Understanding seismic waves generated by train traffic via modelling

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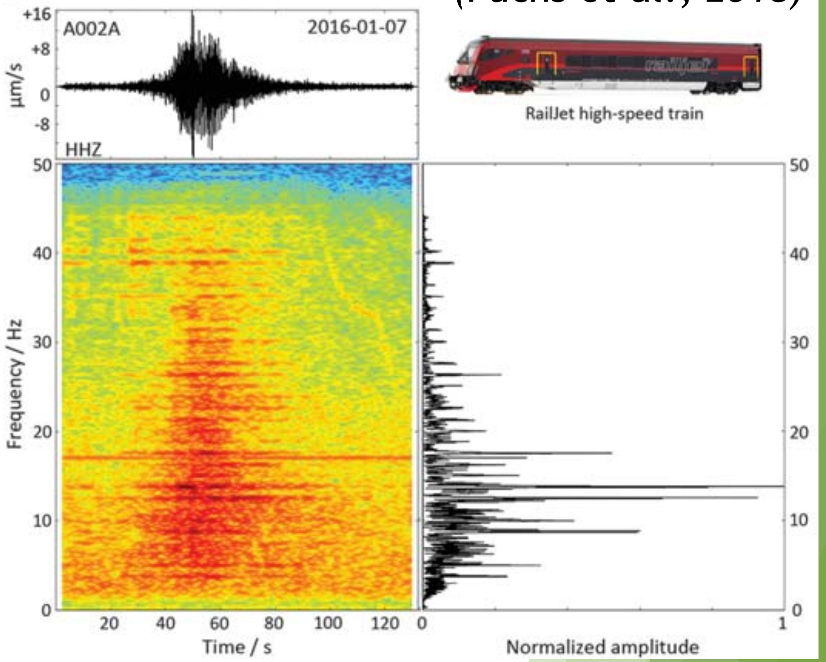
Outline

- Context and motivation
- Observations
- Modelling strategy
- Train source time functions
- Results
- Conclusions and perspectives

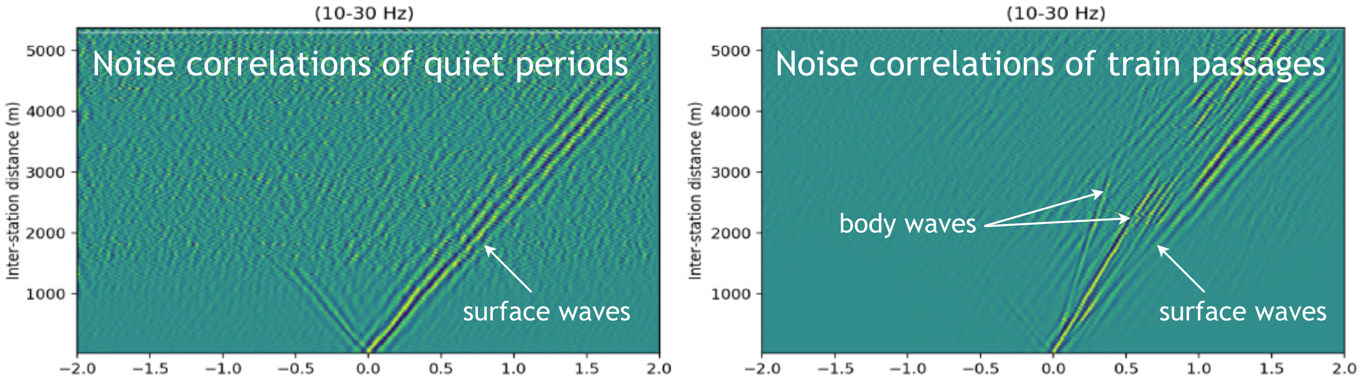
Context and motivation

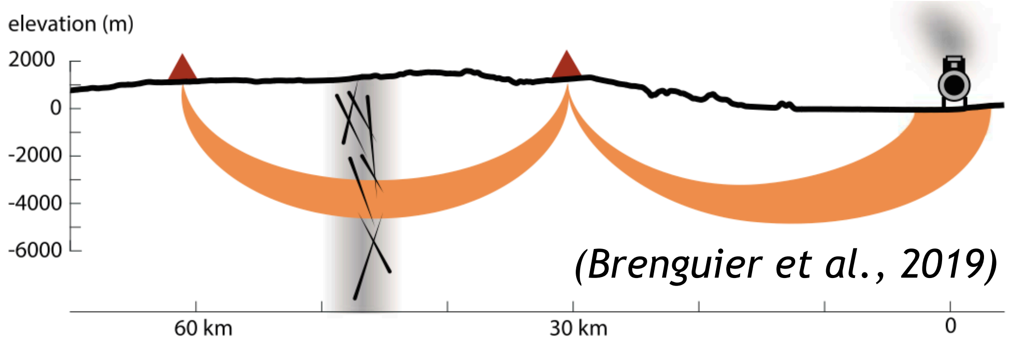
- Trains are now recognized as powerful sources of seismic noise for imaging and monitoring (e.g. Nakata et al., 2011; Quiros et al., 2016; Brenguier et al., 2019; Dales et al., in revision) but we need to understand them better to use them properly.
- State of the art:
  - detailed observations by Fuchs et al. (2018) with good explanatory hypothesis.
  - detailed modelling of the coupled train/track/ground system in the engineering community (e.g. Kouroussis et al., 2011; Connolly et al., 2015; Li et al., 2018) but restricted to the near field.
- Aims of this study:
  - Investigate Fuchs et al’s hypothesis.
  - Draw implications for seismic imaging and monitoring.

(Fuchs et al., 2018)



(Dales et al., in revision)



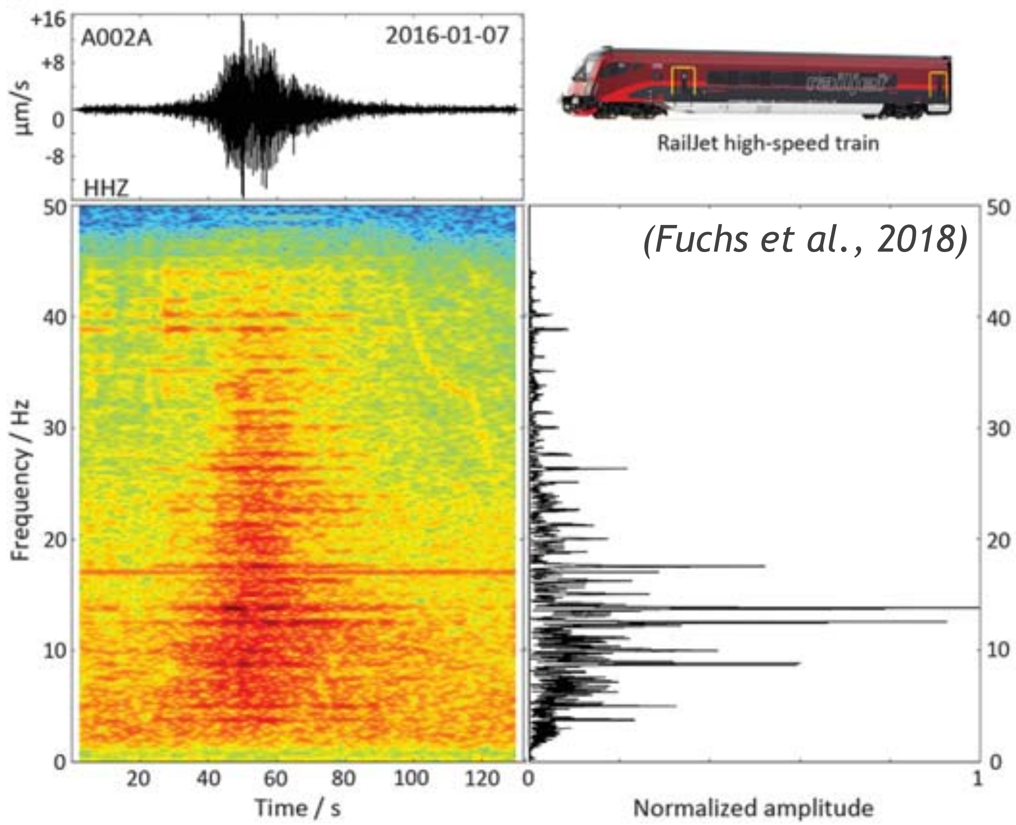


(Brenguier et al., 2019)

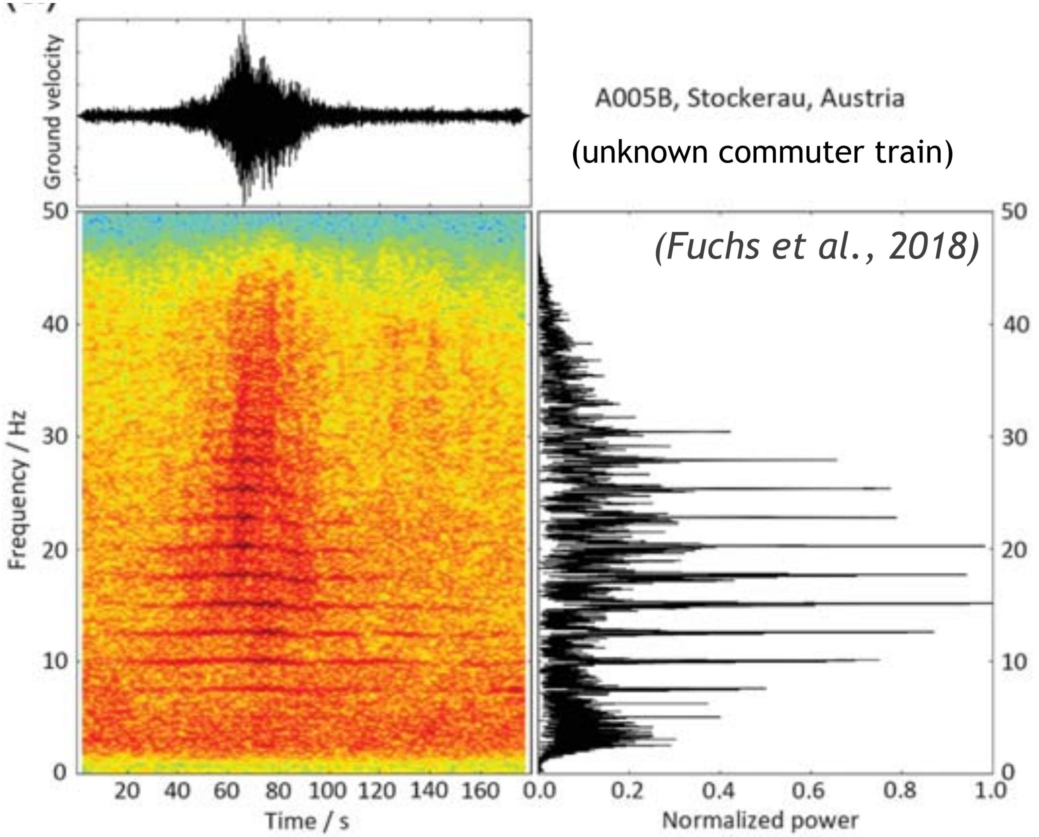
Observations

- Figures: examples of train signals from Fuchs et al. (2018) (without/with Doppler effect).
- Suggested explanation: spectral line spacing related to the passage of train bogies over stationary sources, with a fundamental frequency $f_1 = V_{train}$ / *(bogie distance)*.

(a) $\Delta f = f_1 = 1.25$ Hz ==> V_{train} = 85 km/h, no Doppler effect.

