Noise and Ground Vibrations LRT Truck Design Optimization

Sergio Pérez | Stadler Rail

Ground Vibrations and Noise | Truck Design

Agenda

1. Outline and Introduction
2. What we understand as ground vibrations and noise?
3. Requirements impacting LRV truck designs
4. Truck design - main relevant solutions
5. Optimized Truck designs
6. Takeaways

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MOTIVATION

The motivation of this presentation is to provide vehicle builder insights to the **ground and noise vibration requirements and introduce the discussion about the available truck design solutions** to fulfil those in the context of **Light Rail Vehicles** (LRVs/LRTs)

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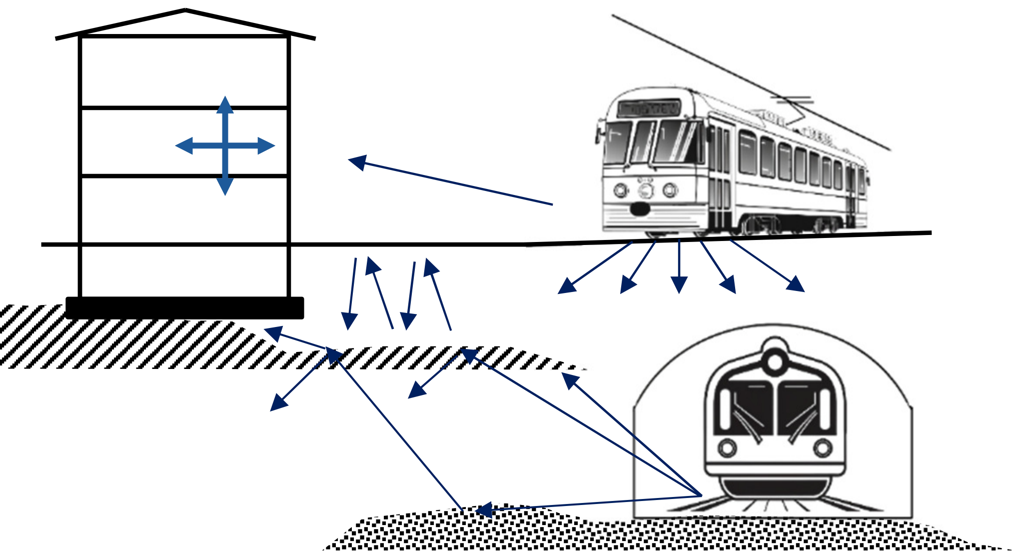
What we understand as ground vibrations and noise?



- Excitation (Force Density)
- Vibration Propagation (Transfer mobility)
- Building / Surface Vibration
- Audible Noise

Source: Excitation (Force Density)

Propagation: Vibration Propagation (Transfer mobility)

Receiver: Building / Surface Vibration; Audible Noise

COMPLEX PHENOMENA INVOLVING ROLLING STOCK AND INFRASTRUCTURE

What we understand as ground vibrations and noise?

Source of vibration excitation:

- Moving loads on a flexible supporting foundation
- Forced excitation caused by
  - Wheel/rail roughness and irregularities
  - Wheel/rail defects: corrugation, flats, and discontinuities

- Vehicle suspension non-linearities/friction
- Lateral loads due to curving/switches

- Other: driving conditions (braking/traction), environmental conditions

What we understand as ground vibrations and noise?

Source of vibration excitation:

- Moving loads on a flexible supporting foundation
- Forced excitation caused by
  - Wheel/rail roughness and irregularities
  - Wheel/rail defects: corrugation, flats, and discontinuities

  - Unsprung mass
  - Vehicle Suspensions
  - Axle load

- Vehicle suspension non-linearities/friction
- Lateral loads due to curving/switches

  - Suspension design

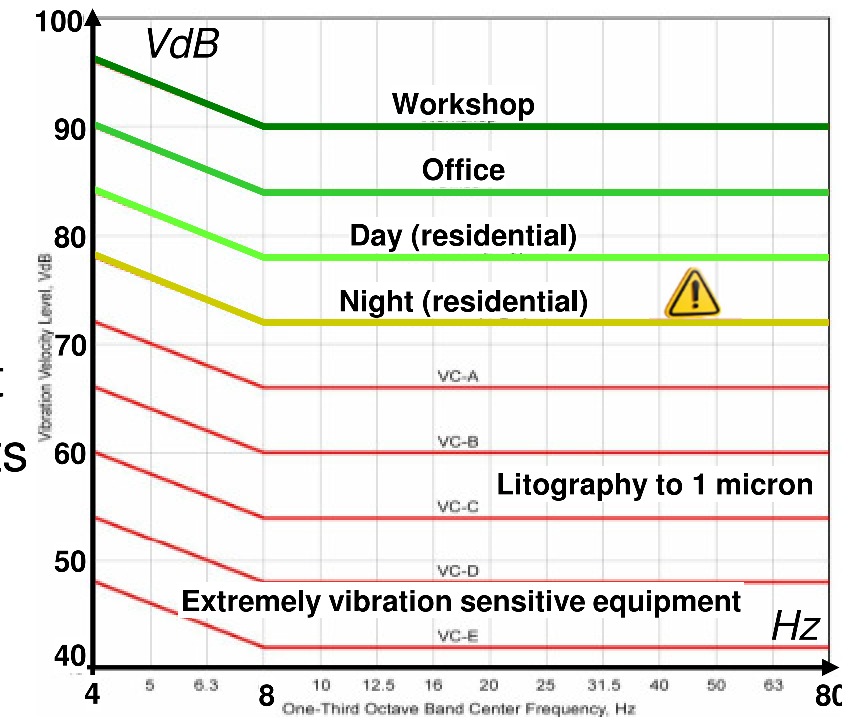
- Other: driving conditions (braking/traction), environmental conditions

What we understand as ground vibrations and noise?

