Italy

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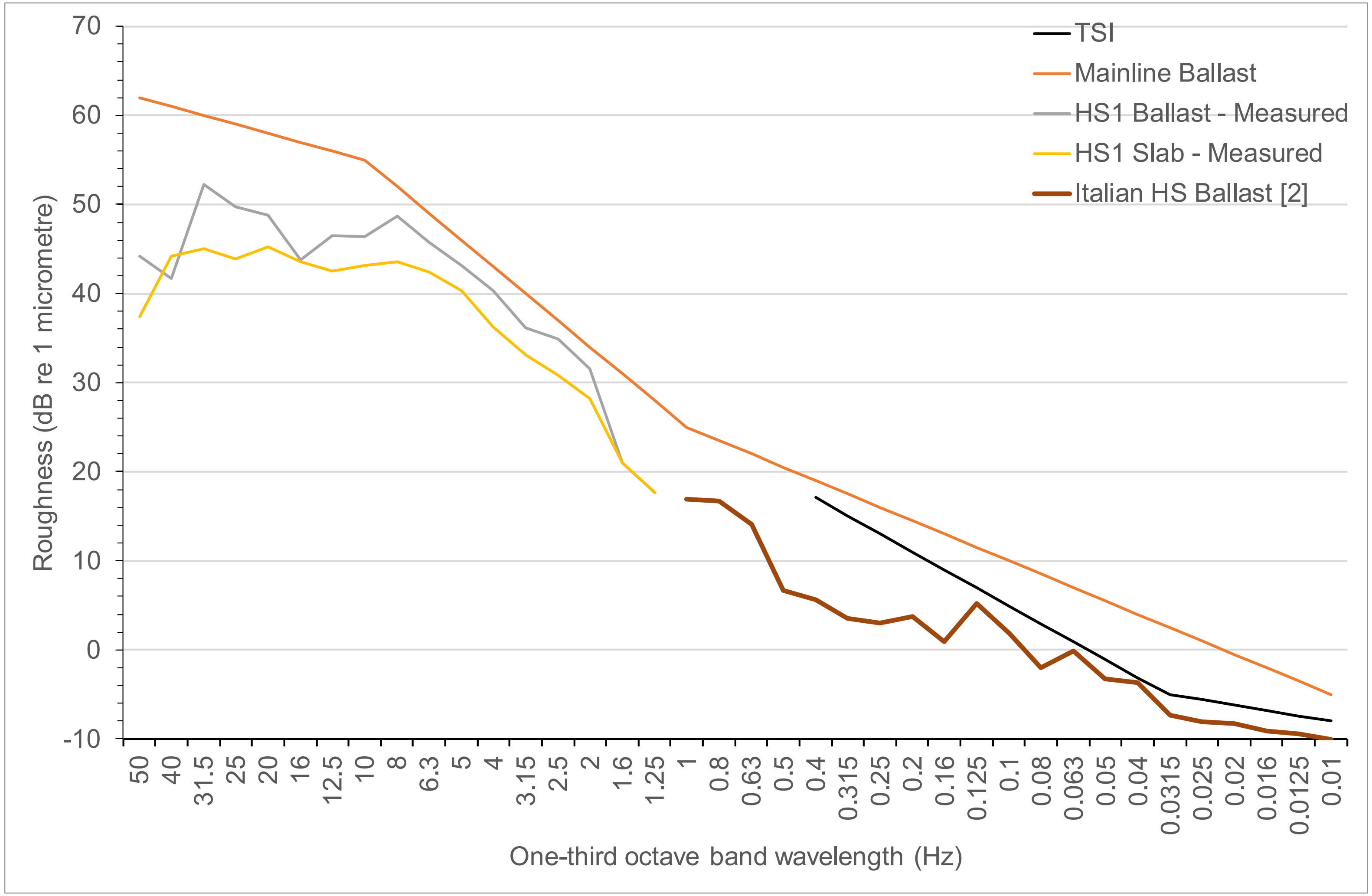
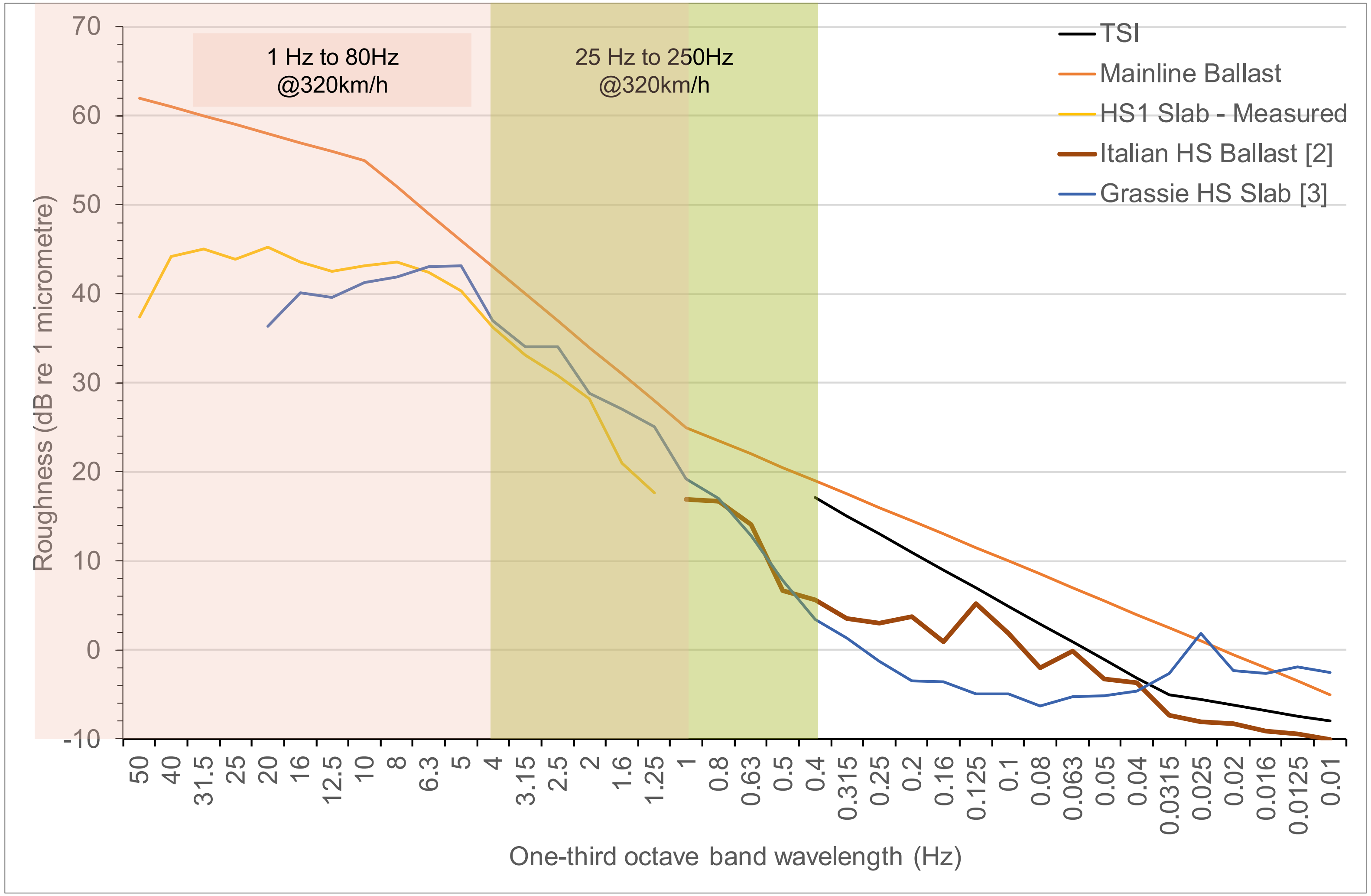


