Institution of MECHANICAL ENGINEERS
Improving the world through engineering

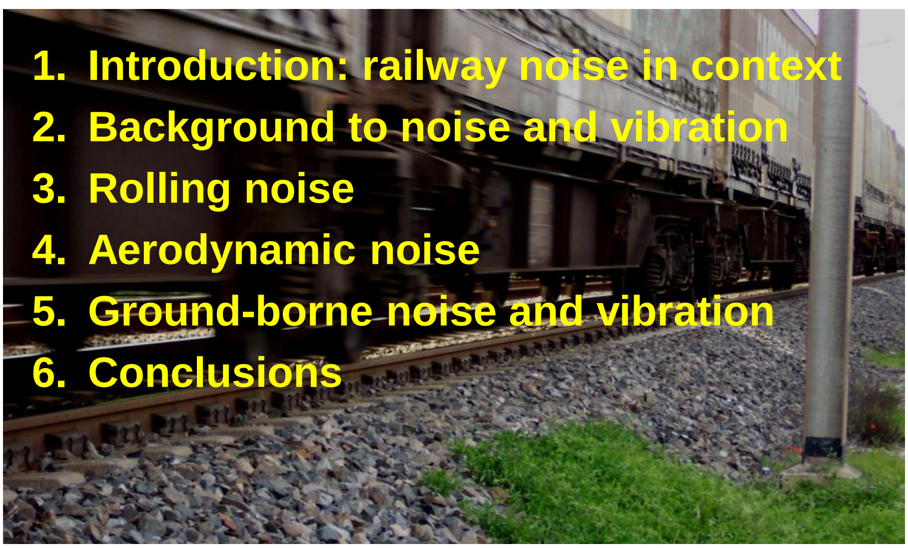
UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

Understanding and Controlling
Noise and Vibration from Railways

David Thompson

Institute of Sound and Vibration Research,
University of Southampton

Contents



Introduction: railway noise in context

- Expansion of railways in urban areas and high speed (‘low carbon’ sustainable transport option)
- Reduced journey times facilitate modal shift to rail (especially in range 400 to 800 km)

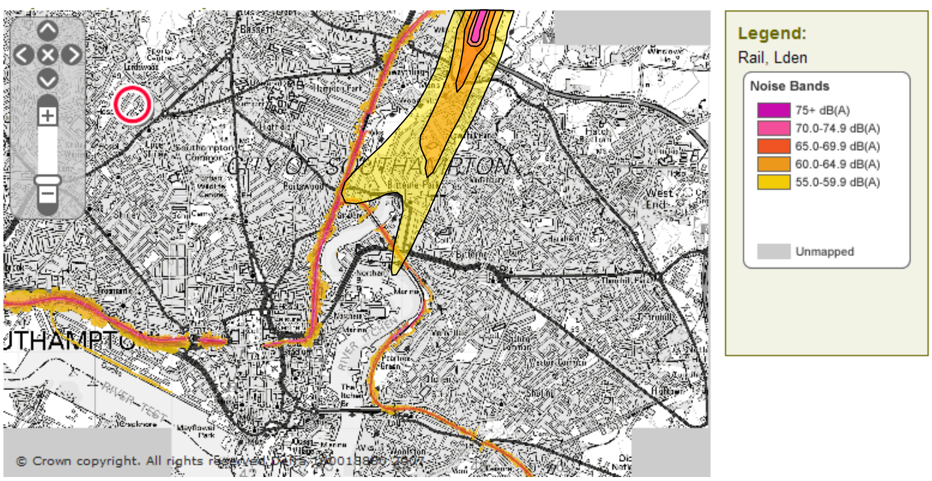
But…

- There is a perception that rail is noisy – objections to new railway projects usually dominated by noise.
- Railway noise is much more localised than road traffic, affects fewer people, but it is important to them.

3

Noise map example: Southampton

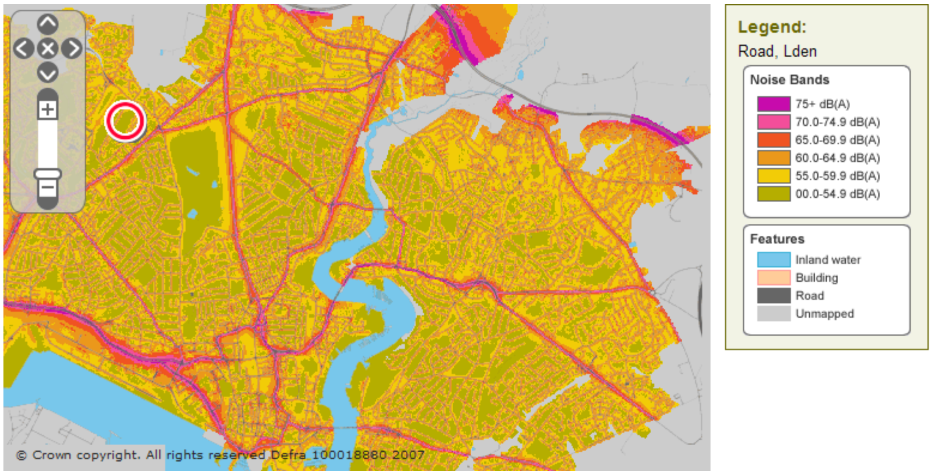
Rail Air



4

Noise map example: Southampton

Road



5

High speed 2

Railway noise – not a new problem

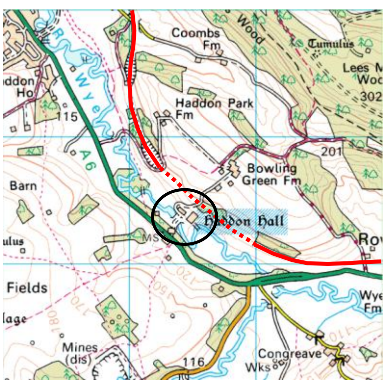
"Now judge, my friend, of my mortification, whilst I am sitting comfortably at breakfast with my family, enjoying the purity of the summer air, in a moment my dwelling … is filled with dense smoke, …. Nothing is heard but the clanking iron, the blasphemous song, or the appalling curses of the directors of these infernal machines"

…written in 1825, in a letter to the Leeds Intelligencer

quoted by W.R. Siddall,
Comparative Studies in Society and History 16, 2-23 (1974)

7

Haddon Hall, Derbyshire



In 1863, the Manchester, Buxton, Matlock and Midlands Junction Railway had to build a 1 km long cut-and-cover tunnel so that the railway was not visible from the Hall

8

Objections to railways

Most of the objections to the early railways were based on:

- Aesthetics ("spoiling the countryside")
- Economics ("ruining my livelihood")

Today, **noise** is usually the most common reason given for objecting to railway developments.

- Easier to complain about than aesthetics?
- Genuine annoyance with noise?

9

EU noise limits for vehicles

- Noise limits for road vehicles and aircraft in force since early 1970s.
  - Noise from aircraft has been reduced by 20-30 dB since 1970.
  - EU limits for cars reduced by 8 dB between 1973 and 1996 – although little effect on noise in normal use.
- Rail vehicle noise emission limits introduced since 2002 within 'Technical Specifications for Interoperability' (TSI).
  - Delay due to difficulty in separating vehicle from track

10

Noise limits in Europe

- Technical Specifications for Interoperability are a wider framework for stimulating international competition.
  - Noise limits (and test method) introduced for High Speed (2002) and Conventional Rail vehicles (2004).
  - Only for new vehicles (typical lifetime 30-40 years).
  - Accounts mainly for vehicle contribution to noise.
- Environmental Noise Directive (END) requiring noise maps and Action Plans.

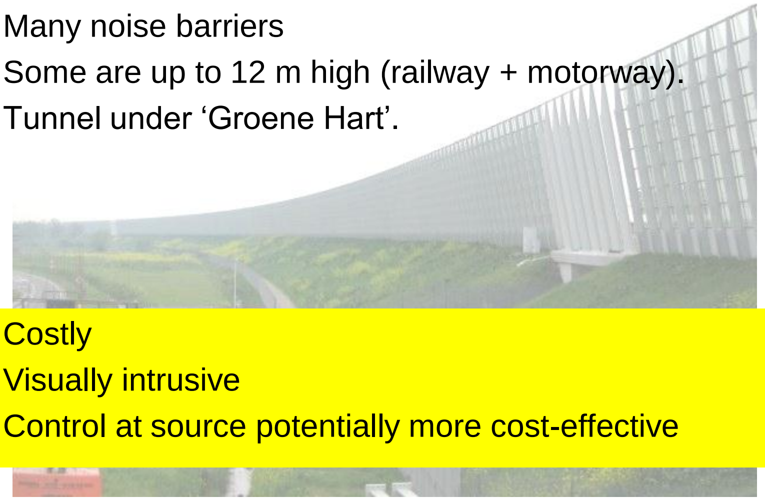
Noise barriers?

Noise barriers – Dutch high speed line

Noise barriers

High speed line in the Netherlands

- Many noise barriers
- Some are up to 12 m high (railway + motorway).
- Tunnel under 'Groene Hart'.



- Costly
- Visually intrusive
- Control at source potentially more cost-effective

13

2. Background to noise and vibration

14

Sound and Noise

Sound - is what we hear: "audible air vibrations".

- human ear responds to sound in the range 20 Hz to 20000 Hz (= cycles/s)

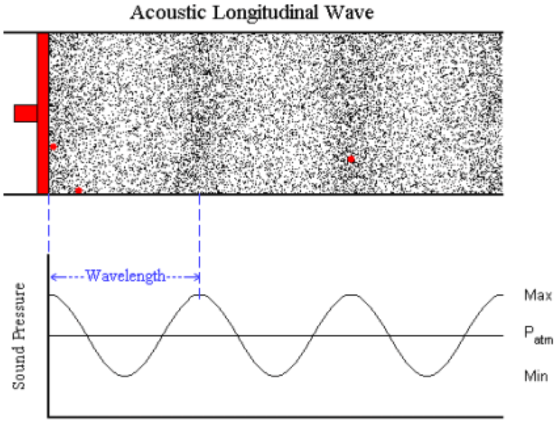
Noise - is unwanted sound, disturbing, annoying.

