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Comparing On-board Vibration and Sound Measurements of Trams with Their Respective Pass-by-levels

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Abstract

In a first step towards mapping the sound and vibration immission produced by trams in Vienna, a trial was conducted in 2016 which saw a tram in the city's public transport network being equipped with an on-board microphone near its unpowered bogie. The tram was previously equipped with four accelerometers on the wheel bearings of the same bogie, one accelerometer on the bogie itself and another one on the chassis. On-board data is collected with a sampling rate of 8192 Hz per accelerometer and 48 kHz for the microphone when the tram is in motion. As the instrumented car covers all of Vienna's tram network at regular intervals, the aim of the study was to examine the correlation between the on-board records (emission) and the pass-by levels (immission) when the tram travels at different velocities. The initial setup examined the correlation along a straight section of grooved rail (gauge 1435 mm), while ongoing work aims to examine the correlation in curves and at junctions when driving over switches.

Keywords: Vibration; Noise; On-board Measurements; Rail-bound Vehicles

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Nomenclature

f_c	centre frequency of 1/3 octave band, in Hz
a_0	standard reference acceleration, in m/s^2
$L_{acc,S}$	vibration acceleration level, slow weighting, in dB
L_{AE}	sound exposure level at the immission point, A weighting, in dB
L_{AS}	on-board sound pressure level near tram bogie, A and slow weighting, average of 5 seconds in dB

1. Introduction

Vienna's tram network undergoes regular maintenance checks in the form of visual inspection on site and network-wide scans using an instrumented carriage. Besides optical sensors, the carriage is equipped with a series of vibration sensors and gyroscopes which were hitherto only used for vehicle positioning and localization of the data in relation to the network layout. In the course of a research project between AIT and Wiener Linien, the inspection tram was additionally equipped with a microphone in order to test the usability of the on-board vibration and sound data in detecting immission hot-spots across the network so as to anticipate potential complaints from residents in densely populated areas or the need for mitigation measures.

In the first step described herein, the on-board emissions were compared to stationary immission measurements carried out during controlled pass-bys on a straight section of double track. The superstructure consisted of a concrete subbase and a 30 cm thick track support plate onto which the grooved rails were fixed, including elastic rail pads. To level the track with the road, the rails are embedded in a layer of gritting material onto which large concrete plates are placed. The sound immission was measured by placing a microphone at a distance of 7.5 m from the centreline of the rails at a height of 1.2 m above ground. The vibration immission was measured along a profile perpendicular to the track using eight geophones at distances between 2 m and 30 m from the rails. The tests involved two different car models to account for the vehicle types typically in operation on Vienna's network. The inspection tram was a so-called E1-vehicle (older build, constructed in the 1970s) and the second was an ULF-vehicle (modern build, constructed in 2016). Several pass-bys of both cars were measured at predefined velocities between 10-50 km/h and compared to the respective on-board data.

2. Vibration measurements

The impact of vibration immission on humans according to ISO 2631-1:1997 is assessed using the vibration acceleration and appropriate weighting filters. For the assessment inside buildings, for example, where residents may be affected by rail-bound traffic inside their homes, the weighting filter according to ISO 2631-2:2003 limits the relevant frequency range from 1-80 Hz and recommended immission levels are suggested in several national standards such as ÖNORM S 9012:2016. The latter standard also recommends limits for ground-borne noise levels radiated from walls or floors and encompasses 1/3 octave bands up to f_c = 250 Hz. When evaluating the potential annoyance of residents due to passing trams, the vibration emission data can thus be restricted to pertinent frequency bands below f_c = 250 Hz, whereas higher frequency bands may be included for use in track diagnostics, in other words, when aiming to find faulty switches, corrugation or other rail defects that could result in higher vibration frequencies.

The study presented herein investigates the correlation between vibration acceleration on the wheel bearings and stationary vibration immission measured along the geophone profile orthogonal to the track. This forms the basis for further work by showing how data gathered during network-wide scans can potentially indicate high-immission spots.