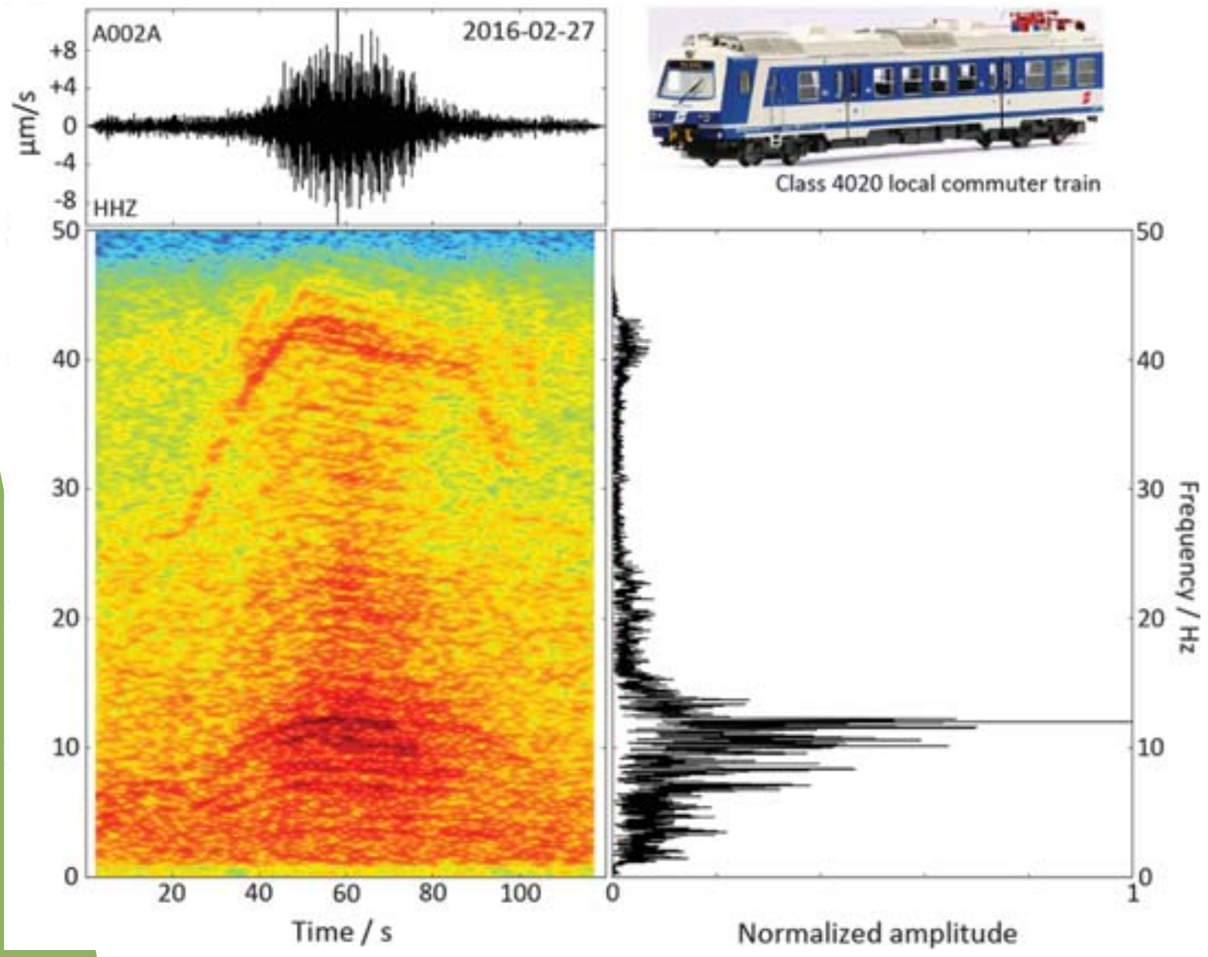


(b) $\Delta f = 2.58$ Hz $\simeq 2 \times f_1$, clear Doppler effect

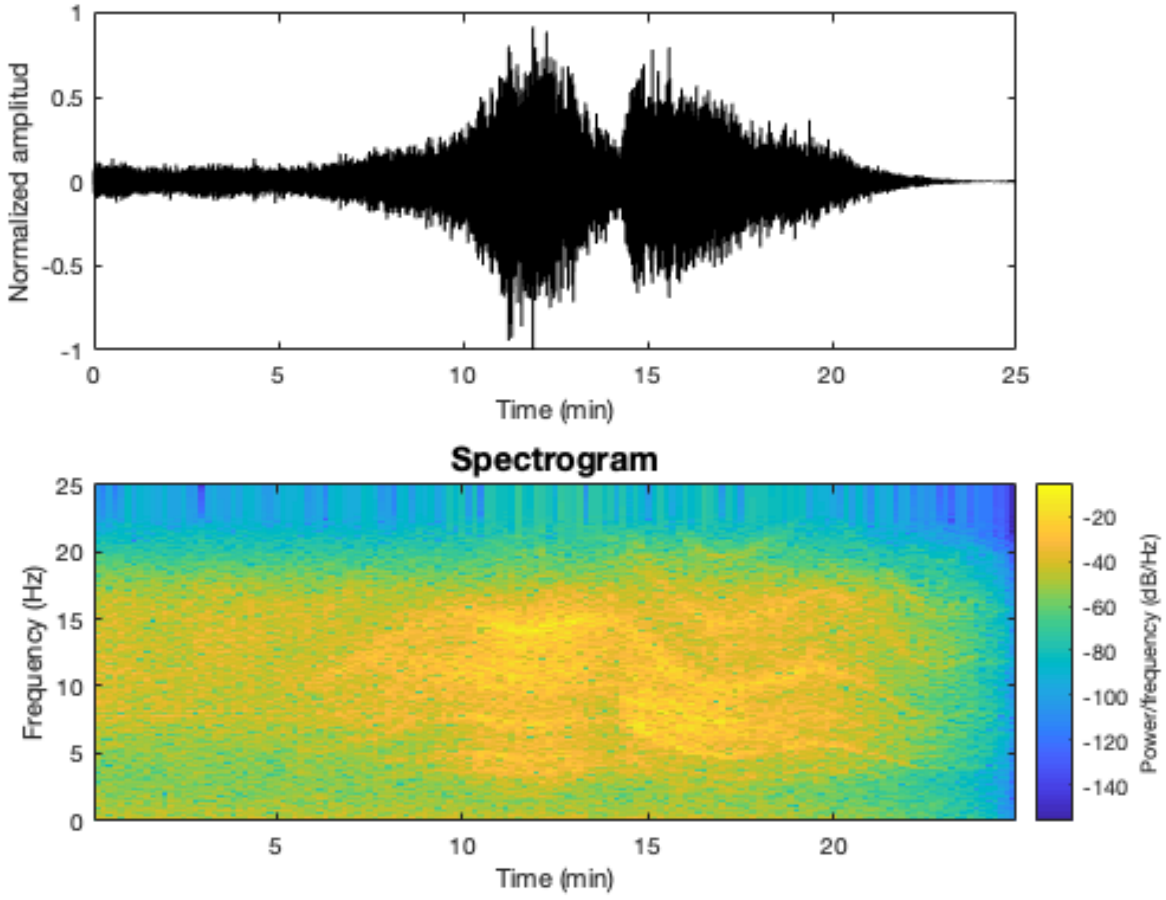


Observations

- Spectral line spacing $\Delta f = f_1 = V_{train}$ / *(bogie distance)* varies with train speed.



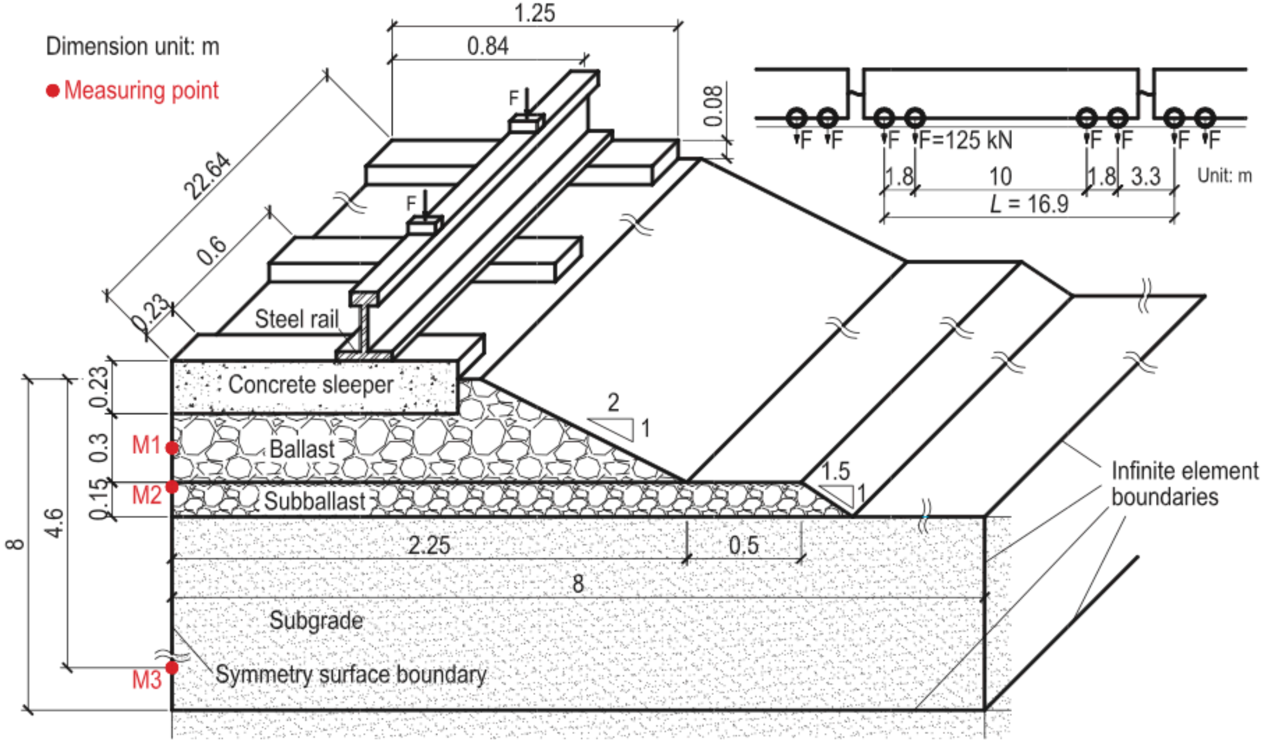
(Fuchs et al., 2018)



(data acquired in Marathon, ON, Canada)

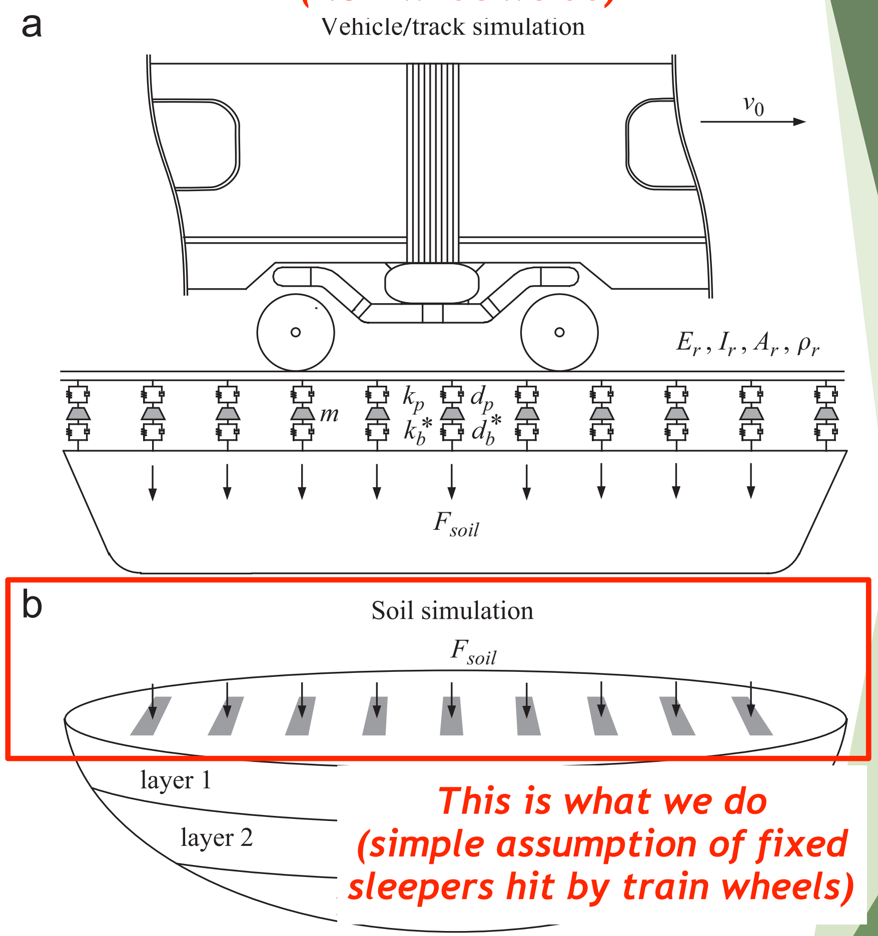
Modelling strategy

Modelling: geometry and mechanisms



Detailed finite-element modelling of a ballasted railway.
(Li et al., 2018)
(NOT what we do)

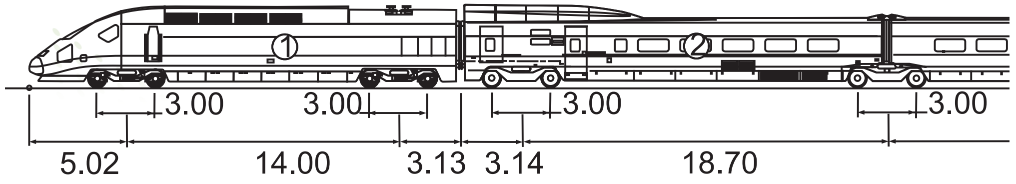
(NOT what we do)



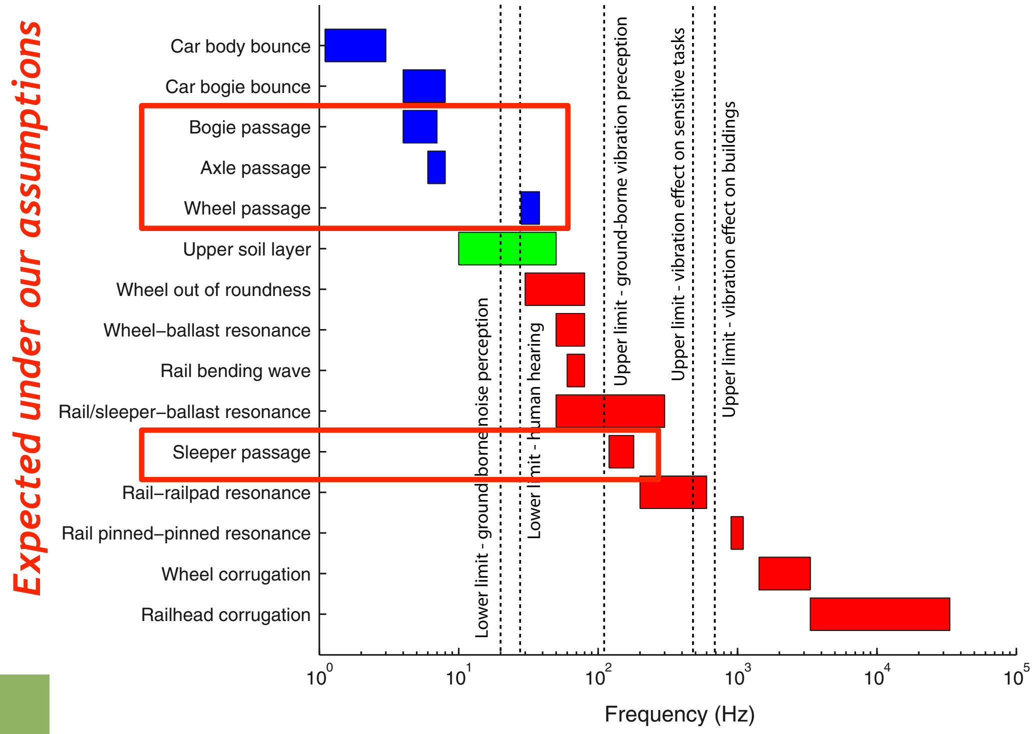
This is what we do (simple assumption of fixed sleepers hit by train wheels)

Decoupled finite-element modelling of (a) the train-track and (b) the soil subsystems.
(Kouroussis et al., 2011)