- everyone responds differently to sounds.
- want measures of sound that reflect its acceptability to an 'average' person

15

Sound waves

- Waves transfer *energy* without transferring matter.
- Fluid is compressed/expanded as 'particles' move.
- Caused by vibrating objects or air motion.

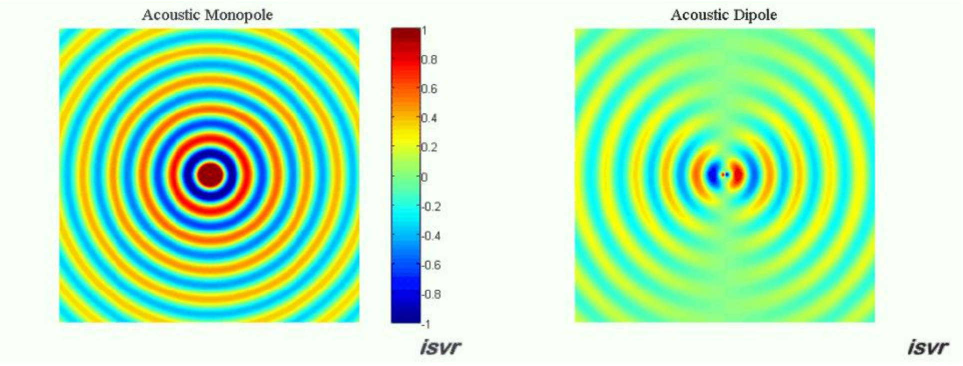


isvr

16

Source efficiency

- Different sources radiate sound with different efficiency.



Typically only about one millionth of energy is converted into sound

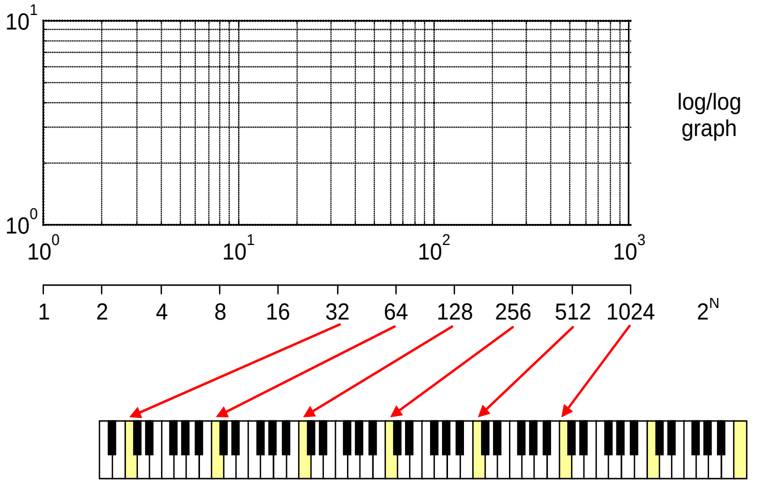
The decibel scale

- A doubling in pressure amplitude corresponds to a fixed change in 'loudness'. Logarithmic scale:

$$L_p = 10\log_{10}\left(\frac{\overline{p^2}}{p_{ref}^{\ 2}}\right)$$

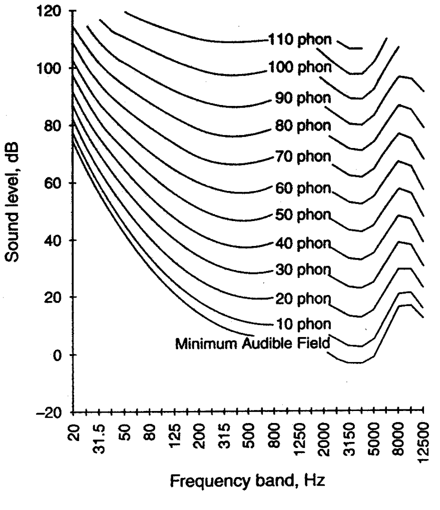
- The large range of pressure amplitudes corresponds to a much smaller range of dB values:
  - threshold of hearing at 1000 Hz: 2×10^{-5} Pa – **0 dB**
  - rustling leaves: 2×10^{-4} Pa – **20 dB**
  - conversation: 0.01 Pa – **54 dB**
  - stationary loco at 7.5 m (typical): 0.1 Pa – **74 dB**
  - typical noise at 7.5 m from 250 km/h train: 1 Pa – **94 dB**
  - threshold of feeling: 20 Pa – **120 dB**
  - threshold of pain: 200 Pa – **140 dB**

Logarithmic scales: octaves



Loudness

- Sound pressure is a physical quantity.
- Loudness is a subjective quantity which depends on frequency and amplitude.
- Equal loudness contours for normal hearing are standardized.
- 'A-weighting' is roughly the inverse of the 40 phon curve (to reflect human response)



Sources of railway noise

- Rolling noise dominant at most speeds.
- Curve squeal is localised but levels can be 20 to 30 dB greater than rolling noise.
- Aerodynamic noise dominant > 300 km/h.
- Traction noise, especially fans and diesel engines, important on locomotives and multiple units at low speeds.
- Bridges give typically 10 dB more noise, again localised.
- Ground-borne vibration / noise can be important e.g. for tunnels or where there are noise barriers.

21

Sources of railway noise

- Rolling noise dominant at most speeds.
- Curve squeal is localised but levels can be 20 to 30 dB greater than rolling noise.
- Aerodynamic noise dominant > 300 km/h.
- Traction noise, especially fans and diesel engines, important on locomotives and multiple units at low speeds.
- Bridges give typically 10 dB more noise, again localised.
- Ground-borne vibration / noise can be important e.g. for tunnels or where there are noise barriers.

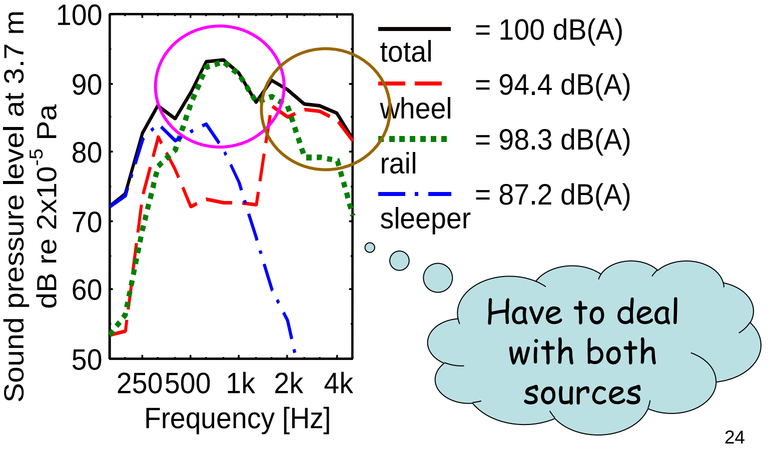
22

3. Rolling noise

23

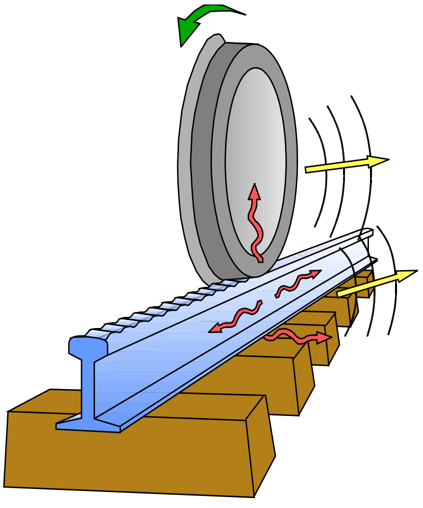
Contributions to rolling noise

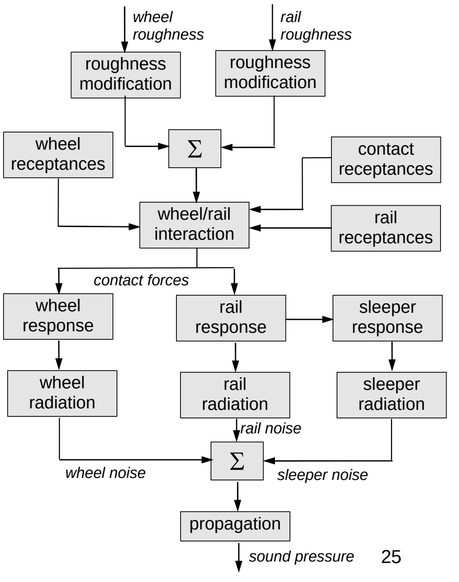
- Example of wheel, rail and sleeper contributions to radiated sound.