2.1. Evaluating the on-board vibration data

The inspection tram, known as *Eva*, is equipped with four triaxial accelerometers on the wheel bearings of an unpowered bogie (sensors B1, B2, C1 and C2), one accelerometer on the bogie itself (sensor D) and one accelerometer on the vehicle body (sensor W), see Fig. 1. Furthermore, there is a triaxial gyroscope next to the accelerometer on the bogie and another one on the vehicle body, which is used to track the curvature of the tram's route and is thus used when mapping the vehicle's location within the rail network. Data acquisition is triggered via the vehicle's odometer, providing no data during standstill and sampling at a rate of 8192 Hz when the tram is moving. The stationary geophones measured vibration velocity (the time derivative was computed for comparison with the on-board accelerometers) and the sensors' bandwidth was 1-315 Hz. For comparison of the overall vibration levels, it was decided to limit the evaluation to this frequency range despite the on-board sensors' greater bandwidth. As all four accelerometers on the wheel bearings showed very similar results, the following analysis will only include one of them for easy readability of the diagrams (sensor B1, which is on the front axle of the instrumented bogie).

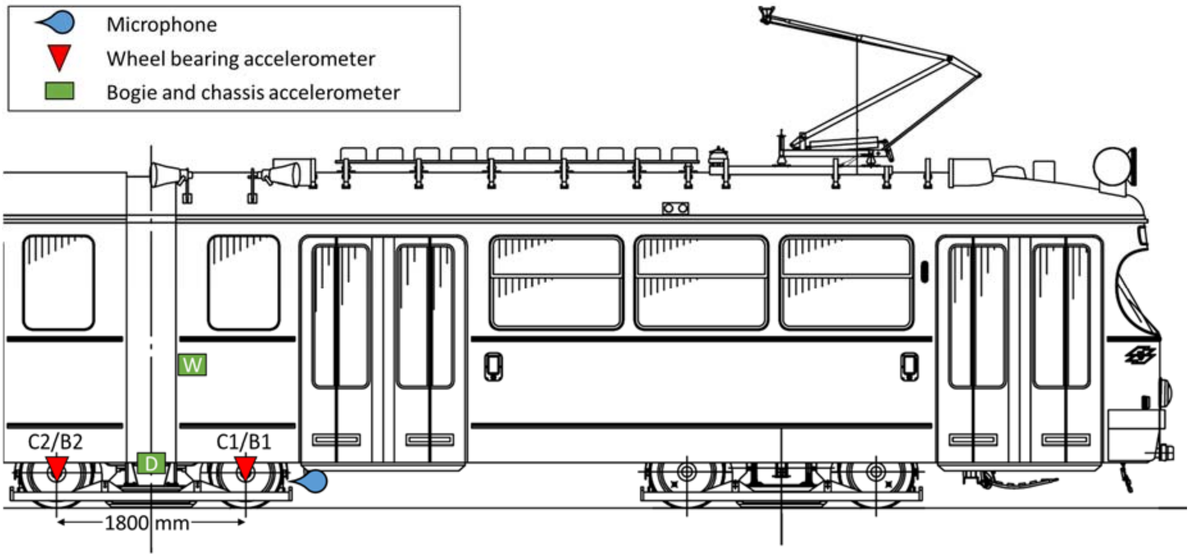

Fig. 1 Schematic drawing of sensor positions on *Eva* (inspection tram, vehicle type E1)

Fig. 2 shows the average 1/3 octave levels of vertical vibration acceleration (in dB using a_0=1x10^{-6} m/s^2) recorded on sensors B1, D and W as *Eva* drove along the same straight in both directions (referred to as track 1 and track 2) several times at different velocities. By keeping the track conditions constant throughout the experiment, the resulting vibration levels show the effect of the vehicle's velocity on the recorded emission. The spectra were computed over a 20 second window in which the tram's velocity was constant along the test track.
All on-board sensors clearly show higher vibration levels when driving at greater speed and for sensors B1 and D this effect is apparent across the entire investigated frequency range. For sensor W, however, the increase with velocity almost disappears at frequencies above 100 Hz, which suggests that the stiffness of the vehicle's suspension between bogie and car body has an eigenfrequency of approx. $100/\sqrt{2} = 70$ Hz. This effect was also observed in the lateral and longitudinal direction.