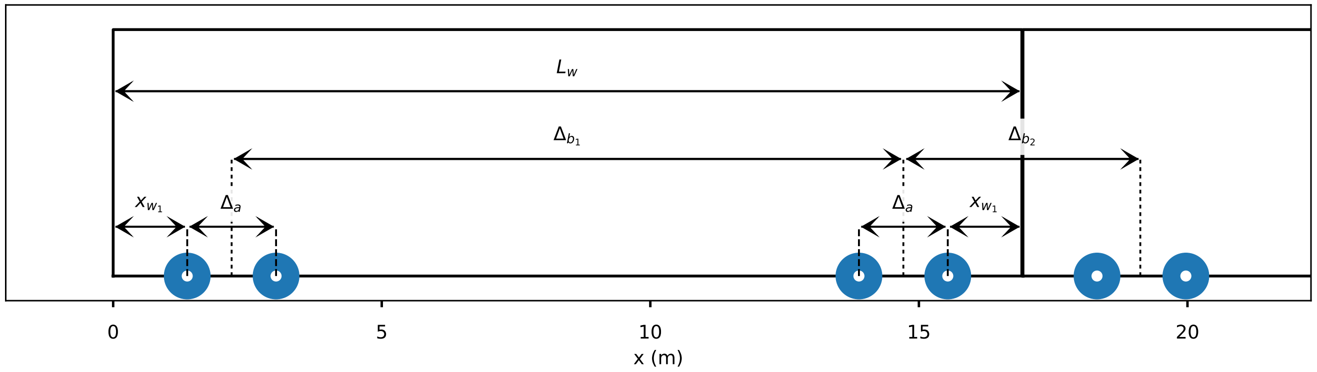
Modelling: expected frequencies

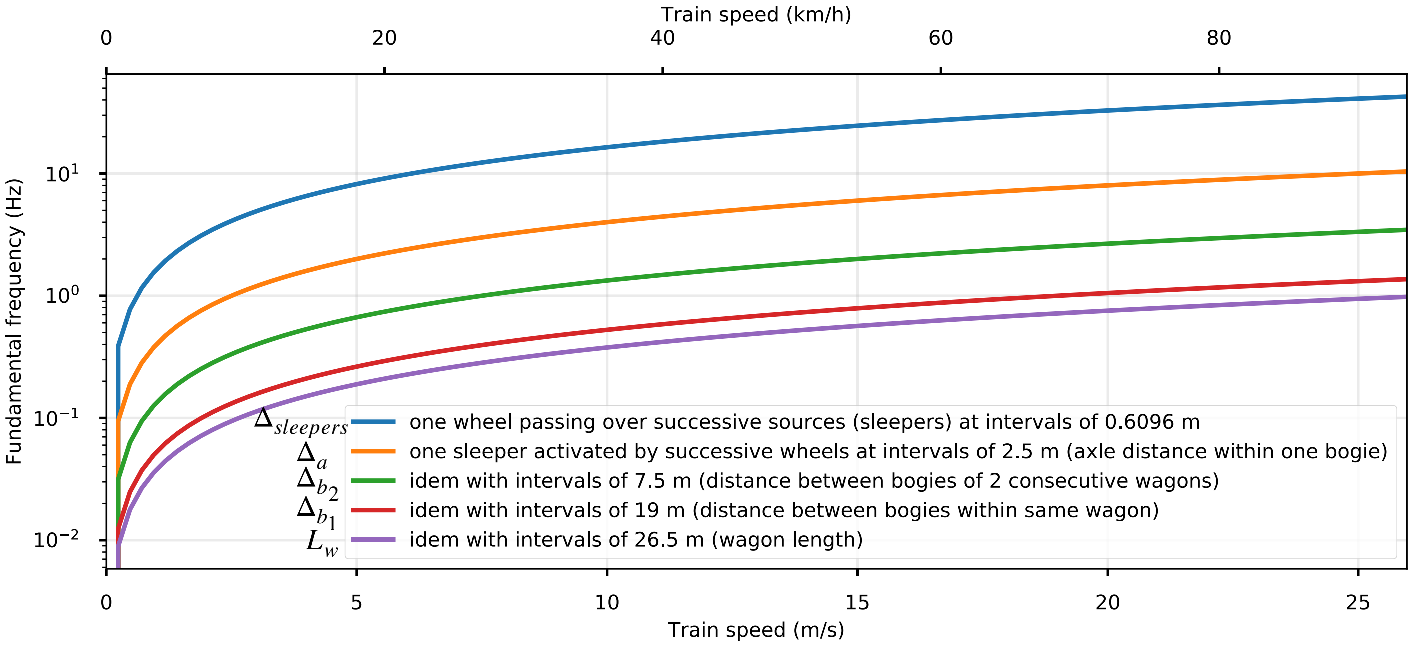


(Kouroussis et al., 2011)



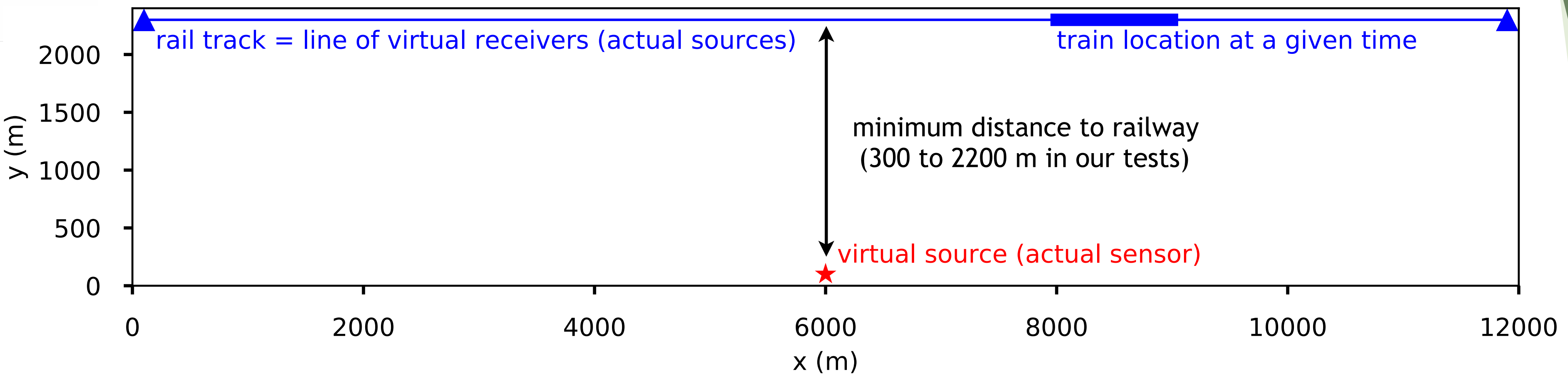
Frequency ranges for various excitation mechanisms.
(Connolly et al., 2015)





Fundamental frequencies expected as a function of train speed, for various characteristic lengths.

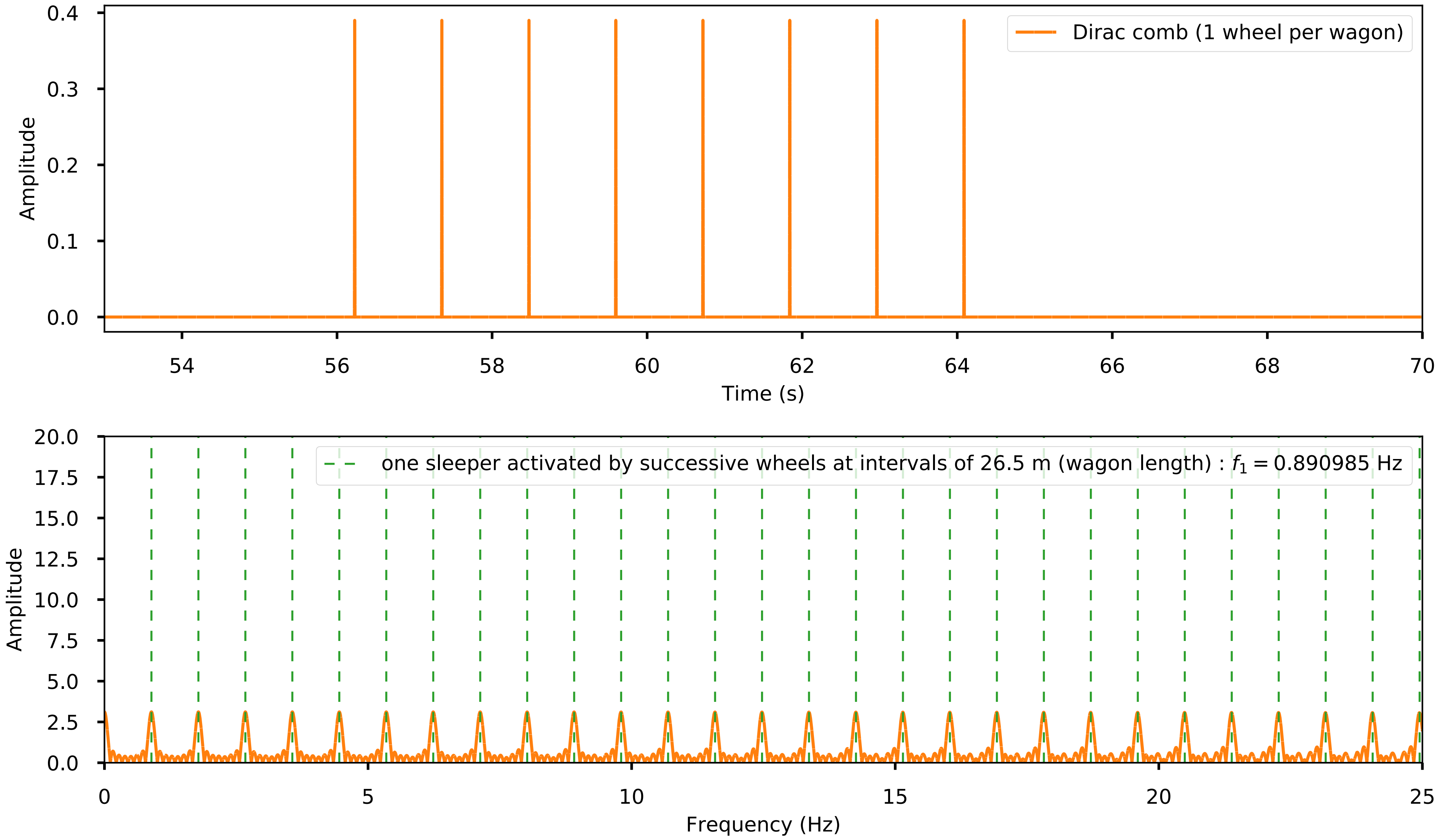
Modelling: simulation and post-processing



1. Simulation of wave propagation between one (virtual) source and all (virtual) receivers (sleepers), using the SEM46 spectral-element software (Trinh et al., 2019) in the visco-elastic approximation in a homogeneous medium (V_P = 3.4 to 5 km/s, V_S = 2 to 3 km/s, ρ = 2600 kg/m3, Q_P = 100 to 500, Q_S = 50 to 200) and with a Dirac source time function.
2. Low-pass filter below 100 Hz (max. frequency for simulation accuracy) and resample at 250 Hz.
3. Take time derivative (displacement -> ground velocity)
4. (optional) Select/mute specific arrivals (e.g. direct P, surface waves).
5. Convolve individual impulse responses with source time functions representing the train passage.
6. Sum all the individual convolved seismograms to get the final seismogram resulting from the contributions of all sleepers.

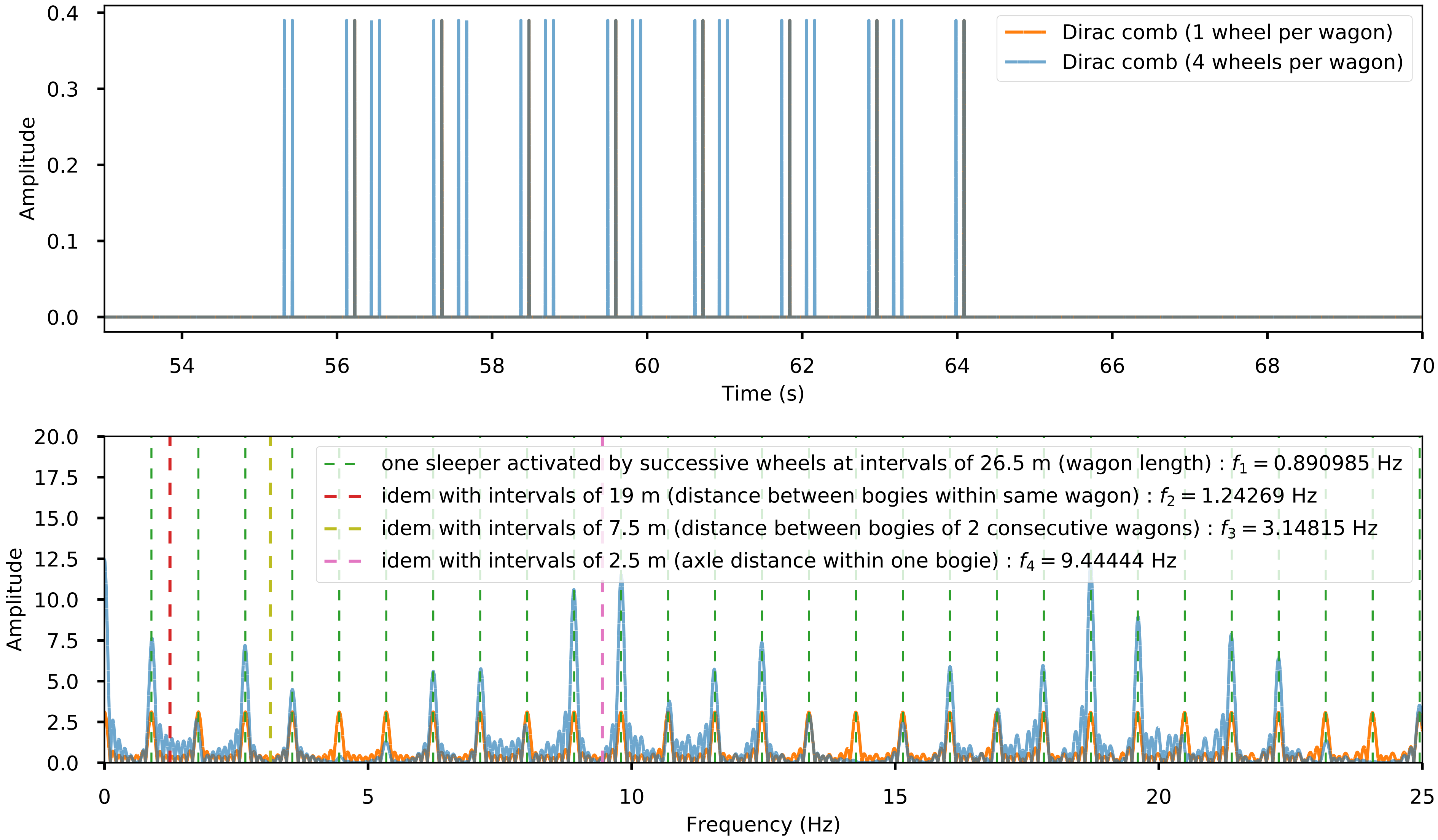
Modelling: source time functions

Modelling: source time functions



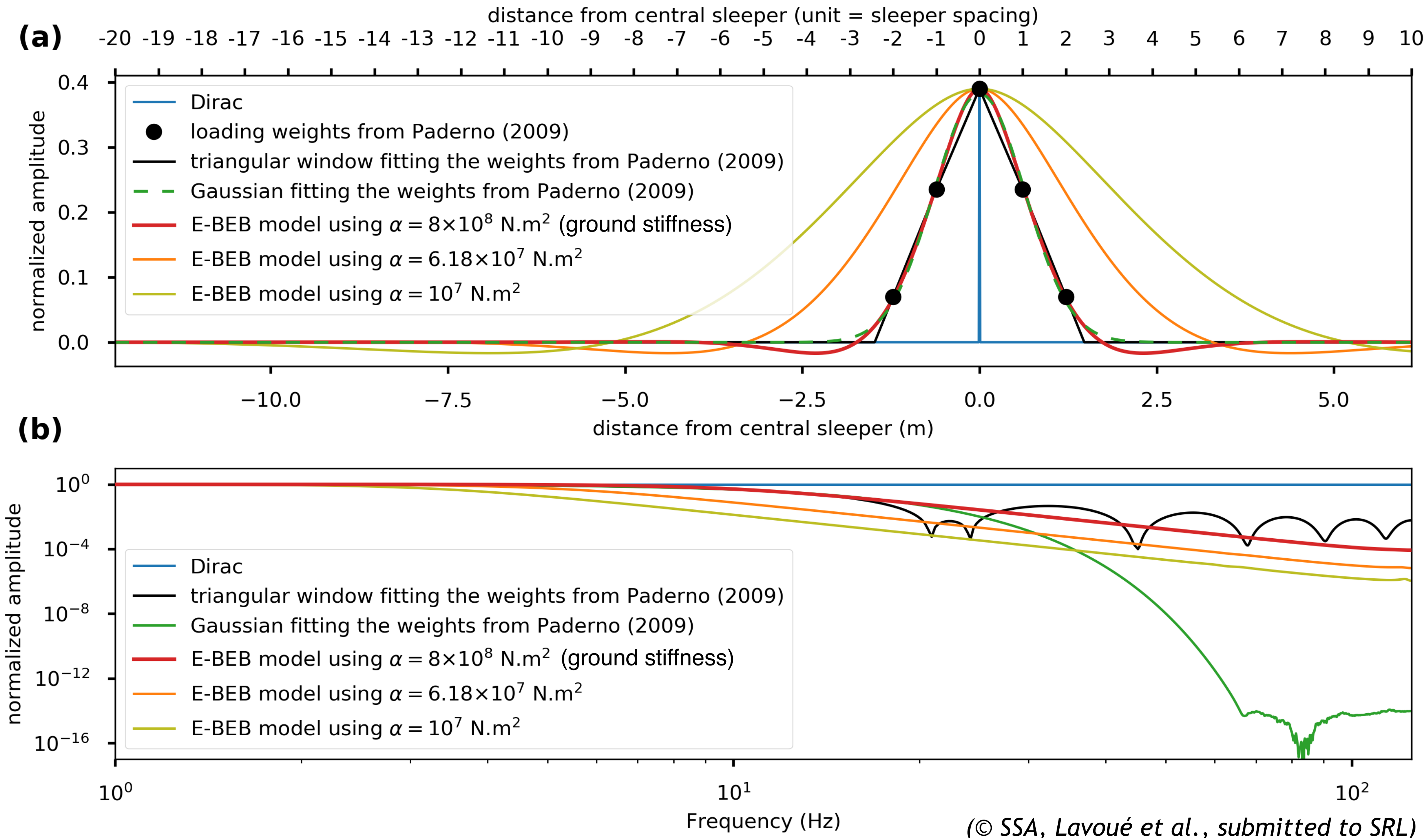
A simple dirac comb and its spectrum, corresponding to 8 wheels spaced every 26.5 m (wagon length), moving over a sleeper at 85 km/h (train speed).