Vibration/noise range

Vibration is perceived by human beings as:

- **Mechanical vibration** (FTA guidelines)
  - Usually on the range of 4-80 Hz
  - Up to 200 Hz affecting technical equipment
- **Ground-borne noise** emitted by vibration parts (FTA guidelines, EN, VDV)
  - 16 to 250 Hz
  - up to 500 Hz in some studies



FTA ground vibrations criteria

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Requirements impacting LRV truck designs

Comparative analysis

Requirements are based on being better or equivalent to previous vehicles

1

Absolute requirements

Requirements are based on an absolute vibration value (Velocity or acceleration levels) or noise absolute value (Equivalent sound pressure).

2

Requirements defining the product

The requirement are based on the description of specific solutions or parameters: unsprung mass, suspensions, resilient wheels, real axle, no friction elements …

3

Requirements impacting LRV truck designs

1 **Comparative analysis**

The objective of the Authority to decrease ground or structure-borne vibration ***below that currently being experienced****. The vehicle designer shall perform a transmissibility analysis of the vehicle and its suspension system in operation on the various track structures […]. The transmissibility analysis shall demonstrate the absence of amplification in the range of the natural frequencies of the structures. […]*

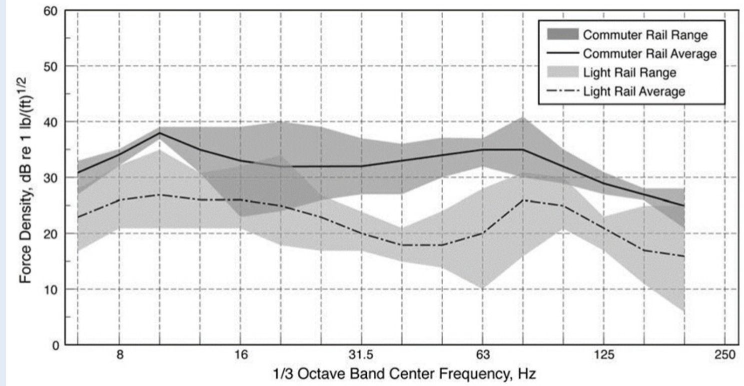
Difficult to be assessed during the tender phase without an extensive annalysis and tests

Requirements impacting LRV truck designs

2

Absolute requirements

- Ground vibration requirements are often based on FTA Transit Noise and Vibration Impact assessment manual
- FTA requirements are mainly oriented to be experimentally verified
- ISO 2631 is also used as ground vibration reference following ISO 14837 although it is more oriented to measure the on-board ride comfort



Typical force-density spectrums for Rail Transit vehicles at 40 mph (From FTA assessment manual)

Requirements are mainly oriented to be verified by test, and therefore once the vehicle is built

Requirements impacting LRV truck designs

3

Defining the product

- **Unsprung mass,** defining a maximum value or defining the type of drive arrangement
- **Type of primary suspension** or its stiffness value, alternatively the eigen frequency for vertical truck modes (e.g. < 15 Hz)
- **Truck steering** (defining the type of primary suspension)
- **Truck turning** (e.g. not allowing friction surfaces on turning bolsters)
- **Defining the type of wheel** (e.g. requesting resilient wheels)

Requirements impacting LRV truck designs

3

Defining the product

- Pros and Cons of some truck solutions can be found in publications or in the operator own experiences
- FTA guideline introduces the benefits only for “soft” primary suspension while other vehicle parameters are not considered in the simplified analysis

Source Factor	Adjustment to Propagation Curve			Comment
		Reference Speed		
	Vehicle Speed	50 mph	30 mph	
Speed	60 mph	+1.6 dB	+6.0 dB	Vibration level is approximately proportional to 20log(speed/$speed_{ref}$), see Eq. 6-4.
	50 mph	0.0 dB	+4.4 dB	
	40 mph	-1.9 dB	+2.5 dB	
	30 mph	-4.4 dB	0.0 dB	
	20 mph	-8.0 dB	-3.5 dB	
Vehicle Parameters (not additive, apply greatest value only)				
Vehicle with stiff primary suspension	+8 dB			Transit vehicles with stiff primary suspensions have been shown to create high vibration levels. Include this adjustment when the primary suspension has a vertical resonance frequency greater than 15 Hz.
Resilient Wheels	0 dB			Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz.
Worn Wheels or Wheels with Flats	+10 dB			Wheel flats or wheels that are unevenly worn can cause high vibration levels.