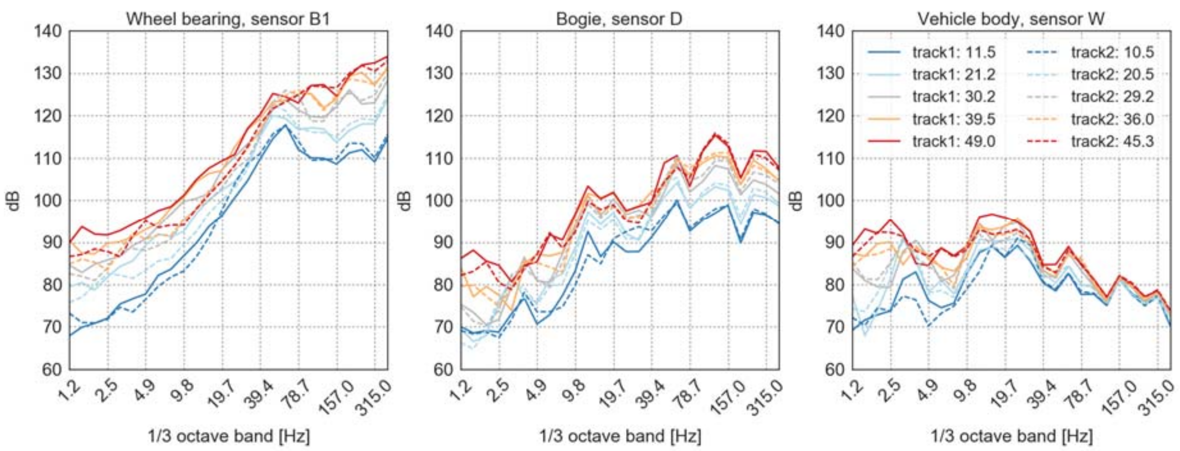

Fig. 2 On-board vibration acceleration levels in 1/3 octave bands. The three plots show data from the vertical sensors on different parts of the instrumented tram as it drove along a straight section in both directions (track 1 and 2). Different colours correspond to different pass-by velocities (in km/h, see legend)

2.2. Evaluating the pass-by immission data

Seeing as a considerable part of the carriages operating in Vienna's tram network today are of the newer vehicle type called ULF (ultra low floor), the pass-by measurements compared the vibrations produced by the heavier ULF vehicles with the lighter, but older E1 vehicles. Besides their very different masses (66 t vs 35 t when fully loaded), the traction of the old vehicles uses powered axles on two of the bogies while the low floor of the new trams requires the axles to be replaced by an electronic traction control.

For the same pass-bys presented above, Fig. 3 shows the vertical vibration immission levels recorded at a distance of 8 m from the centreline of track 1 (i.e. 11 m from the centreline of track 2) during passages of the inspection tram *Eva* and the ULF at varying velocities. The diagrams show that immission levels for both vehicles increase as the trams travel faster on both tracks, particularly when increasing the speed from 10 km/h to 30 km/h. Above 30 km/h, the immission levels show a much smaller increase and will often have reached their maximum at 40 km/h.

In terms of frequency content, the ULF immission lies predominately between 20-100 Hz, while *Eva* shows a peak in the 15.6 Hz band. Note that this peak is not discernible in the on-board data. It may be produced due to local site effects (geology consisting of a fluvial gravel terrace with a loess overburden), but this would need to be confirmed through geophysical tests or through similarly pass-by measurements at different sites.

All 1/3 octave spectra were computed over a time window whose length was defined by a 10 dB drop before and after the maximum $L_{acc,S}$ of each tram passage. Looking at the time domain data, the peak vibration acceleration level with time weighting *slow* ($L_{max,acc,S}$) during all pass-by measurements were on average approx. 4 dB higher for the ULF than for *Eva*, see Fig. 4.