Modelling: source time functions



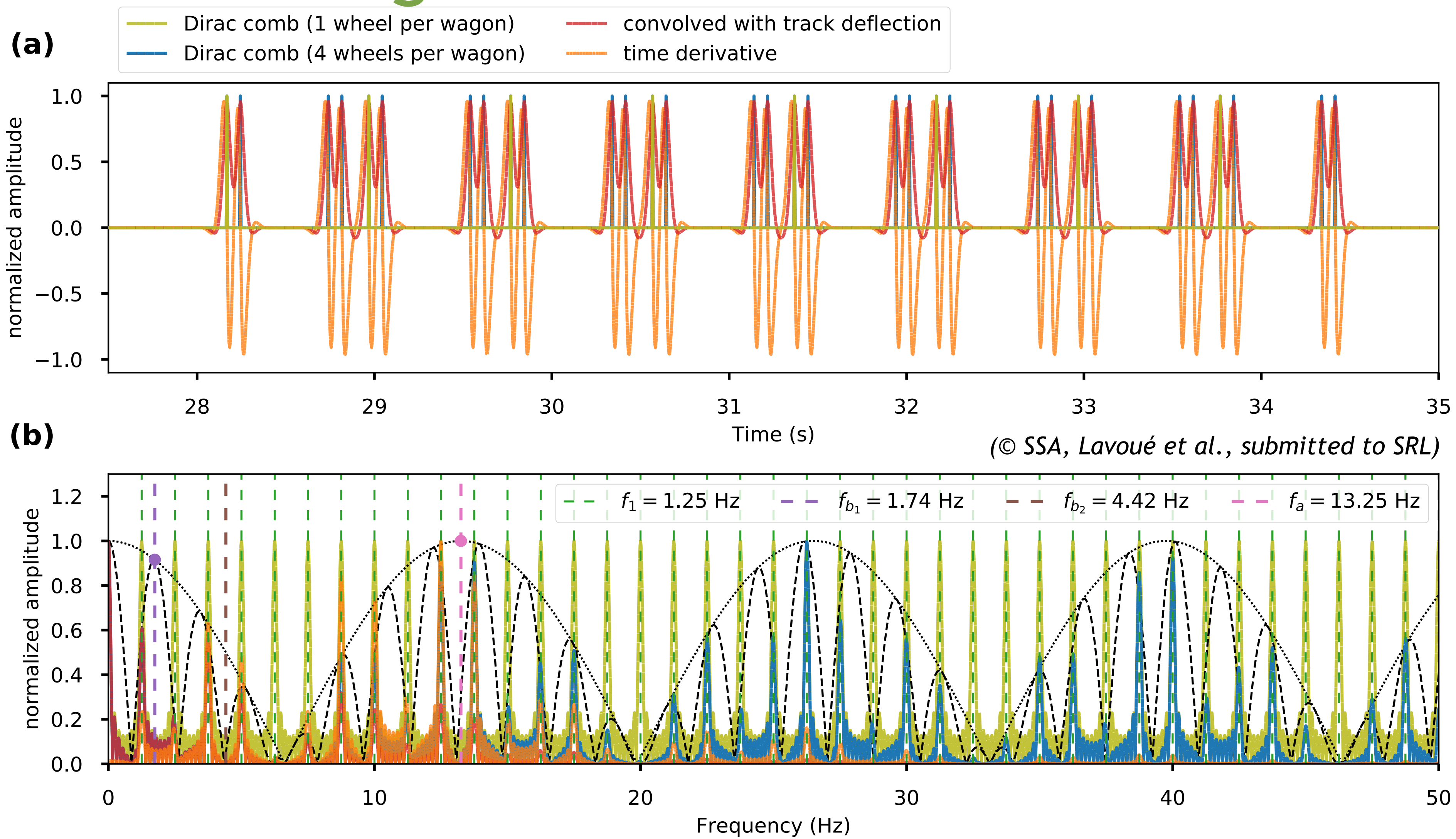
A more complex dirac comb and its spectrum, corresponding to 8 wagons with 4 wheels each, moving over a sleeper at a train speed of 85 km/h. Additional wheels do not introduce more fundamental frequencies, but modulate the initial spectrum (Krylov and Ferguson, 1994, eq. 18).

Modelling: source time functions



Weighting functions representing the spatial distribution of the load of each axle over the track and sleepers, and their associated spectra after conversion to time with a train speed of 85 km/h. The choice of this function has an effect on the high-frequency content of the resulting source time function.

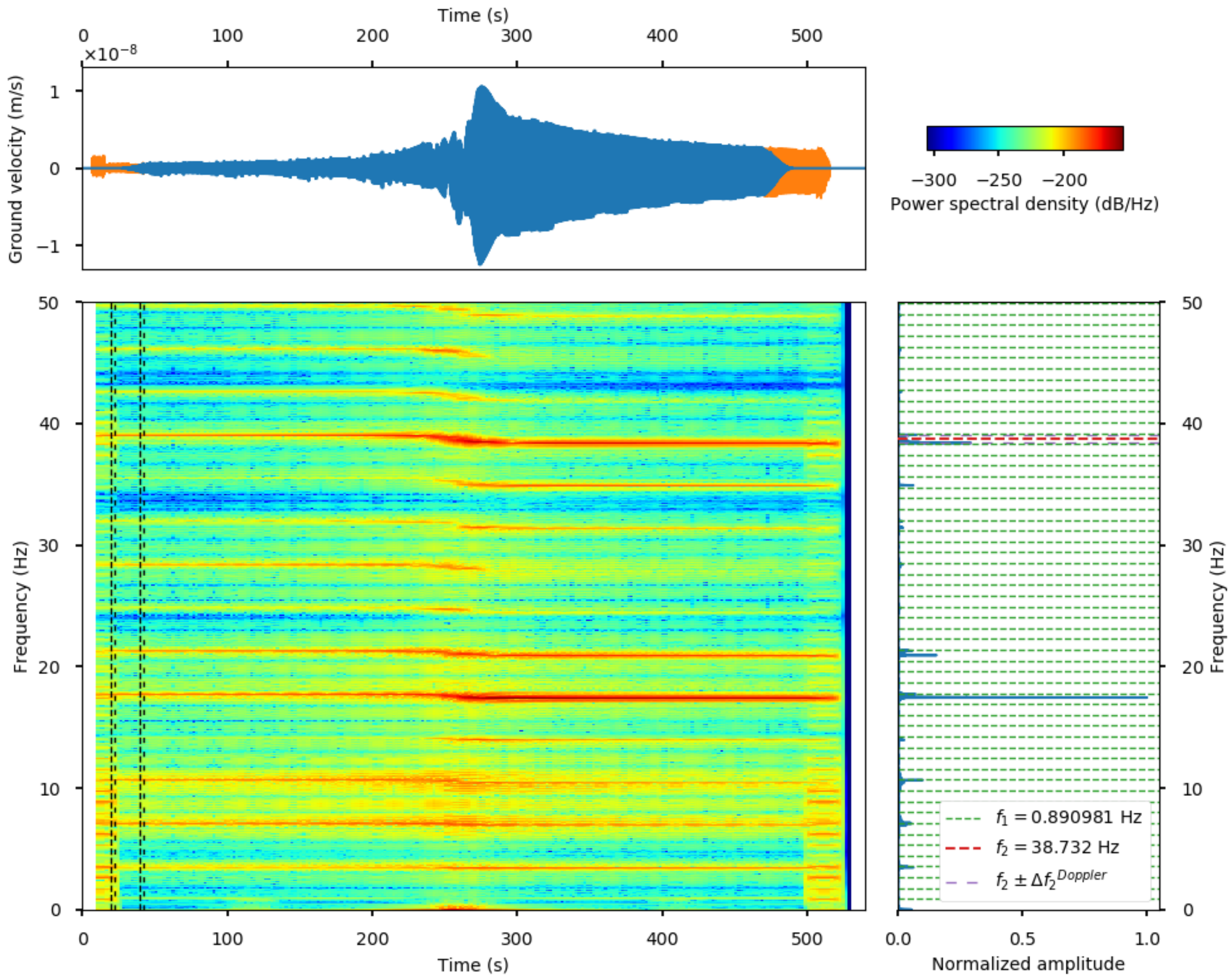
Modelling: source time functions



Final source time function for 8 wagons (26.5-m long, 4 wheels each), moving over a sleeper at 120 km/h, considering the spatial distribution of axle load due to track deflection, and after conversion from displacement to ground velocities (time derivative). As a simple rule of thumb, we note that most of the energy is contained in the range [0.5 f_a - 1.5 f_a], with f_a = V_{train} / (axle distance).

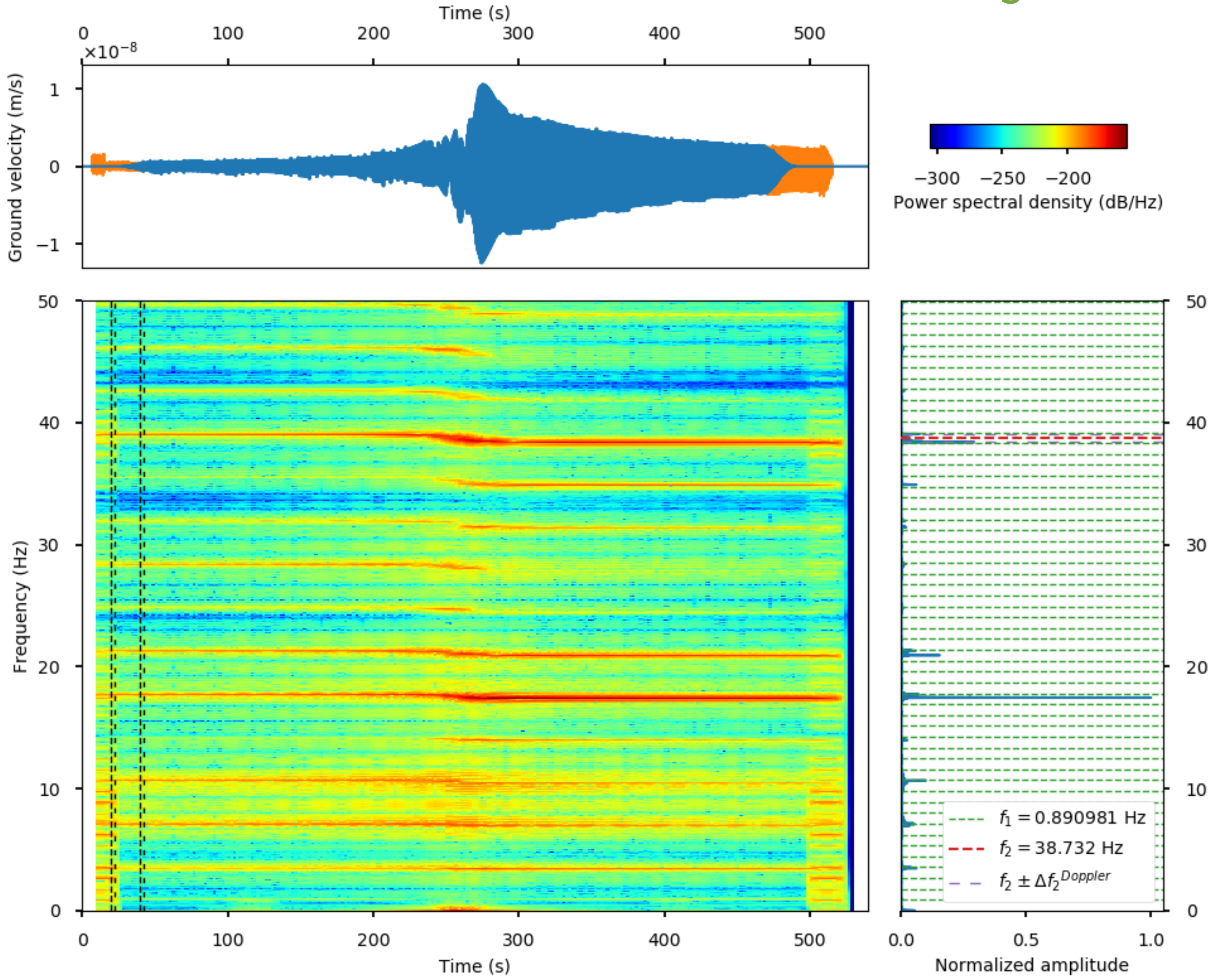
Modelling results

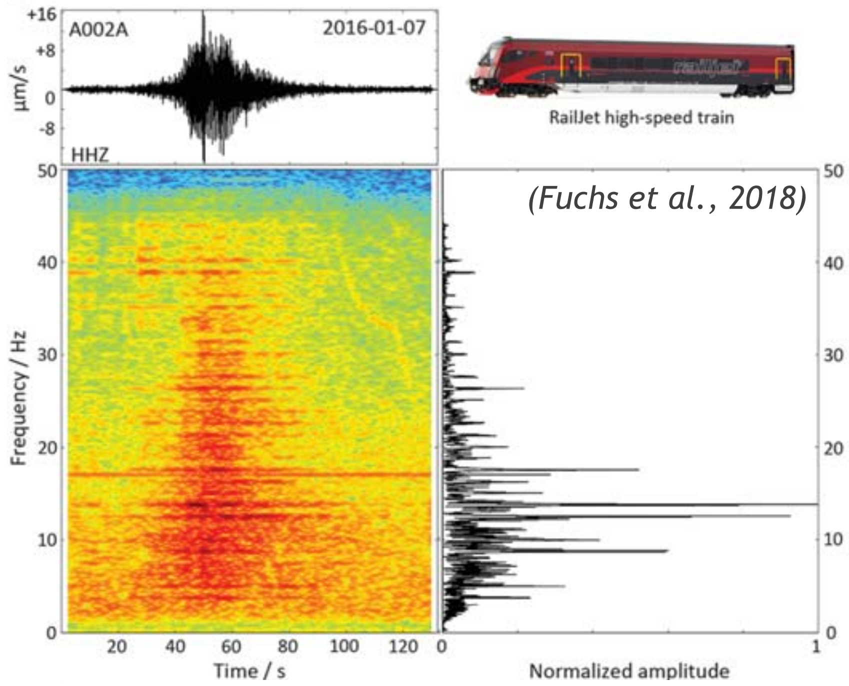
Modelling results (all sleepers, all wheels)