24

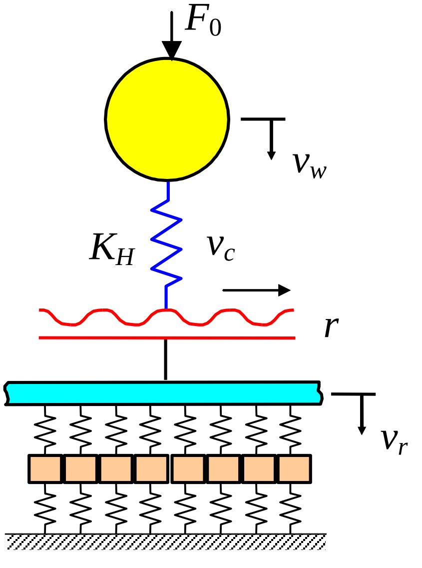
TWINS: Track-Wheel Interaction Noise Software





25

Wheel/rail interaction



$$f = \frac{v}{\lambda}$$

26

Roughness wavelengths (mm)

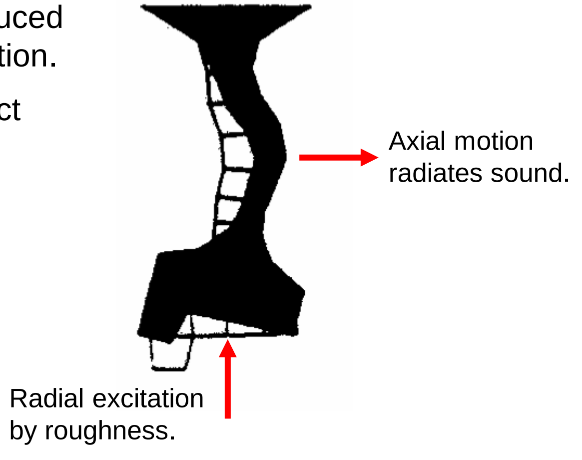
$$f = \frac{v}{\lambda}$$

Speed (km/h)	40	80	160	320
50 Hz	230	450	900	1800
100 Hz	110	230	450	900
250 Hz	45	90	180	360
500 Hz	23	45	90	180
1000 Hz	11	23	45	90
2500 Hz	4.5	9	18	36
5000 Hz	2.3	4.5	9	18

- λ of 5 to 500 mm important
- Very small amplitudes: 0.1 to 50 μm

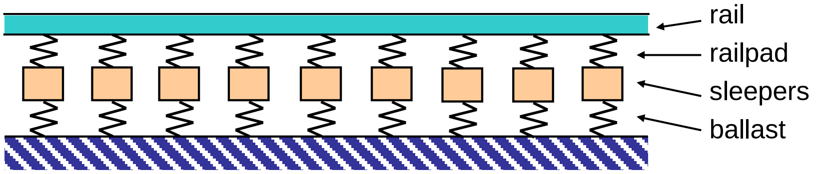
Wheel radiation

- Wheel noise produced by modes of vibration.
- Damped by contact with rail.



Track vibration

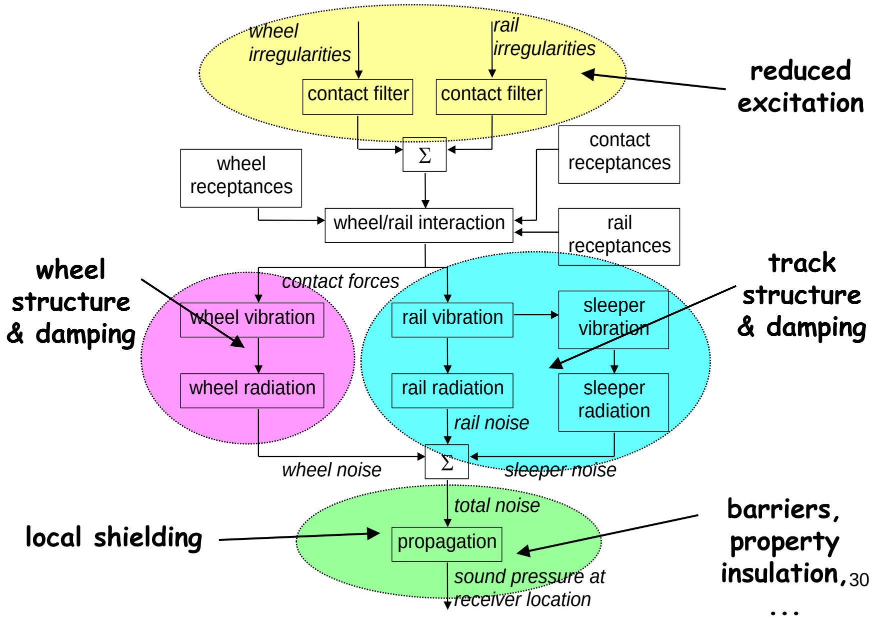
- wheel
  - finite system
  - modal behaviour
- track
  - infinite system
  - wave propagation



- decay rate with distance important.
- low frequencies: sleepers well coupled to rail, larger area so dominate sound radiation

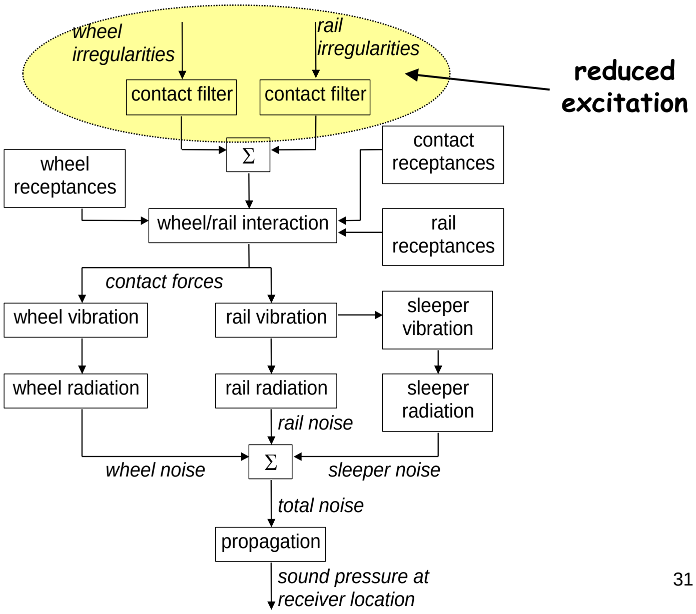
29

Controlling rolling noise



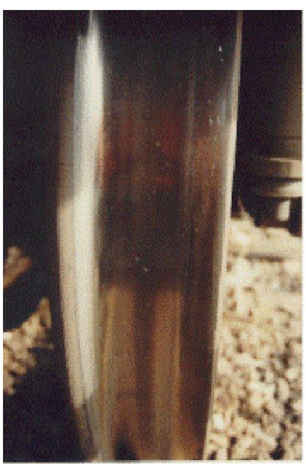
30

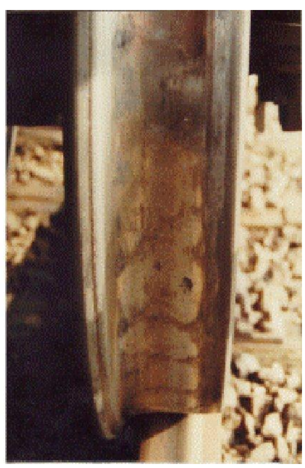
Reduced excitation



31

Effect of braking system on roughness





- Disc brakes.
- Cast-iron brake blocks.

Development of K and LL blocks

- Disc-braked vehicles are about 10 dB quieter than traditional tread-braked vehicles.
- Freight vehicles in Europe traditionally have cast-iron blocks (old rules for international interoperability)
- Various composite blocks also leave wheel smooth.
- UIC initiative to implement them
  - K blocks: composite blocks, several available. But need different brake cylinders, different wheels.
  - LL blocks: intended for simple retrofit. Problems with homologation.

33

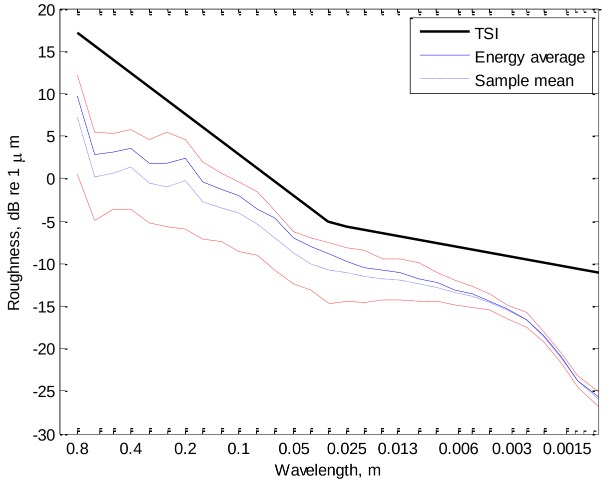
Wheel roughness measurement

- Triceratops

34

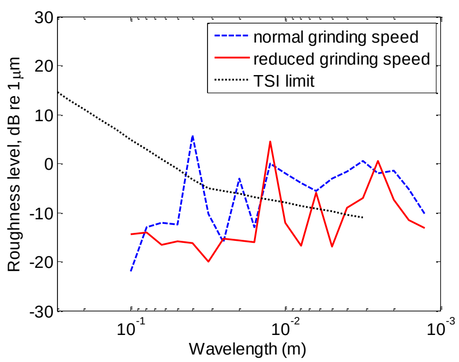
Disc braked wheel roughness

- Roughness of 64 disc braked wheels (UK EMUs)



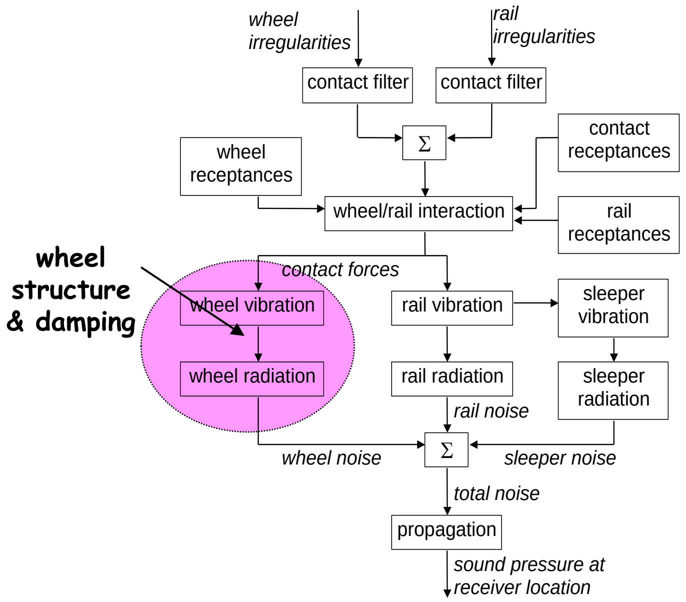
Rail grinding

- To restore transverse profiles and remove surface cracks
- Can also reduce noise
- Grinding can introduce periodic roughness ~ 2 cm
- Noisy operation often carried out at night!