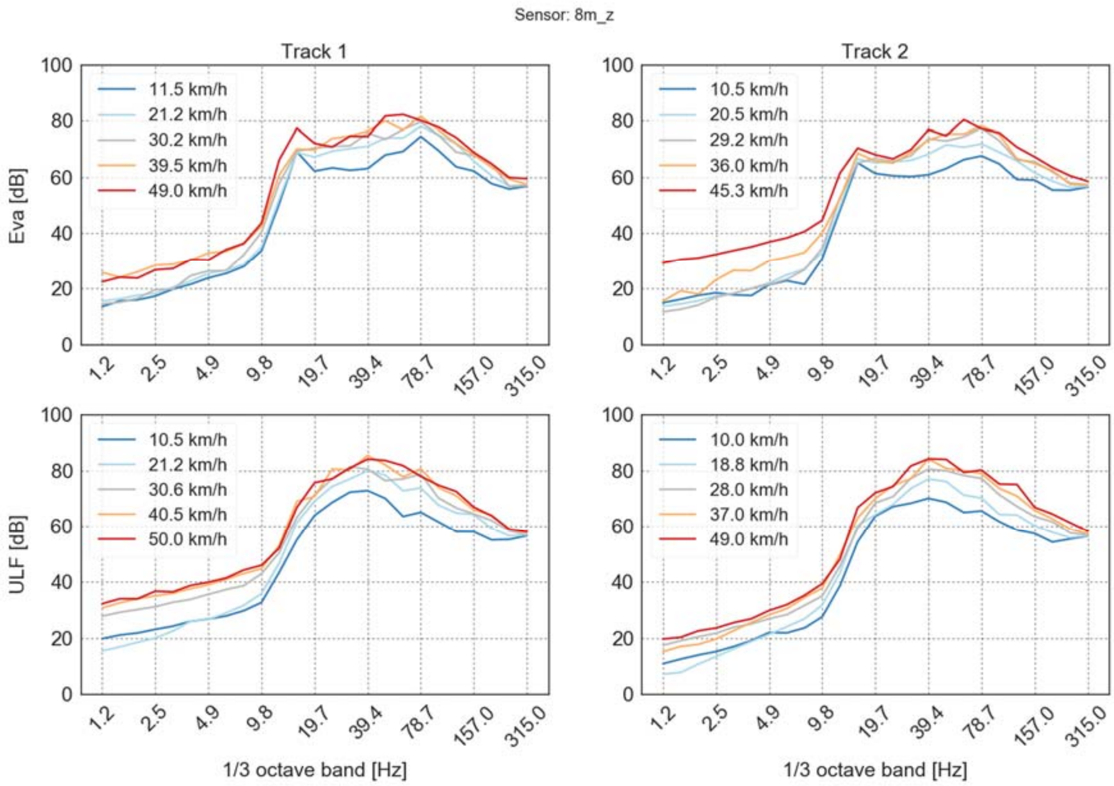

Fig. 3 Vertical vibration acceleration levels per 1/3 octave band recorded at a geophone 8 m from the centreline of the nearest track (track 1) during controlled pass-bys in both directions at different velocities (see legend) using two different vehicle types: *Eva* (top row) and ULF (bottom row)

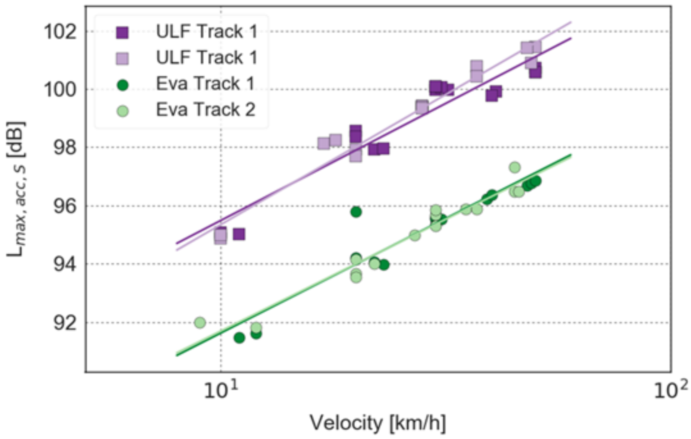

Fig. 4 Peak vibration immission level as a function of velocity for both vehicle types on both tracks incl. linear best-fit lines

3. Sound measurements

The instrumented car (*Eva*, microphone position shown in Fig 1) performs network-wide scans of the sound level near the bogie. This value may be used for a relative comparison of the rail characteristics over the whole network and can also be used to predict the sound immission caused by the vehicle. The latter requires the underlying assumption of a constant transfer path from the microphone in front of the bogie to an outside sound immission point. Also, the prediction is bound to a specific sound field condition.

