Harmonic Vehicle/Track Interaction: Using Simulation Tools to Increase Train Speeds and Safety Assurance

Raphael Marotta

Lucas Valente

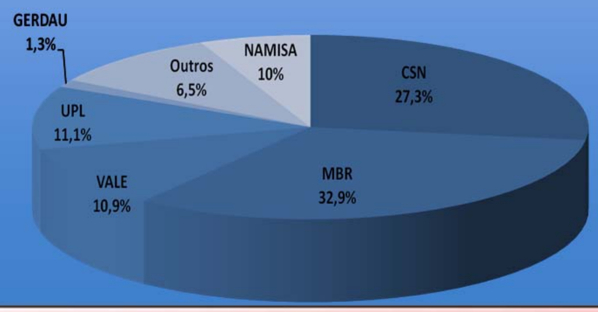
MRS Logistic in Brazil

MRS Logística is a concessionary that controls, operates and monitors the Southeastern Federal Railroad Network.

The company has been in operation in cargo railway transportation since 1996

Across the rails, connect the three main economic centers of Brazil: Rio de Janeiro, Minas Gerais and São Paulo.

MRS' Shareholders



Why a presentation on harmonic excitations?

- Some derailments are related with harmonic excitations.

Methodology developed to analyze the vehicle dynamic behaviour taking in account the MRS's features of vehicles, track and operation.

- Operation's need to increase speed in many sections of MRS track safety.
- Case: Derailment with a GHS (Gondola-Hopper) wagon with worn truck conditions.

What is a resonance phenomenon ?

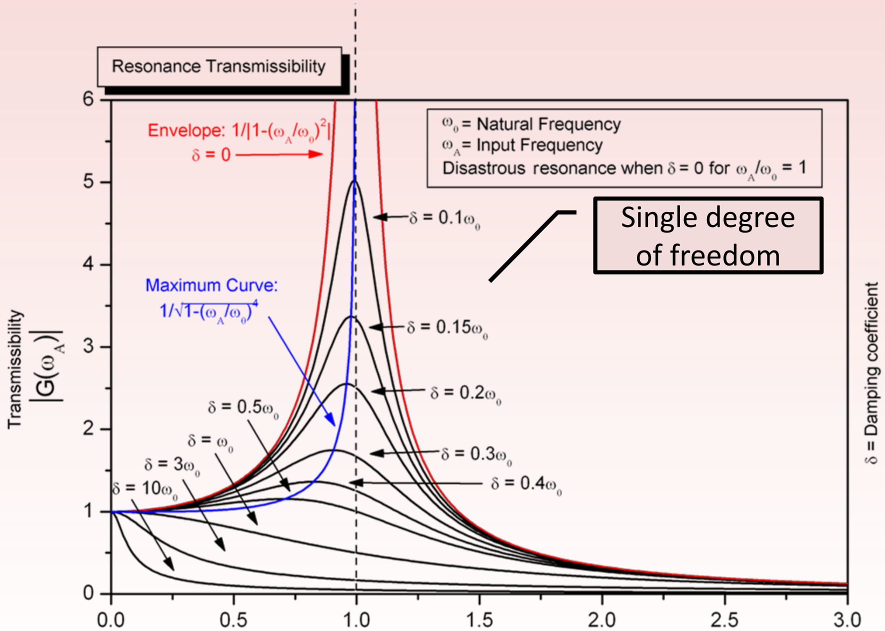
In a railway track irregularities are harmonic motion of the base

- A vibratory system will have energy dissipated when oscillating only under an initial disturbance.

- An external force must be applied to maintain an oscillation motion, such as: harmonic, nonharmonic, transient or random.

- Resonance is a harmonic excitation, when the frequency of excitation coincides with the natural frequency of the system.

What is a resonance phenomenon ?

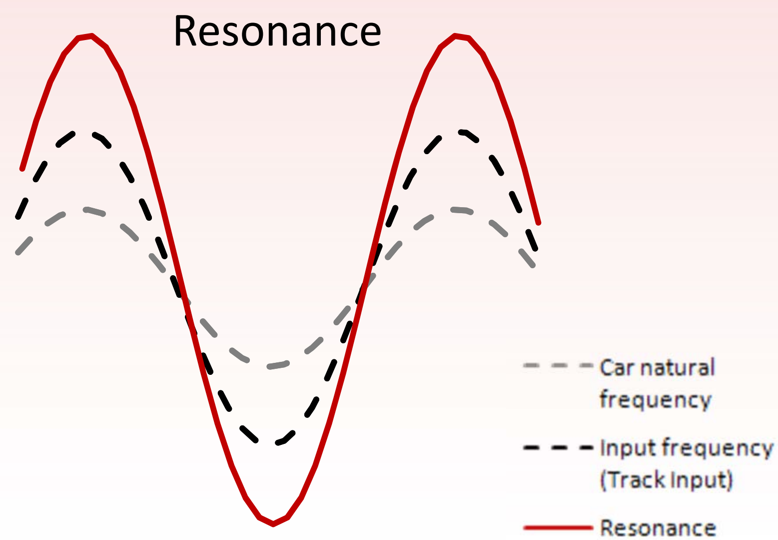


$$fr = \frac{f1}{f2}$$

$$fr = \frac{f1}{f2} = 1$$

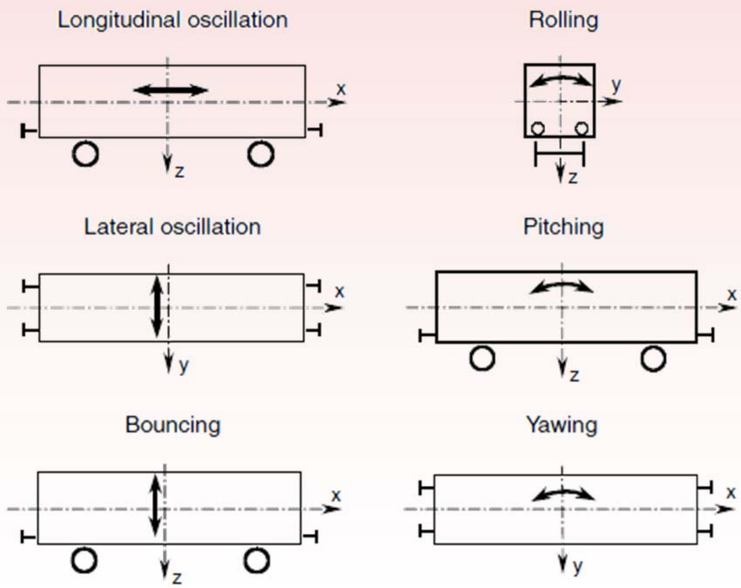
$f1 \longrightarrow$ Natural frequency

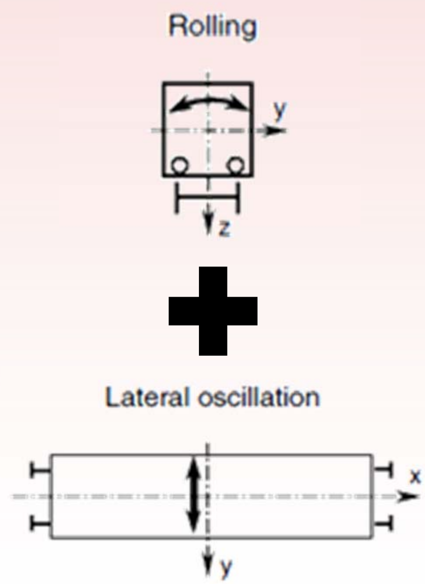
$f2 \longrightarrow$ Excitation frequency