(From FTA assessment manual)

Requirements impacting LRV truck designs

- Requirements involving the transmission path are difficult to be assessed during the tender process giving uncertainty about the final outcome on both sides
- Requirements imposing technical solutions should be weighted carefully as could lead to non-optimal vehicle level solutions

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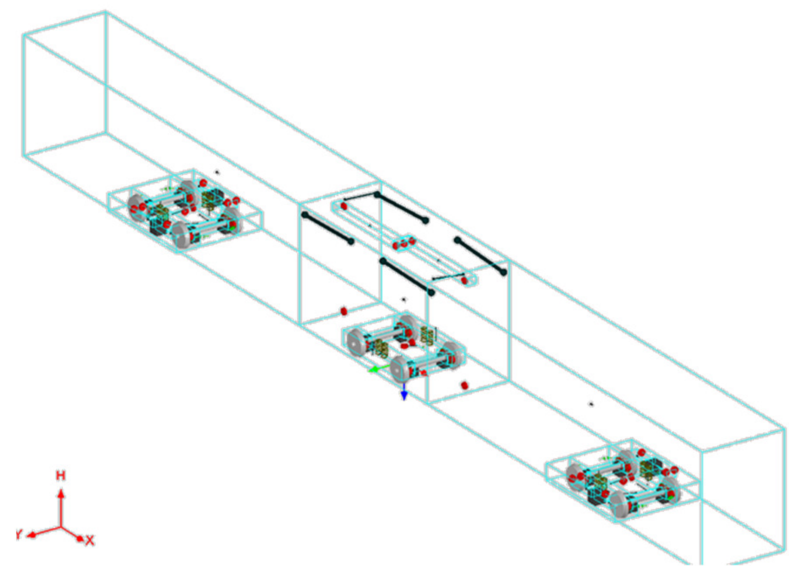
Truck design - main relevant solutions

Suspensions	Unsprung masses	Steering & Turning capability
▪ Primary suspension	▪ Wheelset optimization ▪ Drive arrangement ▪ Resilient wheel	▪ Carbody connection ▪ Guiding concept ▪ Railway wheelset
1	2	3

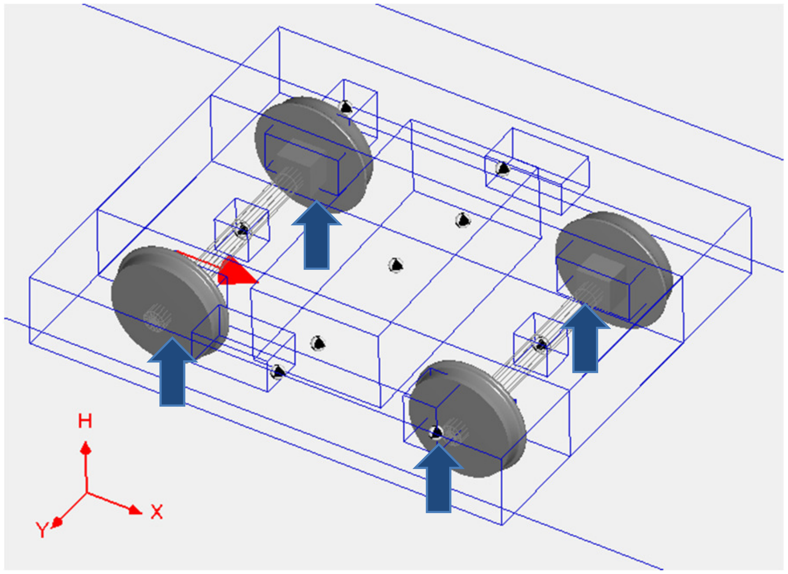
Truck design - main relevant solutions

- A **M**ulti**B**ody **S**imulation (MBS) LRT model has been used to quantify the influence of different truck solutions.
- The used MBS model was originally indented for running dynamics and comfort safety and therefore with reliable content up to 40hz.
- In detailed studies, specific models will be required to cover all frequency range of interest.



Truck design - main relevant solutions

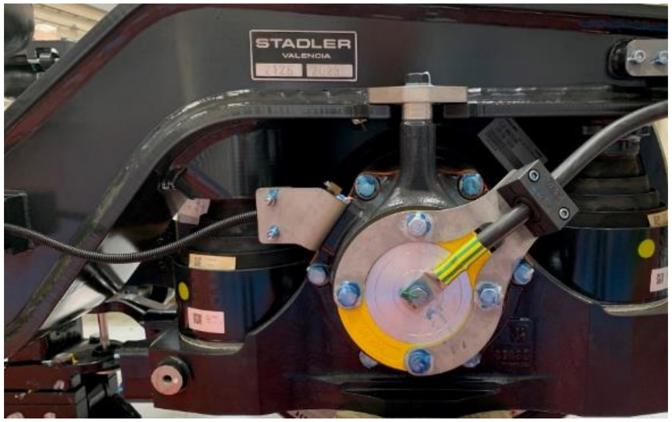
- The outcome of the MBS model is the force spectrum results (N/Hz^2) obtained at the wheel/rail interface on the front wheelset for each configuration.
- Note that presented spectrums are not comparable with FTA experimental force density graphs (lbs/ft^1/2)



