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LÄRM FORSCHUNG EISEN BAHN
EXCHANGE of EXPERTS 2|'22

Novel railpad design using a multi-level digital twin method

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COMATEC, HEIG-VD/HES-SO, Switzerland

Novel rail pad design methodology

"Novel Rail Pad" project funded by Swiss Federal Office for Environment (FOEN)

***Optimized rail pads to*:**

1. Reduce the sound emission of the tracks.
2. Improve ballast protection, reduce maintenance.

***Modelling*:**

To achieve this goal several models have been developed to predict the effect of the rail pad on:

- the rail, sleeper & ballast vibrations level (FRF & TDR).
- the rail-borne sound emissions.
- the ballast loading & degradation (relative settlement rate).

Optimization:

- Single/multi material pad with tailored materials properties & complex geometry
- Optimal frequency dependent pad stiffness and damping:
  - Soft at low frequencies for ballast protection
  - Stiff & high damping at high frequencies to reduce noise

=> need to use <u>detailed 3D finite elements models</u> and <u>3D constitutive models</u> for the pads material to account for shear / confinement effects.

Photo by Jo L'Helvète on Unsplash

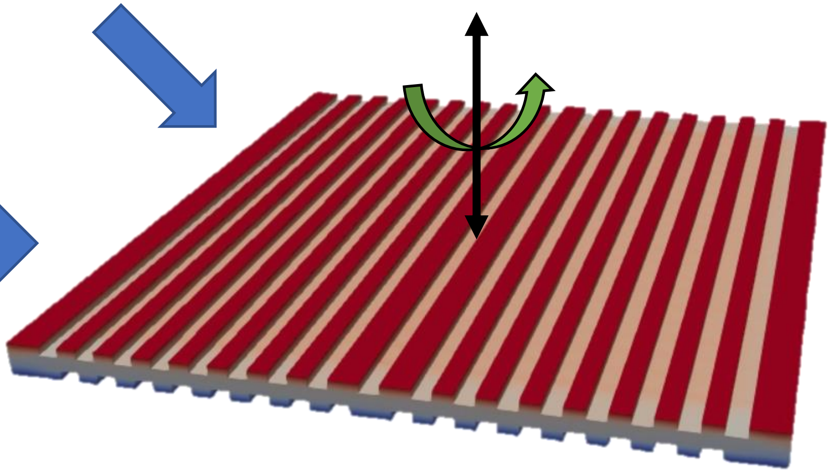
Digital twin approach “level 1”:

Quick design /evaluation of the pad dynamic response for optimum track performance

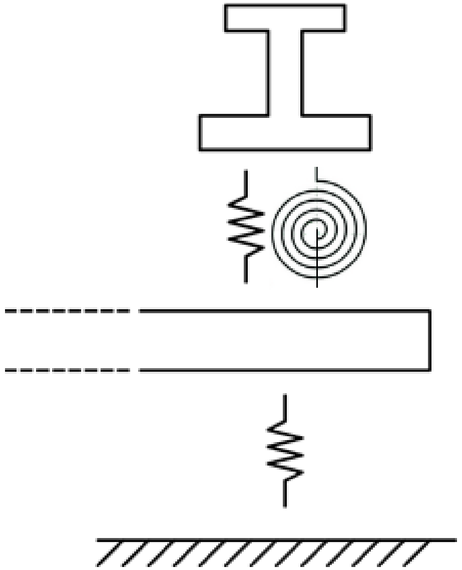
Experimental validation

DMA material properties
E, tan(δ) = f(ω,T)

3D geometry of the pad
(FE mesh)



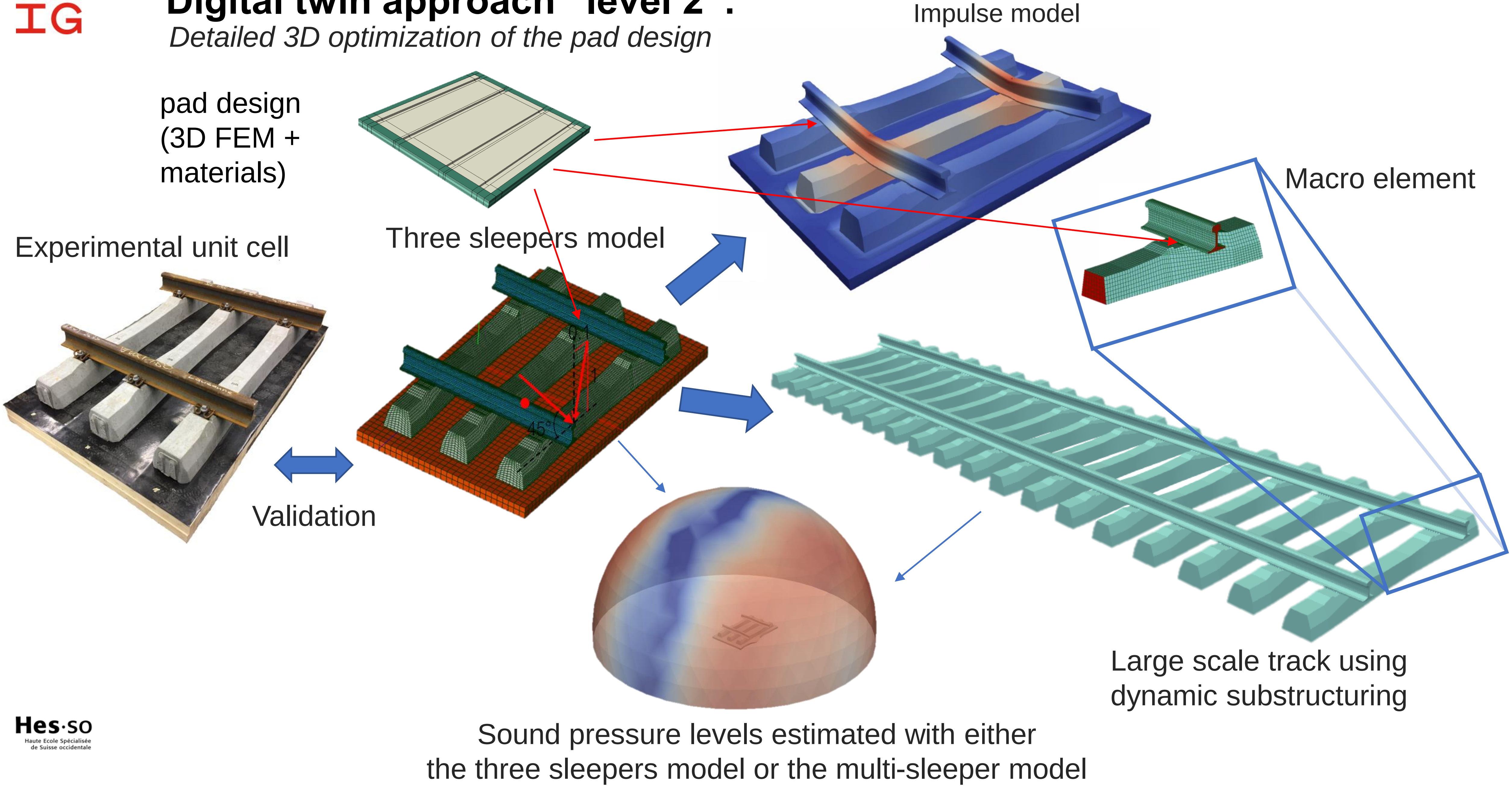
Pad Stiffness & Damping model
K(ω) and **tan(δ(ω))** computed for 4 DOF
(Compression, rotations and shear)



Fast semi-Analytical track model:
FRF & TDR, sound radiation

Digital twin approach “level 2”:

Detailed 3D optimization of the pad design



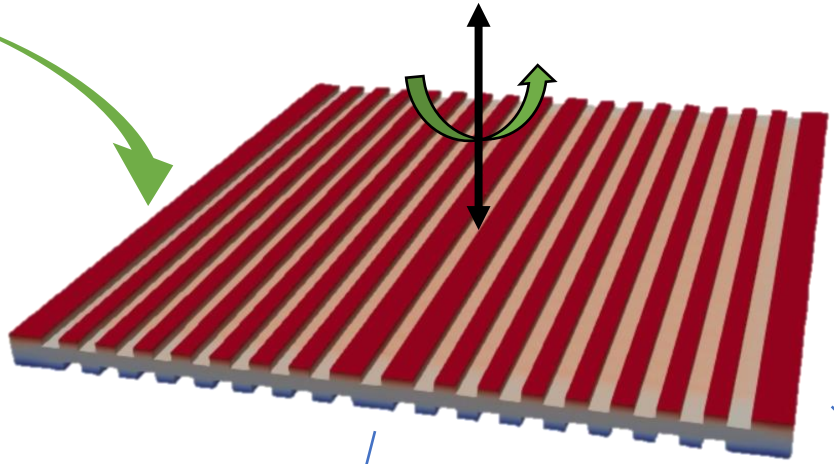
Digital Twin Level 1 : first design loop

Pad Stiffness & Damping model

Experimental

DMA material properties

Numerical models

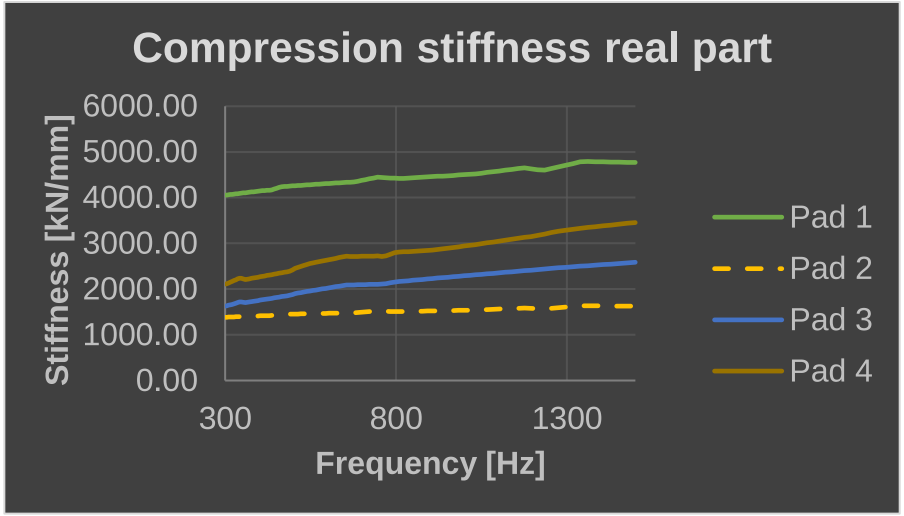


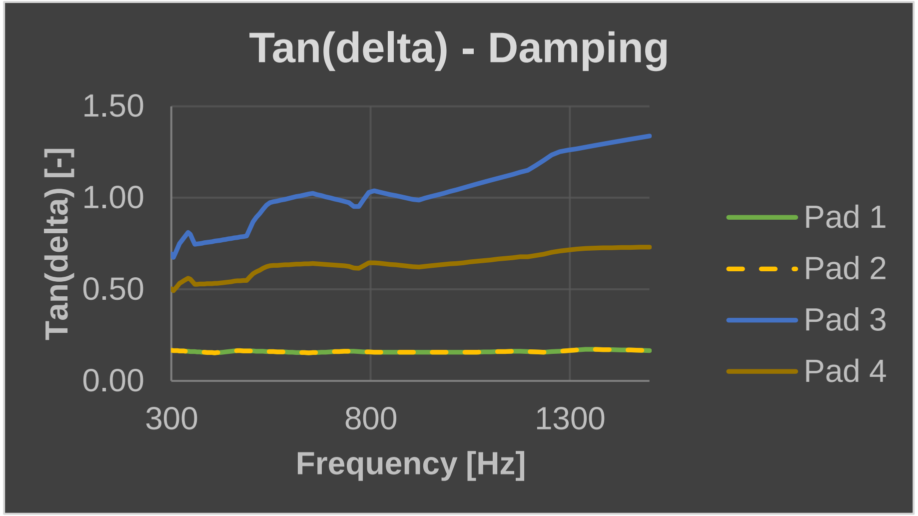
Pad Stiffness & Damping model

K(ω) and **tan(δ(ω))** computed for 4 DOF (Compression, rotations and shear)

Compute the Acoustic index of a pad

$$I_a = \frac{k''_{pad}\,[1000\ Hz]^{0.365} \cdot \tan(\delta)_{pad}\,[1000\ Hz]^{0.347}}{k''_{EVA}\,[1000\ Hz]^{0.365} \cdot \tan(\delta)_{EVA}[1000\ Hz]^{0.347}}$$





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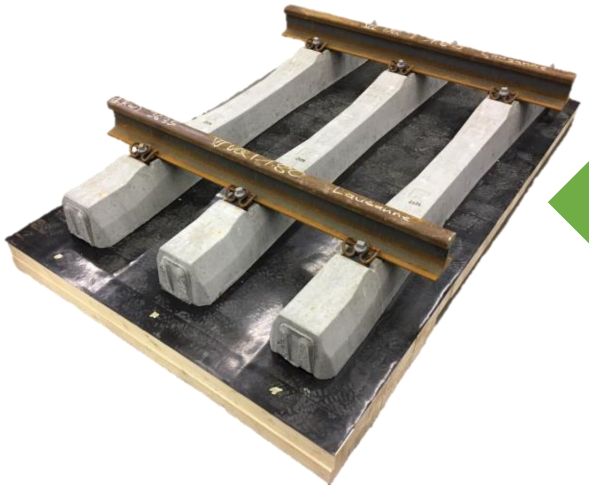
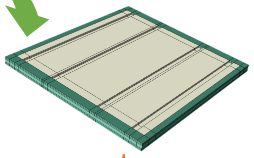
Impulse model