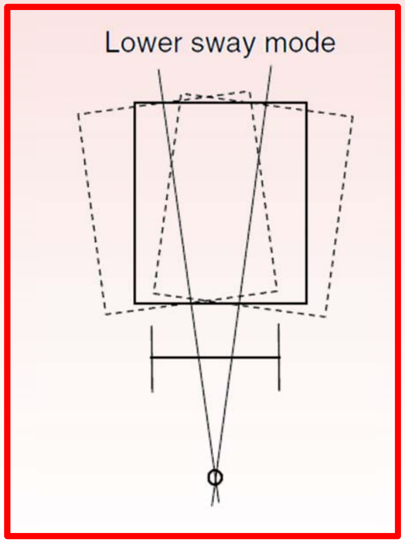


Carbody modes

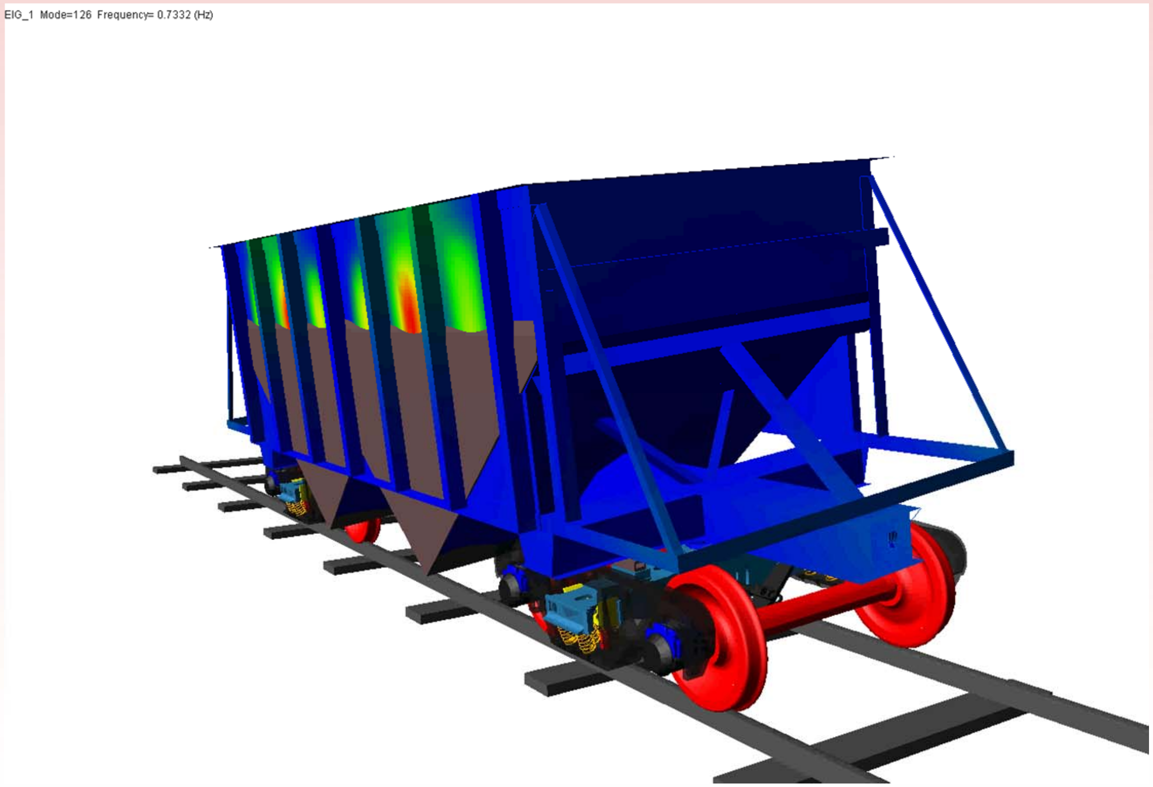
The lower sway is a combination between rolling and lateral oscilation.





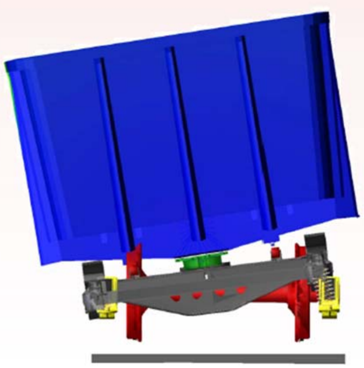


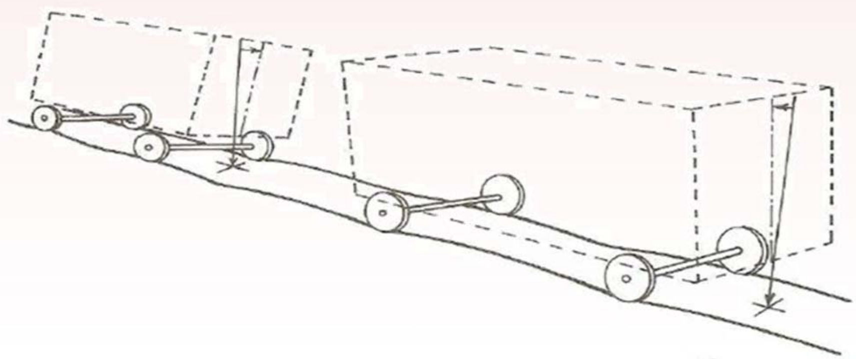
Carbody modes

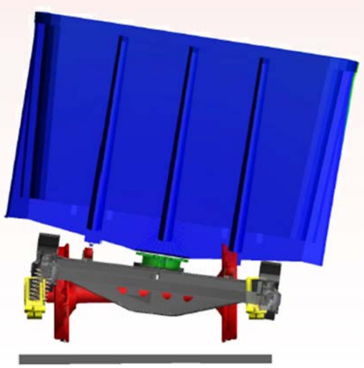


Lower sway

- The lower sway motion is related to the cross level irregularity.
- The harmonic instability occurs when the excitation frequency is near to the carbody natural frequency of sway mode.