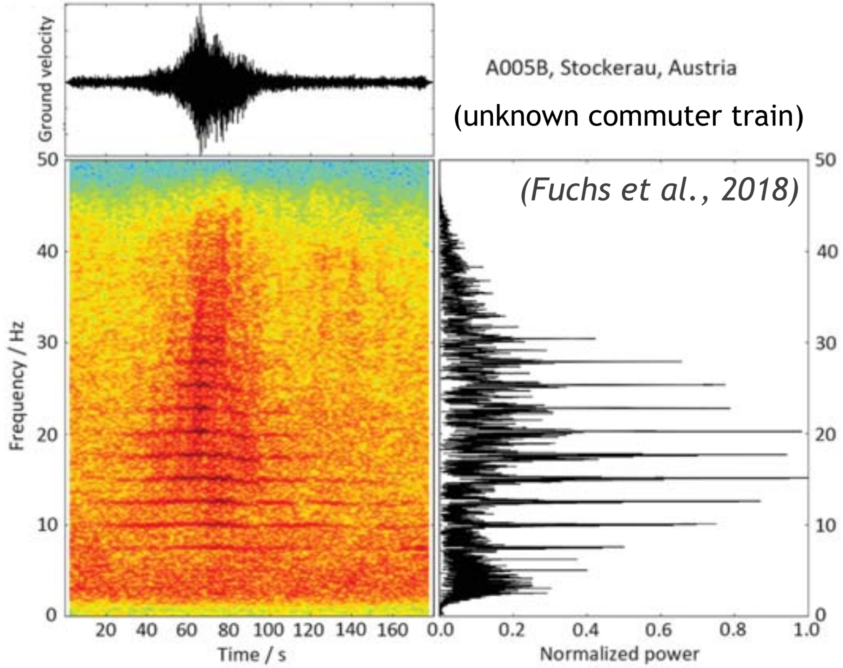


Modelling results…

… matching observations?





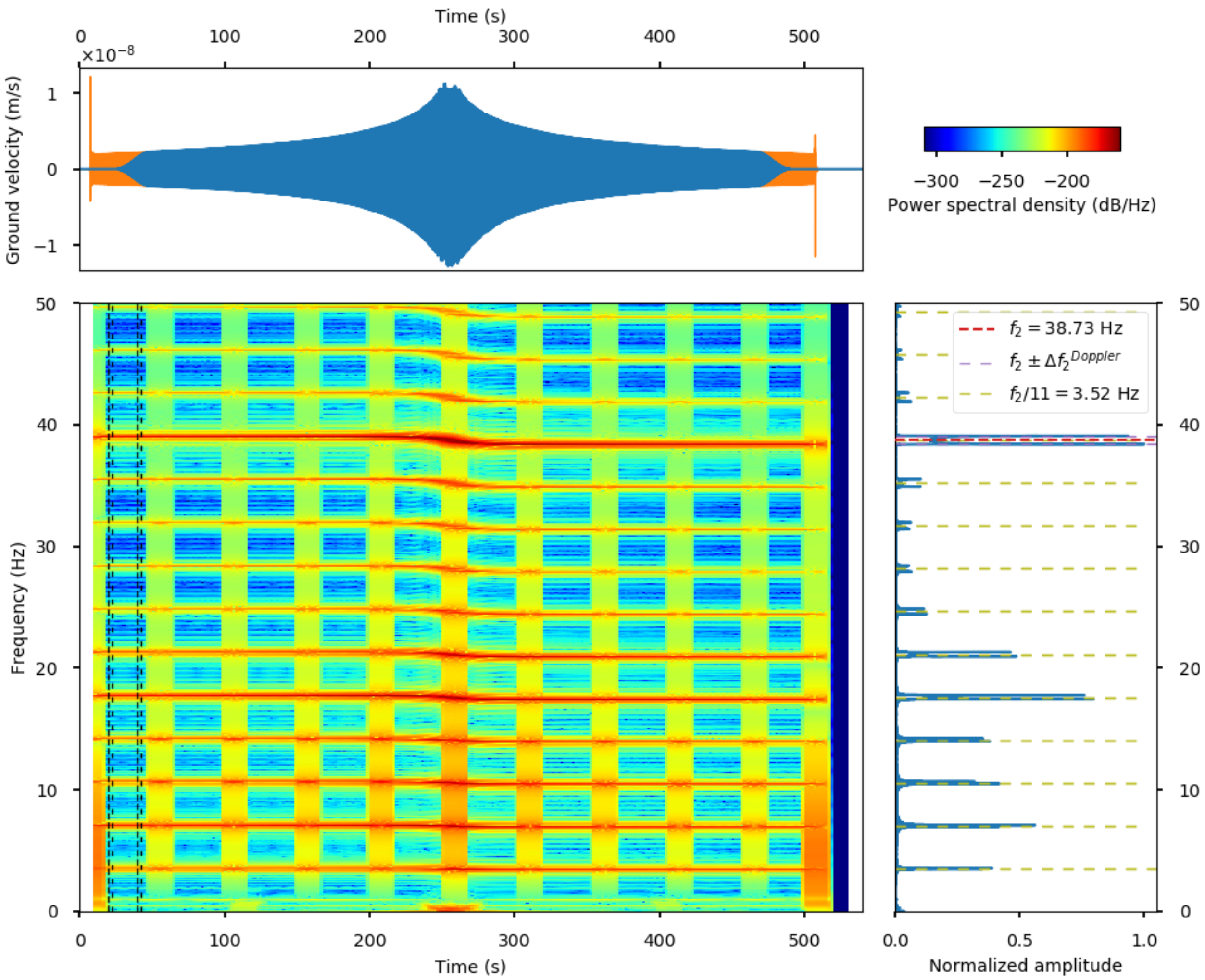


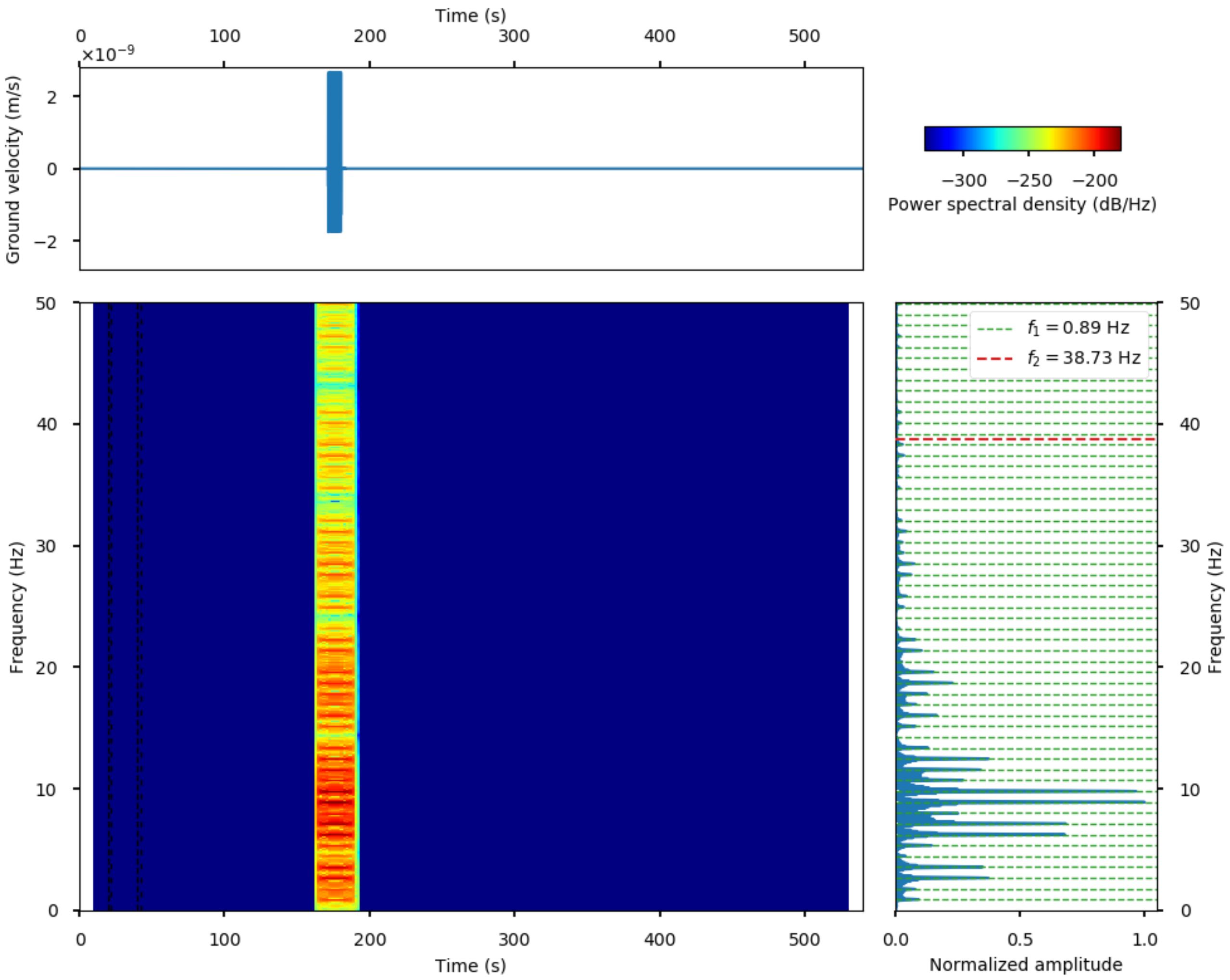
Step back: look at 2 end-member mechanisms

1 single moving load over all sleepers
vs.
all wheels passing over 1 single sleeper

Modelling: two end-member cases

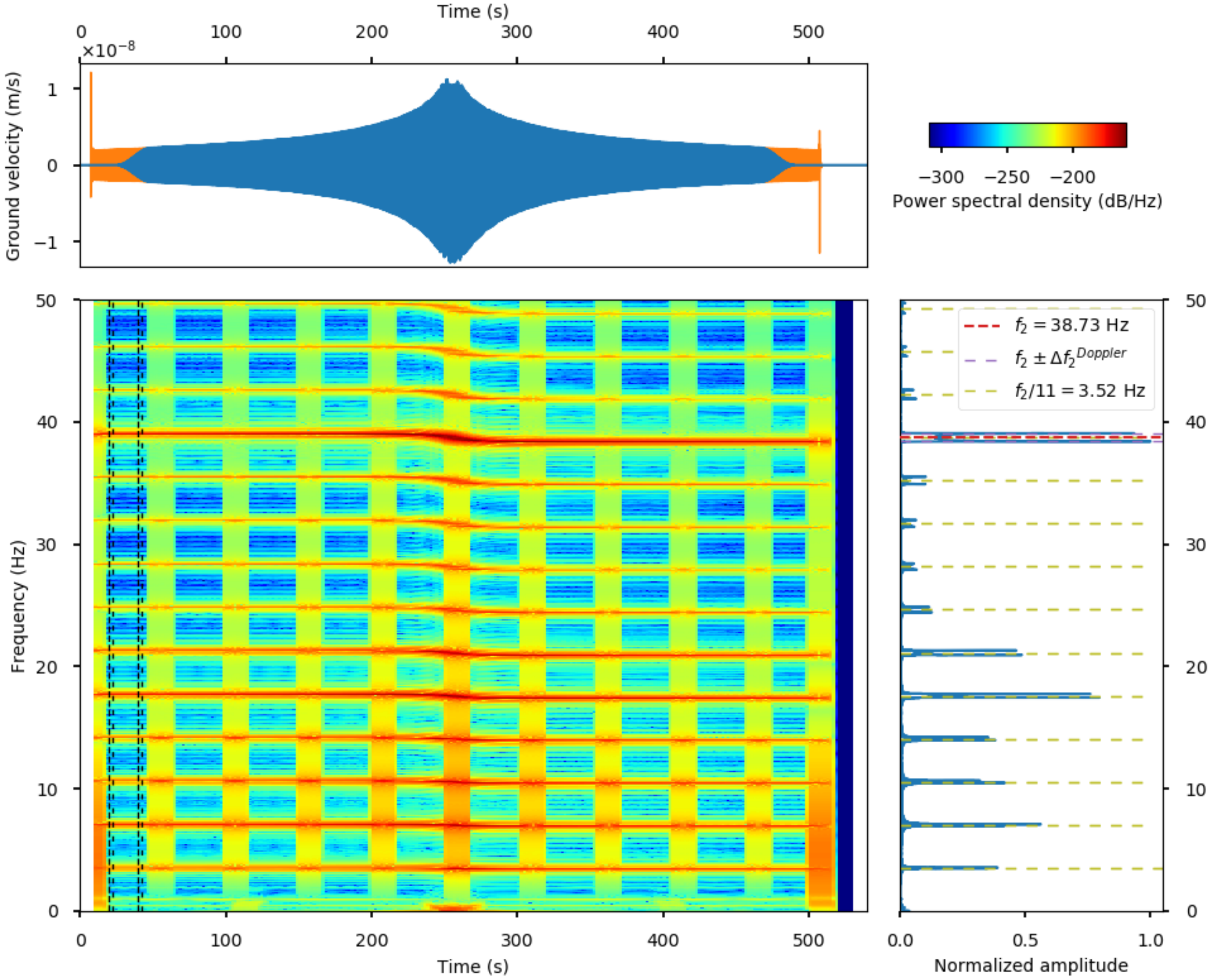
Single moving load vs. Single stationary source