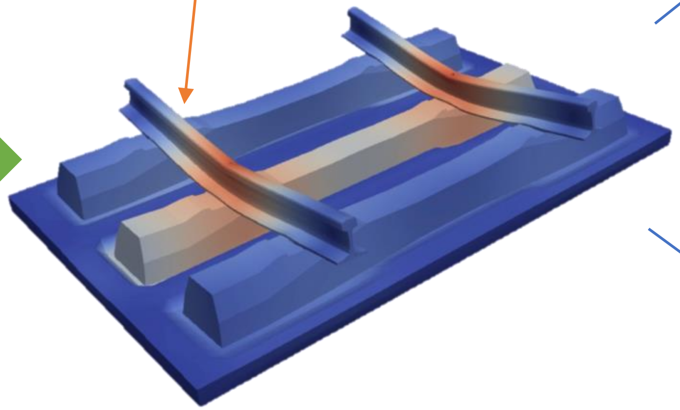
Experimental

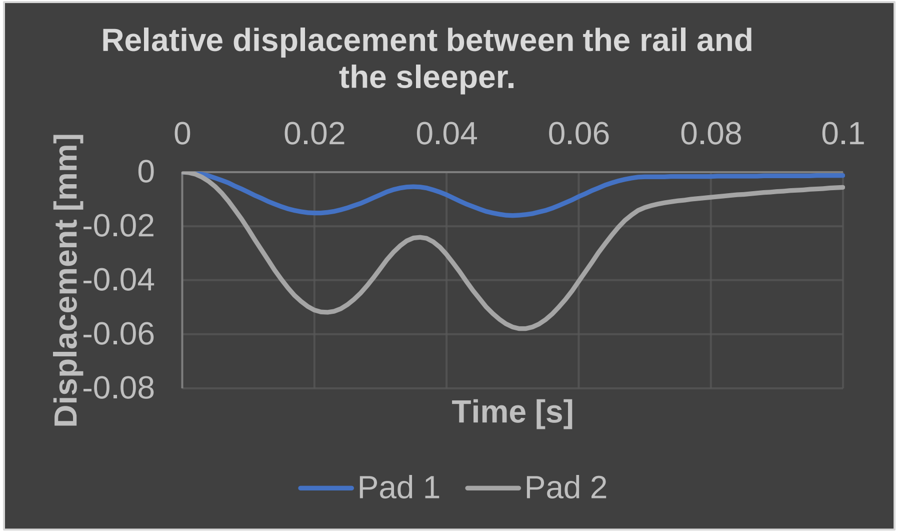
DMA material properties

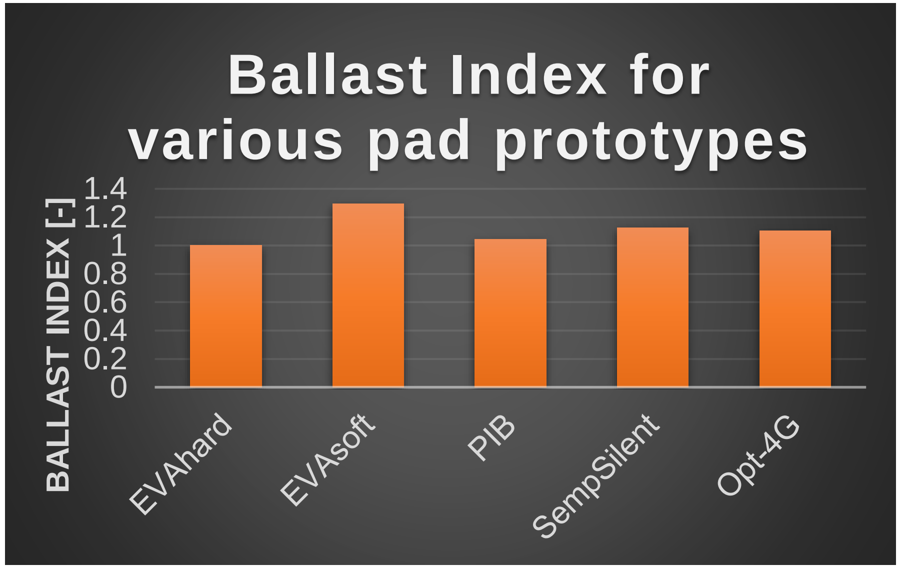


Numerical models







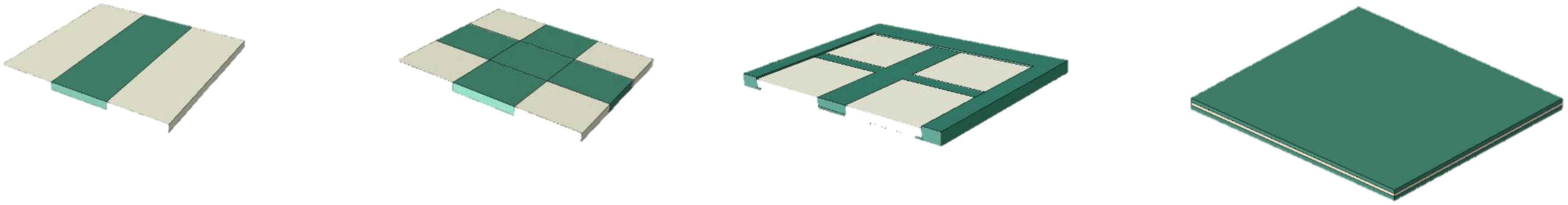


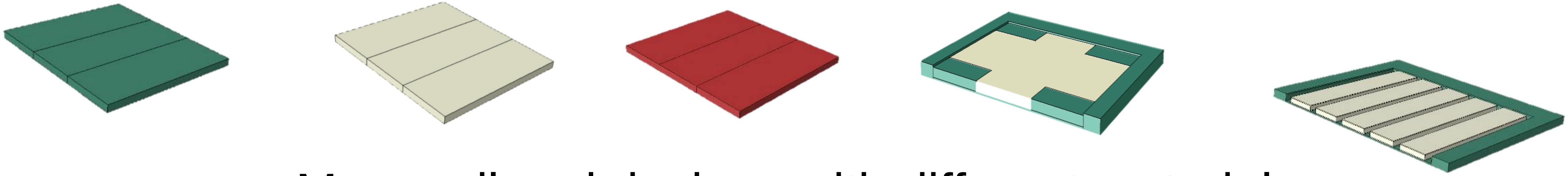
Impulse model

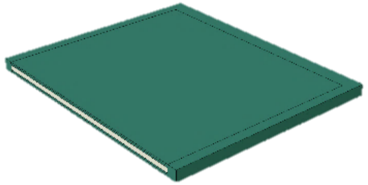
Reproduction of a bogie pass-by, compute the ballast and pads solicitation.

$$I_b = \frac{N_{pad}}{N_{EVA}}, \qquad N = exp_{10}\left(\sqrt{S\,\frac{160}{\sigma}\,\frac{47}{K_s}} + 2.4\right)$$

HEIG-VD

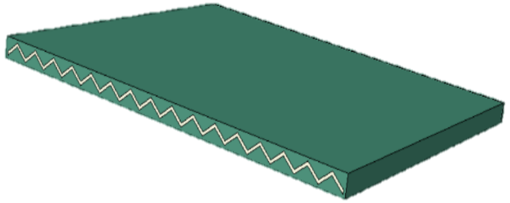


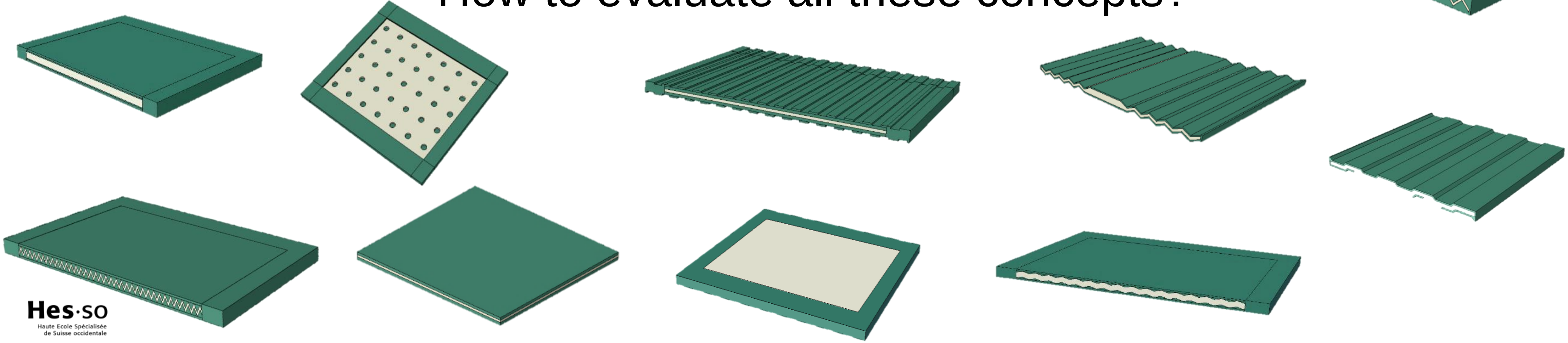




Many rail pad designs with different material combinations & geometry

How to evaluate all these concepts?





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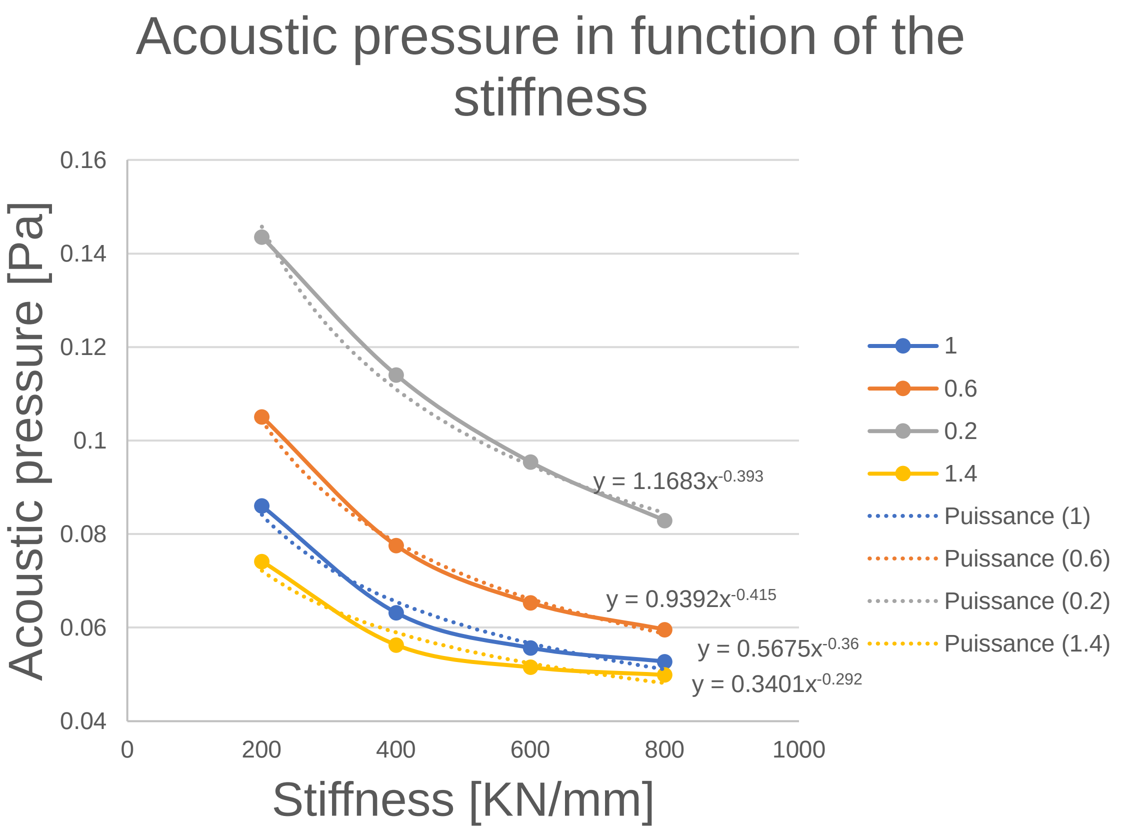
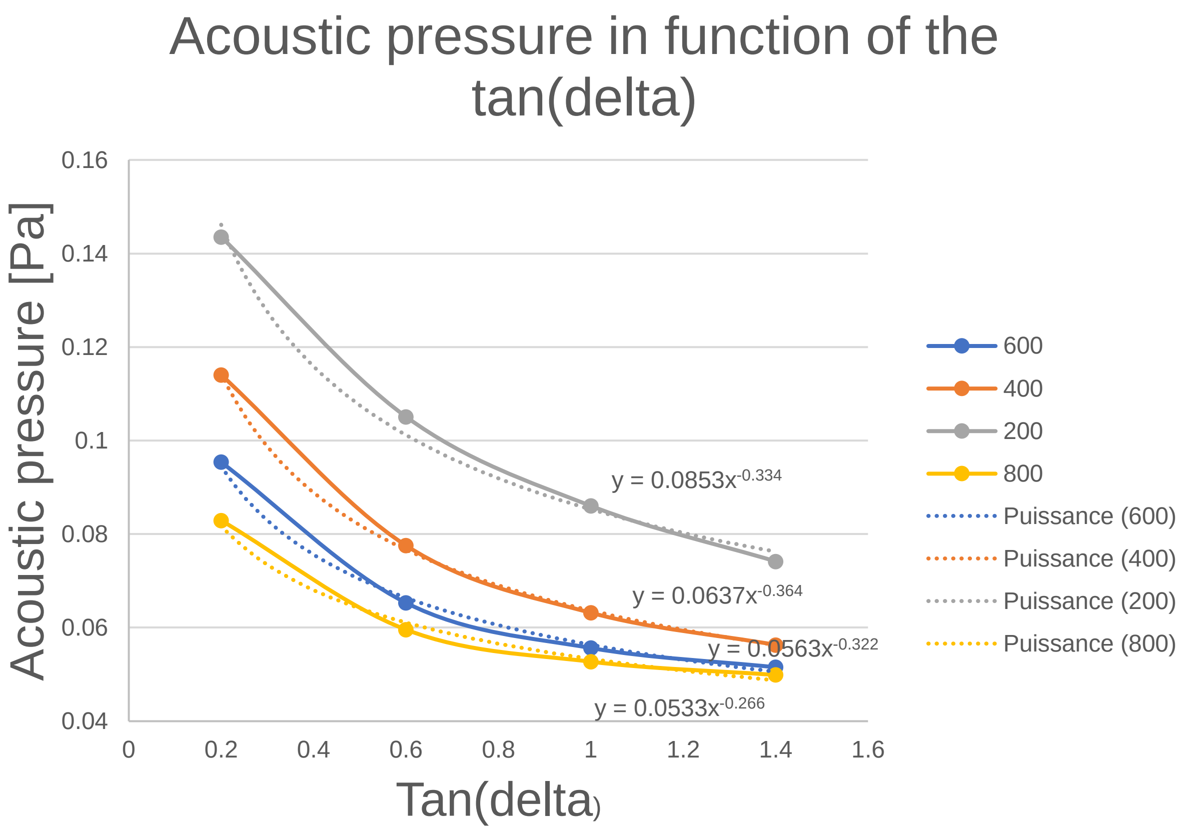
Acoustic Index