Pass-by measurements were performed in an open space with a concrete ground surface to get the result for an acoustic free-field. With the exception of very narrow streets and tunnels, the on-board sound level can be seen to be independent from the geometry outside the tram due to the close positioning to the sound source (rail/wheel contact).

3.1. Evaluating the on on-board acoustic data

As the measurements are performed on a straight track in normal conditions, the sound emission is at a constant level. Therefore the average L_{AS} level for an interval of five seconds around the timestamp of the pass-by at the immission point are evaluated with a frequency-weighting ‘A’ and a ‘SLOW’ time-weighting (time-constant of one second). The level is calculated as an overall level and in third-octave bands. Fig 5 shows the third-octave band levels for the two different tracks. For both tracks a characteristic shape of the spectrum is seen. Also, a clear dependency of the sound emission on the tram velocity is visible in nearly all frequency bands. As is common for vehicle pass-by sound measurements, a good linear correlation can be found between the sound pressure level and the logarithm of the velocity, especially for the frequency range from 100 Hz to 8 kHz. At around 30 km/h a distinct peak is visible at 200 Hz, which is most likely caused by a resonance phenomenon on the tram itself.

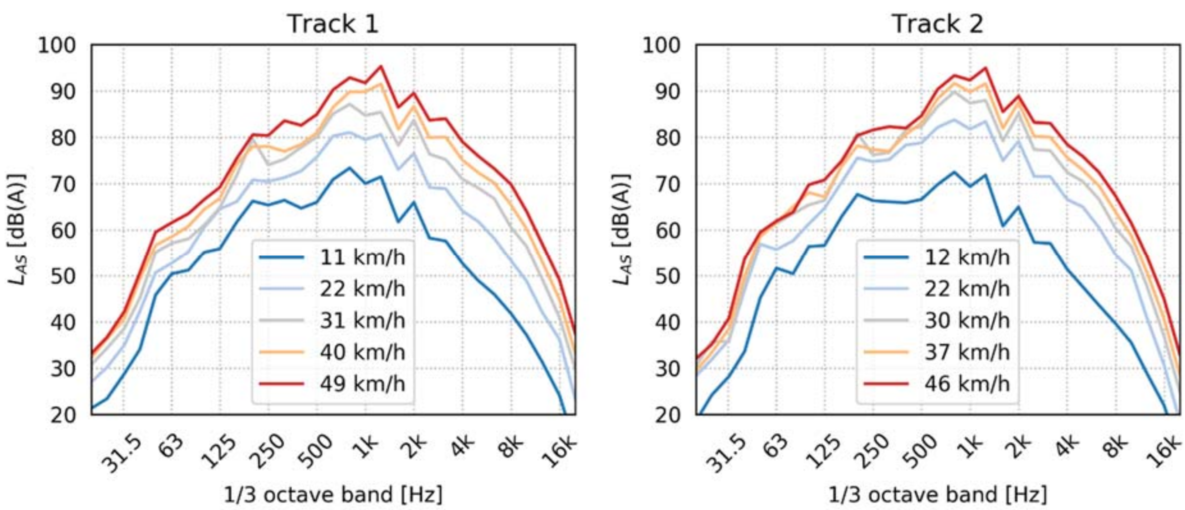

Fig. 5 On-board measured sound emission level in third-octave bands for the two tracks for different pass-by velocities (see legend).