Truck design - main relevant solutions

1 Primary suspension analysis

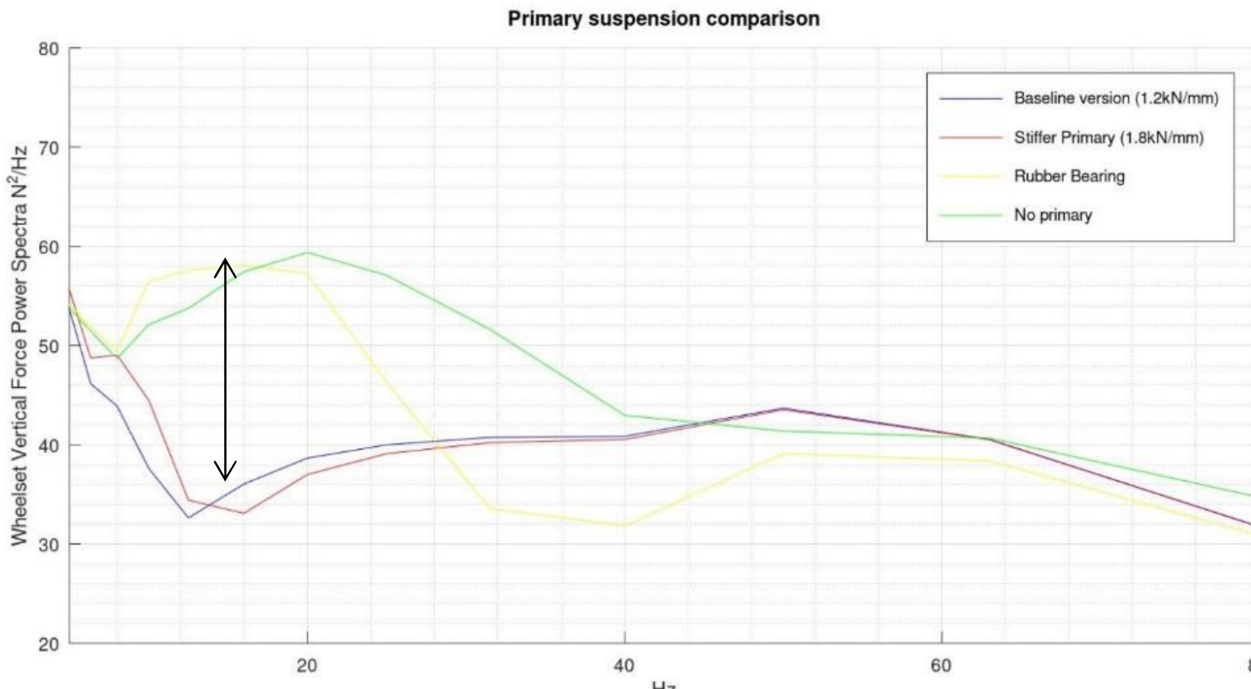
MODES	Baseline Primary 1.2kN/mm	Stiffer Primary 1.8kN/mm	Rubber Bearing 8kN/mm	No primary
Carbody Bounce (Hz)	2	2.1	2.2	2.2
Bogie Bounce (Hz)	9.6	10.3	19.8	28.7
Bogie Pitch (Hz)	8.6	9.8	26.4	38.2



Truck design - main relevant solutions

1 Primary suspension

Type of primary 4-80hz filtered	RMS kN	
Baseline Primary 1.2kN/mm	1.63 (baseline)	
Stiffer Primary 1.8kN/mm	1.73	+6.7%
Rubber Bearing 8kN/mm	3.85	+137 %
No primary	4.67	+187%