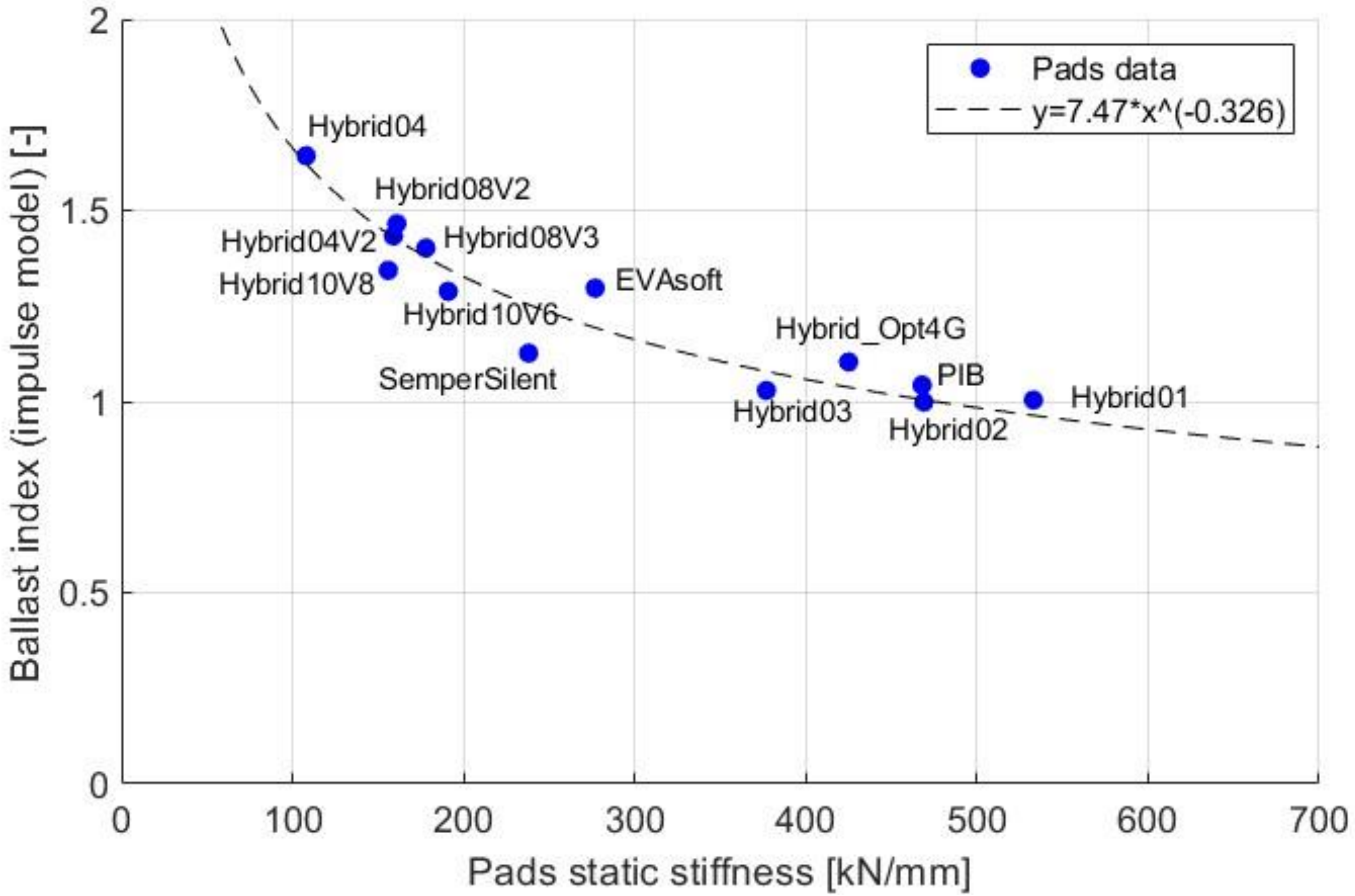




$$\text{Noise reduction} \sim K'^{0.365} * \tan(\delta)^{0.347}$$

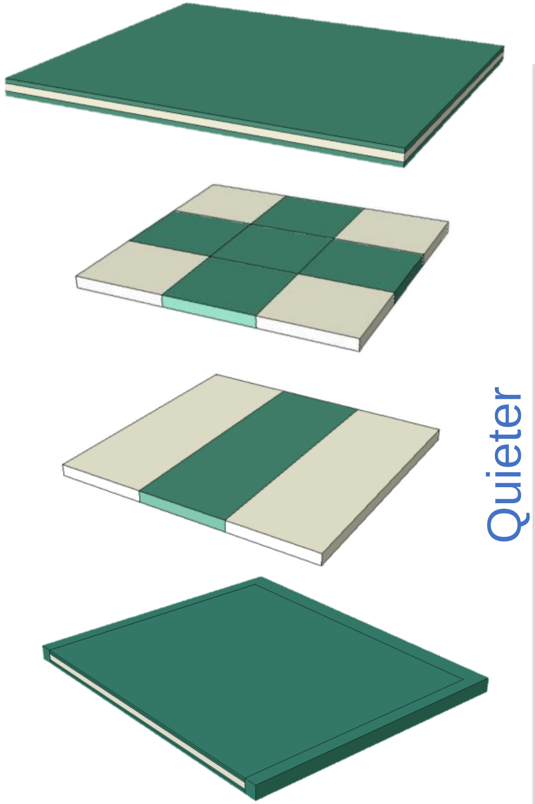
where K' and tan(δ) are the dynamic stiffness and damping are the simulated pad properties at 1000hz

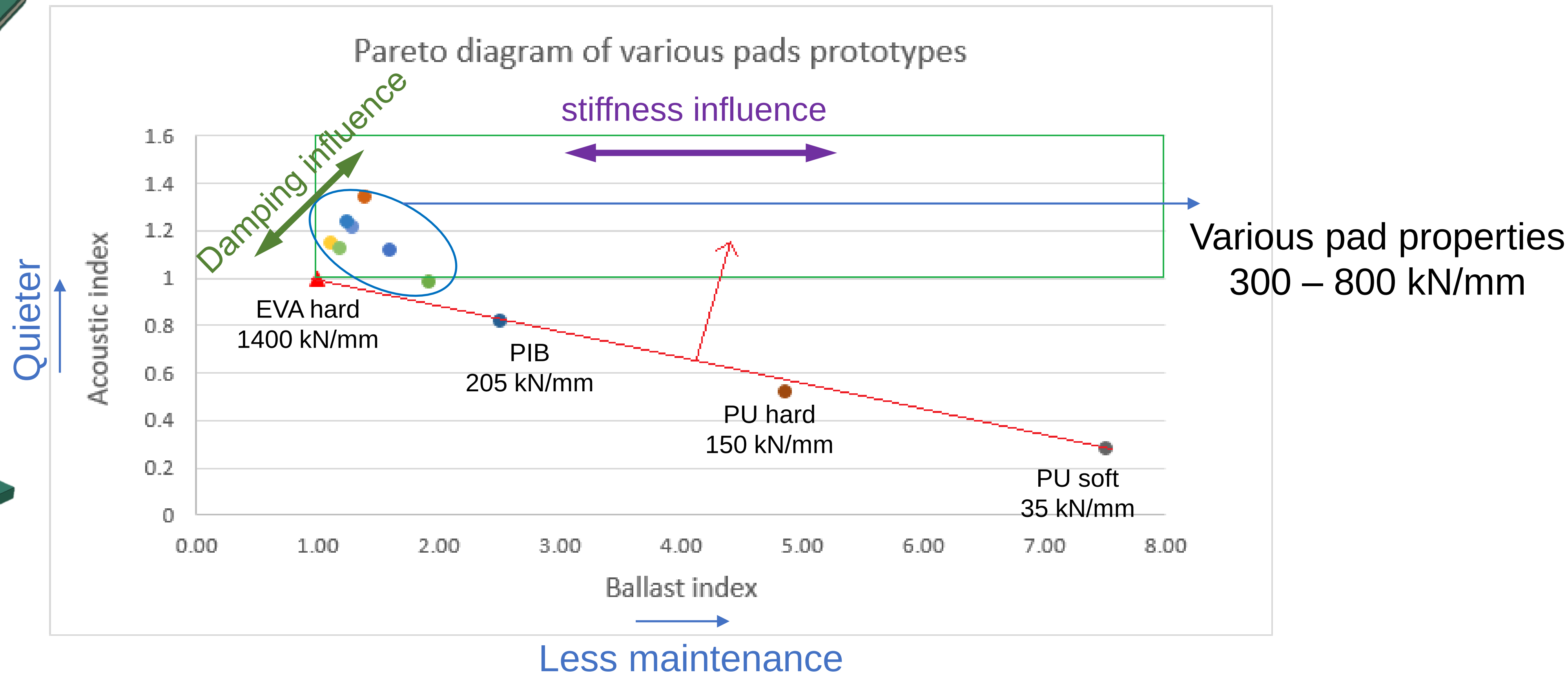
Ballast Index



$$I_b = \frac{N_{pad}}{N_{EVA}}, \qquad N = exp_{10}\left(\sqrt{S\frac{160}{\sigma}\frac{47}{K_s}} + 2.4\right)$$

Noise vs Ballast protection optimzation: First design loop





$$I_a = \frac{k''_{pad}\,[1000\ Hz]^{0.365} \cdot \tan(\delta)_{pad}\,[1000\ Hz]^{0.347}}{k''_{EVA}\,[1000\ Hz]^{0.365} \cdot \tan(\delta)_{EVA}[1000\ Hz]^{0.347}}$$

$$I_b = \frac{N_{pad}}{N_{EVA}}, \qquad N = exp_{10}\left(\sqrt{S\frac{160}{\sigma}\frac{47}{K_s}} + 2.4\right)$$

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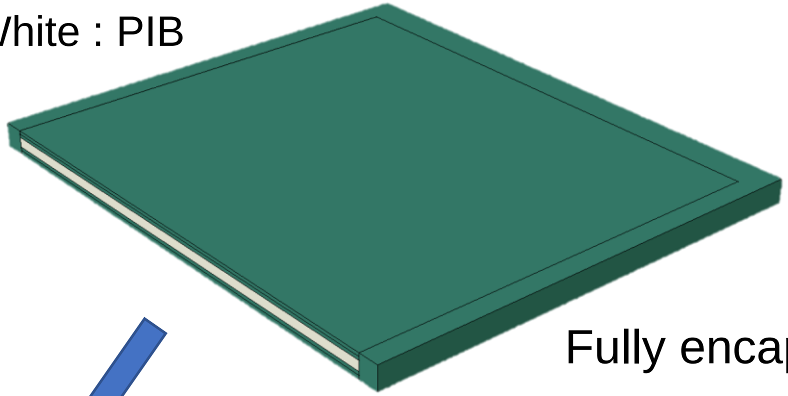
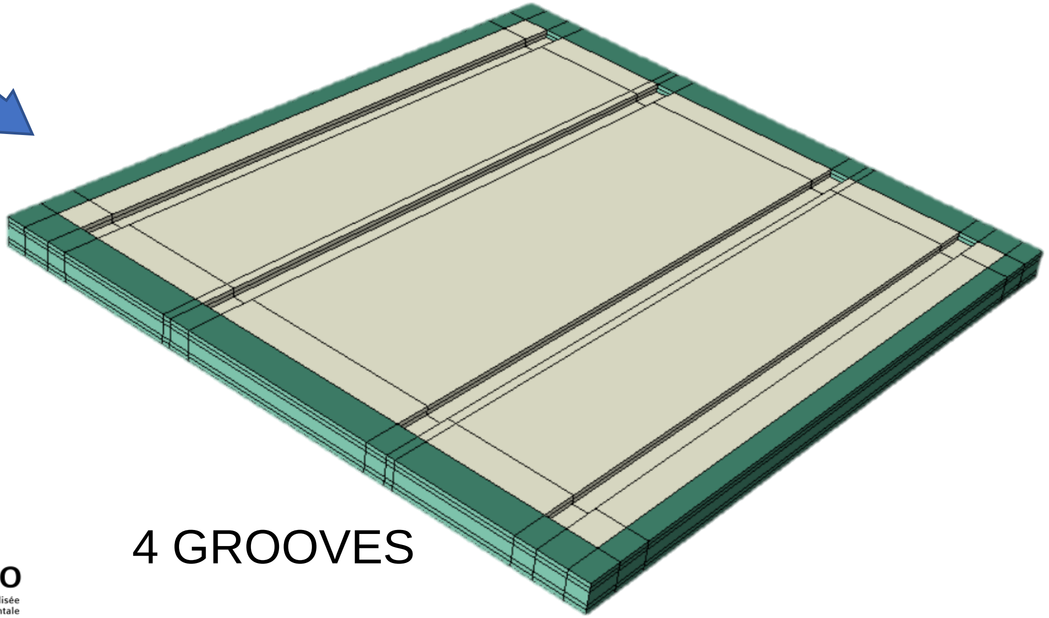
Hybrid Design EVA-PIB Evolution