Vehicle modal analysis

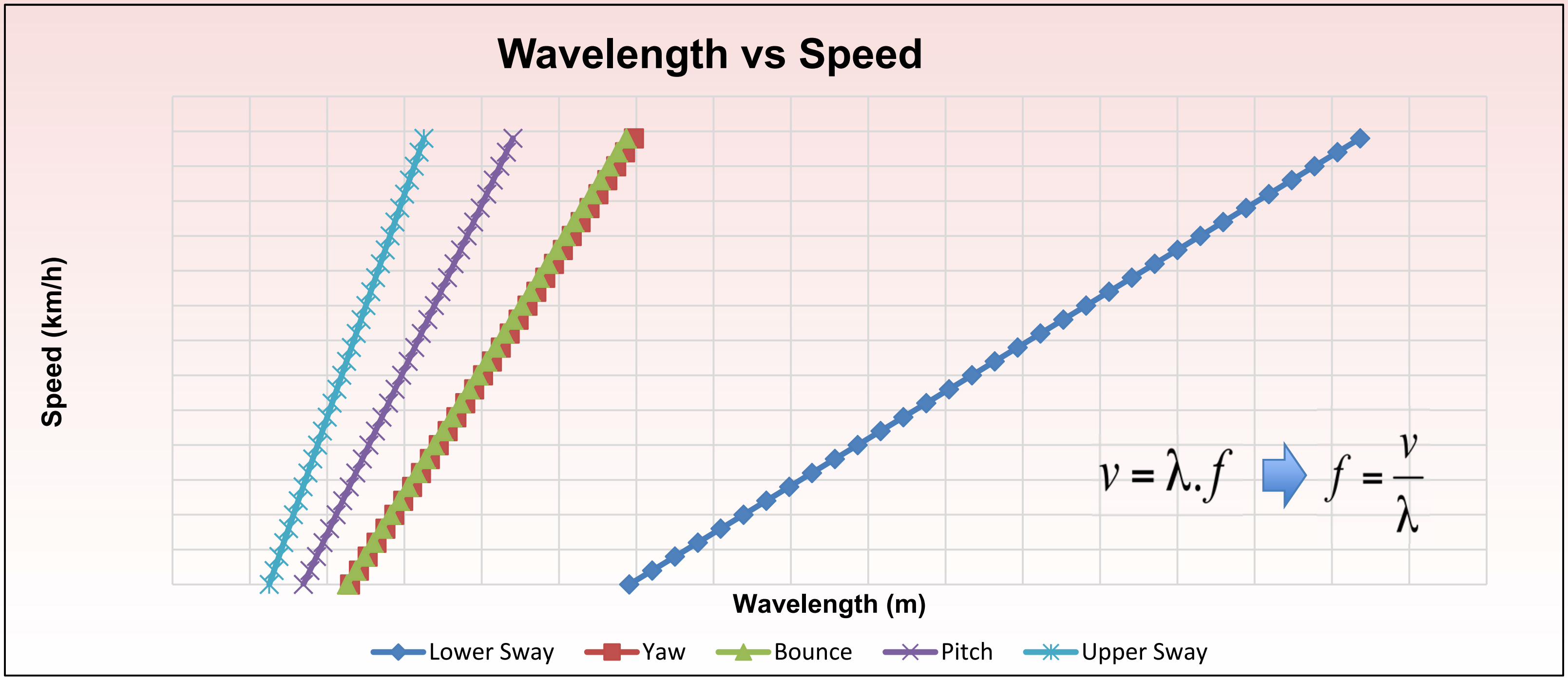
- Eingenvalue method
  - Although the freight car is suspension is non-linear, this analysis allows to examine and understand about the carbody mode. The result is the free response of the system.

Frequency	Mode	f_n(Hz)	ζ	f_d(Hz)
1	Lower sway	f_{LS}	*LS*	f_{LS}
2	Yaw	f_{Y}	*Y*	f_{Y}
3	Bounce	f_{B}	*B*	f_{B}
4	Pitch	f_{P}	*P*	f_{P}
5	Upper sway	f_{US}	*US*	f_{US}

f_n: Natural frequency
ζ: Damping factor
f_d: Natural frequency

Harmonic combination

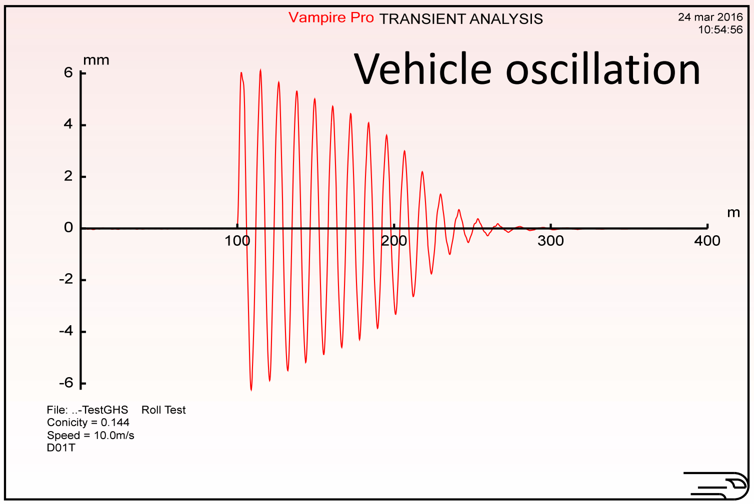
Connecting speed, frequency and wavelength, thus:



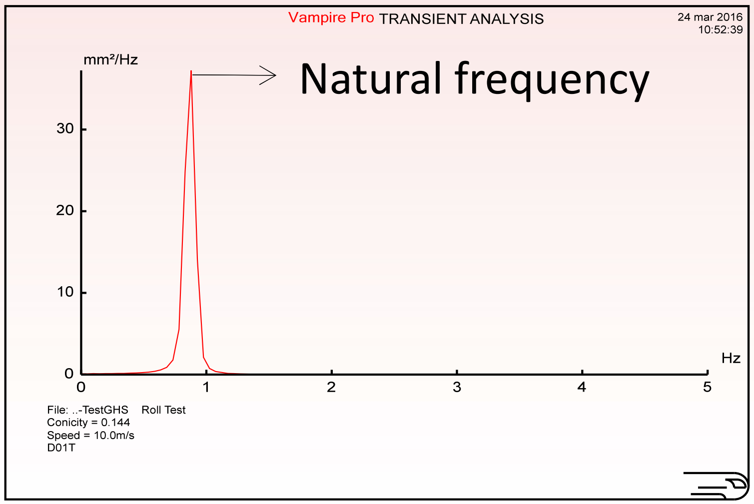
$$v = \lambda . f \Rightarrow f = \frac{v}{\lambda}$$

Lower sway frequency

- Transient method
- An external force is applied in the carbody center of gravity.
- 2 simulations were performed, one with friction wedges(damping natural frequency) and the other without(natural frequency).