3.2. Evaluating the acoustic immission data

For each track a microphone was placed at a distance of 7.5 m from the centerline of the rails, 1.2 m above ground. Both microphones were on the same side of the double track. The surrounding area with a concrete ground surface was free from any sound reflecting objects. To compare the different pass-bys, the sound exposure level in third-octave bands is used, which is calculated from the third-octave band filtered L_{AF} level. Fig 6 shows these pass-by levels for both tracks and for both tram types. As mentioned above, the measured level depends on the velocity of the tram, but for the older E1 vehicle this relationship is lost below 250 Hz. For the new ULF vehicle the dependency can be seen at frequencies as low as 100 Hz. Therefore it is also possible to calculate a linear regression model between the third-octave levels and the logarithm of the velocity. The peak at 200 Hz at 30 km/h for the *Eva* measurements is also visible in the pass-by noise, although the peak there is less dominant. For the ULF tram higher levels were recorded in the frequency range below 125 Hz, whereas the E1 vehicle shows higher levels in the frequency range above 125 Hz. This also results in a higher overall L_{AE} of about 3-5 dB(A) for the E1 type (*Eva*).

3.3. Estimation of the pass-by level by calculating a transfer path

With a regression model it is possible to calculate an average level for each third-octave band for each given velocity. As a regression model is available for the on-board level near the bogie as well as for the immission point, it is possible to estimate the transfer path from below the tram to the point beside the track. This transfer path is the difference between the regression models for the on-board acoustic data and the immission data, and is calculated for each third-octave band frequency, velocity and track separately. Fig 7 shows the resulting transfer paths. Ideally the transfer path would be the same for both tracks and also independent of velocity. The dependency on velocity can be explained by the fact that a constant level (L_{AS}) is compared to a sound exposure level (L_{AE}), which captures a different time interval depending on the pass-by velocity. The differences between the two tracks are most likely due to random influences during the measurements. Nevertheless, for higher speeds in the mid-frequency range (125 Hz to 5 kHz) the two transfer paths are surprisingly similar.