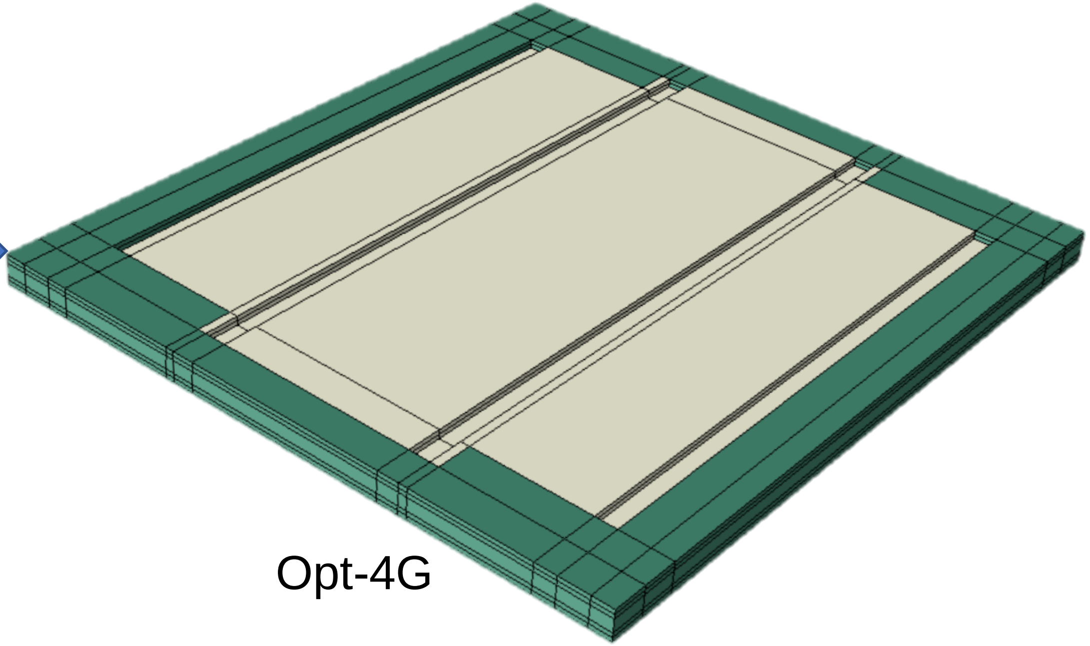
Green : EVA
White : PIB



Fully encapsulated



4 GROOVES



Opt-4G

Design principles:

- Frame to stability & avoid creep of soft PIB

- Grooves and corrugation for lower stiffness and increase shear & damping

- Use the contrast of properties to enhance deformation of soft material

- Used the same methodology to optimize prototype pad with Semperit’s materials

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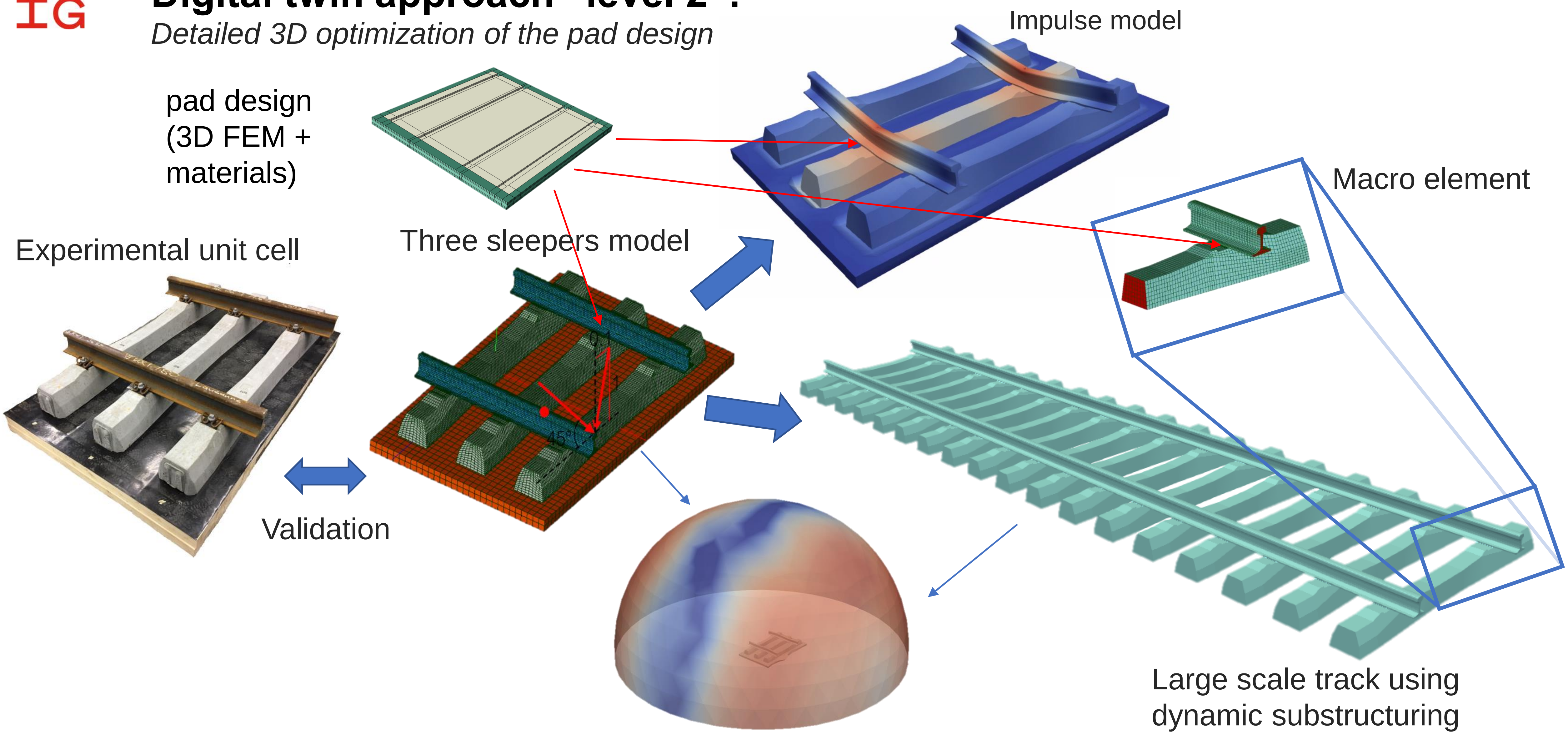
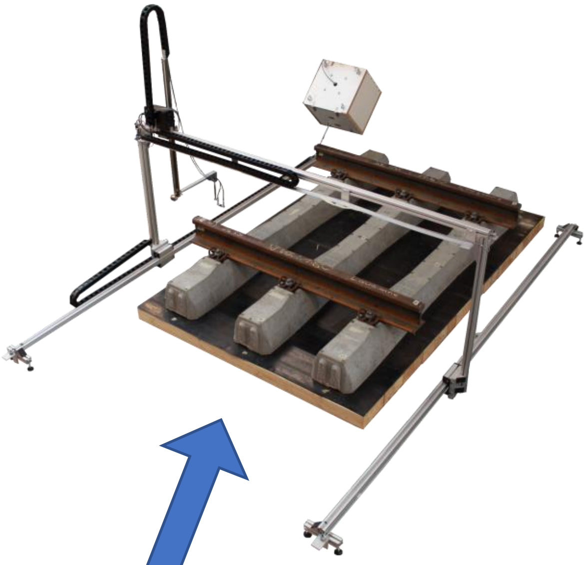
Digital twin level 2: further design optimization

Digital twin approach "level 2":

Detailed 3D optimization of the pad design



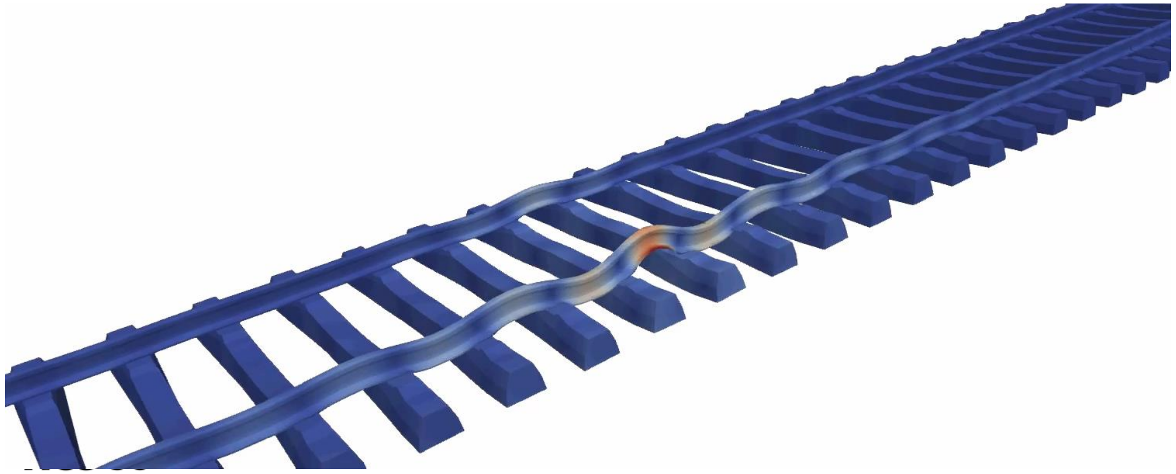
Three-Sleeper & Multi-Sleeper models

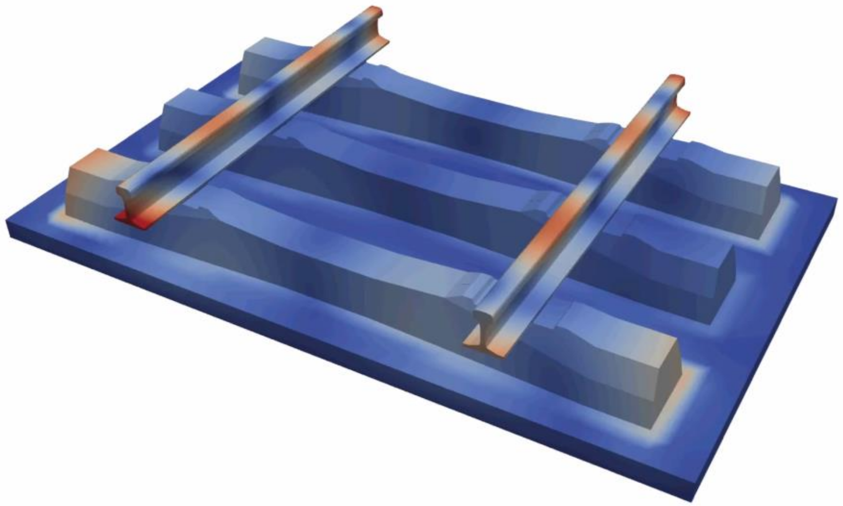


- 3D vibro-acoustic simulations
- Frequency spectrum → 300Hz to 1500Hz
- Acoustic pressure field using (monopoles superposition)

✓ Digital twin
✓ Calibration
✓ Validation

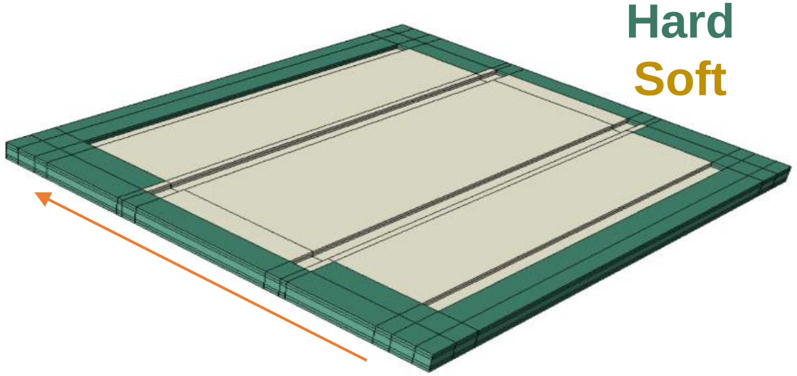
✓ Actual rail tracks prediction
✓ Model improvements → Fast