VAMPIRE Plot



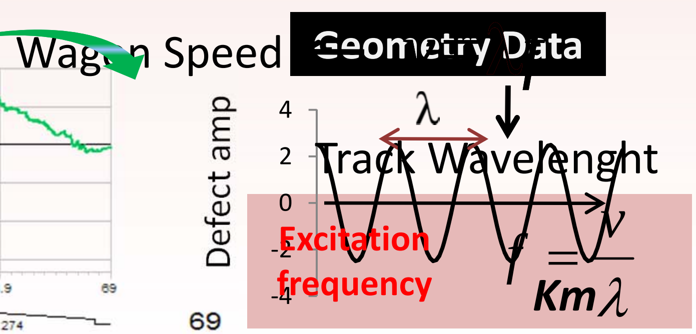
VAMPIRE Plot

Lower sway frequency

Geometry data processing

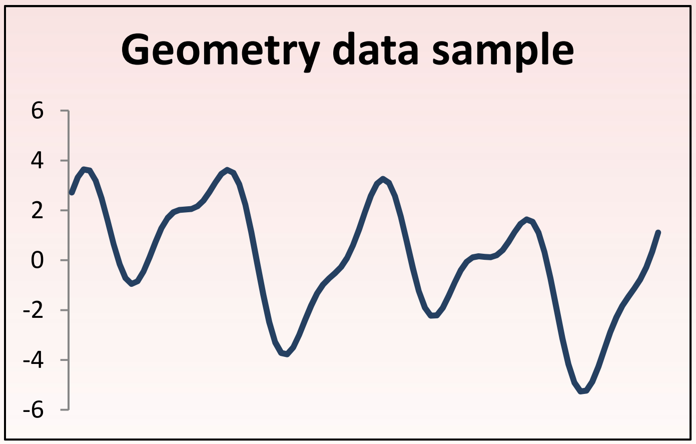
- After modal analysis it is necessary identify the λ from geometry data provided by the TrackSTAR
- It is usual to apply Signal Processing Tools for this purpose

Strip Chart (Cross level)



Geometry data processing

- The geometry data is defined as a sum of sines and cosines
- λ is determinated using the Fast Fourier Transform method



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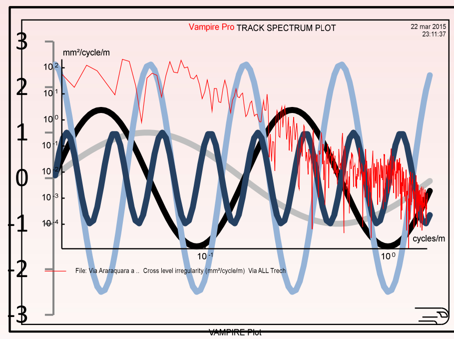
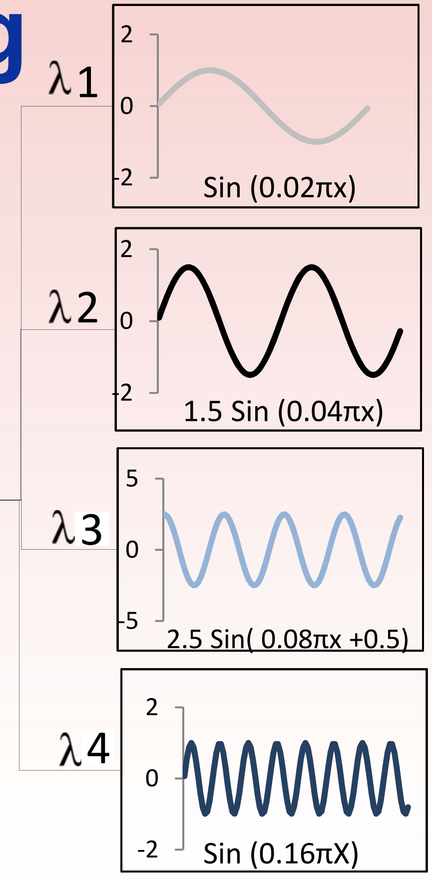
PSD



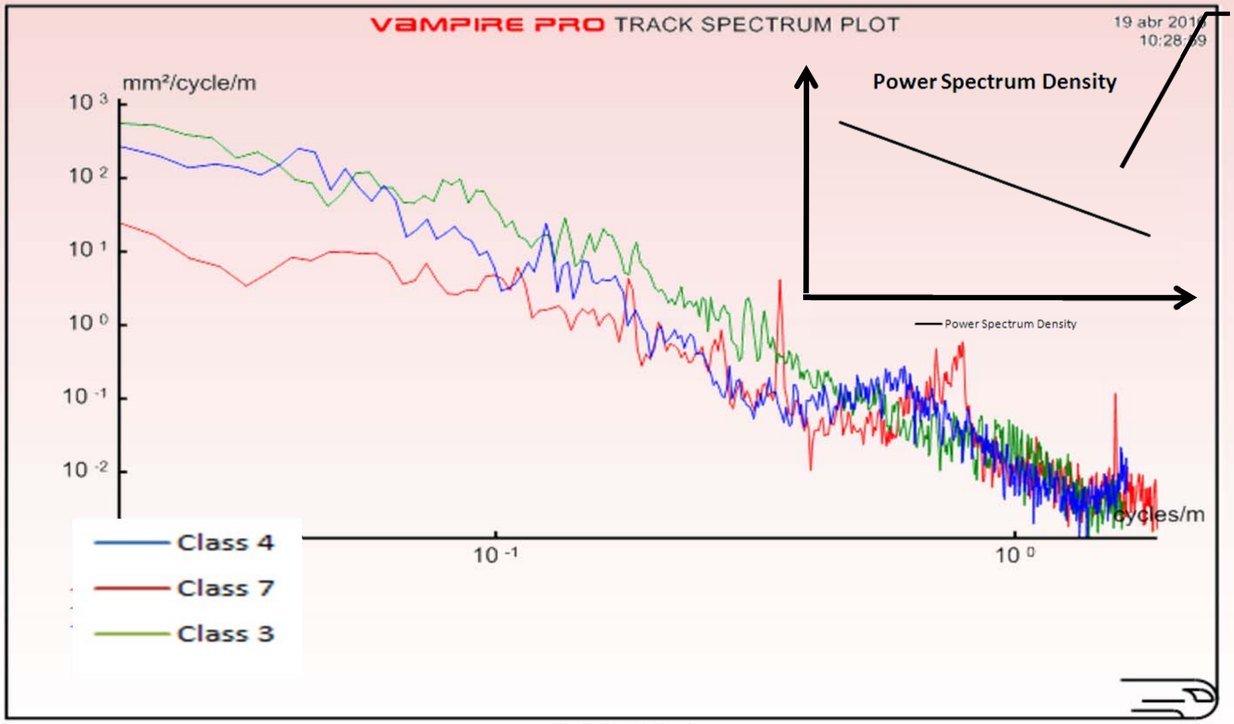


$$f(x) = \sin(0.02\pi x) + 1.5\sin(0.04\pi x) + 2.5\sin(0.08\pi x + 0.5) + \sin(0.16\pi x)$$

An alternative way to represent track geometry

Geometry data processing

P
O
W
E
R



VAMPIRE Plot

Frequency

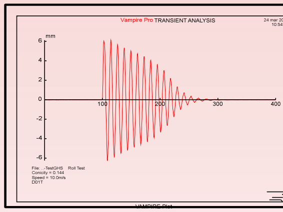
Expected behavior of a PSD

Geometry data processing

- With the modal analisys completed, the next step is to determine the frequency bands of interest.
- Upper and Low frequency limits must be defined.

What do we need to identify if the resonance phenomenon occurs?

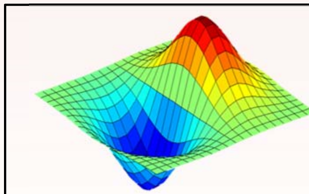
- Determinate power within the frequency band.
- A higher power level correspond to most likely resonance.
- Diagnosticate risk areas (mile post) and confirm the diagnosis through simulation.