Results in line with the FTA assessment manual

Truck design - main relevant solutions

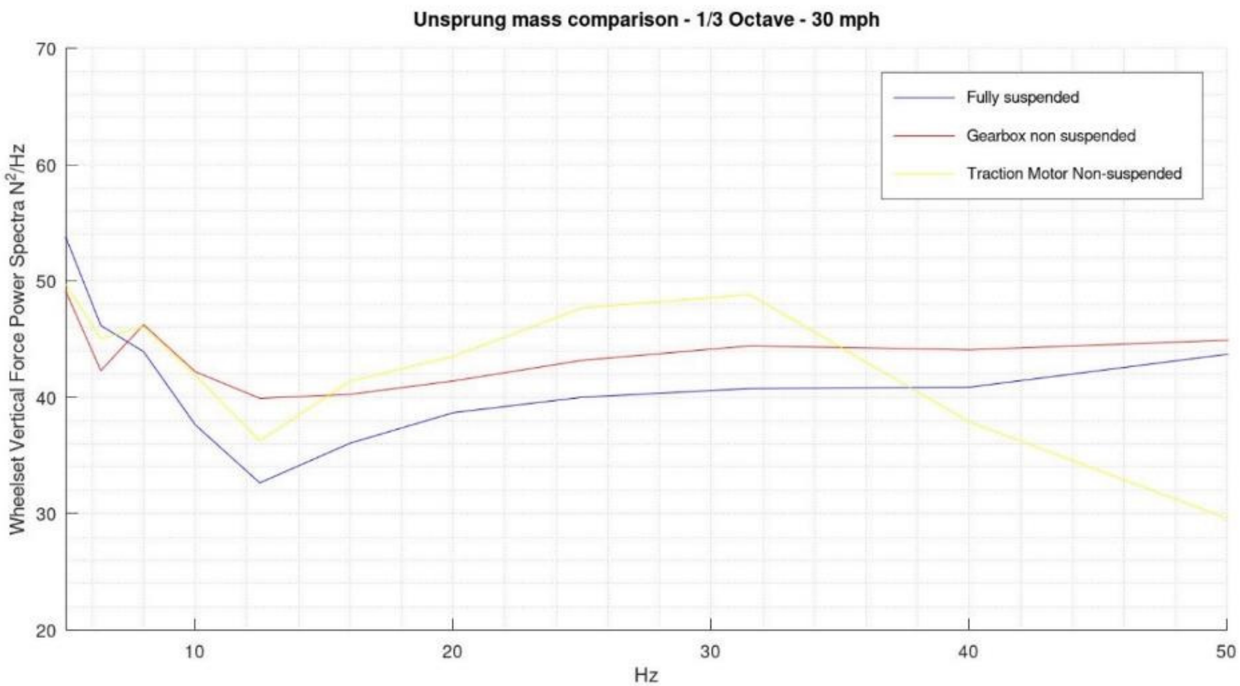
2 Unsprung Masses

- Optimized fully suspended drive
- Partially suspended drive
- Non-suspended drive and motor

Truck design - main relevant solutions

2 Unsprung Masses

Type of primary 4-80hz filtered	RMS kN	
Baseline Fully suspended	1.63 (baseline)	
Gearbox non-suspended	1.66	+2%
Traction Motor non-suspended	1.64	+1 %



No relevant overall average impact (likely >40hz underestimated)

Truck design - main relevant solutions

2 Resilient Wheel

There are several wheel typologies:

- Classic solid wheels
- Resilient wheels (usually 150-250 kN/mm)
- So-called Ultra Resilient wheels (usually 25 kN/mm)

In LRV, resilient wheels are currently standard because of high frequency vibration and noise benefits

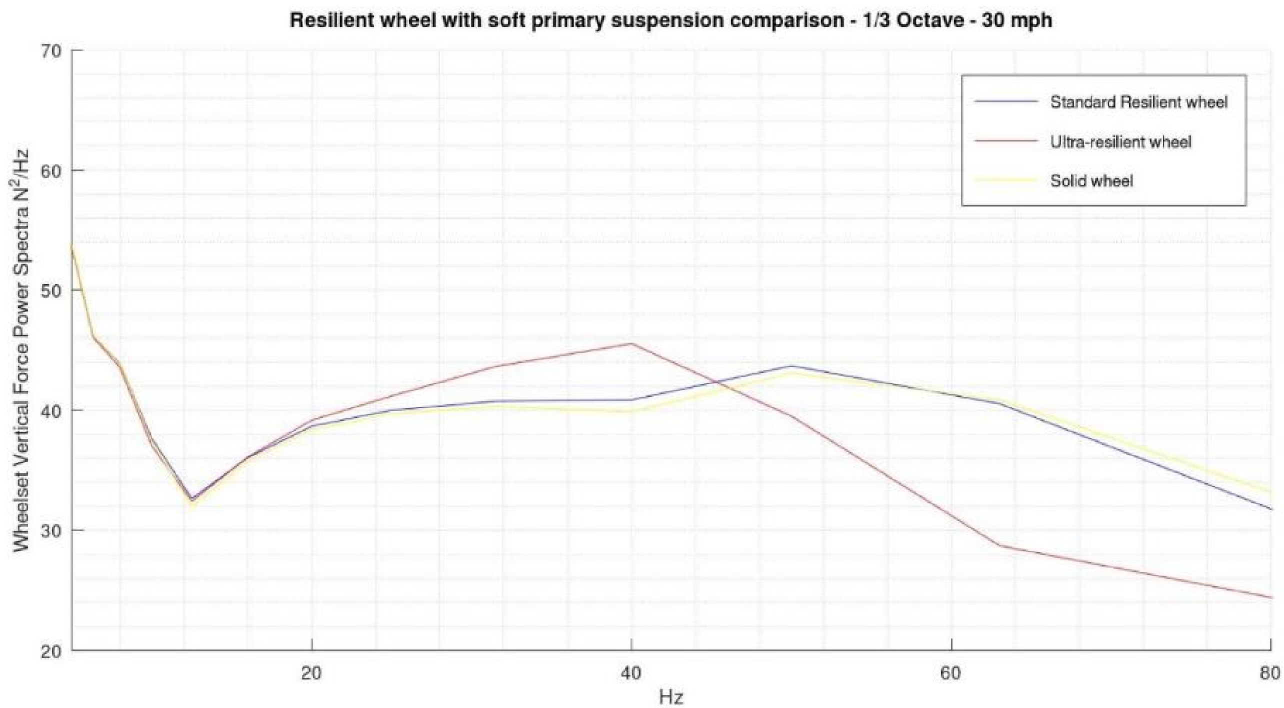
Ultra Resilient wheels are usually used in vehicles with high unsprung mass or no primary suspension

Truck design - main relevant solutions

2 Resilient Wheels

Soft primary suspension

Type of primary 4-80hz filtered	RMS kN	
Resilient wheel	1.63 (baseline)	
Solid wheel	1.60	-2.0%
Ultra resilient wheel	1.67	+2.7 %



No relevant overall average impact although resilient wheels effect (>40h) is underestimated

Truck design - main relevant solutions

2 Unsprung Masses

On top of the ground vibrations requirements there are **other considerations** like track damage and noise where **unsprung mass and the standard resilient wheel have an important role**.