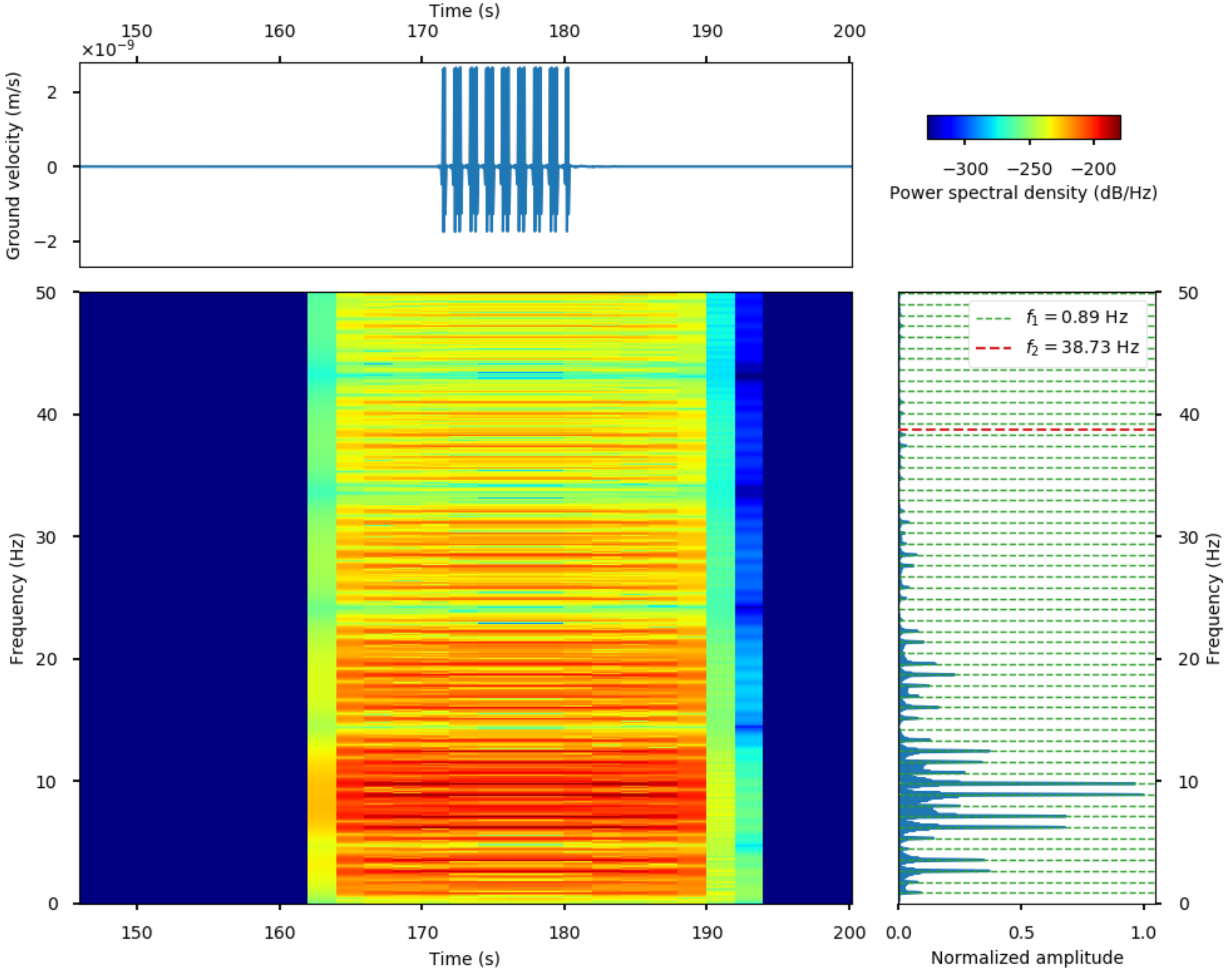




Modelling: two end-member cases

Single moving load vs. Single stationary source

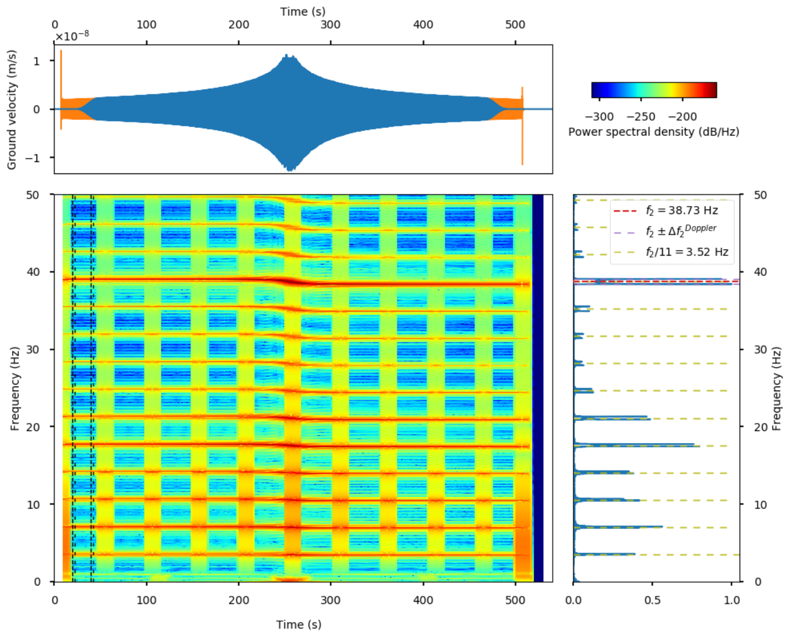


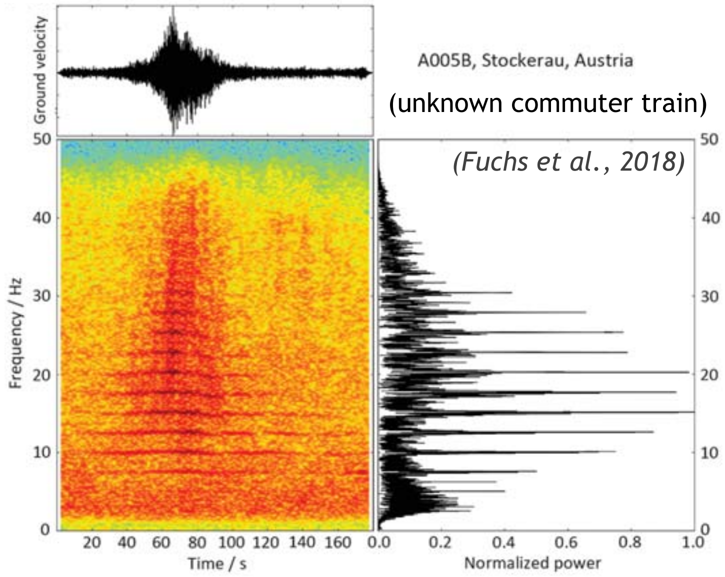


Modelling: two end-member cases…

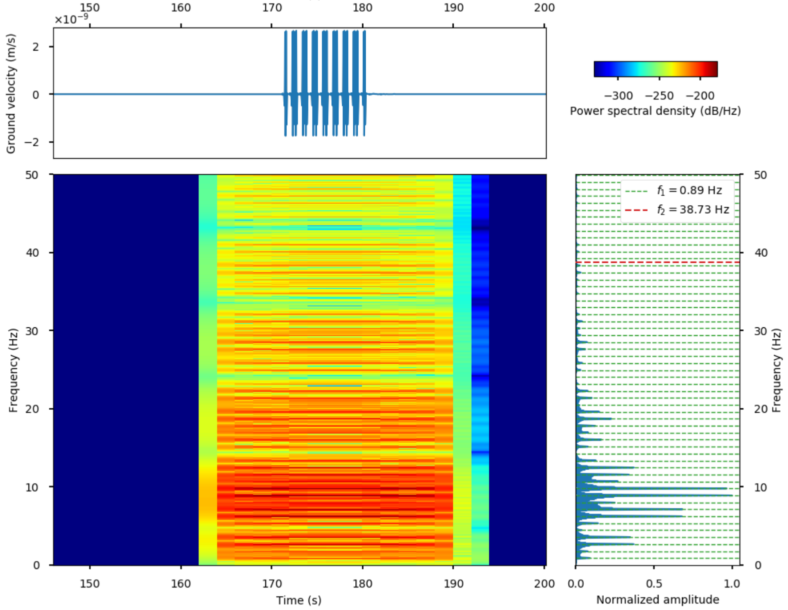
… that well explain the observations!

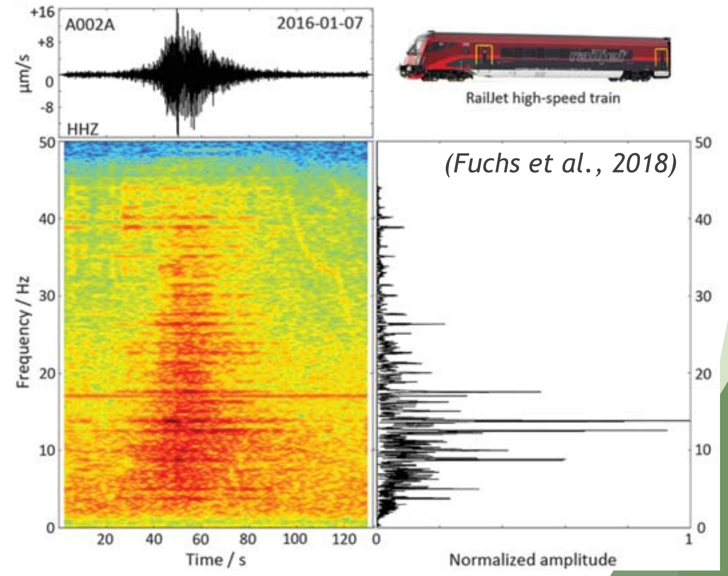
Single moving load





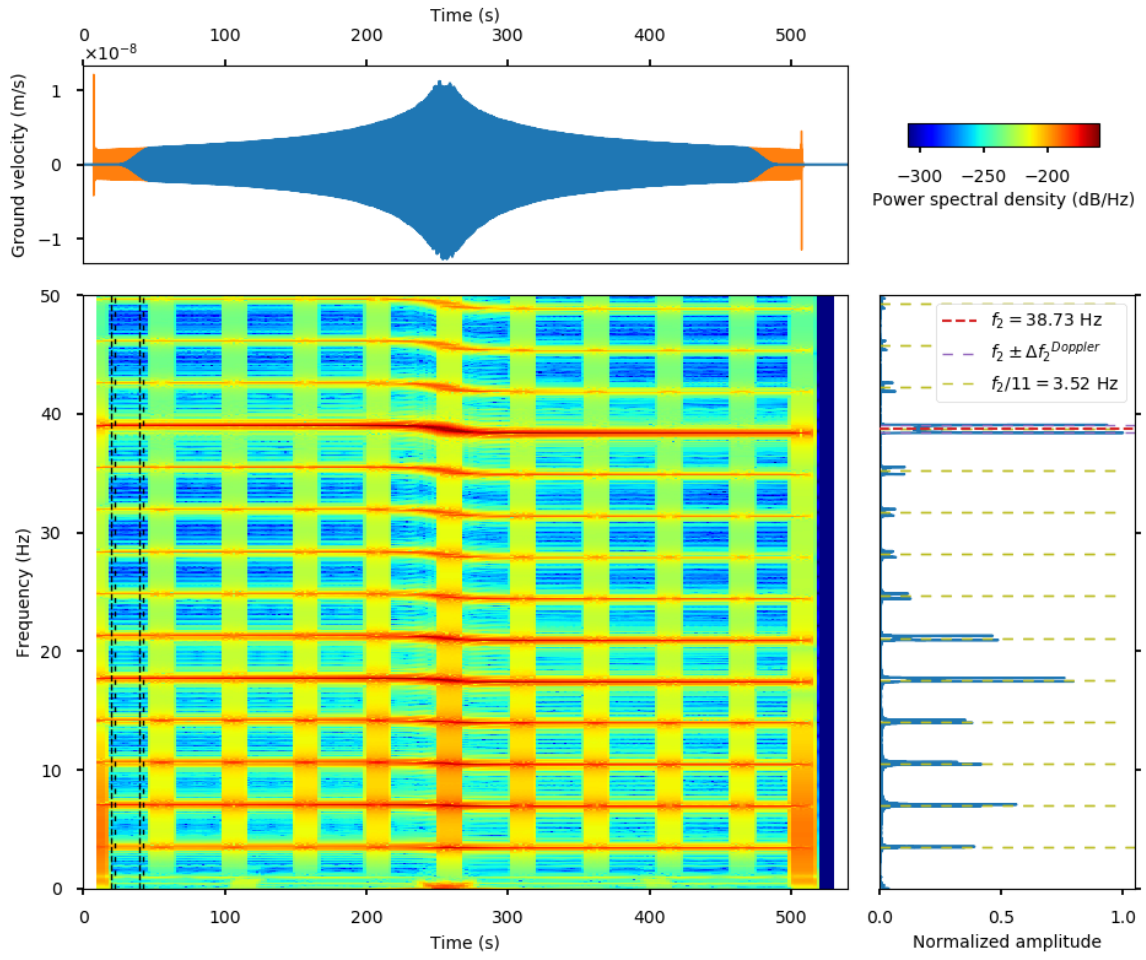
Single stationary source

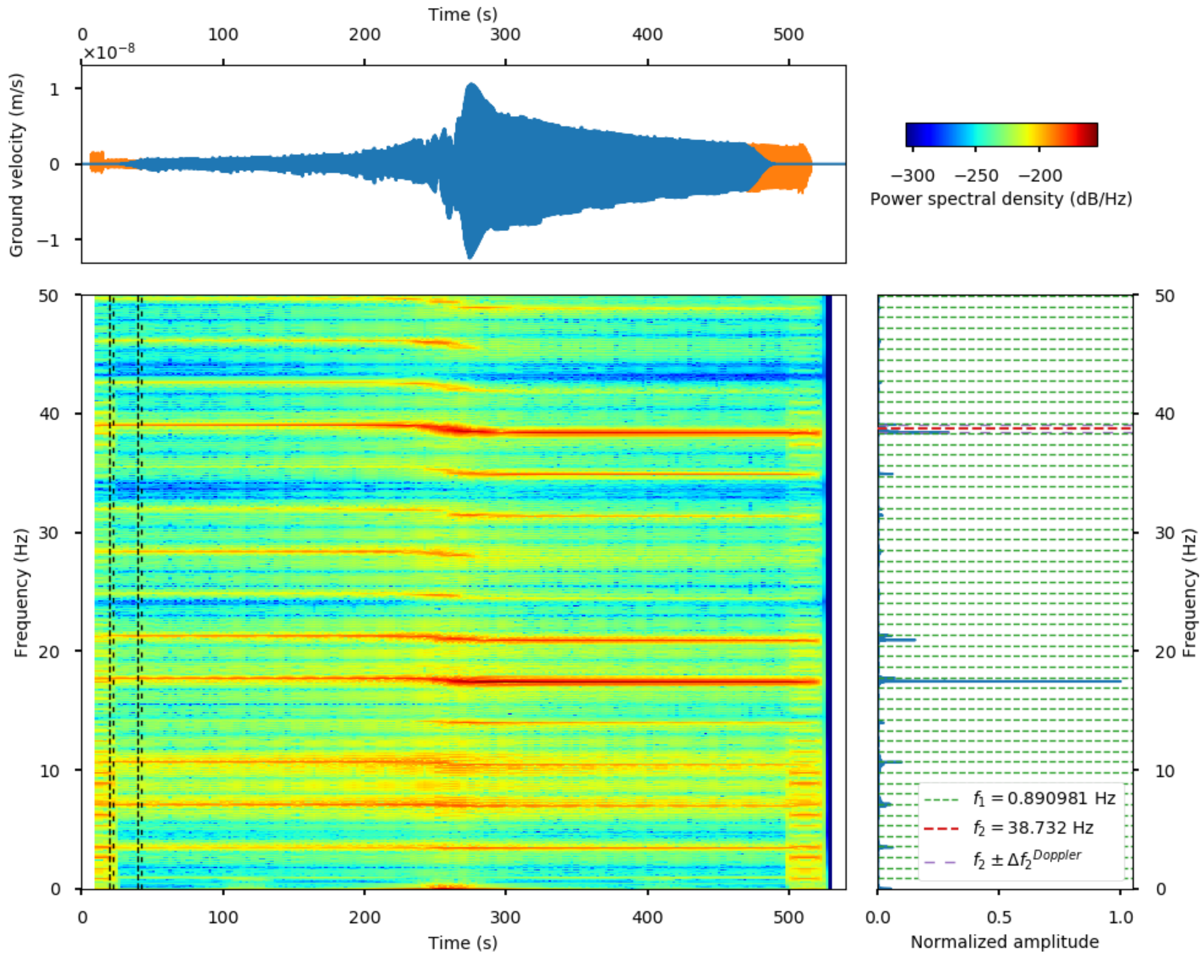




How to reproduce the observations with all wheels?