Modal Analisys

Track Inspetion

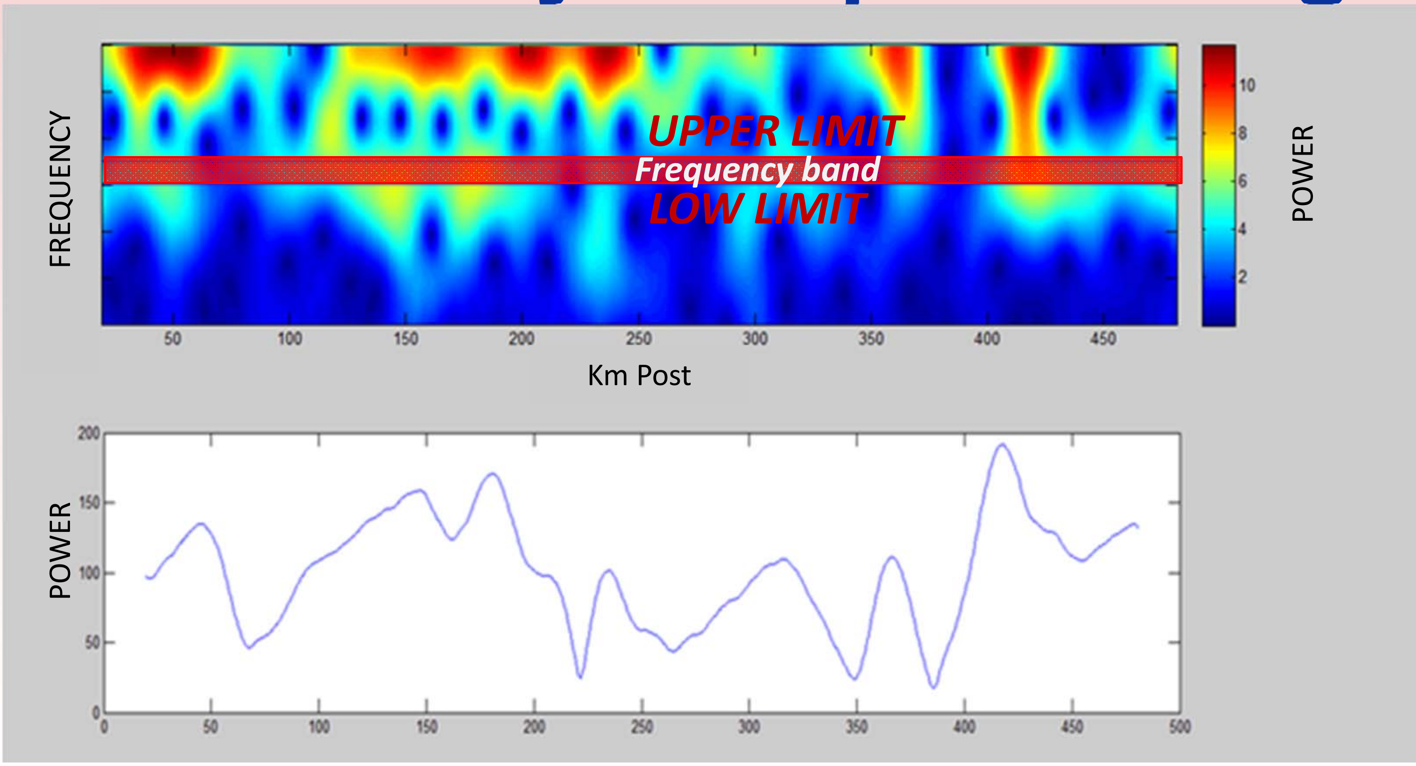
Input data



Geometry data processing

Simulation

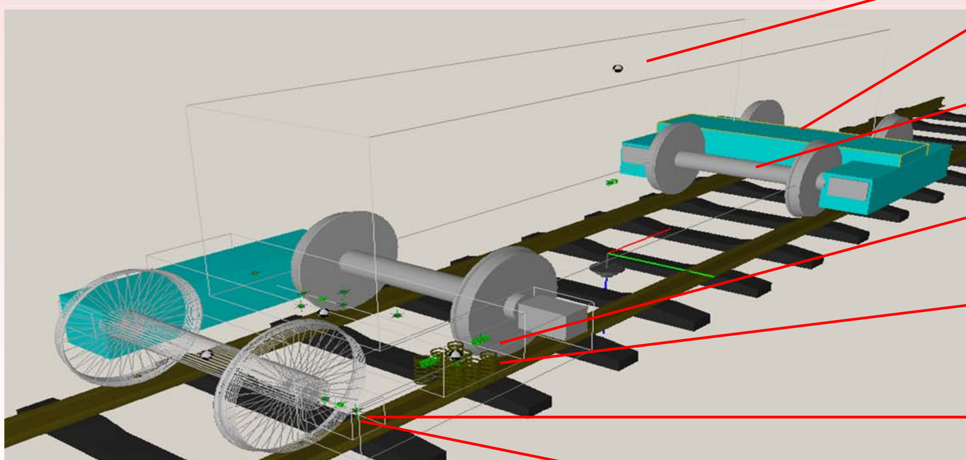
Geometry data processing



Power within the frequency band

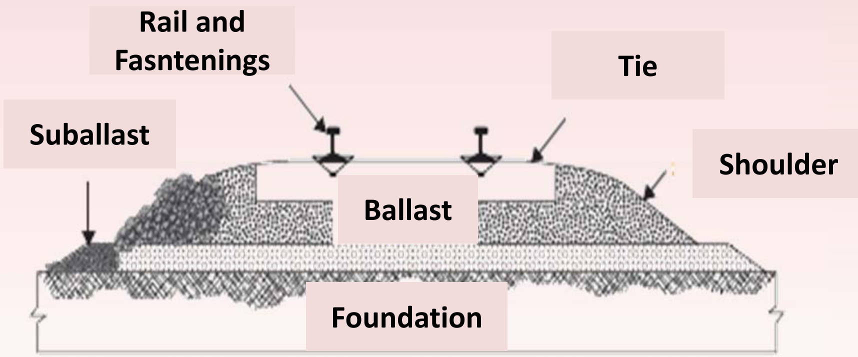
Simulation – Vehicle Modeling

Main vehicle modeling elements in VAMPIRE



Simulation – Track Modeling

Main track modeling elements in VAMPIRE



Geometry – Track Geometry Car

Vertical Stiffness

- Track Modulus – Field Instrumentation, Track Inspection Vehicle.