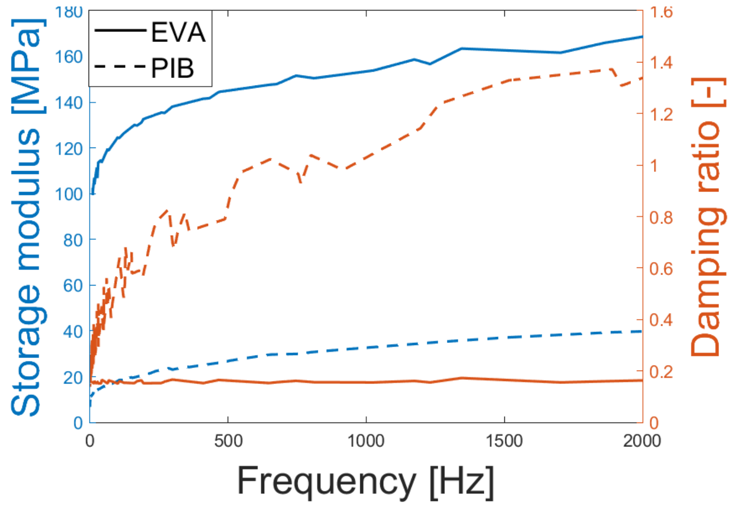


Main inputs/outputs

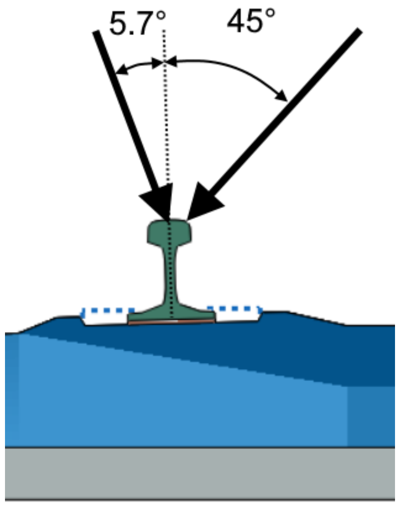
INPUTS



3D pad mesh

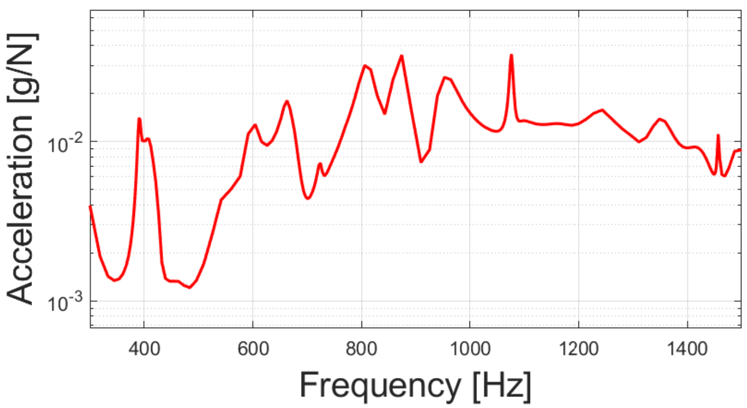


Pad & ballast frequency-dependent materials properties

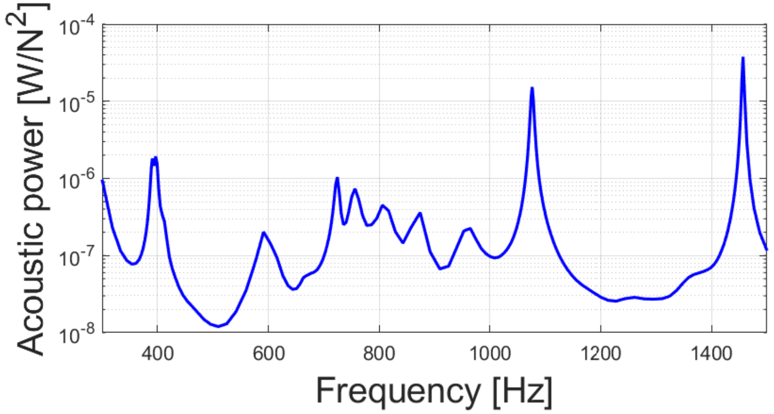


Load direction

OUTPUTS



Rail & sleeper acceleration FRF



Total radiated acoustic power FRF

$$L_w = \cdots \text{ dB}$$

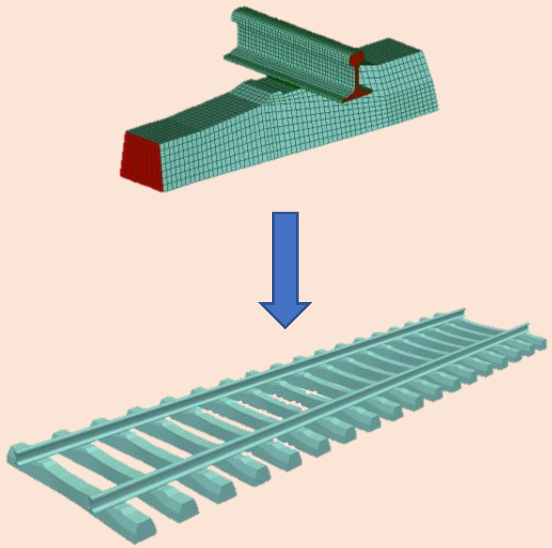
Multi-sleeper FE model

Introduction - challenges

Discrete ballast

$(k = k(\omega), c = c(\omega))$

Optimize computation time

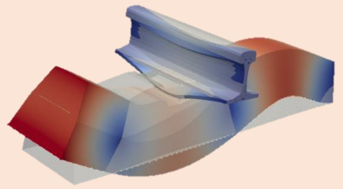


Dynamic Substructuring

Parallelization

=

Spectrum division



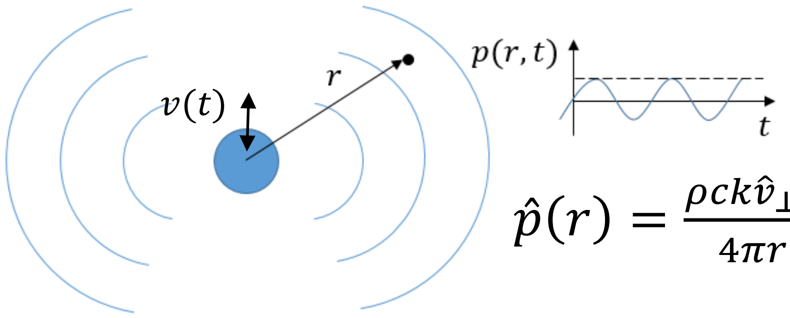
Reuse subset of pre-computed mode shapes

Update K, C, M matrices in each frequency band

Arbitrary frequency-dependent properties

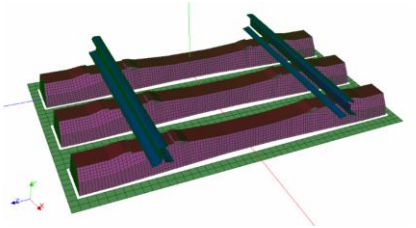
Monopole superposition

Monopole source assumption

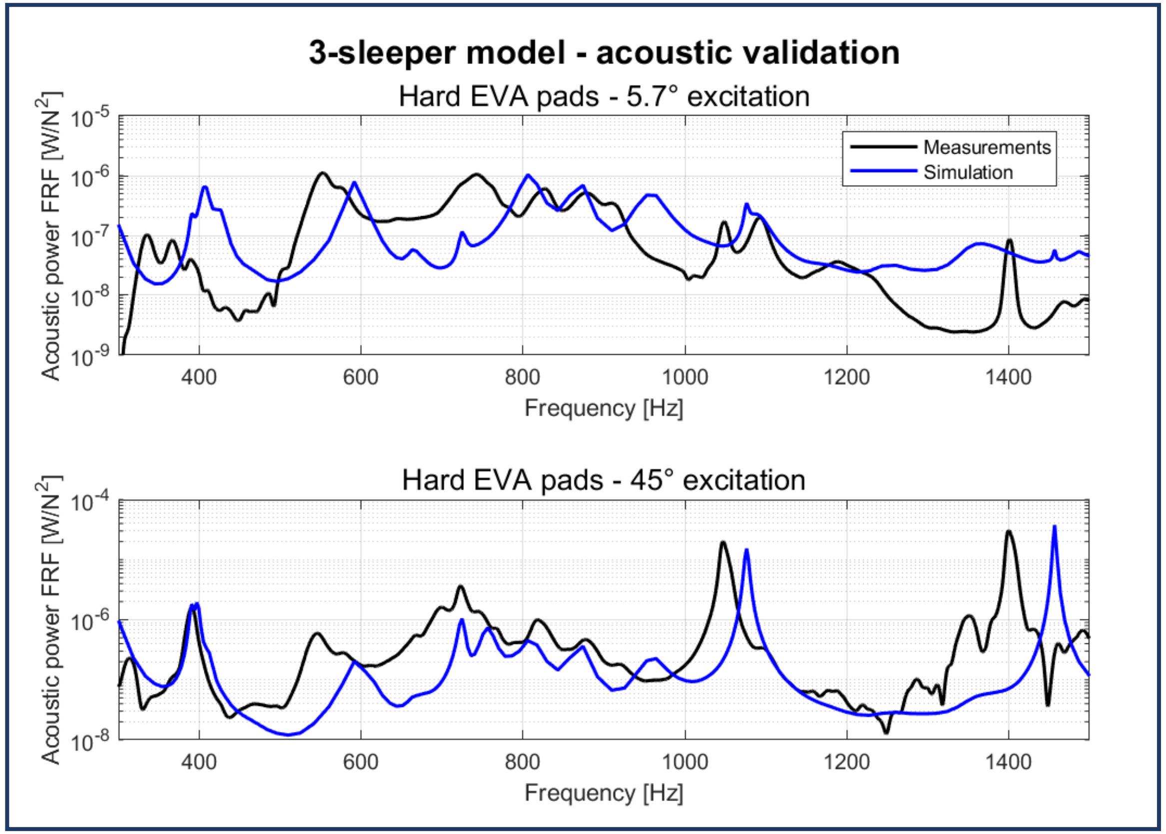


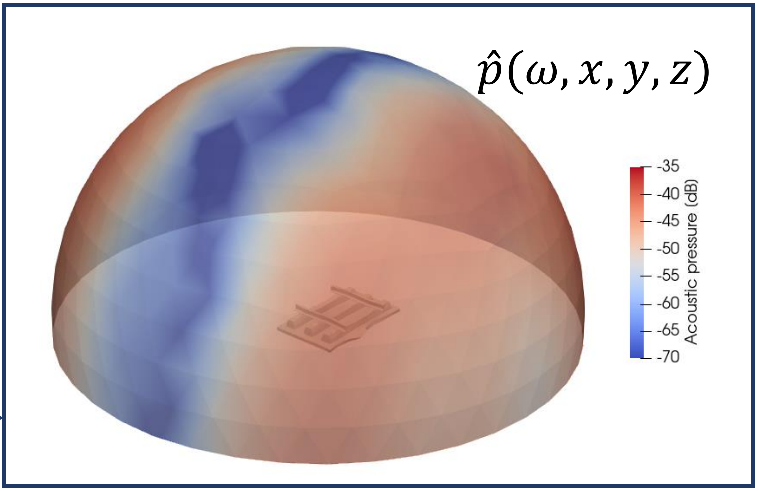
$$\hat{p}(r) = \frac{\rho c k \hat{v}_{\perp} S}{4\pi r}$$

$$\sum \text{(radiant surfaces contributions)}$$



Pressure field $\xrightarrow{\frac{(\cdot)^2}{\rho c}}$ Intensity field $\xrightarrow{\iint (\cdot)\mathrm{d}S}$ **Acoustic power**