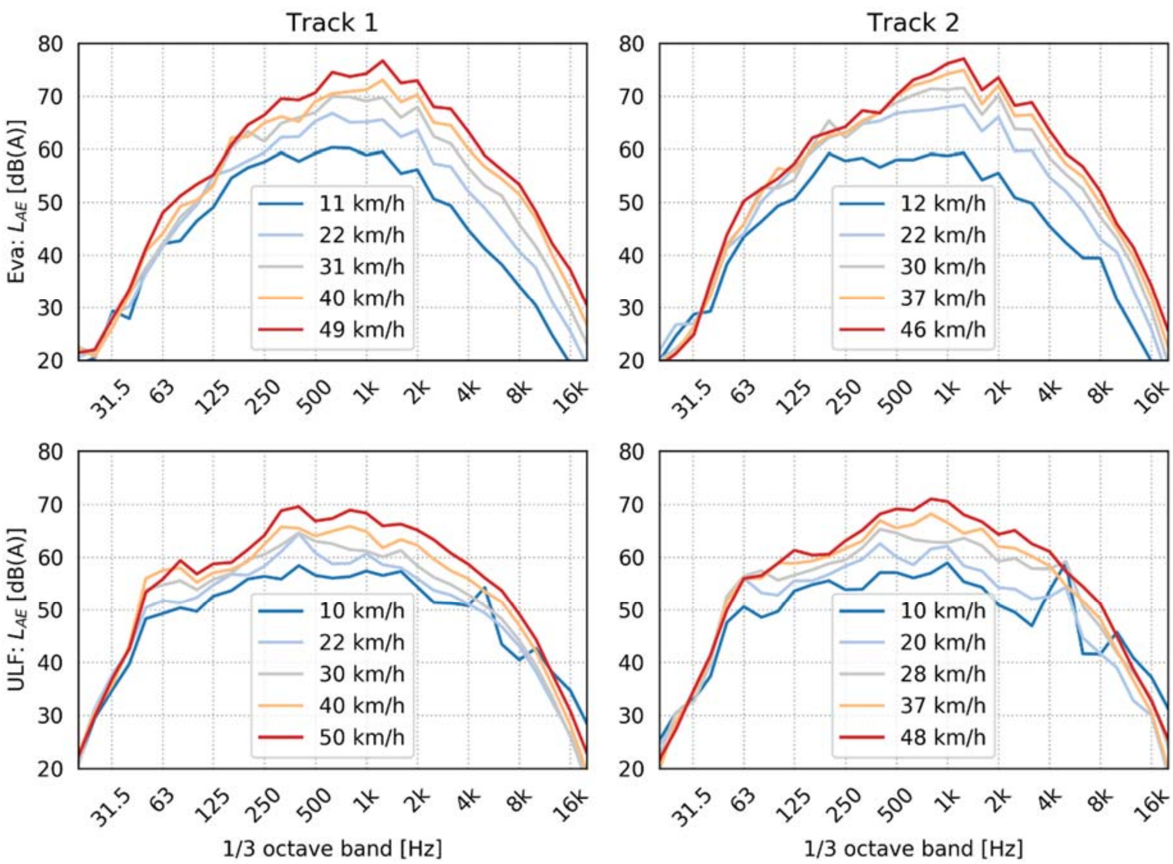

Fig. 6 Pass-by sound exposure level in third-octave bands for the two tracks for different pass-by velocities (see legend).

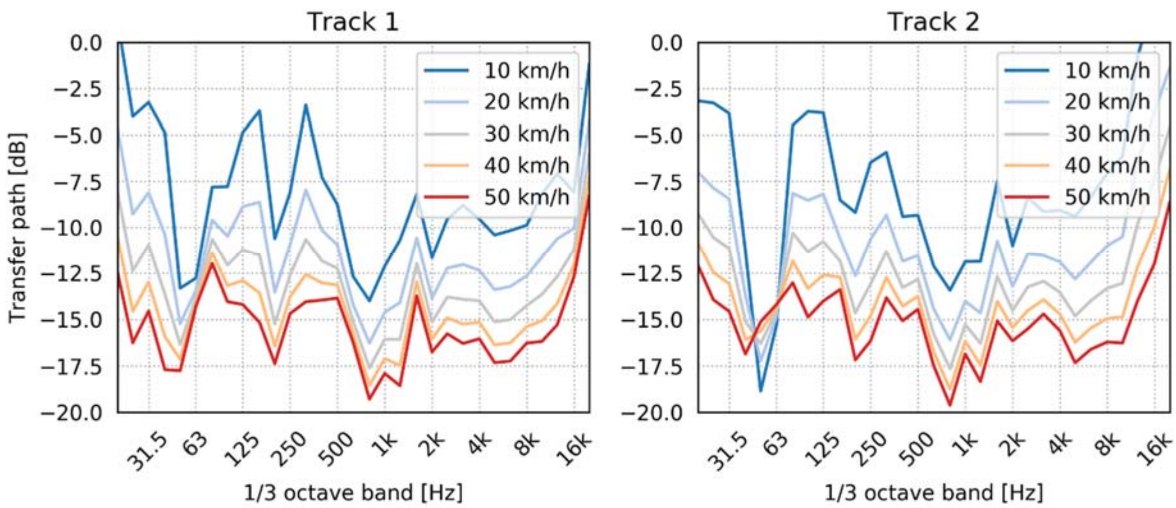

Fig. 7 Transfer path in third-octave bands for the two tracks as difference between the regression models evaluated at different velocities.

An average transfer path is calculated from the two tracks and used to predict the immission level (L_{AE}^{TP}) from the on-board data (L_{AS}). As the transfer paths from the two tracks are most similar in the mid-frequency range, the third-octave transfer paths are used to predict the overall immission level. Therefore any errors introduced by the inconsistent transfer paths for high and low frequencies have less effect on the prediction as the levels in these third-octave bands are not significant in the A-weighted spectrum.