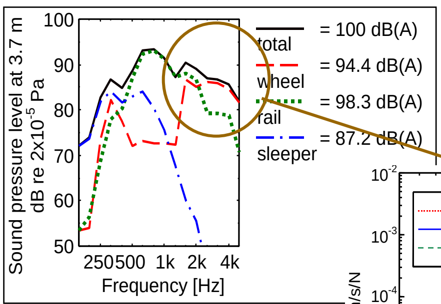
- Rail roughness after grinding (data from SNCF)

Wheel vibration and noise

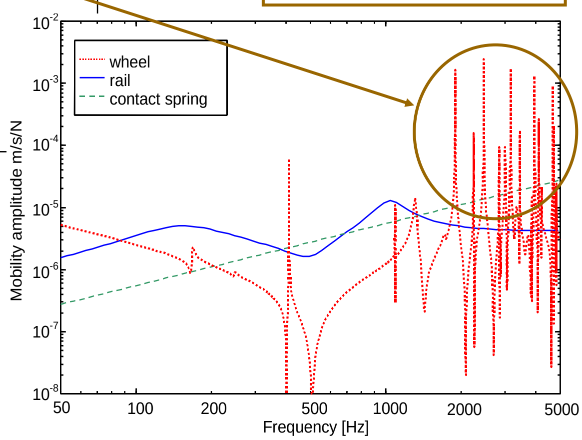


37

Reducing wheel noise

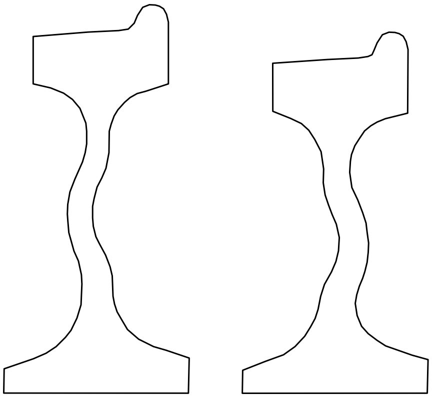


- Damping
- Shift resonances
- Reduce coupling



Wheel shape

- Tread braking requires curved web
- Retrofit implies no change in size
  – ‘Optimise without changing anything’?

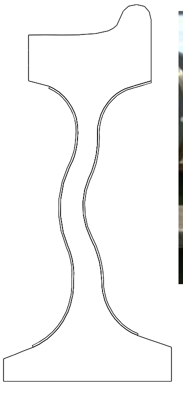


- Silent Freight wheel design ~ 3 dB quieter than reference.

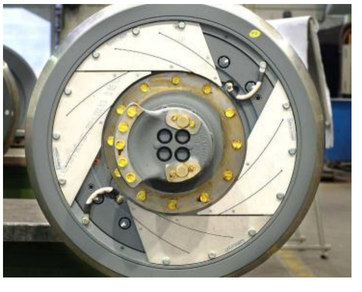
Wheel damping

- Need to add enough damping to overcome effective damping from wheel/rail interaction. Spectacular results in the lab may be disappointing in the field.

Tuned resonant devices

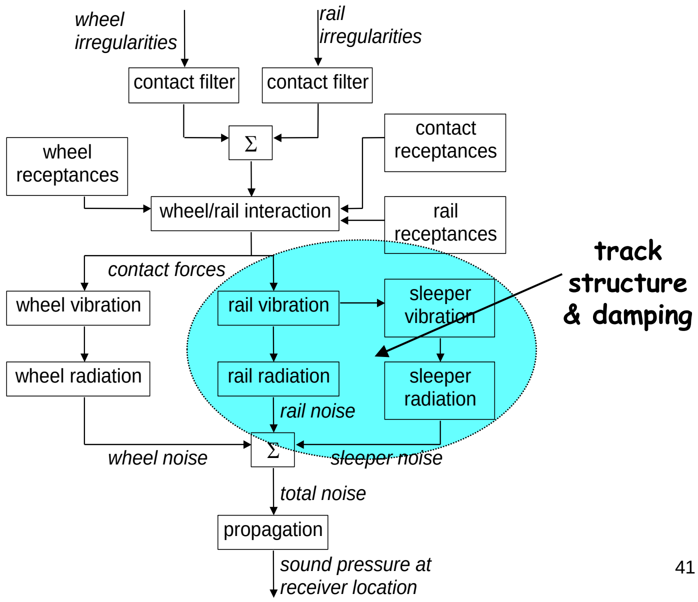


Constrained layer damping



Shark-fin damper

Track vibration and noise



41

"Slab track is noisy"

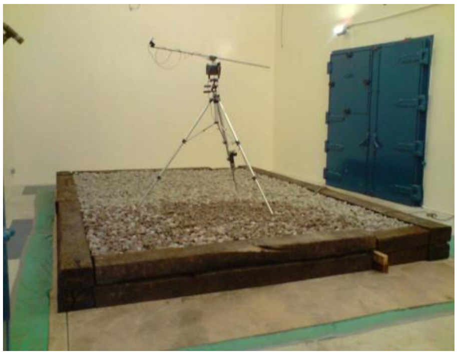
- Slab track is used for high speed lines in Germany and Netherlands
- Slab track has a reputation for being noisy

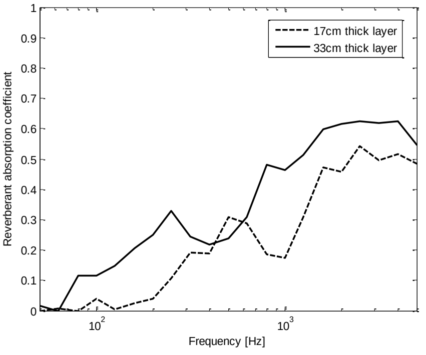
- Dutch high speed line has recent high profile noise problems with interim domestic trains (cast-iron brake blocks)
- Thalys noisier on slab track than on ballasted track

42

Effect of ballast absorption

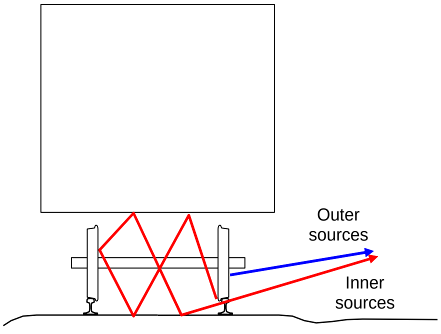
- Ballast is an absorptive medium, not present on slab track – absorption coefficient rises to 0.6 at high frequencies.

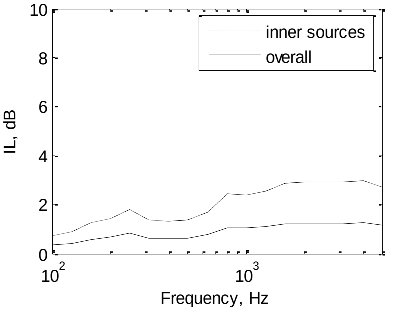




Effect of ballast absorption

- But this only affects noise sources *inside* the bogie region (and noise inside train).
- Radiated noise is reduced by about 1 dB.
- So missing ballast absorption is not the main reason slab track is noisier.

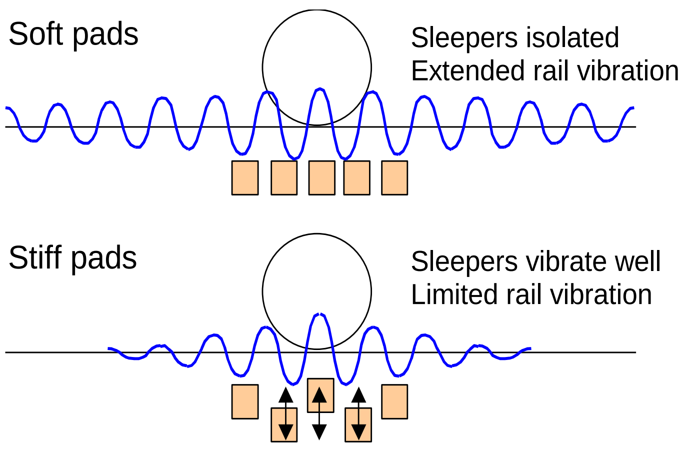




- Track decay rates more important.

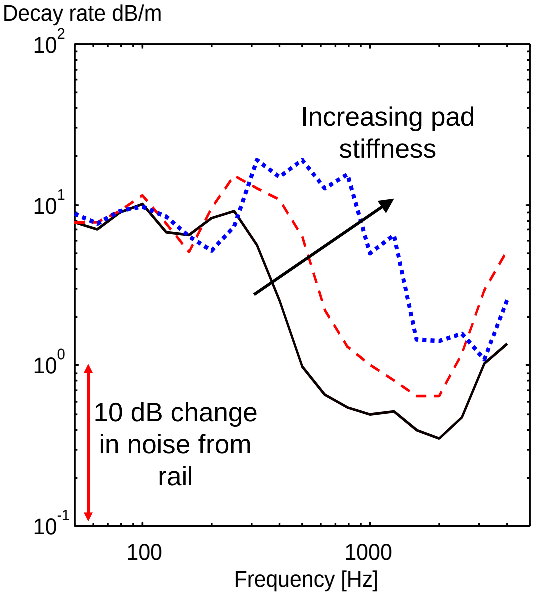
Track vibration: effect of pad stiffness

- Rail pads have a large influence on the noise.