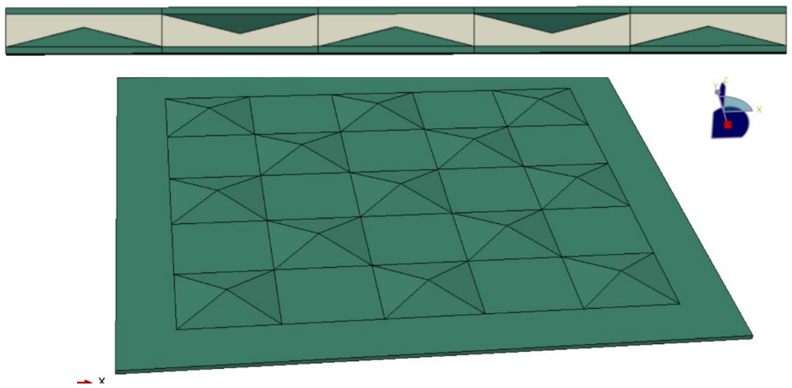


Hybrid pad design using Semperit high damping rubber - Hytrel

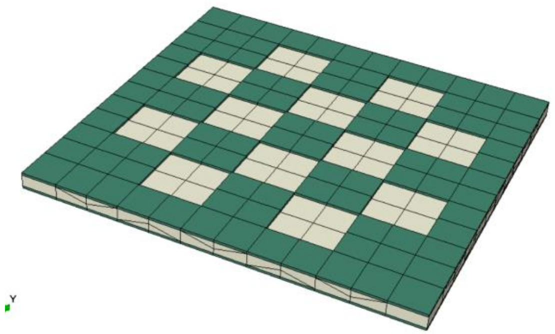
Pyramid / shear amplification concept

Pad Hybrid08

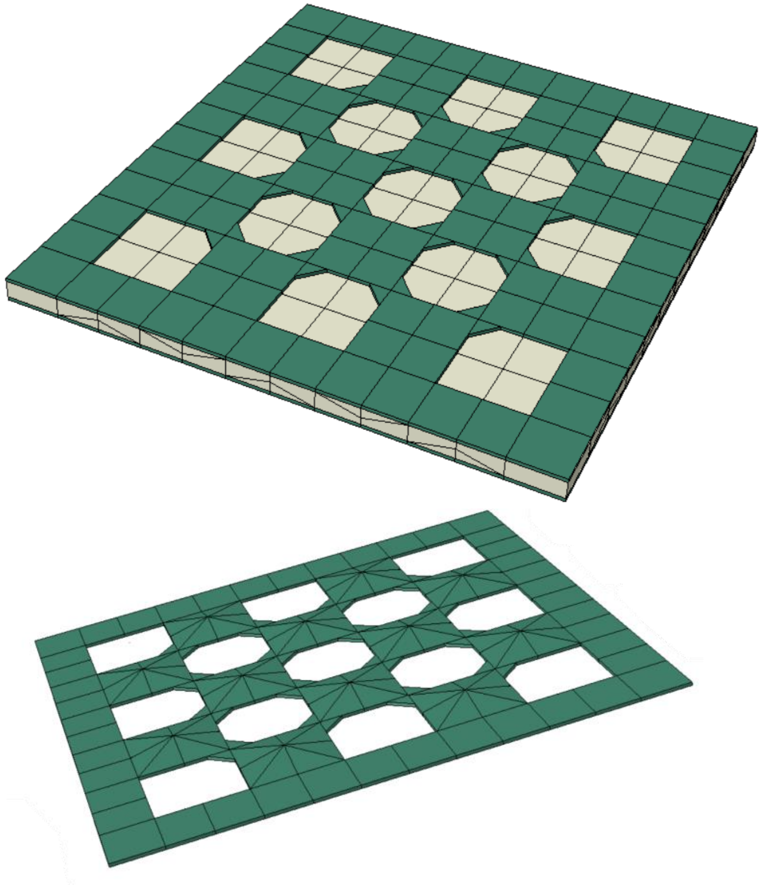
V1



V2

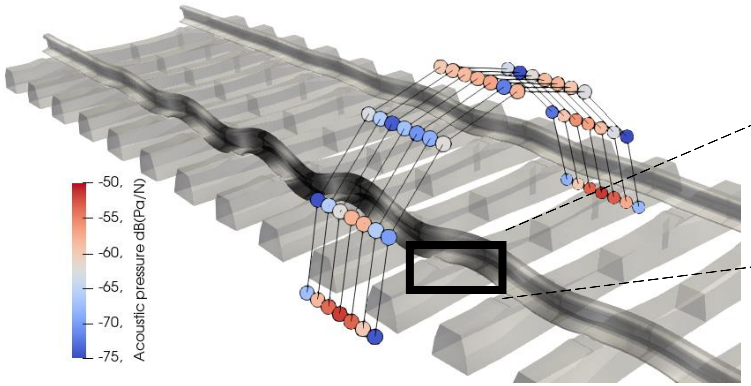


V3

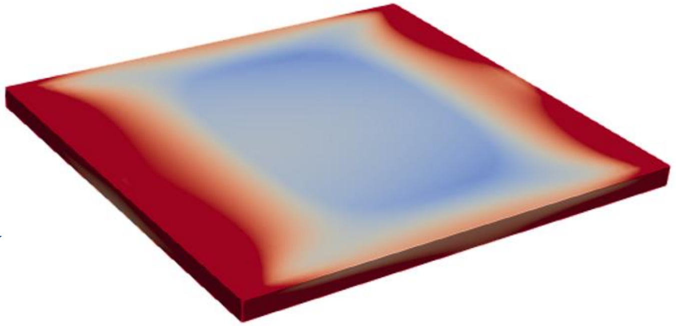


Hybrid pad design using Multi-Sleeper Model

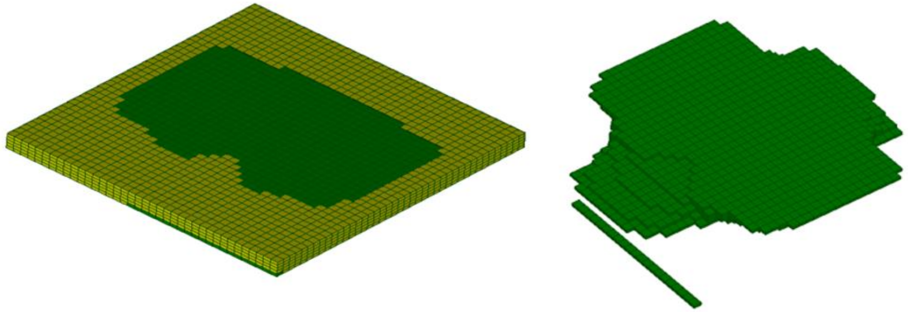
Vibro-acoustic simulation



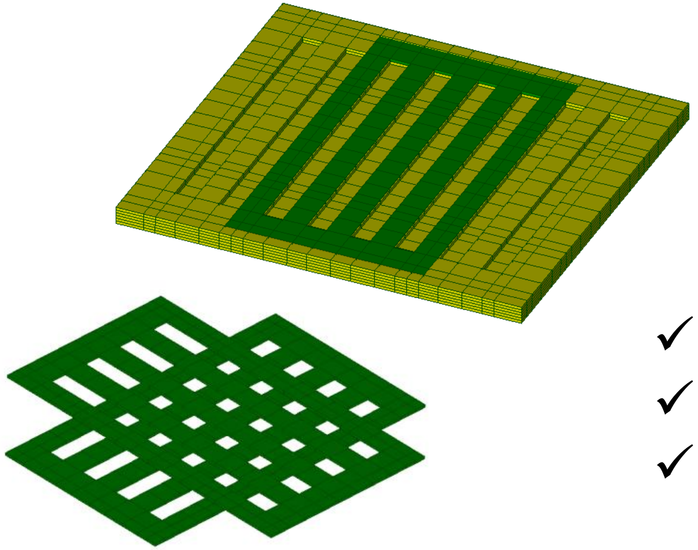
Rail pad deformation field



Place high-damping soft material in large deformation zone



Use stiff material to amplifiy strain in high damping material

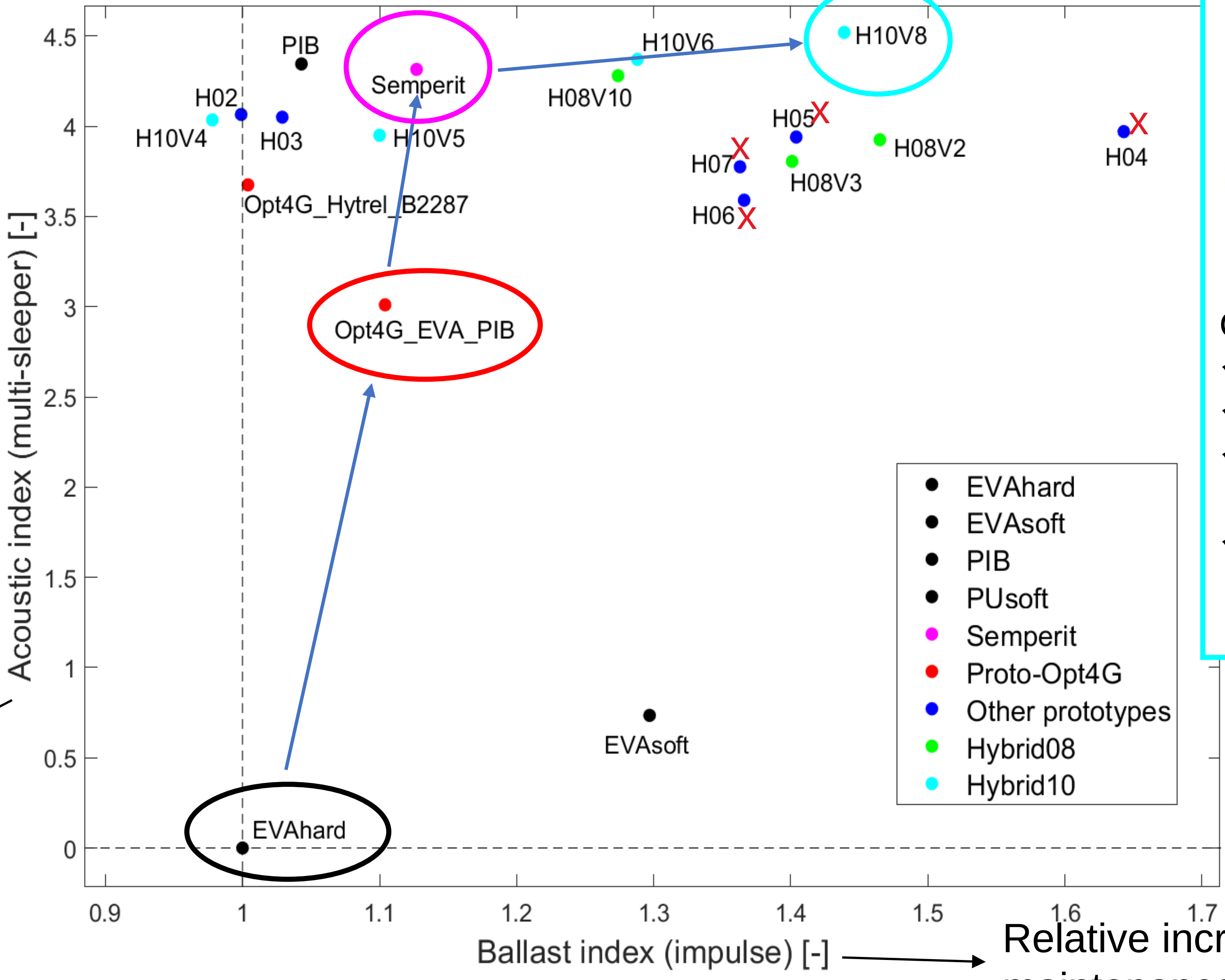


- ✓ Clean CAD
- ✓ Process compatible
- ✓ Grooves → tailored stiffness

Results: Pareto diagrams

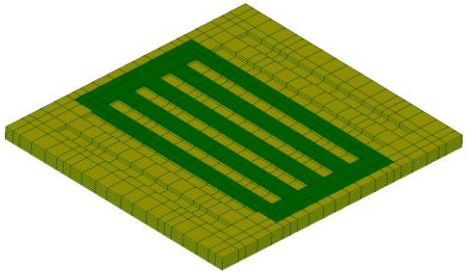
SemperSilent
- ✓ Single-material
- ✓ -4.3 dB (300-1500Hz)
- ✓ 13% ballast protection improvement
- ✓ ~240 kN/mm (static)

Core-Shell EVA-PIB
- ✓ Bi-material
- ✓ -3.0 dB (300-1500Hz)
- ✓ 10% ballast protection improvement
- ✓ ~460 kN/mm (static)



dB noise reduction

Relative increase of maintenance interval



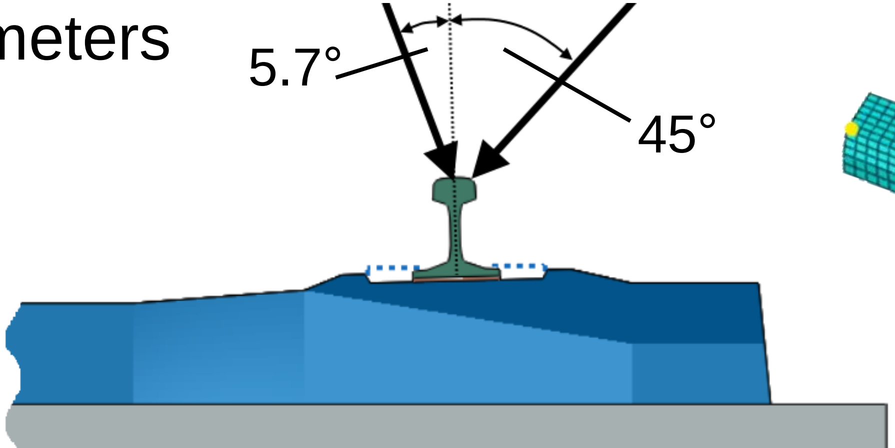
Optimum Hybrid Design
- ✓ Bi-material
- ✓ -4.5 dB (300-1500Hz)
- ✓ 40% ballast protection improvement
- ✓ ~160 kN/mm (static)

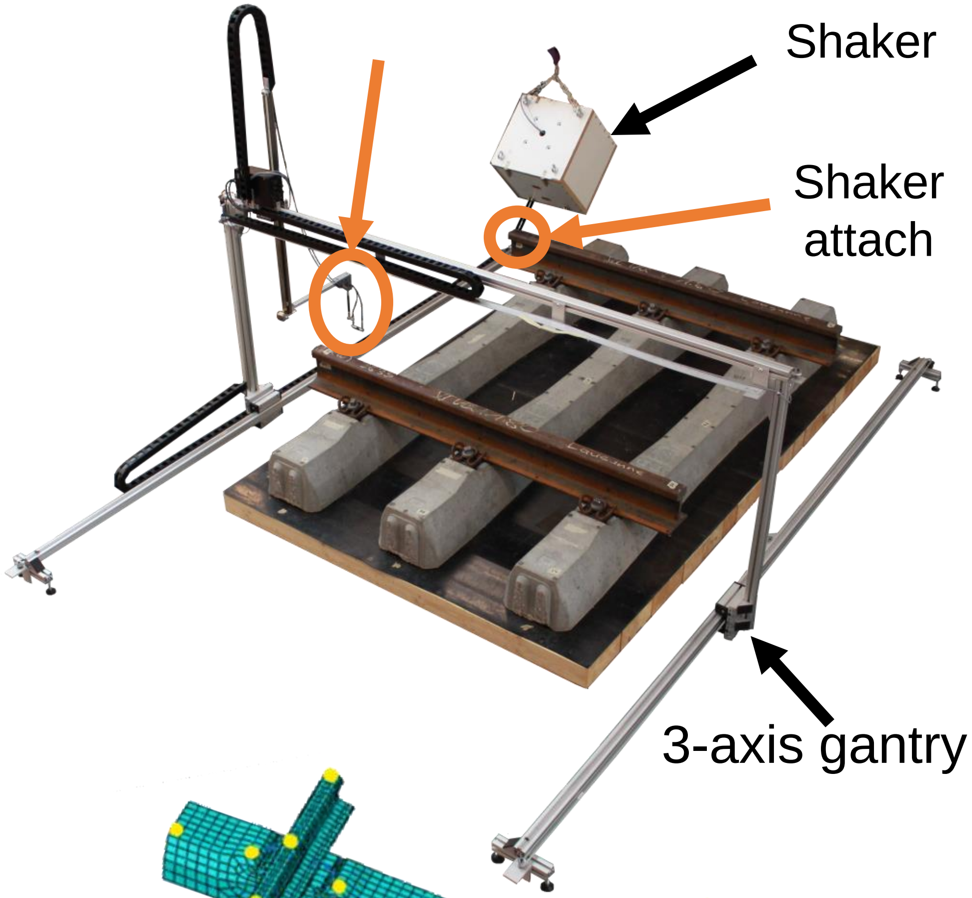
X = fatigue failure or manufacturing issues

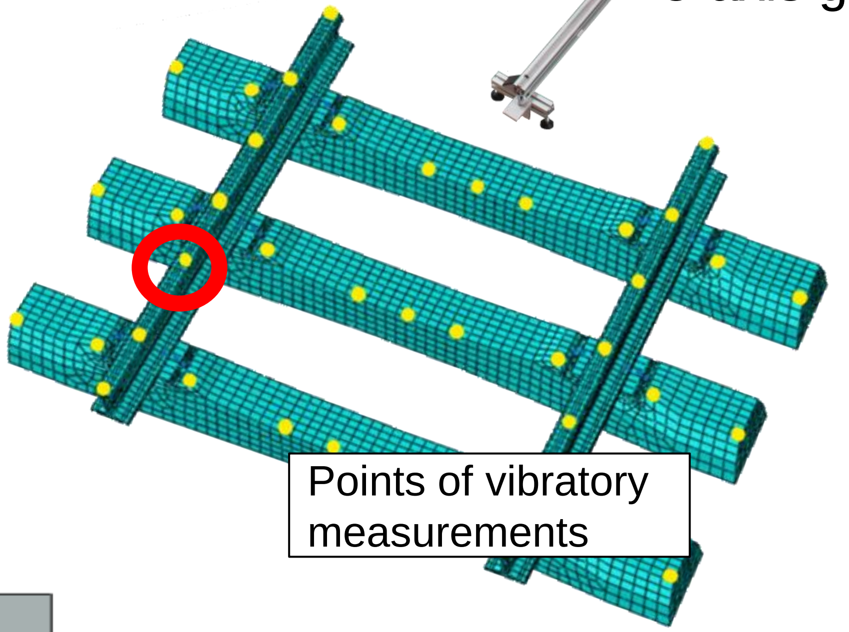
Experimental validation & performance evaluation