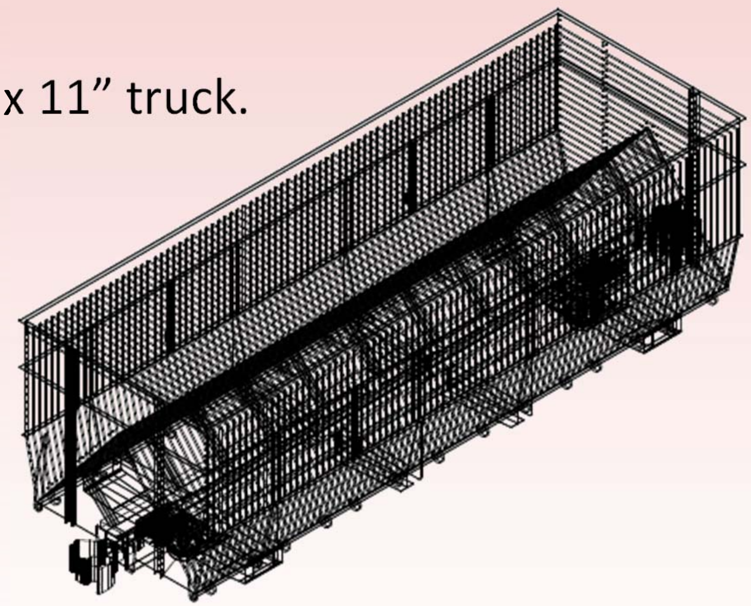
Lateral Stiffness

- Rail to tie – TrackSTAR
- Tie to ballast – STPT, Tamping Machines.

Case – GHS derailment

GHS – Vehicle Modeling

- Vehicle GHS 100 tons with Ride Control 6” x 11” truck.
- High conicity wheel profile.
- Center of gravity height: 2.21 m.
- Block side bearing.
- Constant damping with worn wedges.
- 62 degree-of-freedom.



Note: Friction wedges in worn conditions due to failure in the manufacturing process

Vehicle modal analysis

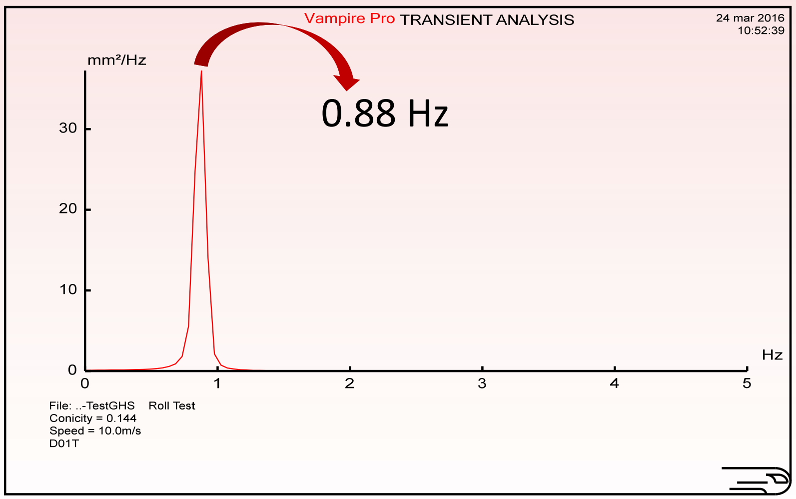
- Eingenvalue method results:

Frequency	Mode	f_n(Hz)	ζ	f_d(Hz)
1	Lower sway	0.94	0.04	0.94
2	Yaw	2.42	0.14	2.40
3	Bounce	2.46	0.07	2.45
4	Pitch	3.28	0.09	3.27
5	Upper sway	4.44	0.18	4.37

Lower sway frequency

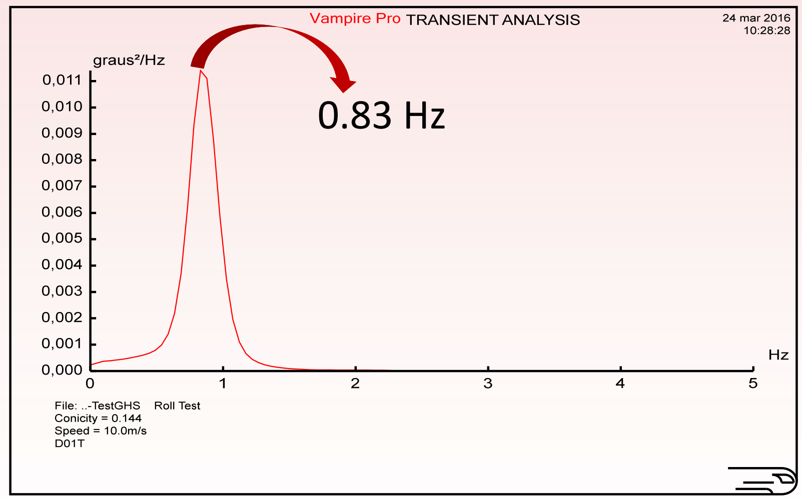
- Transient method results:

Natural frequency



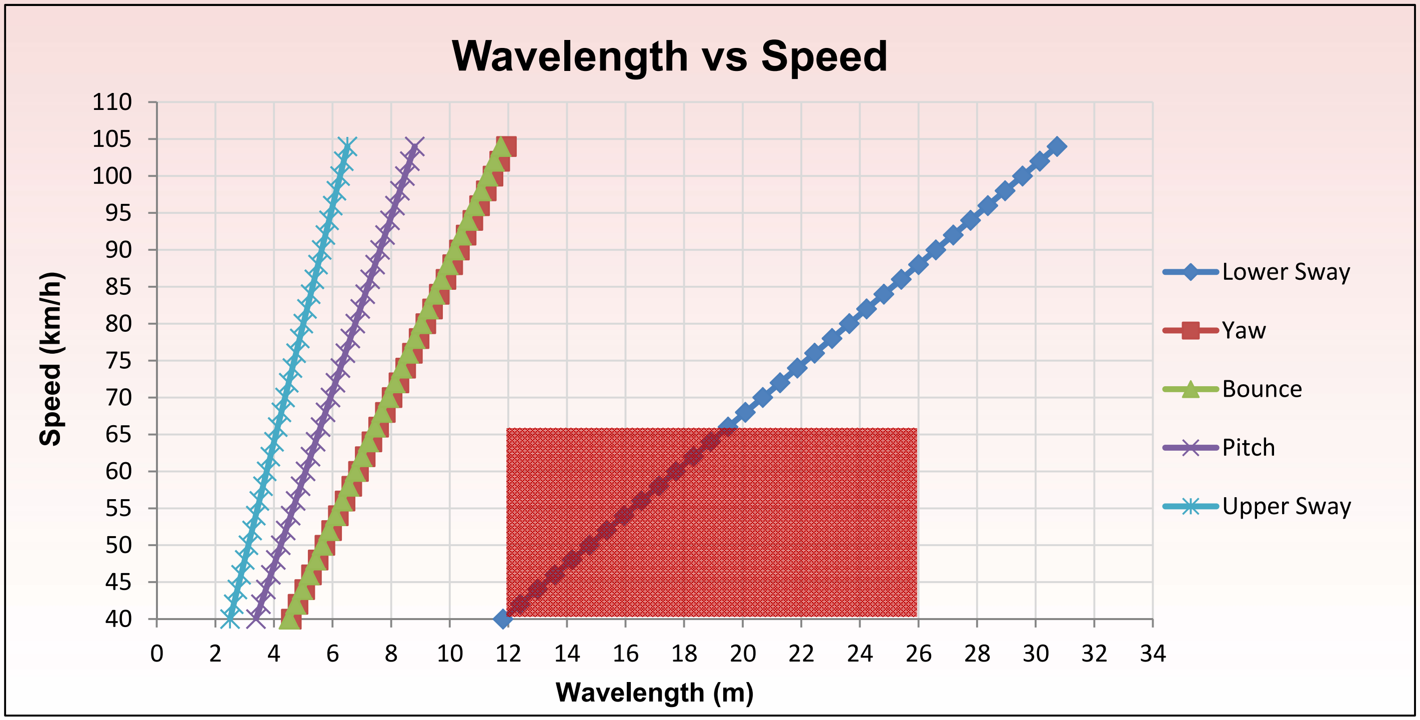
VAMPIRE Plot

Damping natural frequency



VAMPIRE Plot

Harmonic combination



Harmonic combination

- CWR length at MRS   240 m
- Bar length – 24 m

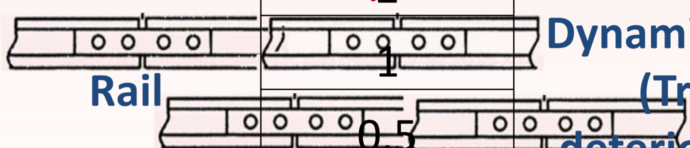
If the rail or welds joints were applied in a alternating way the λ will be 12 m

- The wavelength is more or less the same CWR length due the low stiffness region

Dominant Component	Wavelength (m)	Parameter Affected
Ballast	50	Vehicle (Comfort)
	20	
	10	
	5	
Rail	2	Dynamic forces (Track deterioration)
	1	
	0.5	
	0.05	

Low stiffness

λ = 24 m



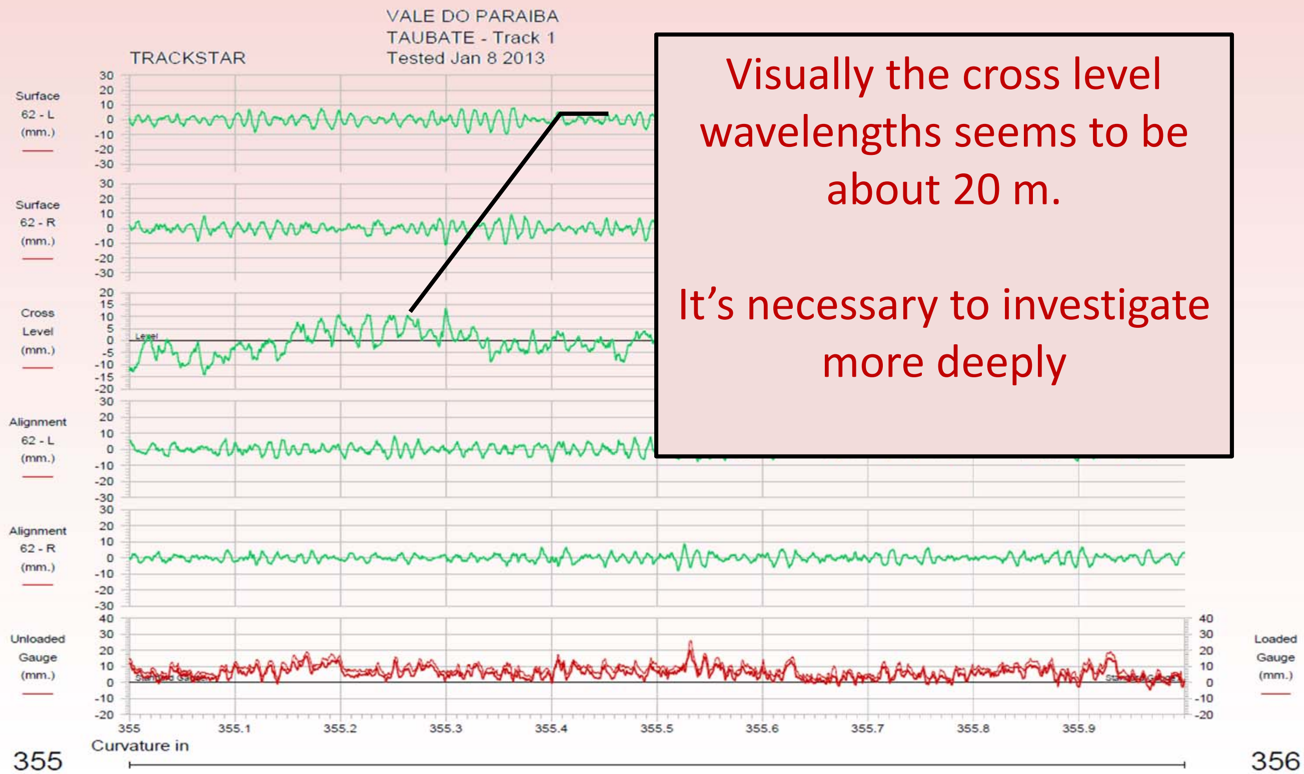
Low stiffness

Mode	f_n(Hz)
Lower sway	0.94
Yaw	2.42

50 km/h → $v = \lambda . f$ → 2.42

$$\lambda_{yaw} = 5.72\ m$$

Track geometry at derailment site



Visually the cross level wavelengths seems to be about 20 m.