[2] Grassie S.L.
Rail irregularities, corrugation and acoustic roughness: characteristics, significance and effects of reprofiling, Journal of Rail and Rapid Transit 226 (5), 2012

Full wavelength measurements on high speed slab track



Rail Corrugation Analyser

[3] Grassie, S.
Routine measurement of long wavelength irregularities from vehicle-based equipment.
Proceedings of the 12th International Workshop on Railway Noise. Terrigal, Australia 12-16 September 2016

PART 4

Detailed predictions

Overview of detailed modelling

- Between 2015 and 2017 HS2 undertook detailed modelling of GBSV to inform the initial specification for HS2 track
- Modelling undertaken using the numerical modelling software Findwave by Rupert Taylor limited
- A numerical model was chosen because it allowed more detailed consideration of the key parameters for example roughness:
  - The ES model uses measured train source-terms measured on ballast track in the 90s and the roughness characteristics not known
- Some of the results of the modelling were published in T Marshall et al *The predicted vibration and ground-borne noise performance of modern high speed railway tracks.* Internoise , San Francisco, 2015
- Models based on hybrid Bill design parameters

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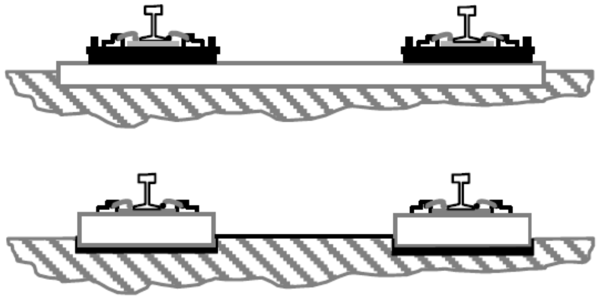
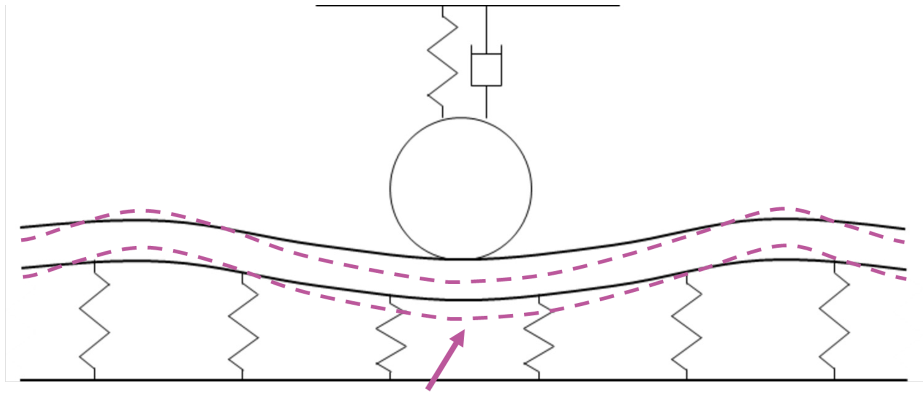
Scenarios considered

Two generic types of track were considered:

- "Standard" – a resilient slab track system with characteristics proven for operation of speeds up to 320km/h
- "Mitigating" – a resilient slab track system with characteristics proven for lower speeds



See Figure E.1 on page 222 of red book for more generic types of track



The 'softer' the track the more the rail will deflect under the load of the train