Experimental test bench

- *Three-sleeper cell* consisting of :
  - 2x 60E1 rail segments, 1.8 m long
  - 3x B91 sleepers
  - 12x Vossloh W14 clamps
  - 10 cm-thick wooden ballast substitute
- Excitation by electromagnetic **shaker attached to the rail**, 45° or 5.7° angle
- Semi-automated **3-axis gantry to move microphone** for acoustic measurements
- Vibratory measurements performed with 3-axis accelerometers







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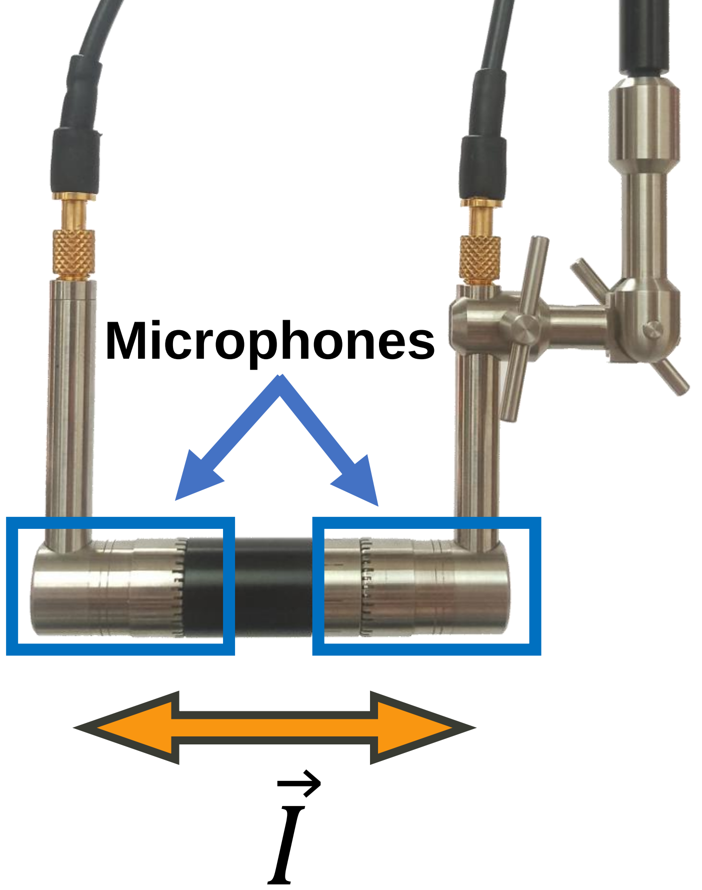
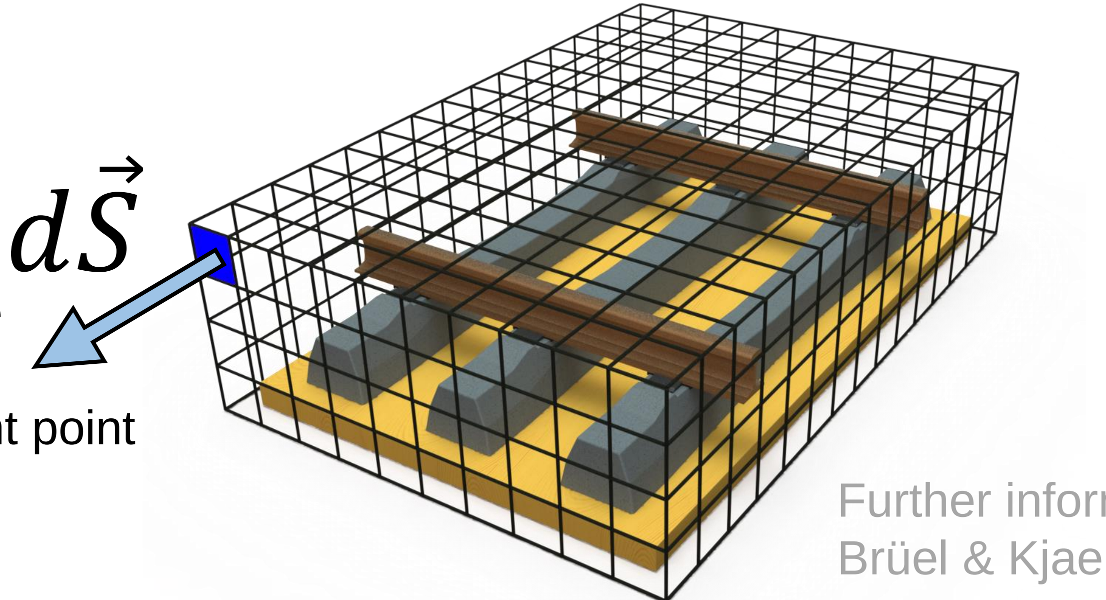
Acoustic measurements : intensimetry

- **Sound intensity** (in $\boldsymbol{W/m^2}$) measurement
- Using a pair of phase-matched microphones
- Measurement at discrete points evenly spaced on an enclosing surface
- Integration of intensity over the enclosing surface to obtain radiated **sound power** (in $\boldsymbol{W}$)
- Rail-induced noise is measured



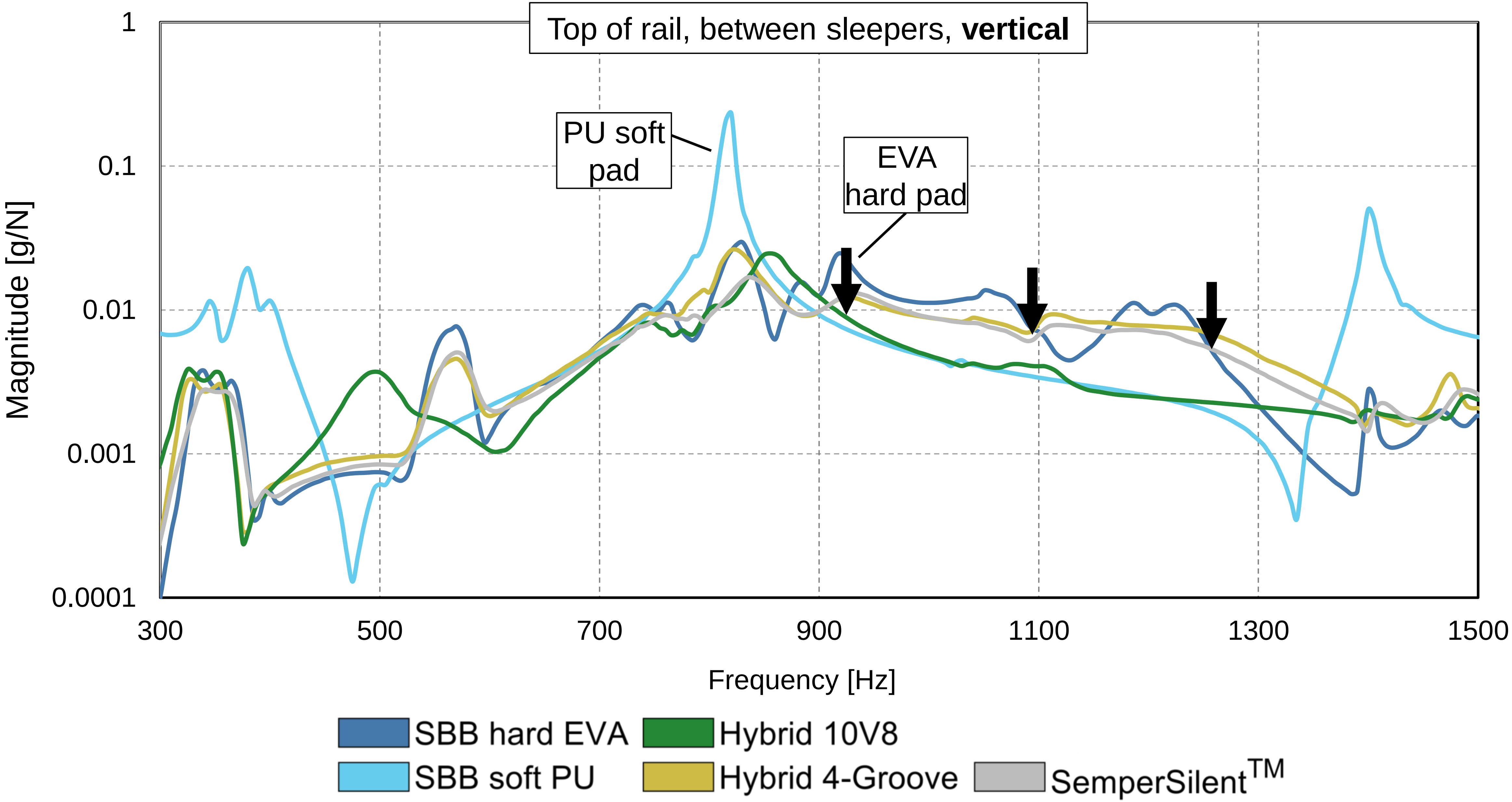


1 square
=
1 measurement point

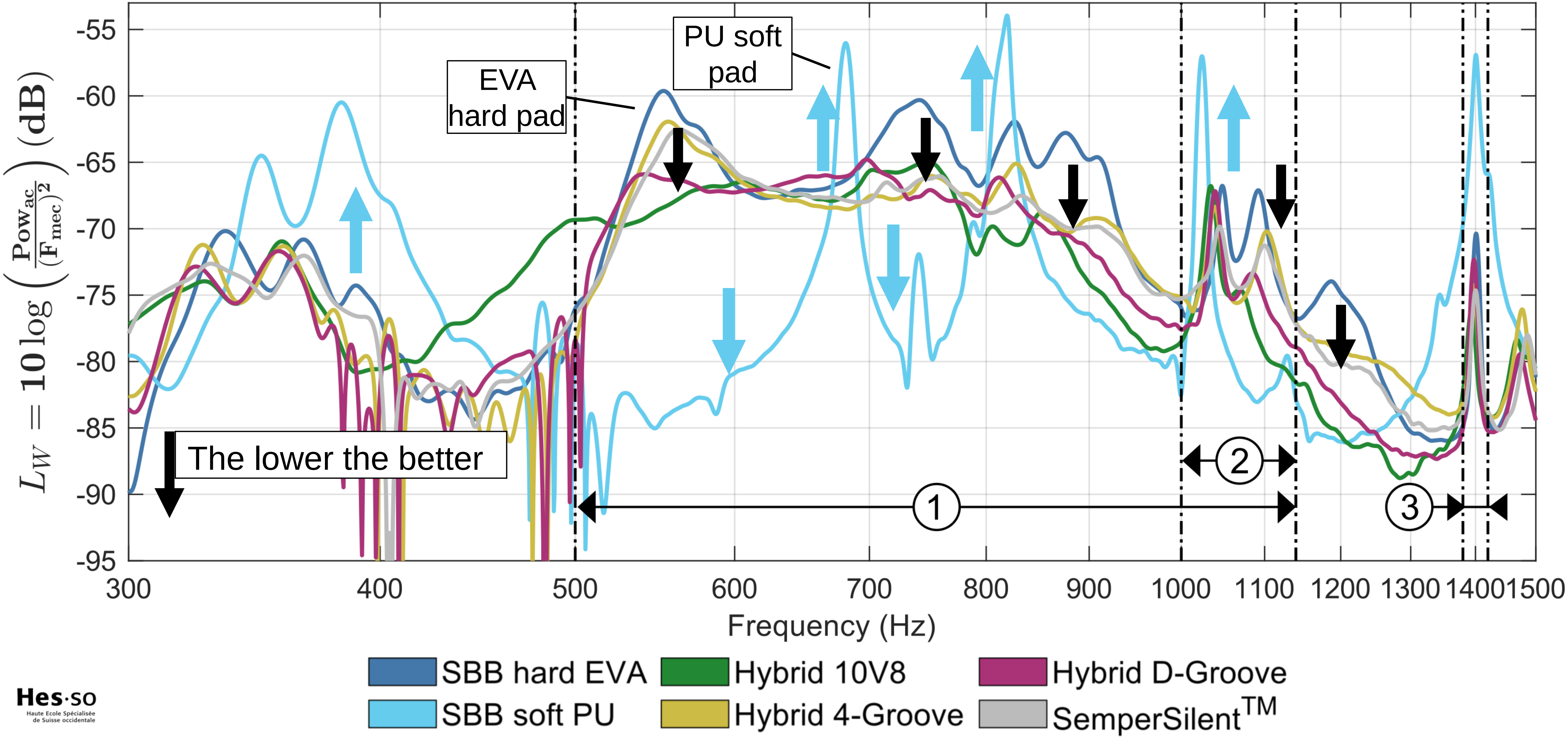
$$\int_S \vec{I} \cdot d\vec{S} = Pow_{ac}$$

Further information on intensimetry : EN ISO 9614-1:2009, Brüel & Kjaer “Sound Intensity: Theory and Measurements”