It's necessary to investigate more deeply

MAXIMUM DEFECTS AMPLITUDES

Surface – 10 mm

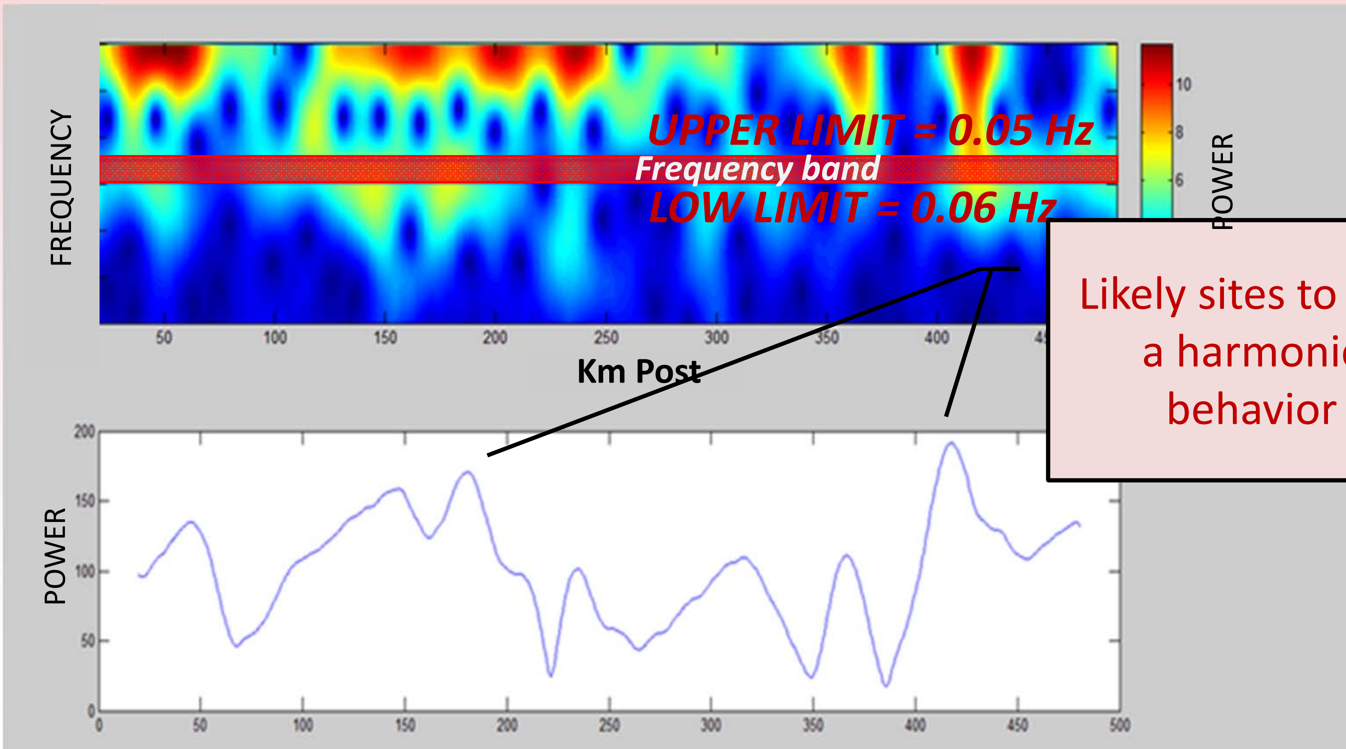
Alignment 12 mm

Cross level – 17 mm

Gauge – 20 mm

No geometry exceptions

Track Geometry Analysis



Likely sites to find a harmonic behavior

From the modal analysis

Damping natural frequency - 0.83 Hz

Natural frequency - 0.88 Hz

Frequency band lower sway 0.83Hz to 0.88Hz

Speed

λ = 15m - 16 m

$f = 1/\lambda$

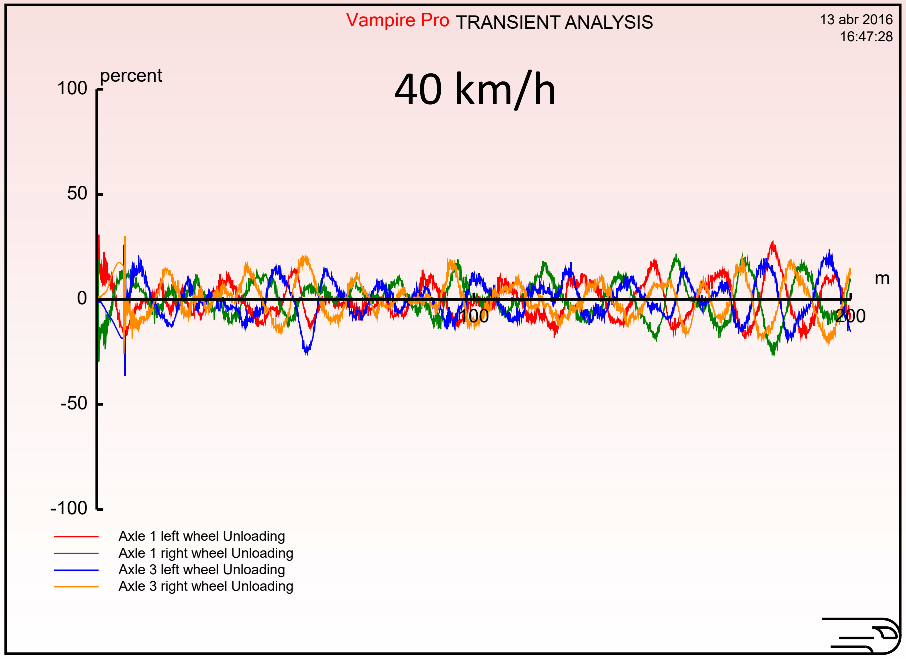
$v_f = \lambda . f$

$f = 0.05Hz - 0.06Hz$

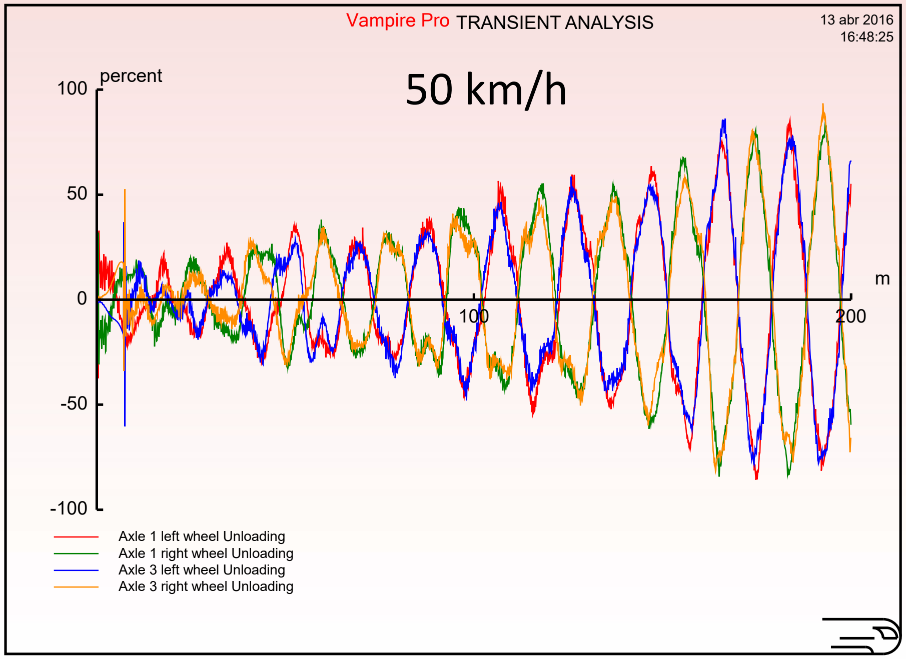
Natural frequency 0.83Hz to 0.88Hz

Simulation results

- Wheel unloading results:



VAMPIRE Plot



VAMPIRE Plot

Results reached through simulation

Location	Speed Gain	Car type
Ferrovia do Aço	50 ➡ 64	Gondola
Paraopeba	30 ➡ 40	Fuel tank car
Paraopeba	40 ➡ 50	Cement tank car
Vale Paraíba	50 ➡ 64	-

STEPS TO INCREASE SPEED SAFELY

- L/V
- Hunting
- **Harmonic Behavior**
- Longitudinal Dynamic

- After the derailment at Vale do Paraiba, the harmonic behavior is taken into account to increase train speeds at MRS.
- **No derailments related to harmonic behavior since 2013 !**

Conclusions

- Harmonic excitation analysis is an important step to increase speed safely.
- Multibody simulations can be applied to support new operation conditions.
- The simulations can reduce cost and time in instrumentation field tests, if necessary.
- The methodology presented is applicable for any vehicle, speed, and carbody modes.

Questions ?

Raphael Marota
raphael.marotta@mrs.com.br

Lucas Valente
lucas.valente@mrs.com.br