Parameter	Definition	Units	Baseline	Non_suspended GB	Non_suspended Drive
P0	wheel load	kN	49,05	49,05	49,05
Mu	vehicle unsprung mass per wheel	kgs	325	500	1000
V	vehicle velocity	mph	50	50	50
P2	P2-Force	kN	66,4	73,1	87,7
Delta from baseline		%		**10%**	**29%**

Vertical dynamic forces (P2) Calculation

Truck design - main relevant solutions

3 Carbody connection

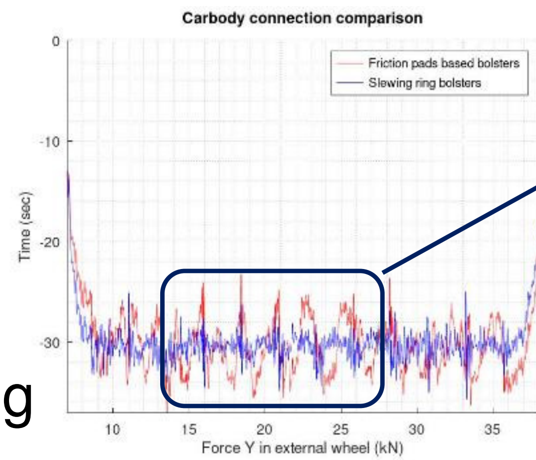
Vehicle concepts requiring truck to carbody turning angles above 6-7º use turning bolsters. The more common solutions are:

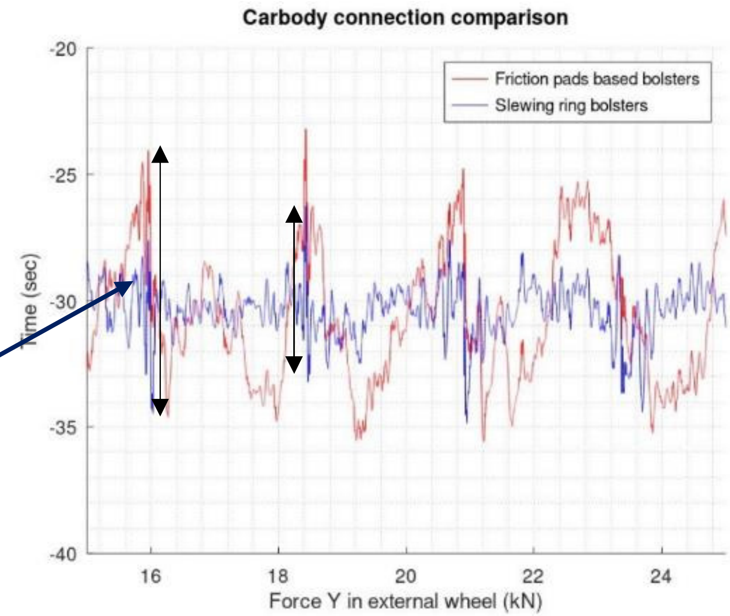
- Slewing ring bolsters
- Side friction pad based bolsters

Truck design - main relevant solutions

3 Carbody connection

Friction based bolsters introduce higher forces, vibrations and noise than alternative solutions because the related sliding and stick motion





50 m curve simulation & outer wheel lateral force

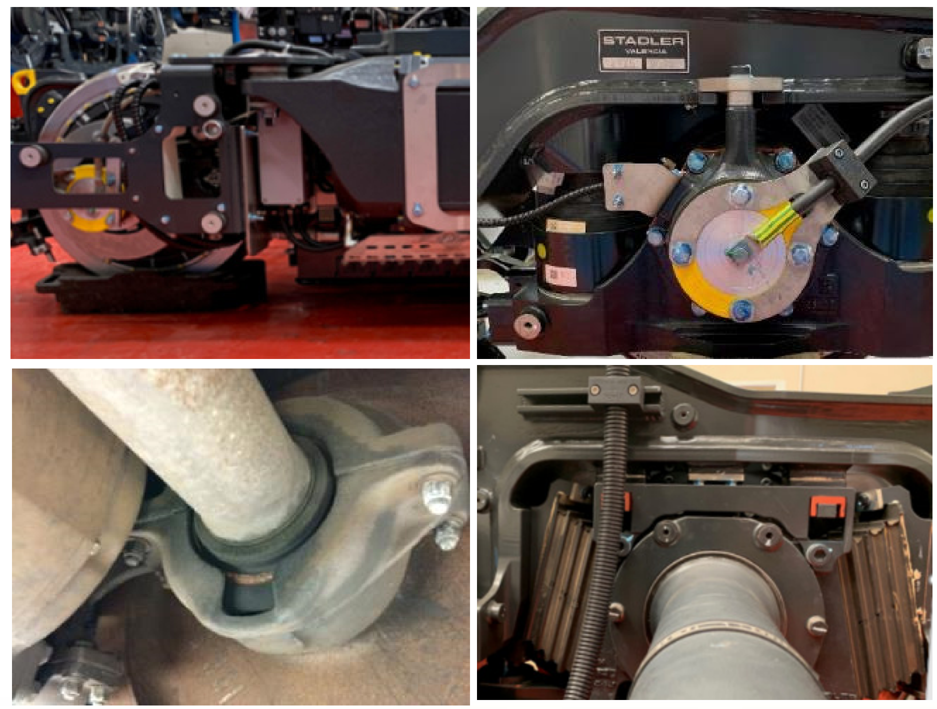
4-5 kN improvement of oscillation with slewing ring