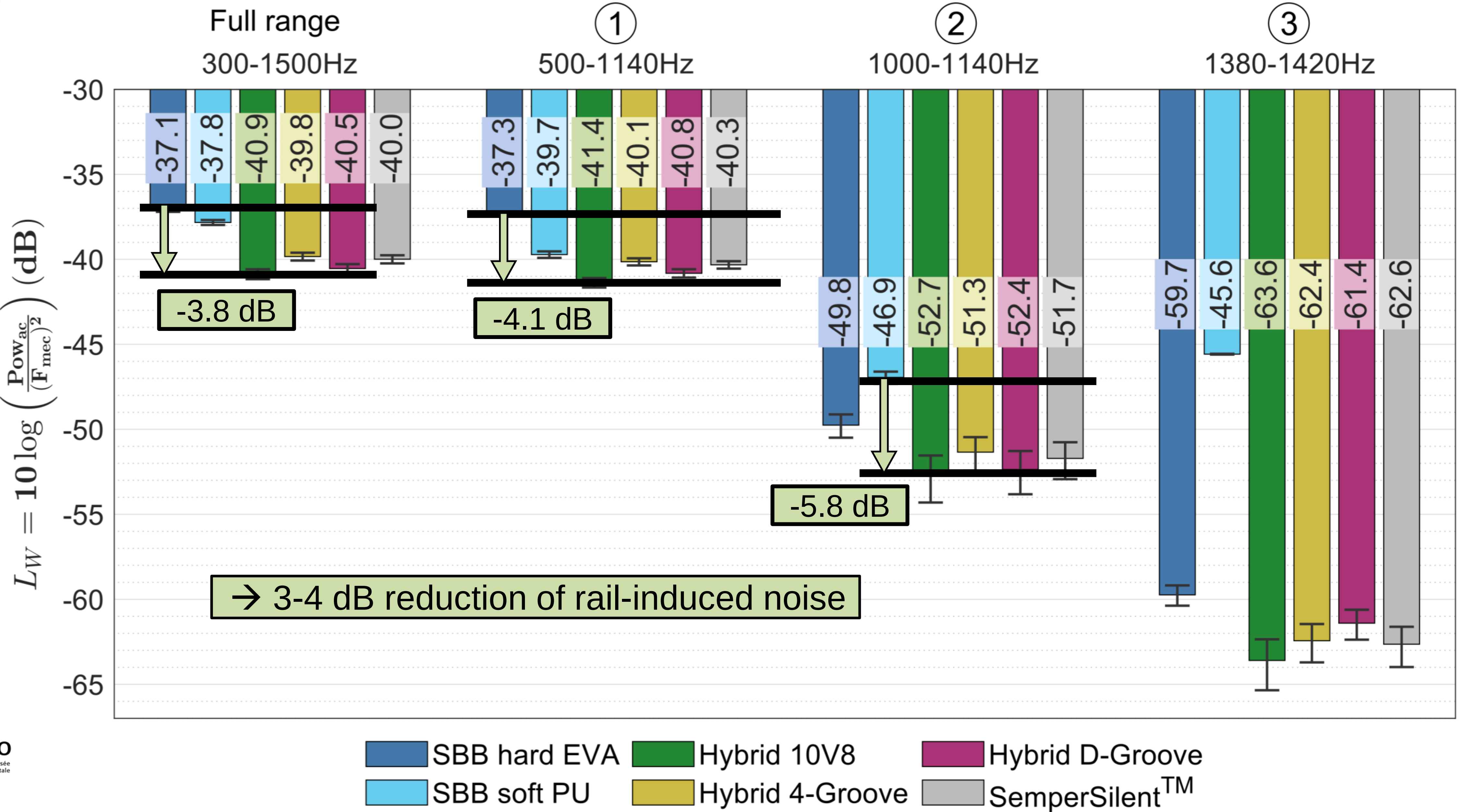
Experimental results – Vibrations, load at 5.7° (mostly vertical)



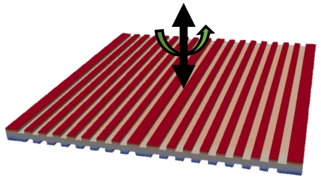
Experimental results – Acoustic , load at 5.7°



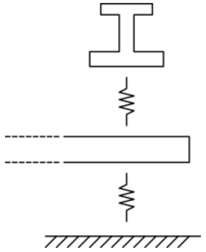
Experimental results – Acoustic, load at 5.7°



Open source rail track modelling toolchain

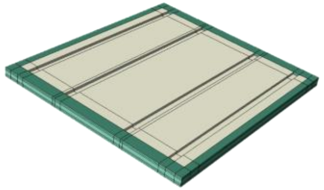


Pad Stiffness Model
Frequency dependent stiffness and damping

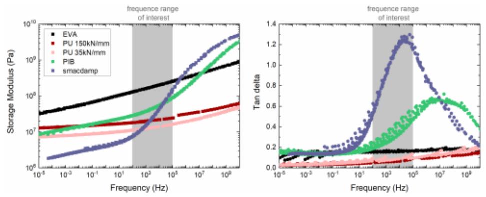


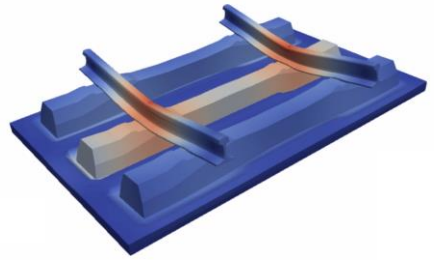
Semi-analytical track model
TDR, noise, vibration

Railpad FE Model
Mesh in Salome MED format

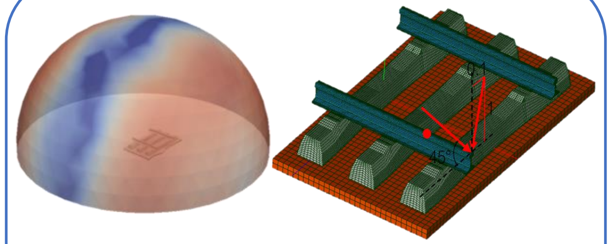


Material properties: pad, ballast,…
.csv file, space separator

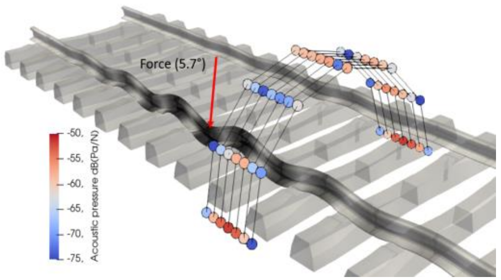




Impulse model
Ballast stress & clamp displacement



Three sleepers model
Vibration & noise radiation



Multi sleeper model
Vibration & noise radiation

Source code, user and installation documentation available at :
https://github.com/jcugnoni-heig/RailTrackModellingToolbox

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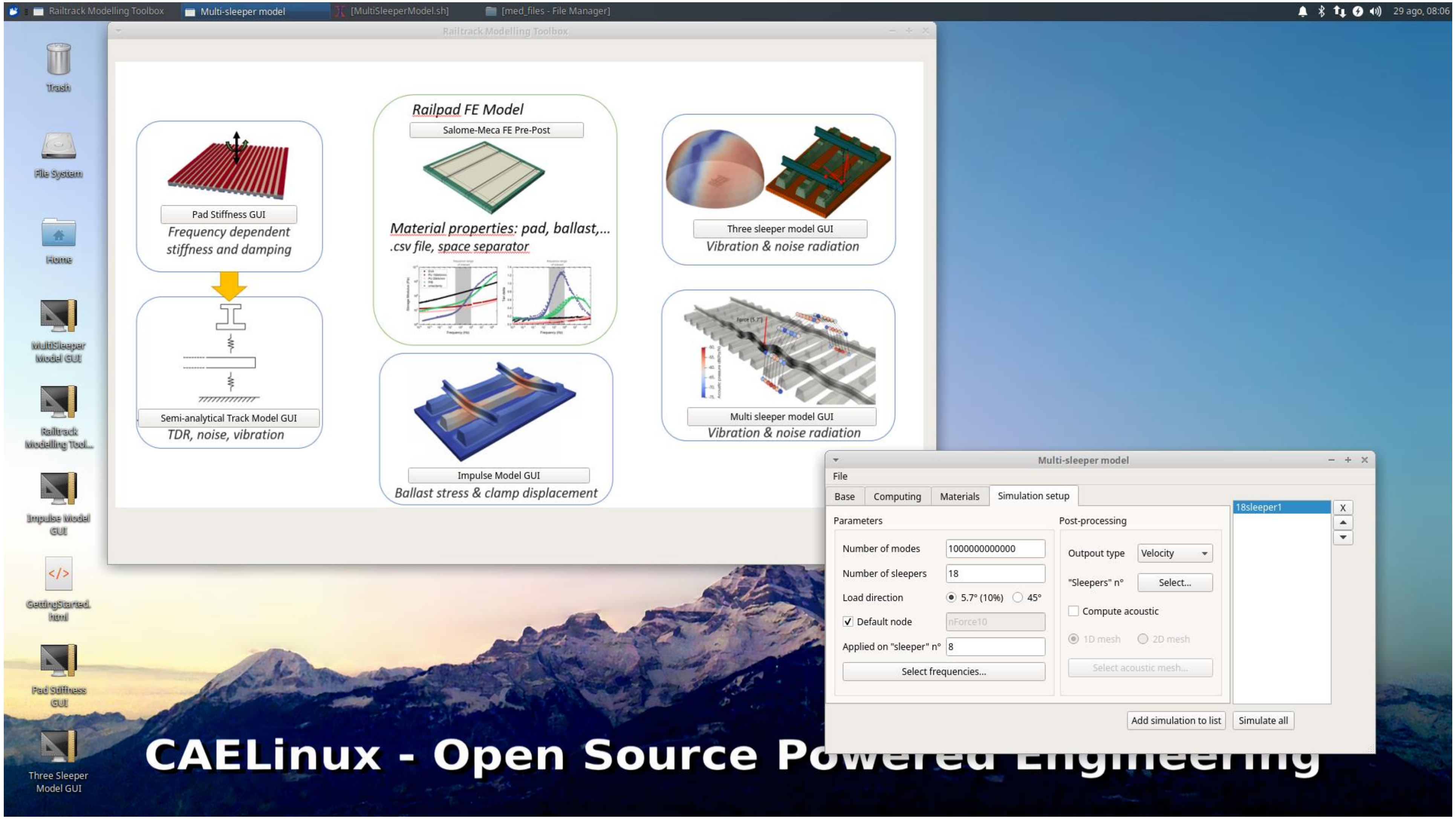
Open source rail track modelling toolchain



Pre built installation (ISO & Container images) available from:
https://github.com/jcugnoni-heig/RailTrackModellingToolbox/tree/main/ToolboxVM

Conclusion

Pad design & optimization

Multiple novel railpad designs using different combination of hard & high damping materials

Noise / ballast protection performance compromise, design guided by Pareto chart

Single material pad optimized with Semperit: good performance / cost tradeoff

Further performance increase using hybrid prototype Hytrel – high damping Semperit rubber

Experimental performance evaluation in line with prediction by models

Rail-borne noise reduction -3-4dB, Maintenance interval + 10-30%

Modelling toolbox

Complete modelling toolbox to evaluate track performance for different pad / material designs

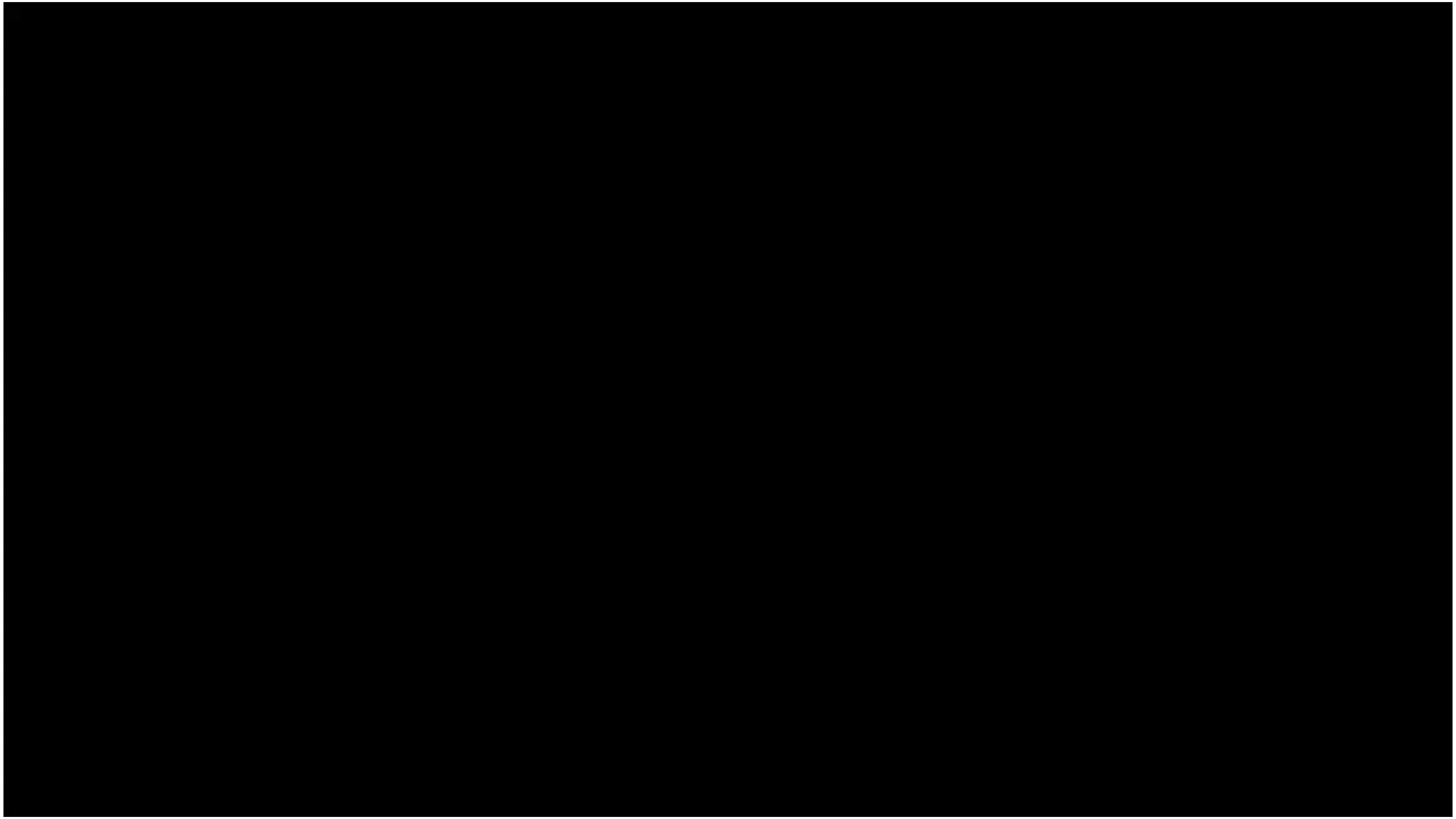
Include USPs & frequency dependent properties of the ballast (EMPA) and materials (EPFL)

Evaluate pad stiffness & damping, radiated noise, vibrations (sleeper, rail),
ballast stress & pad / clamp deformations during dynamic axle loading.

Validated across multiple experiments on 3 & 18 sleeper tracks

Published as open source code with detailed documentation

For the story: this is how the « magic » happens…



… with passionate, creative and dedicated engineers !