Single moving load (all sleepers) vs. All sleepers, all wheels





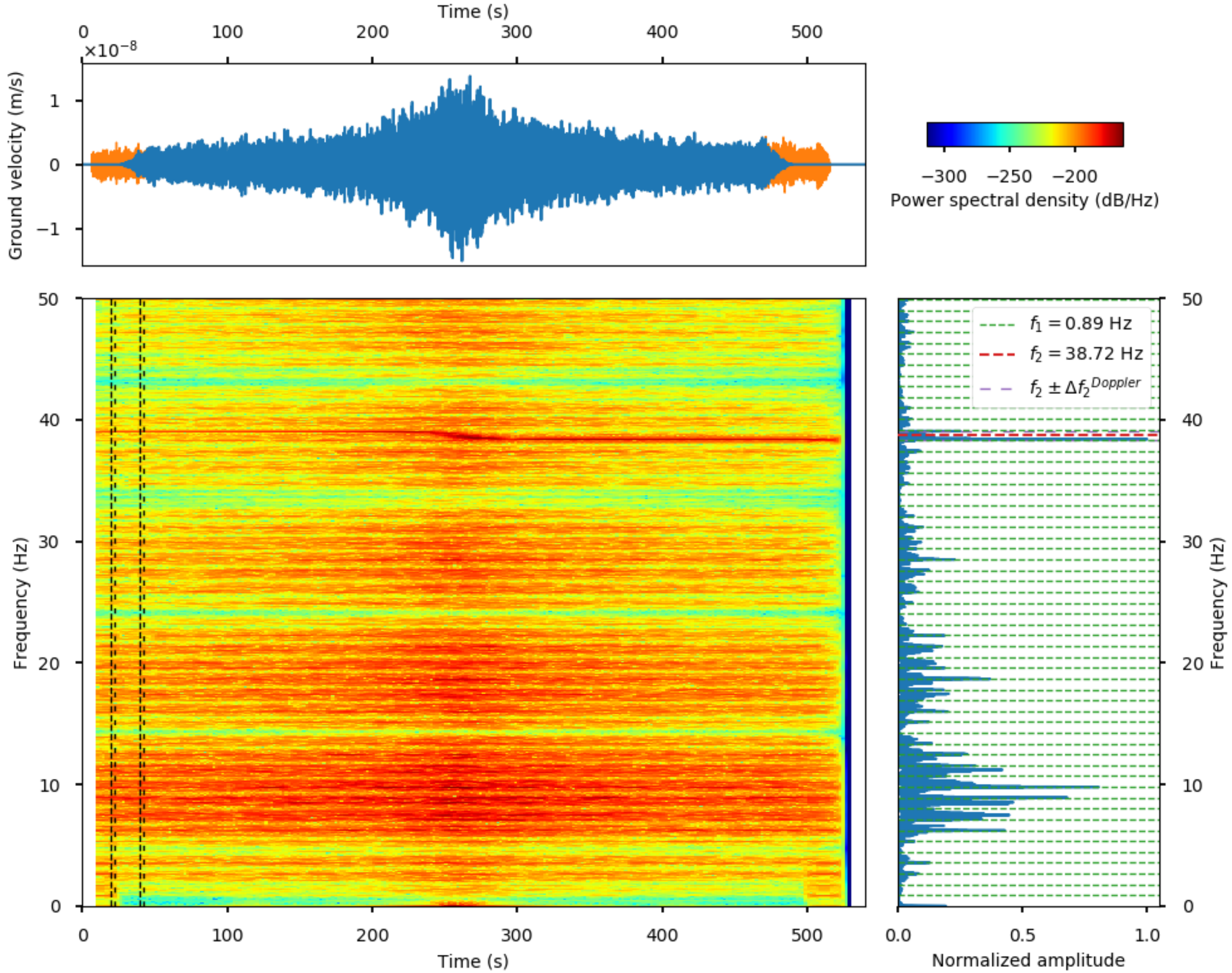
Modelling: all wheels on (slightly) irregular sleepers

Sleeper spacing
0.6096 m (24 in)
+
random perturbation
of max. +/- 5 cm

Nice tremor-like signal

Spectrum dominated by harmonics of f_1.

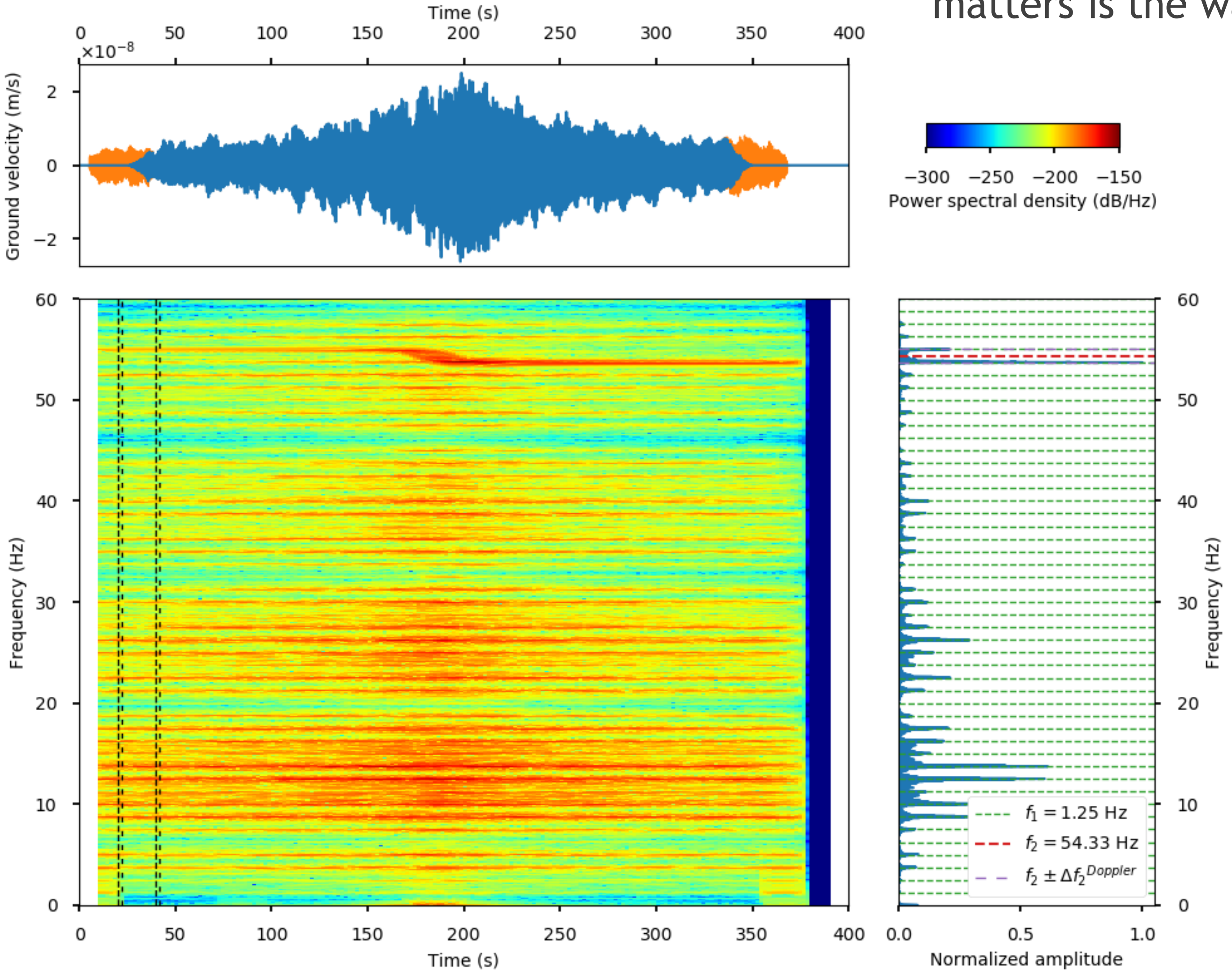
f_2 still visible but not its resonances.



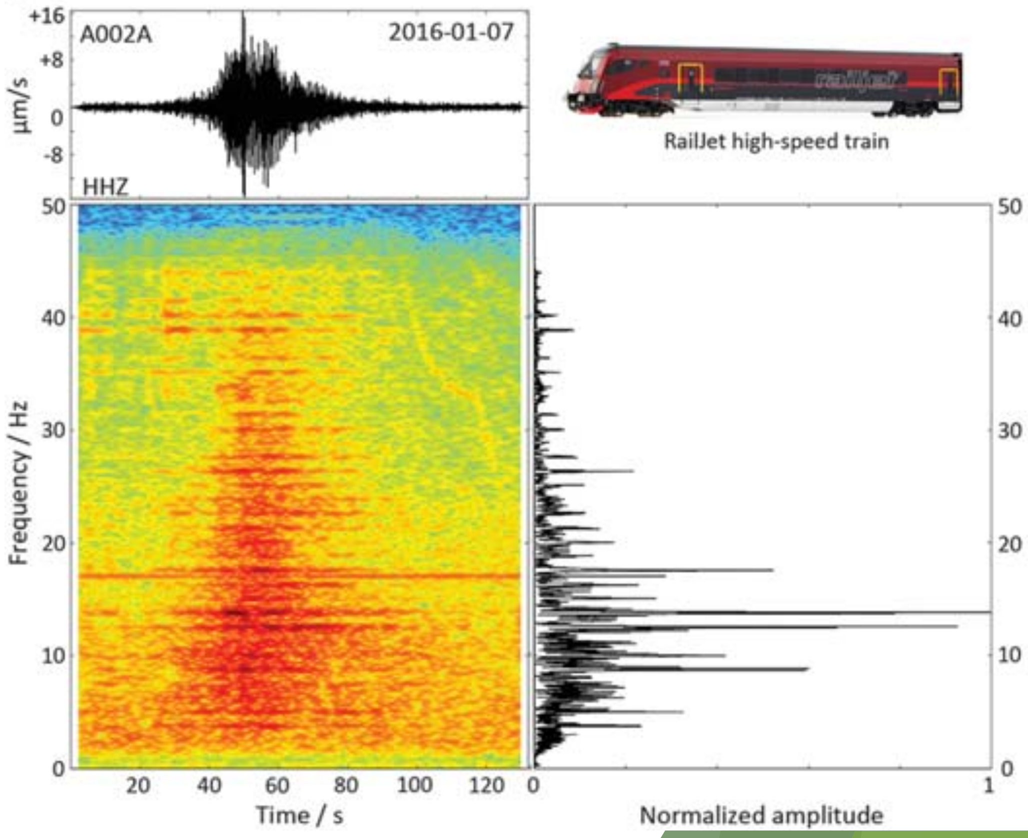
Conclusions

Conclusion: Revisiting Fuchs et al's interpretation

- $\Delta f = f_1 = 1.25$ Hz ==> $V_{train} = 120$ km/h instead of 85 km/h (because the length that matters is the wagon length and not the bogie distance)



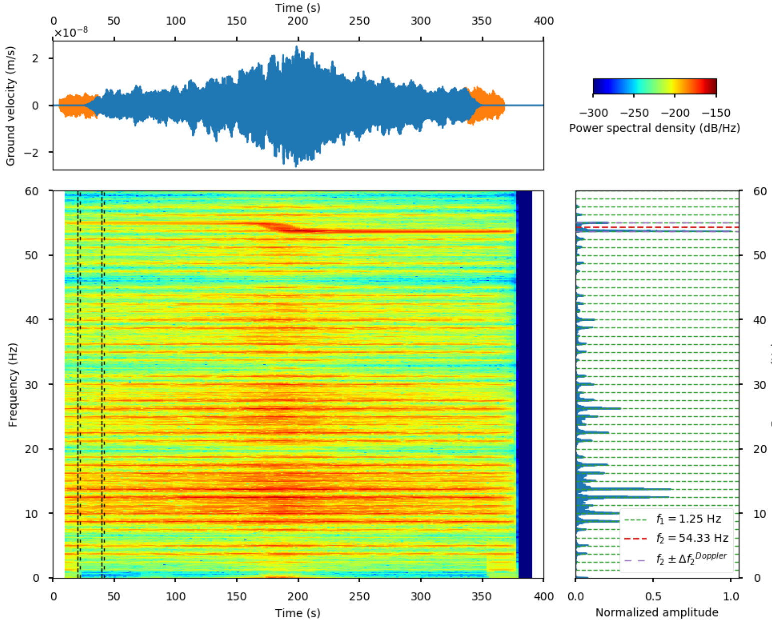
(Fuchs et al., 2018)