Truck design - main relevant solutions

3 Guiding concept

Primary suspension common steering arrangements are:

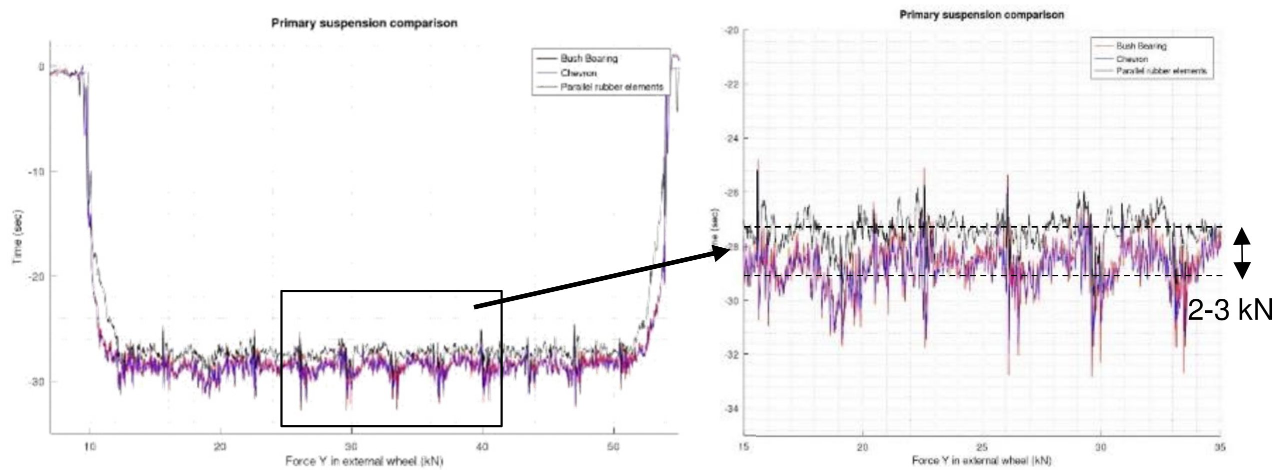
- Chevron type
- Parallel rubber element type
- Bush Bearing type



Truck design - main relevant solutions

3 Guiding concept

Although not directly linked to ground vibrations, optimized steering systems are recommended to reduce the track lateral forces and track damage



Lateral forces on a 50 m curve

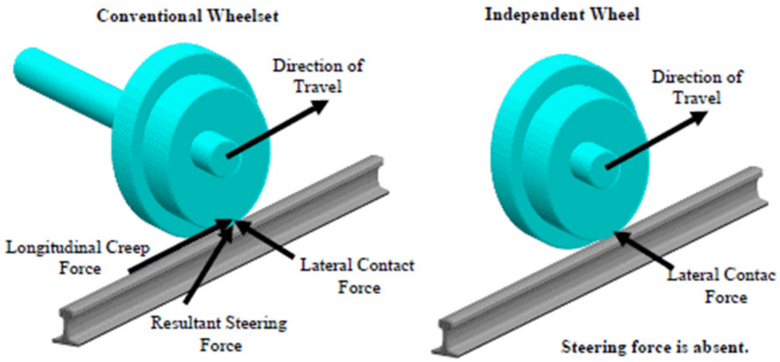
2-3 kN improvement with an optimized parallel rubber primary suspension