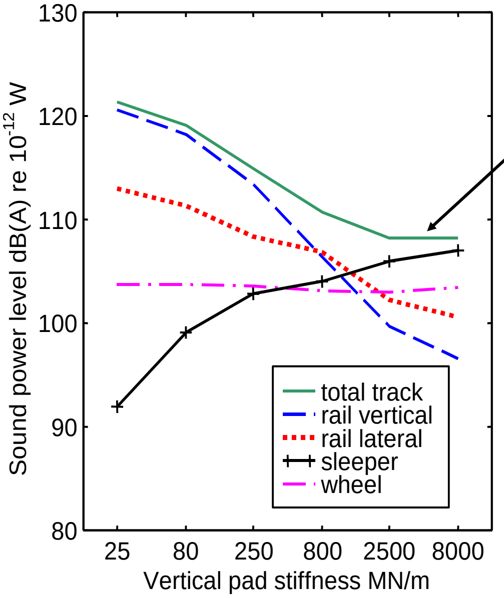
45

Measured track decay rates



46

Dependence of rolling noise on pad stiffness



Optimum pad stiffness: but this is too stiff

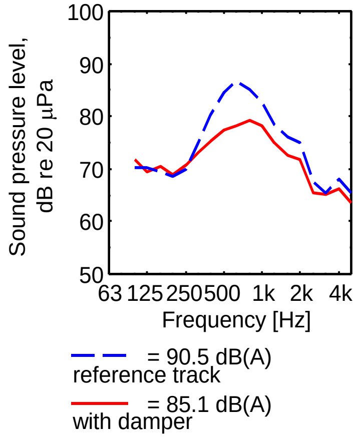
These predictions probably over-state the effect of soft pads (effects of non-linearities are important)

Ideally we want soft pads to protect sleepers with increased decay rates to reduce noise

47

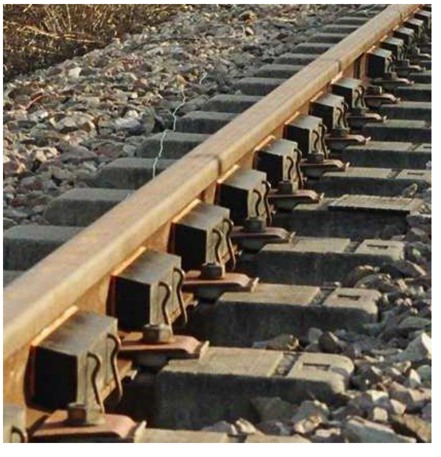
Reducing rolling noise: rail dampers

Measured at 3m for low noise wheels



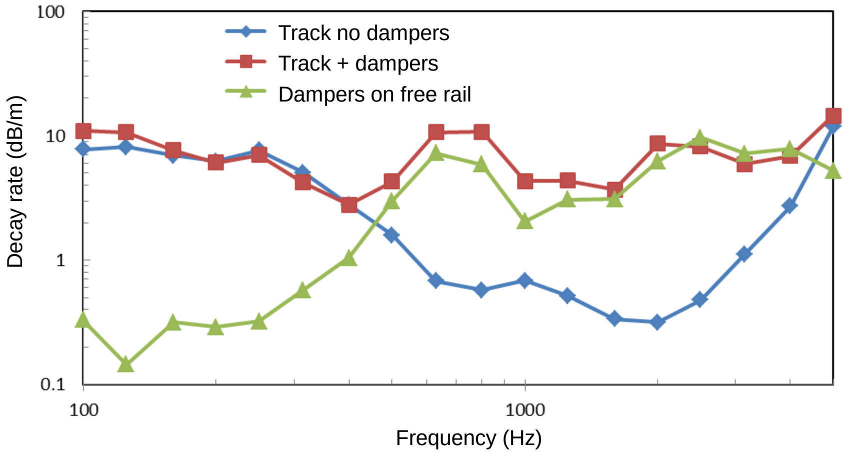
Measured reduction in overall noise: 5.4 dB(A)

Developed in EU project Silent Track with Tata Steel



Noise reduction depends on initial situation

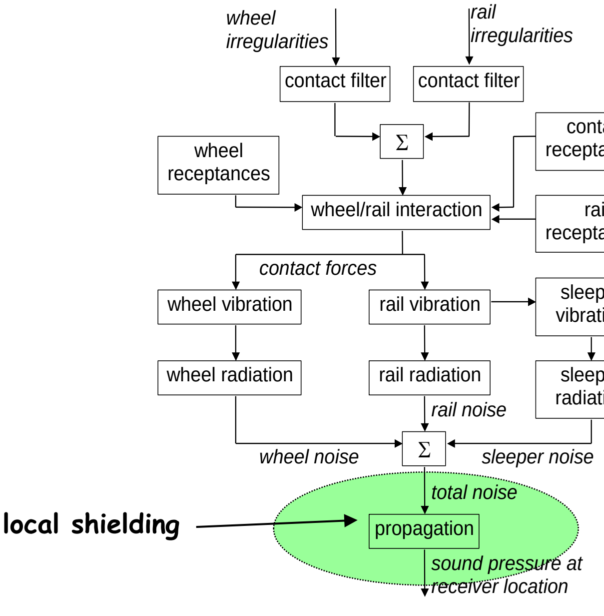
Effect of rail damper on vertical decay rates



Method developed in Stardamp project

49

Shielding



50

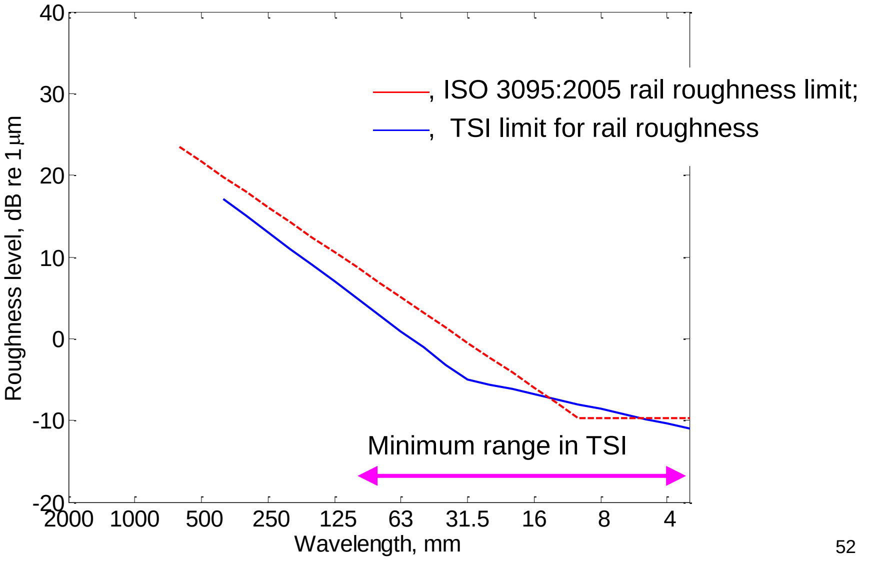
Measurements and regulations

- ISO 3095:2005
- TSI (Technical Specifications for Interoperability)
- Principle: to measure noise from vehicles for emission limits, need to minimise contribution from the track.
- Not representative of normal operation.

- Upper bound on **rail roughness**.
  – So wheel roughness dominates?
  – Not intended as limits for normal operation.
  – Different for TSI and ISO
- Lower bound on **track decay rate** (only in TSI).
  – So track radiation minimised.

51

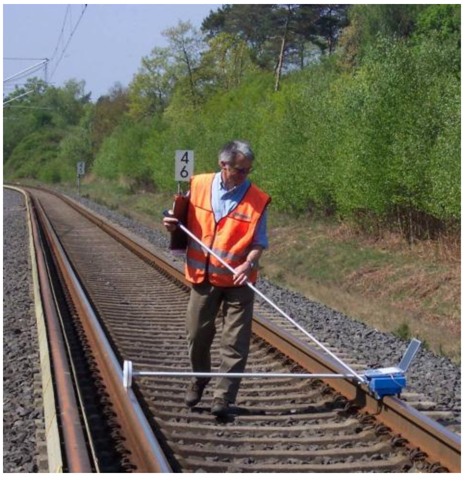
Roughness limits (upper bounds)



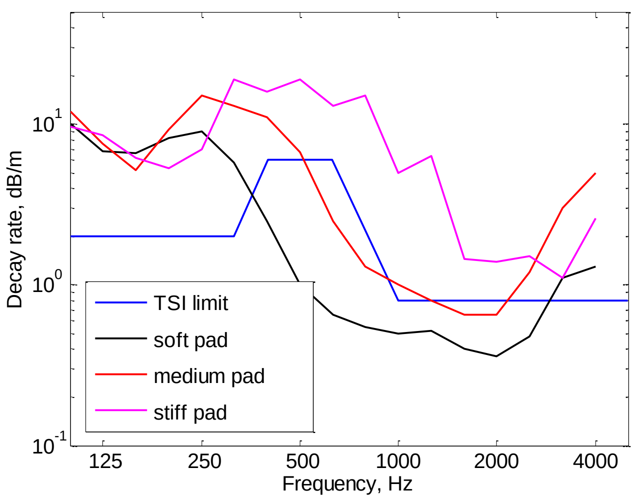
52

Roughness measurement

- Straight edge systems (1.2 m) are limited to 100 mm 1/3 octave band. Trolley systems not limited.