The available data is subsequently used for evaluating the prediction. For each recorded pass-by the predicted level (L_{AE}^{TP}) is compared to the actually measured sound exposure level (L_{AE}^{IM}). The left diagram in Fig 8 shows both levels for each track separately. Apparently, track 1 shows a lower immission level than track 2 by approximately 2 dB. Although the unprocessed on-board data shows a significantly higher level (by approx. 16 dB) than the outside pass-by level due to the close position to the tram bogie, the prediction of the outside level with the transfer path from the on-board data is very close to the actually measured level. As the difference in the two tracks is also visible in the predicted level, this comparison shows the usefulness of the on-board data to assess the rail condition. On the right side of Fig 8 the deviation between the predicted level (L_{AE}^{TP}) and the actually measured level (L_{AE}^{IM}) is shown for each measured pass-by. For most of the pass-bys the error is below 1 dB. The root-mean-squared error for track 1 is 0.8 dB and for track 2 it is 0.3 dB. Therefore it is possible to predict the outside (free-field) immission value with reasonable certainty. For a complex geometry the on-board level is most likely not affected due to the close position to the sound source, whereas immission levels will increase due to reflections. Therefore, the predicted free-field immission level will most likely underestimate the real immission level in an urban environment.

4. Application of on-board data

The main benefit of on-board data is the possibility to monitor and assess the quality of the whole tram network. For maintenance planning a relative level is most relevant. Nevertheless, a good correlation to an absolute

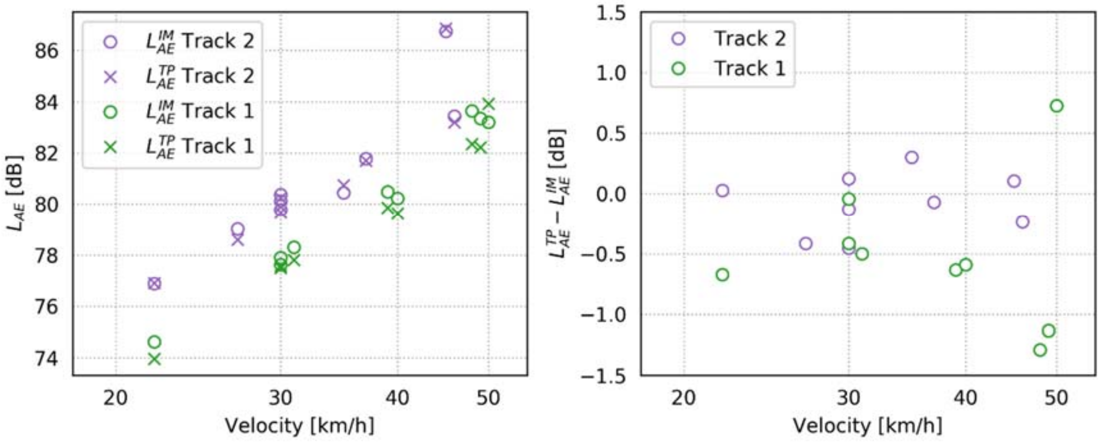

Fig. 8 Pass-by sound exposure level in third-octave bands for the two tracks for different pass-by velocities (see legend).

immission level provides two further applications. First, as the on-board data shows similar qualities of the rail/track interaction due to the correlation, the on-board data can actually be used for maintenance planning to improve immission levels. This is currently under active development. Second, with the transfer path model for the acoustic data it is possible to predict the free-field immission level. This level could be used in the calculation of noise maps for the city, whereas the tram type must be considered additionally. Other uses of on-board data include the detection of corrugation and curve squeal, which are also currently under development. As both of these phenomena lead to higher immission values, on-board data can again be used to improve sound and vibration immission by locating hotspots and assisting maintenance measures. Nevertheless, for a better quantification and especially for an independent evaluation of the transfer path model, more pass-by measurements are needed.

5. Discussion

Strictly speaking, the on-board data is only representative for the instrumented (type of) vehicle and the observed hot-spots may not necessarily be a problem for other carriage types. Vice versa, other tram types with their respective axle loads and bogie configurations may be a source of annoyance in places where the instrumented carriage indicates no such hot-spot. As the instrumented tram is of a vehicle type that regularly operates on Vienna's network, however, it was deemed representative of Vienna's carriage stock in this initial study. It has to be noted though, that as the old E1-vehicle may be phased out over the next decades, future work will have to investigate the validity of the inspection tram's data in regard to newer vehicle types such as the ULF or the Flexity which will go into operation at the end of 2018.

Acknowledgements

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6. References

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