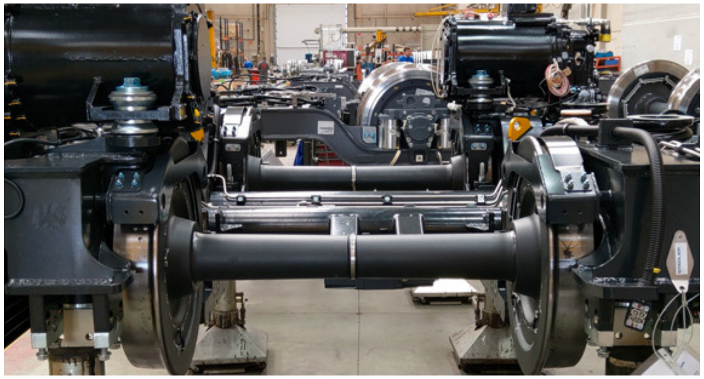
Truck design - main relevant solutions

3 Railway wheelset

- Railway wheelsets
- Independent wheel arrangements

Railway wheelsets give better steering features and less flange / rail wear



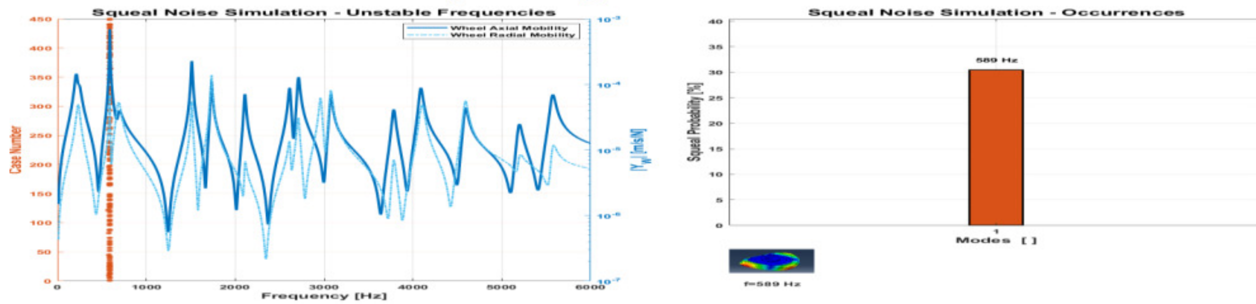


Truck design - main relevant solutions

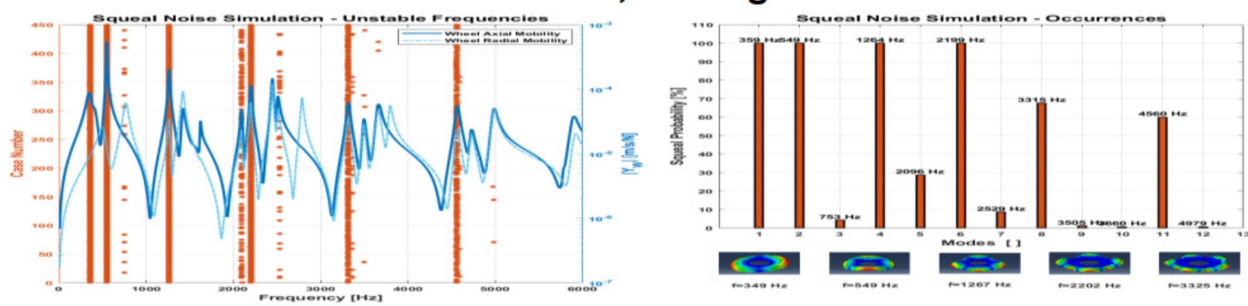
3 Railway wheelset

We have also verified a lower probability of squeal noise phenomena with a railway wheelset

Tramlink – inner wheel, leading wheelset



Reference vehicle – inner wheel, leading wheelset



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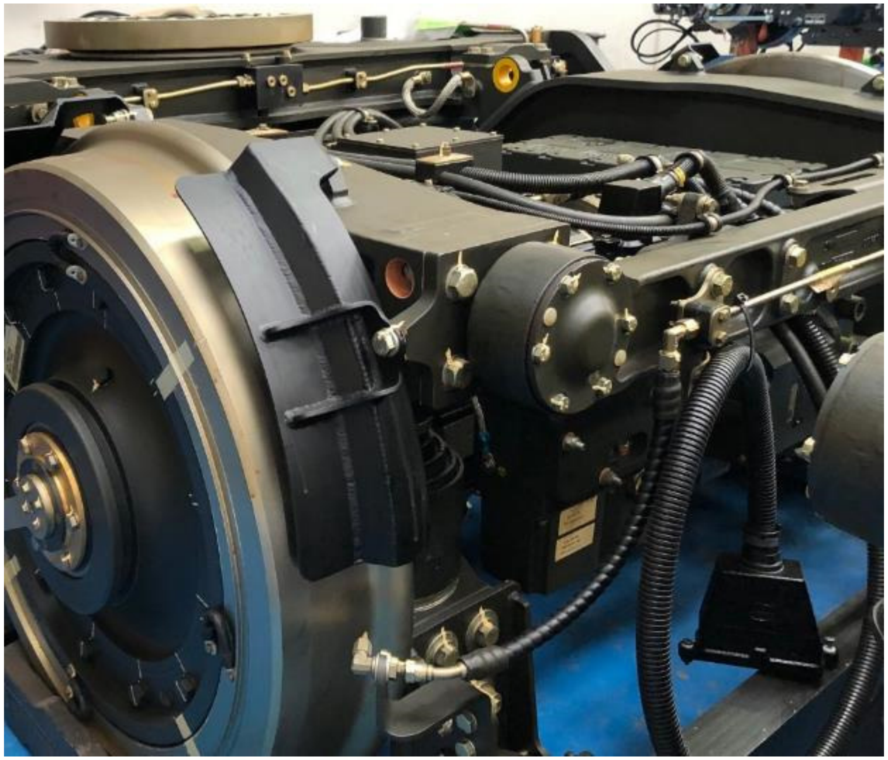
Optimized Truck designs

- The soft primary suspension is the main vehicle parameter influencing ground vibrations, followed by a low unsprung mass.
- Ultra-resilient wheels are likely only justified when combined with stiff primary suspensions although higher frequency models are needed to prove it by calculations.
- Friction free suspensions systems should be preferred
- Optimized primary suspension steering systems and real railway axles should be the preference when possible

Optimized Truck designs

Additionally to the ground vibrations, the following requirements need to be considered on the truck design:

- Safety
- Passenger comfort
- Overall truck weight
- Vehicle integration (low floor)
- Installed braking/traction power
- Life Cycle Cost



Optimized Truck designs

Requirements must be incorporated into the vehicle concept

Ground Vibrations and Noise | Truck Design

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Takeaways

1. Define **<u>specific and measurable</u>** requirements
2. **<u>Holistic vehicle concept</u>,** incorporating different requirements
3. **<u>Soft vertical primary suspension</u>** is mandatory
4. **<u>Frictionless suspension</u>** system are recommended
5. **<u>Minimize unsprung masses</u>** by suspending the full drive
6. **<u>Solid axle</u>** wheelset truck architecture when possible

Thank you for your time!
Questions?

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