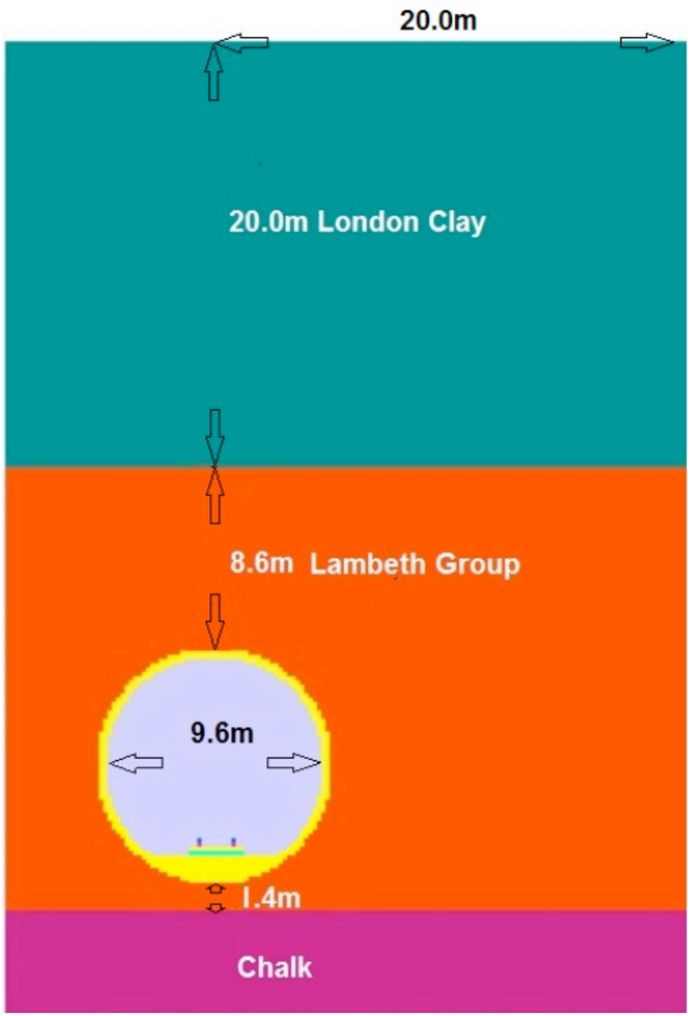
Scenarios considered

Two roughness spectra were considered (equivalent to roughness in previous slides):

- Conventional mainline ballast track
- High speed slab track

Speeds up to 320km/h investigated

5 locations representative of residential properties above Phase 1 tunnels



Results

Mainline ballast roughness (referred to as ES roughness in paper)

Table 7 – predicted ground-borne noise and vibration levels using FW models and ES roughness.

Track	Train speed	L_{pASmax} dB re 2×10^{-5} Pa / $eVDV_{g,first\text{-}floor}$ m/s$^{-1.75}$									
		Location 1		Location 2		Location 3		Location 4		Location 5	
Standard	'journey'	36	0.12	35	0.06	28	0.03	34	0.05	31	0.06
Mitigating		27	0.05	26	0.03	21	0.02	25	0.03	19	0.02
Standard	320km/h	36	0.11	33	0.05	27	0.03	33	0.04	31	0.04
Mitigating		28	0.06	26	0.04	21	0.02	26	0.03	22	0.02

1. Shading represents exceedance of IP E21 LOAEL
2. 'journey' time refers to the maximum anticipated speed of the train where 320km/h is the maximum design speed of the line

"Standard" track leads to some small exceedances of E21 criteria at some locations

"Mitigating" track would reduce noise and vibration below E21 criteria

Results

High speed slab roughness (referred to as HS roughness in paper)

Table 8 – predicted ground-borne noise and vibration levels using FW models and HS roughness.

Track	Train speed	L_{pASmax} dB re 2×10^{-5} Pa / $eVDV_{g,first\text{-}floor}$ m/s$^{-1.75}$									
		Location 1		Location 2		Location 3		Location 4		Location 5	
Standard	'journey'	32	0.07	29	0.03	23	0.02	28	0.02	28	0.03
Mitigating		23	0.03	21	0.01	16	0.01	19	0.01	13	0.01
Standard	320km/h	32	0.07	28	0.03	22	0.02	26	0.02	26	0.02
Mitigating		24	0.03	21	0.02	17	0.01	21	0.01	18	0.01

1. 'journey' time refers to the maximum anticipated speed of the train where 320km/h is the maximum design speed of the line

4 – 5 dB difference between results for ballast and HS slab roughness

Meaning "Standard" slab track achieves ES criteria with HS roughness

Indicates slab track system proven for speeds of 320km/h is capable of delivering E21 above London tunnels

Prediction uncertainty yet to be considered

CONCLUSIONS

Conclusions

- The potential impact of GBSV from trains at very high speed led us to a new understanding of the mechanisms that generate vibration
- The condition of the railway (roughness) is a key parameter for GBSV generation
- Characterising roughness in key wavelength ranges enabled us to predict vibration at 360km in the ES
- Roughness of HS slab track significantly lower than ballast track on conventional railways
- Initial modelling indicates that this roughness in combination with conventional HS track systems will deliver E21 objectives
- Work is ongoing to update detailed models for latest information, quantify prediction uncertainty & understand how maintenance effects rail roughness