Decay rate limits (vertical)



- Stiff pads are required to meet TSI limits

54

Towards virtual testing

TSI tests are expensive. Can they be (partly) replaced by calculations? For example:

- A train type is certified comprising a three car multiple unit with two powered bogies. What about a new design variant with four cars and three powered bogies?
- A train is certified with one type of diesel engine. What about a variant with a different diesel engine?
- A train type is certified on the basis of one wheel design. What if a new wheel design is to be introduced?
- A test site does not comply with the strict requirements of the TSI. Can we still use results measured here?

Towards virtual testing

- Being addressed in the EU project ACOUTRAIN (2011-14).
- 15 partners.
- Led by UNIFE with technical coordination by SNCF and Bombardier.

ACOUTRAIN

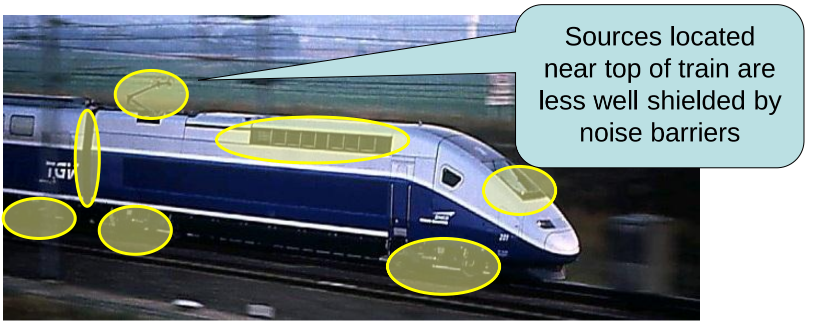
- Role for theoretical models in complementing testing to improve efficiency of approval process (without reducing accuracy).

4. Aerodynamic noise

Aerodynamic noise

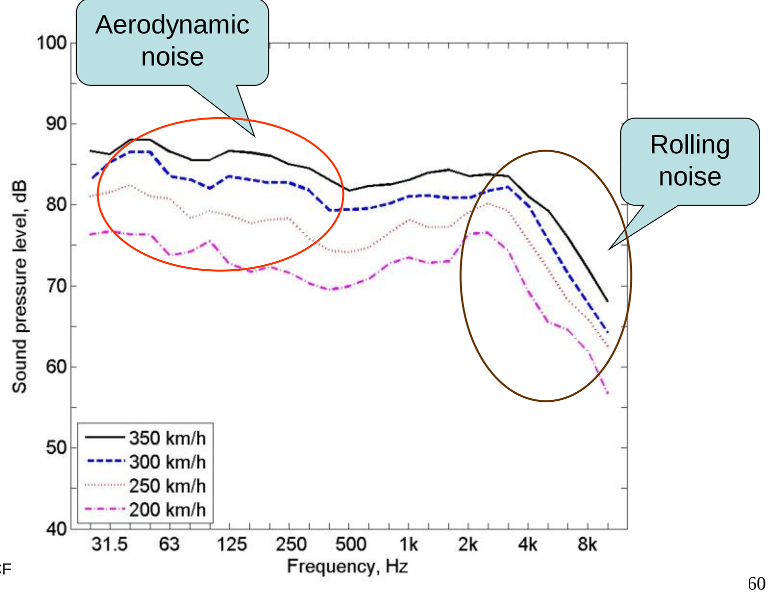
- Increases more rapidly than mechanical (rolling) noise
- Typical speed dependence of $60\ \log_{10}V$ or more
- Important at high speeds, typically above 300 km/h
- Important for interior noise as well as exterior noise
- Sound generated within the acoustic medium increases complexity of analysis and measurement.

Aerodynamic sources on a train



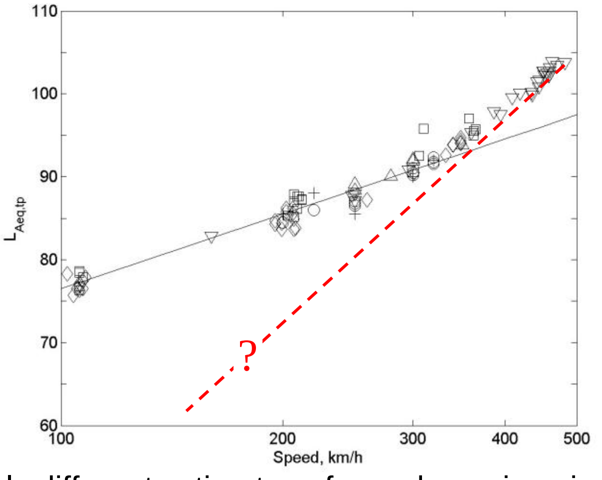
- Bogie regions,
- Pantograph, pantograph recess, roof-mounted equipment
- Nose of the train
- Inter-coach gaps (cavities)
- Ventilation grilles
- Protuberances (door handles, steps, wipers, …)
- Resonant cavities
- Turbulent boundary layer

Typical measured spectra



Data from SNCF

Speed dependence of aerodynamic noise?



- Widely different estimates of aerodynamic noise give similar estimates of total noise.
- *Speed-dependence not well defined.*

61

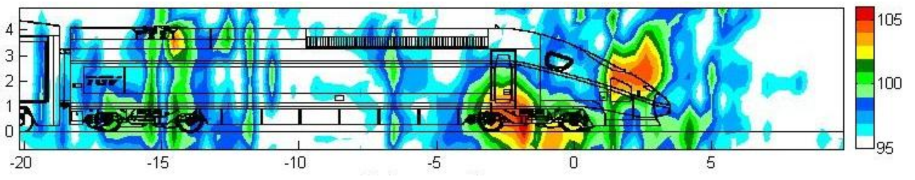
Microphone arrays

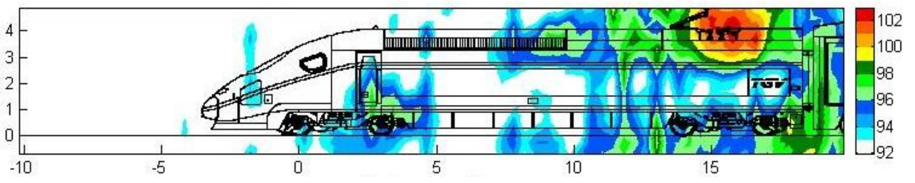
- Allow localisation of noise sources, but…
- Spatial resolution is limited especially at low frequencies
- Cannot distinguish e.g. rolling noise and aerodynamic noise from bogie region

62

Microphone arrays – examples

- TGV Duplex, 350 km/h, 500 Hz band

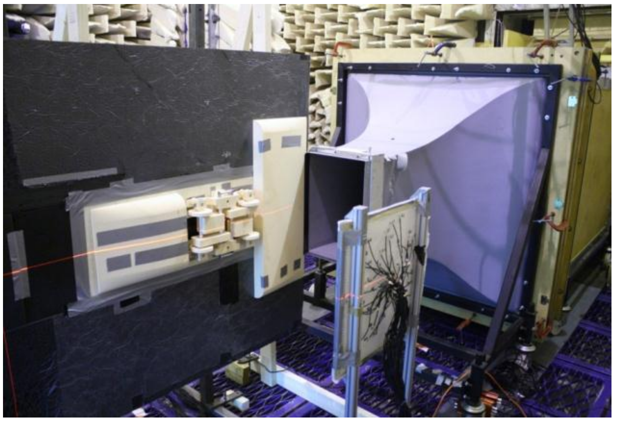




Data from SNCF

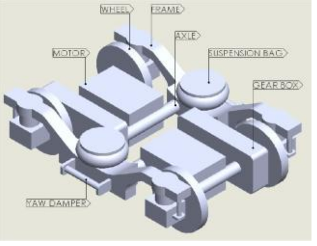
Low noise wind tunnel

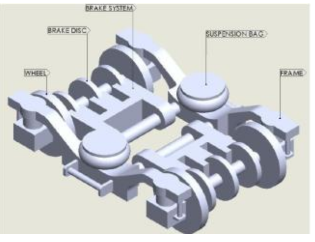
- Low noise ‘wind tunnel’ in ISVR anechoic chamber
- Tests of 1:10 scale bogies

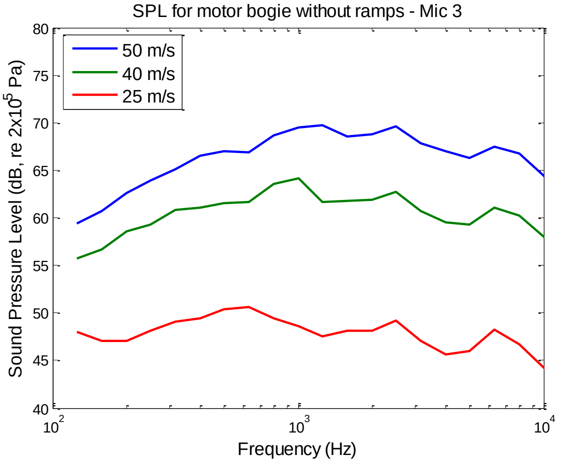


1:10 scale bogie aerodynamic noise

- Effect of speed ('motor' bogie without ramps)



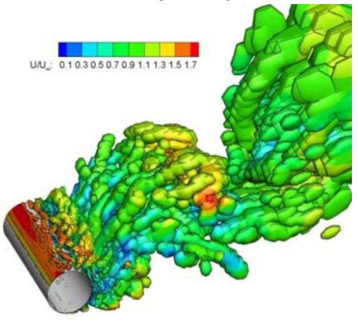


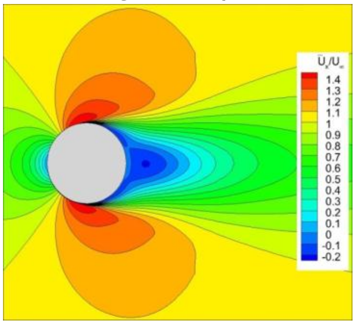


65

Numerical techniques

- CFD – Computational Fluid Dynamics
  – Solves fluid dynamics problem, not in general acoustics problem
- CAA – Computational Aeroacoustics – several methods, e.g. use acoustic analogy to post-process CFD results.
- Even simple cylinder case takes large computation times