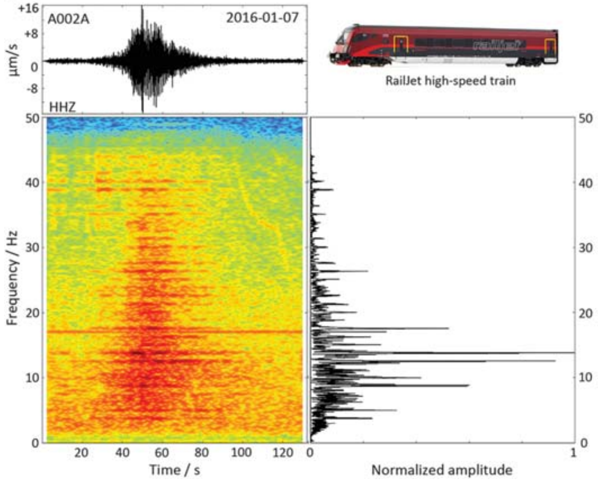


Conclusion: Revisiting Fuchs et al's interpretation

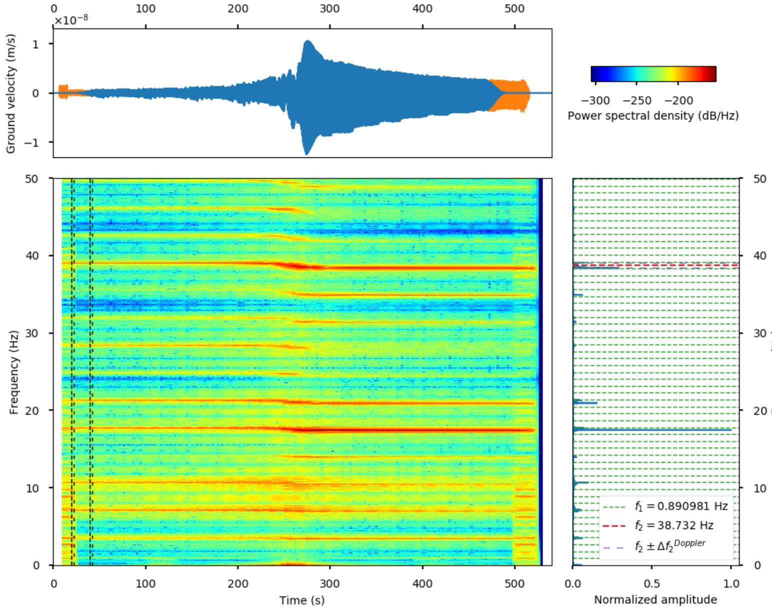
2 mechanisms

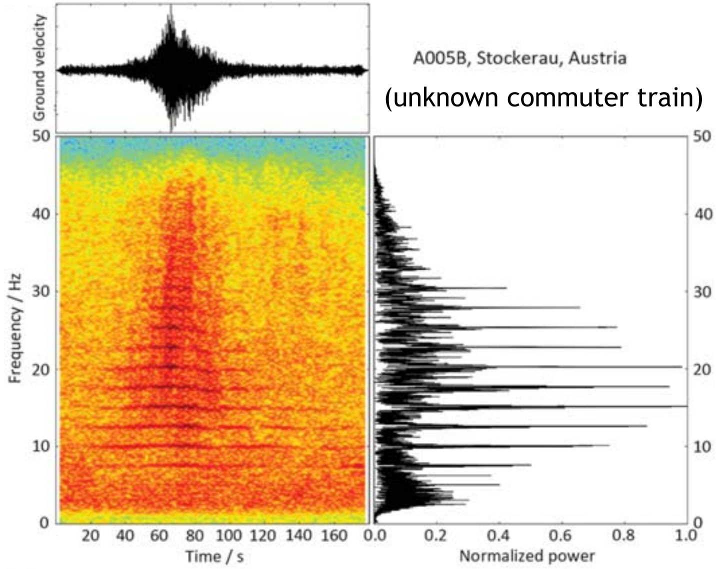
Irregular sleepers:
stationary source signature
$f_1 = V_{train}$ / *(wagon length)*





Regular sleepers:
moving load signature
$f_2 = V_{train}$ / $\Delta_{sleeper}$





Conclusions and perspectives

- Trains generate signals with a very broad and high frequency content [1- 50 Hz or above], because most of the energy comes from harmonics of f_1 and f_2 (+ potential interferences).

  As a consequence, most train traffic worldwide is expected to generate signals of potential use for seismic applications.

- The exact frequency content of these signals depends mainly on
  - ground stiffness under the rail track (spectrum of the source time functions)
  - sleeper *'regularity'* (i.e. track/ballast/soil materials and structure)
  - trains geometry and speed

- Because of the modulation due to wheel spacing, most of the energy is expected in the frequency band [0.5 f_a - 1.5 f_a], with $f_a = V_{train}$ / (axle distance), where the axle distance is usually 1.5 to 3 m. This may serve as a rule of thumb for using these signals to compute cross-correlations.

- Higher frequency bands of the form [(k-0.5) f_a – (k+0.5) f_a] are also expected to contain some energy which may prove useful when looking for body waves (e.g. Nakata et al., 2015; Brenguier et al., 2019; Dales et al., in revision).

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NB: Paper in review

- Lavoué F., Coutant O., Boué P., Pinzon-Rincon L., Brenguier F., Brossier R., Dales P., Rezaeifar M., and Bean C. J. Understanding seismic waves generated by train traffic via modelling: implications for seismic imaging and monitoring. Submitted to the *Seismological Research Letters*.

- For the sake of reproducibility, the computer programs developed for this paper are available at https://gricad-gitlab.univ-grenoble-alpes.fr/pacific/publications/2020_Lavoue-et-al_SRL_supplemental-material. Unlike the paper, this package is susceptible to evolve with time, based on future developments and users' feedback ***(please feel free to provide feedback!)***.

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Questions?

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This work is based on data from the AlpArray Seismic Network (2015) which at the time of publication was not publicly available. Please visit www.alparray.ethz.ch (last accessed March 2020) for more information.

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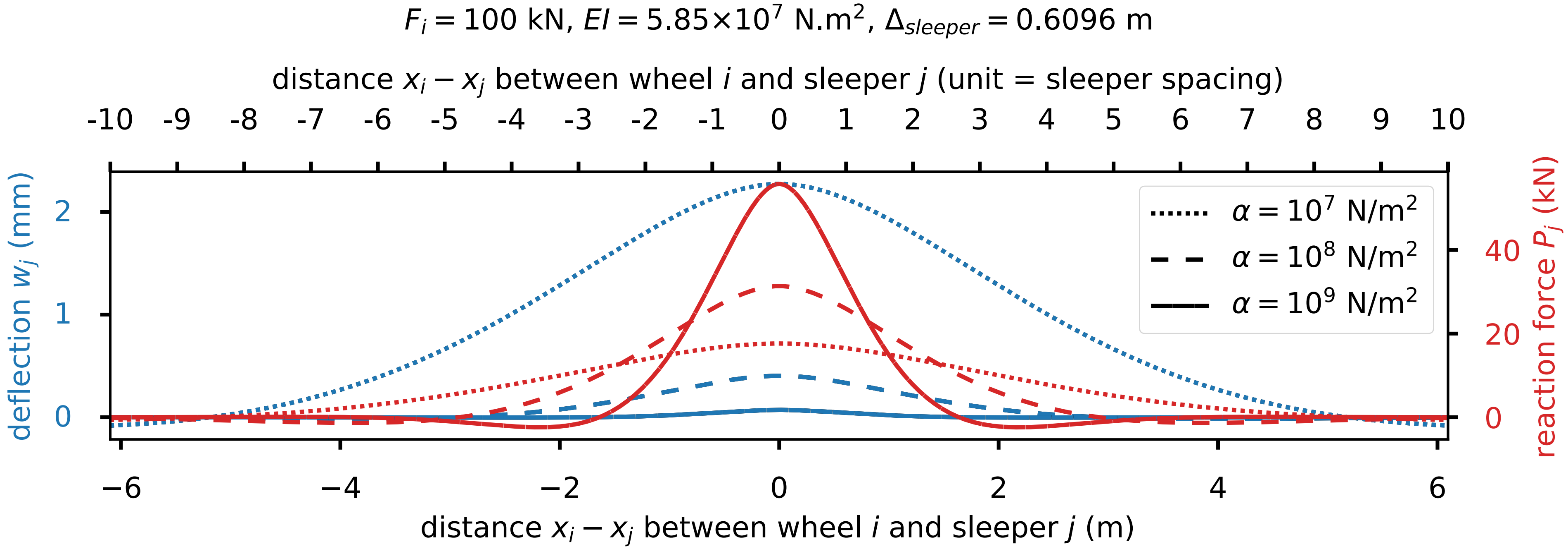
Supplemental material

Elastic reaction force vs. ground stiffness



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Deflection and reaction force of the track as a function of ground stiffness α, according to the Euler-Bernoulli Elastic Beam (E-BEB) model (Krylov and Ferguson, 1994; Li et al., 2018, eq. 3).

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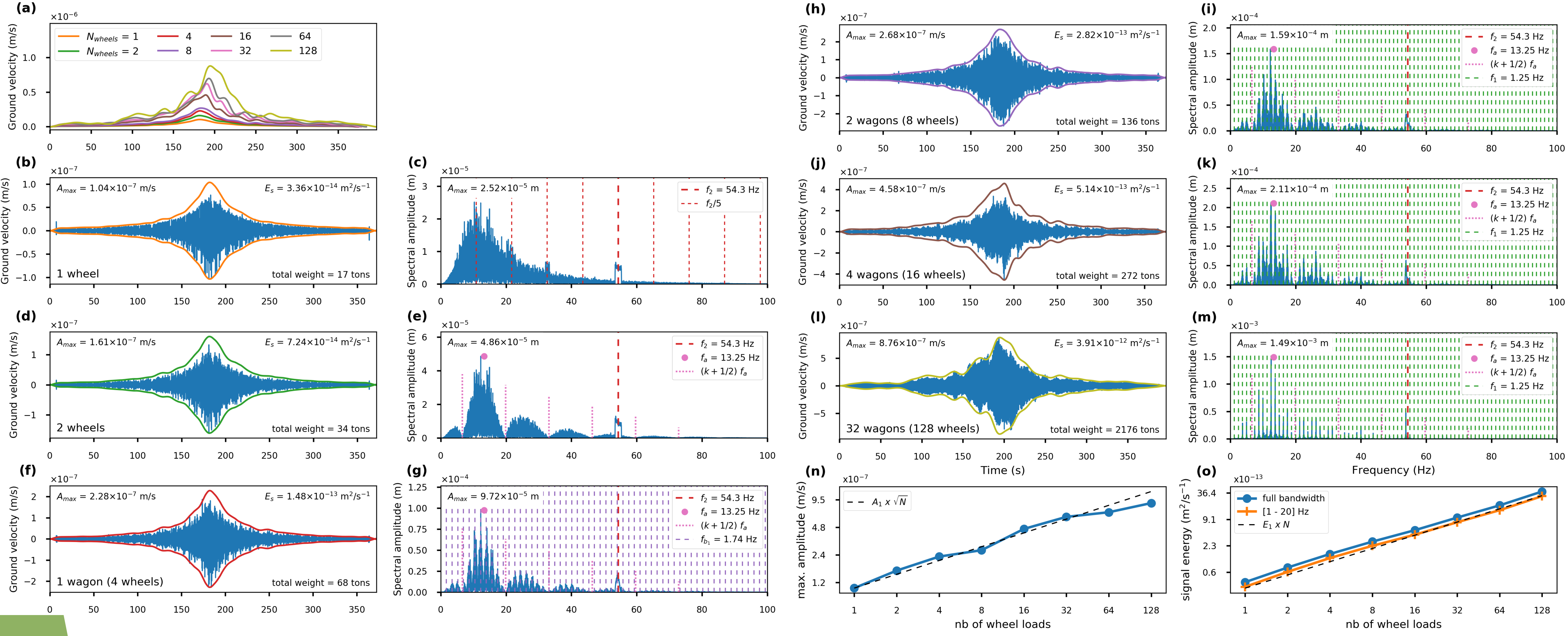
Signal amplitude vs. train length



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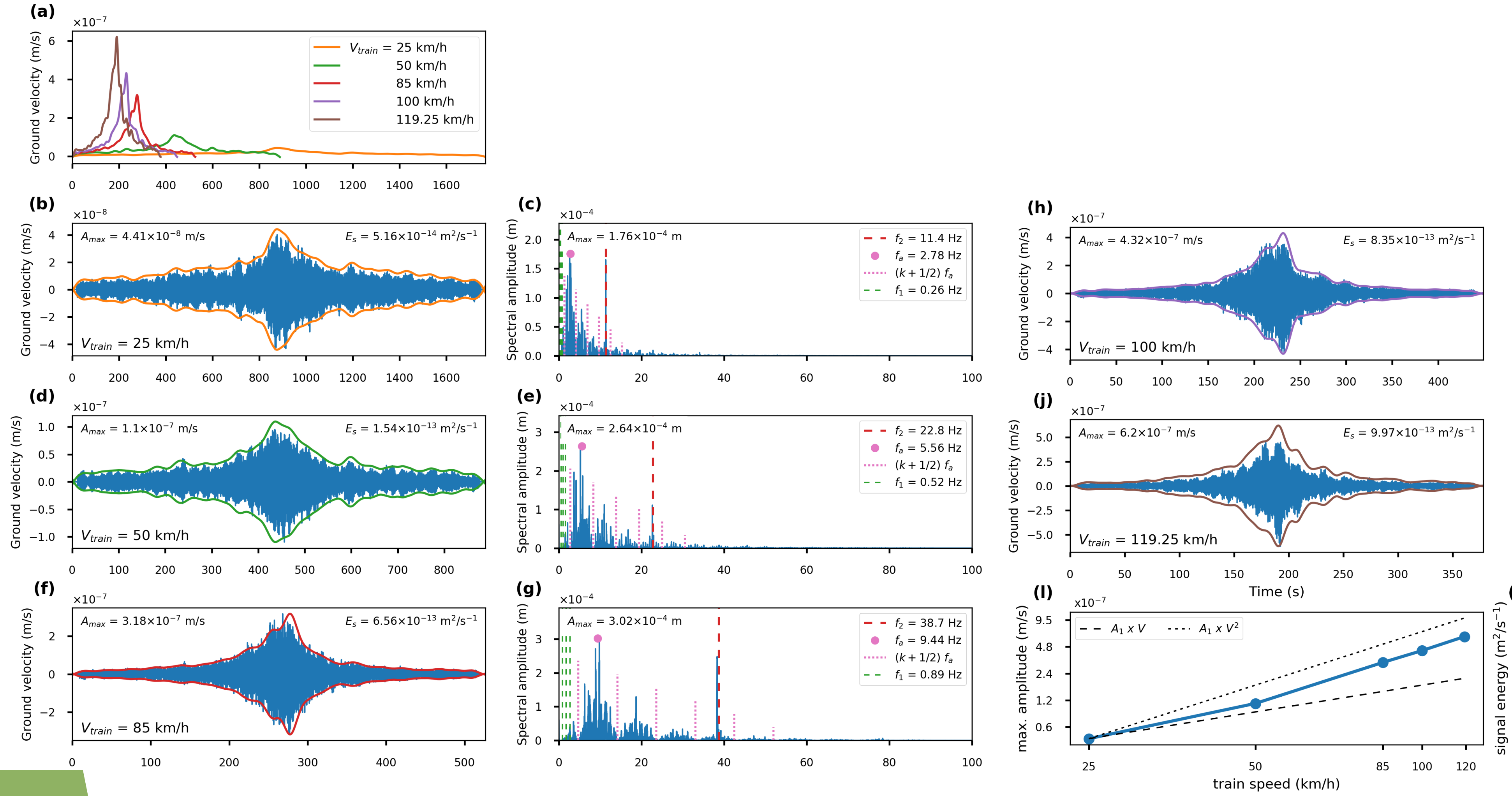
Signal amplitude vs. train speed



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