66

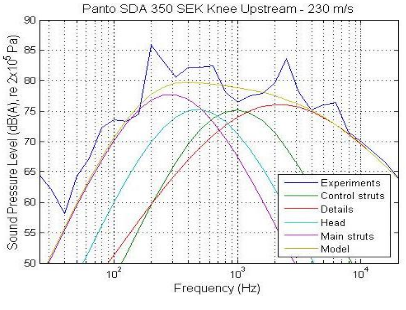
Component-based approach

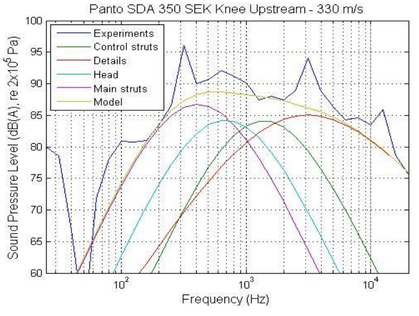
- Based on idealised result for noise from flow over a cylinder
- Developed and validated for aircraft landing gear

67

Pantograph noise

- Model based on spectra of cylinders.
- Data from DB tests made in Japan.
- Work continuing in a PhD





68

Summary (aerodynamic noise)

- Aerodynamic noise is due to a number of sources, each with different speed dependence.
- Estimates of overall speed dependence vary from $50 \log_{10} V$ up to $96 \log_{10} V$
- Corresponding 'transition speeds' (where aerodynamic noise equals rolling noise) vary between 300 and 430 km/h.
- Component-based approach promising. Measurements in low-noise wind tunnel to give source terms.
- CFD/CAA to build up more source data.

69

5. Ground-borne noise and vibration

70

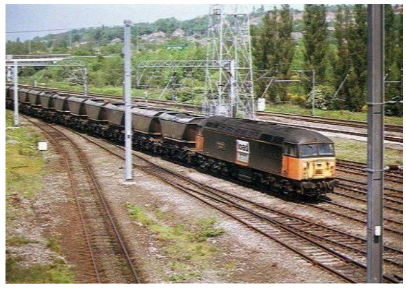
Ground-borne vibration and noise

Feelable vibration

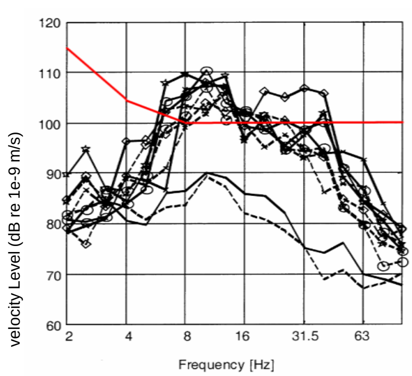
- 2 to 80 Hz
- Mainly an issue for heavy freight trains on surface railways
- Causes annoyance but very unlikely to cause building damage

Ground-borne noise

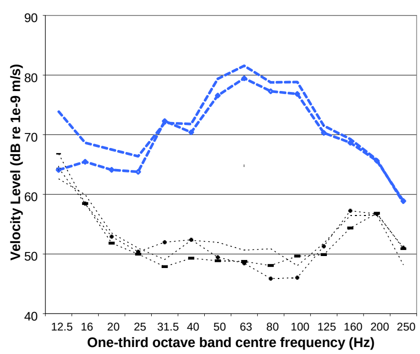
- Rumbling noise 20 to 250 Hz
- Main issue for underground lines (metros and mainline) in cities
- May also be significant for surface railways with noise barriers
- 56,000 homes in London with ground-borne noise over 40 dB(A). Some over 60 dB.



Example vibration spectra



Vibration in a house 50 m from a surface railway



Vibration in an office building close to a bored tunnel 15 m deep

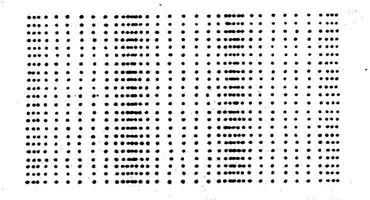
- Lower levels, higher frequency content

72

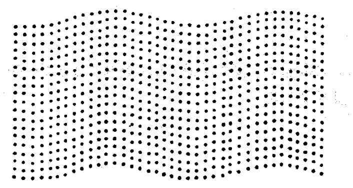
Soil properties

Soil properties can be defined in terms of fundamental wave speeds

Longitudinal waves (P-waves)



Shear waves (S-waves)

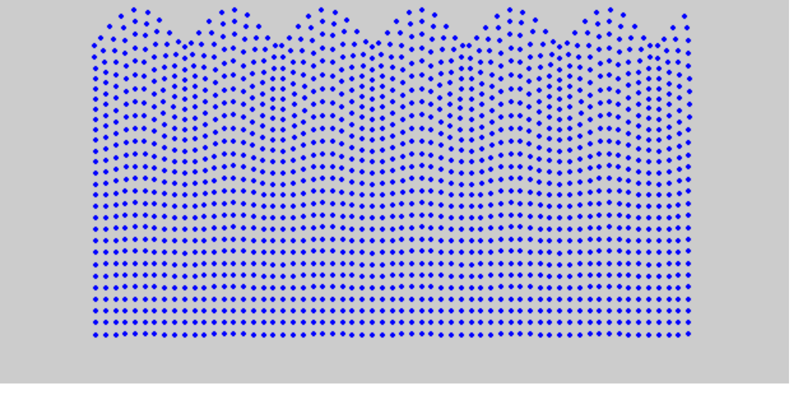


Soil properties vary considerably even for a given type

73

Rayleigh waves in a half-space

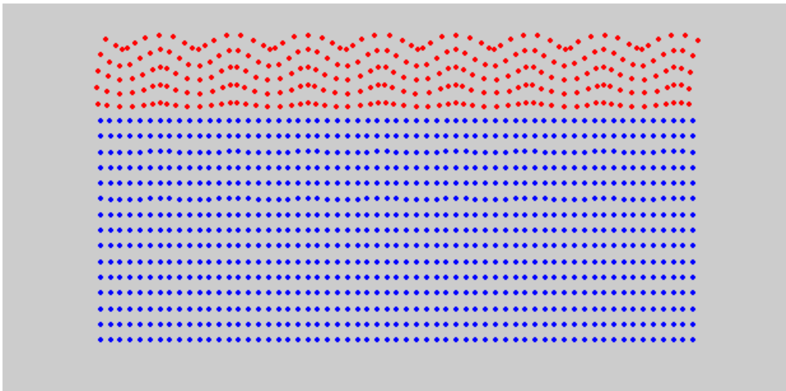
In the presence of a free surface, Rayleigh waves are formed



74

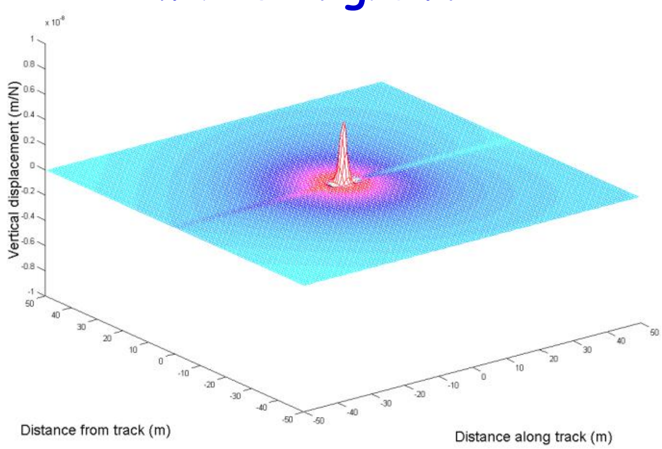
Surface wave in a layer + half-space

Ground usually consists of layers with different properties

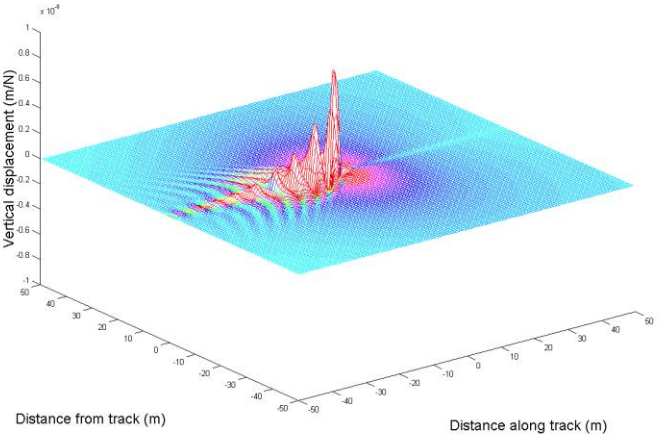


Several different surface-waves can propagate in layered soil

Response to load moving slower than waves in ground



Response to load moving faster than waves in ground



Moving axle load causes increased vibration above the wave speed. But want to prevent large track movements anyway so vibration is not going to be the problem.

77

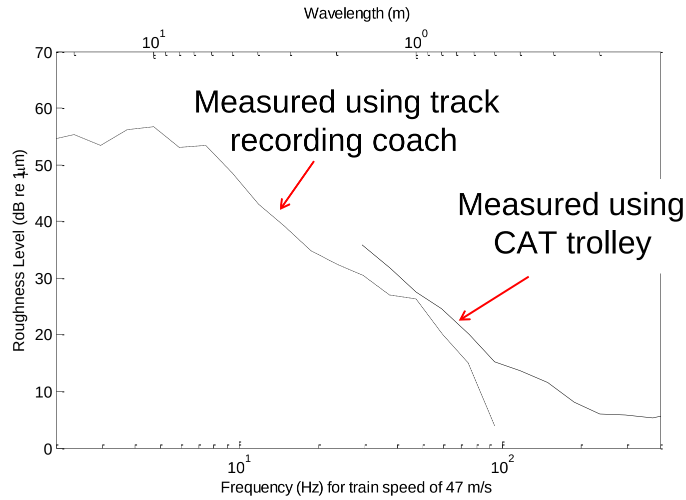
Dynamic excitation: roughness wavelengths

	40 km/h	80 km/h	160 km/h	300 km/h
4 Hz	2.8	5.6	11	21
8 Hz	1.4	2.8	5.6	10
16 Hz	0.69	1.4	2.8	5.2
31.5 Hz	0.35	0.70	1.4	2.6
63 Hz	0.18	0.35	0.71	1.3
125 Hz	0.089	0.18	0.36	0.67
250 Hz	0.044	0.089	0.18	0.33

	range of ‘acoustic’ roughness		range of track recording car data

78

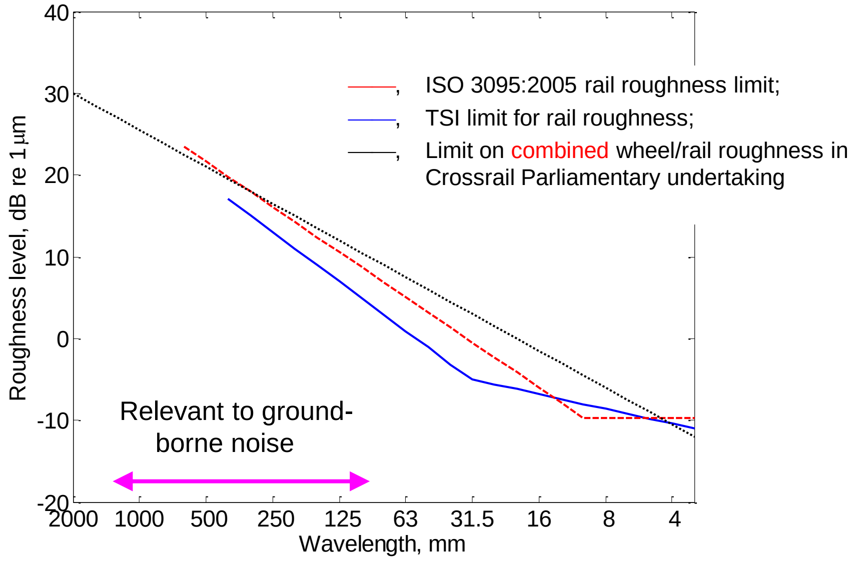
Dynamic excitation: roughness spectrum



Crossrail

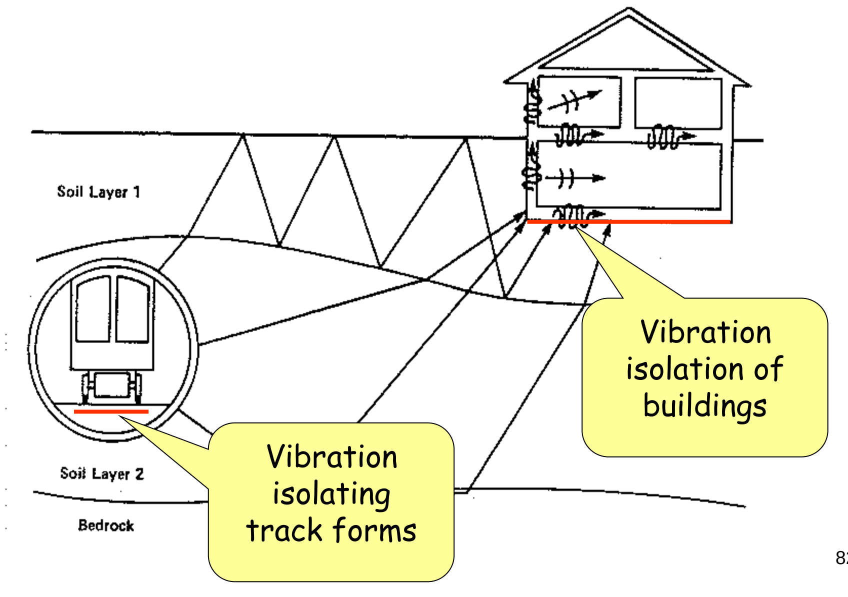
- Parliamentary undertaking to maintain total roughness below a certain threshold.

Roughness limits – Crossrail



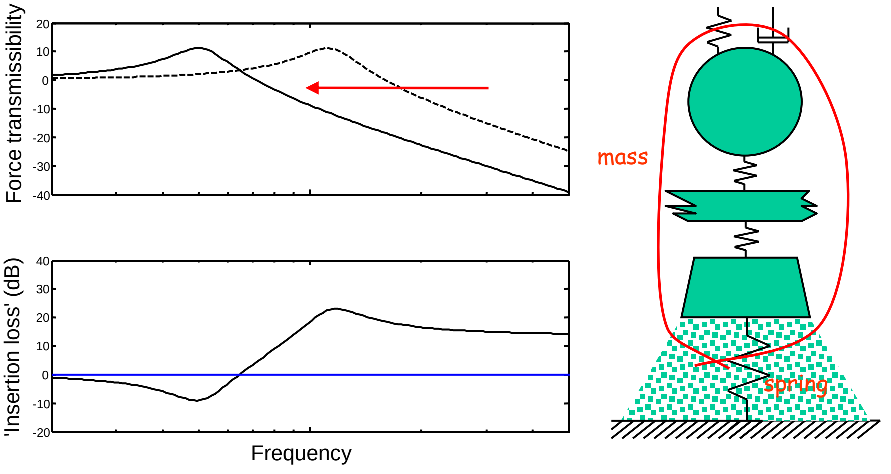
81

Vibration isolation



82

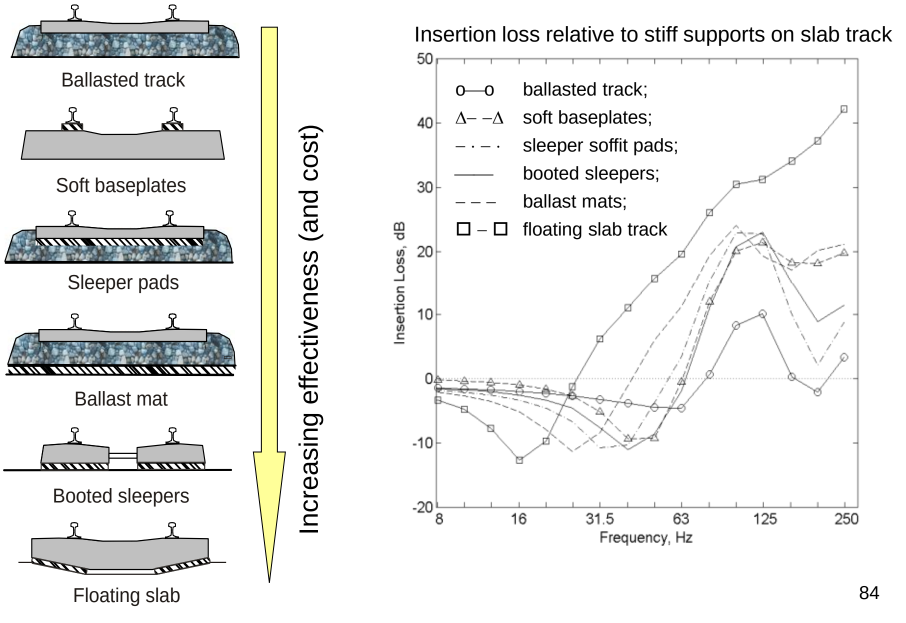
Vibration isolation effect of track



Need more complicated models, but the principle is the same: to reduce the natural frequency by increasing the mass and reducing the stiffness.

83

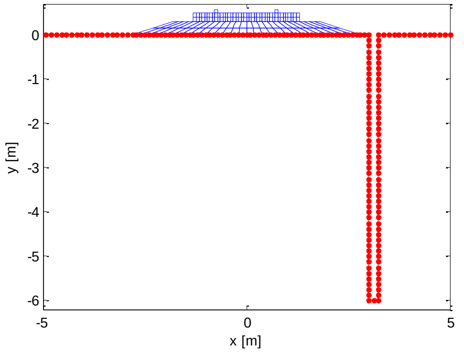
Different vibration isolating tracks



84

Mitigation of feelable vibration – RIVAS project

- Lower frequency means isolation not feasible solution
- EU project studying mitigation for ground vibration and ground-borne noise
  - Trenches, barriers, soil stiffening
  - Track
  - Vehicle
  - Maintenance



Summary – ground-borne noise and vibration

- For trains in tunnels usually ground-borne noise is more important than feelable vibration
- Prediction methods have large uncertainty
  - Variations in ground properties
  - Uncertainty in geometry
  - Complexity of models
- They are more useful for studying parametric dependence than absolute prediction
- Vibration isolation at the track or building are possible.
- For feelable vibration at low frequencies mitigation is much more difficult.

6. Conclusions

- Theoretical models provide the key to understanding and controlling noise and vibration.
- Models for rolling noise are now well established and validated (TWINS) and can be used in the design of quieter wheels and tracks.
- Aerodynamic noise important above ~300 km/h.
- Various tools are available to study aerodynamic noise (CFD, microphone arrays) but each has its problems. Current work based on a simpler component-based model.
- Ground-borne noise: isolation at the track or building is effective. But not feasible for feelable vibration.

87