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CASE STUDY: SIMULATION OF THE EFFECT OF TUNNEL PROPERTIES ON THE INTERIOR NOISE OF DIFFERENT RAILWAY VEHICLES

Alex Sievi[1*] **Otto Martner**[1]
[1] Müller-BBM Industry Solutions GmbH, Helmut-A-Müller-Str. 1-5, 82152 Planegg, Germany

ABSTRACT

In railway tunnels, the interior noise in railway vehicles rises compared to the free-field condition due to sound reflections on the tunnel walls. The aim of the investigation at hand was to systematically investigate the impact of tunnel geometry and tunnel configurations on the inside noise for different trains. For doing that, seven different tunnel geometries with three different absorption characteristics were investigated on two trains with different sound transmission characteristics. For doing so, the sound distribution on the outer shell of the vehicle is to be predicted using a ray-tracing method. Based on the outer sound pressure distributions, the interior noise for the different vehicle classes is predicted using noise prediction models. The impact of a tunnel surface area, type of cross-section and absorption of the track bed and tunnel walls is discussed for different train types. Based on the case study the following acoustic parameters are of main importance: absorptive characteristic of tunnel, train's transmission loss characteristics and the surface area of the cross-section of the tunnel. The dependency of the tunnel shape and the closeness of the train to the next tunnel wall is weak.

Keywords: *interior noise – railway – simulation – tunnel*

1. INTRODUCTION

The requirements for the interior noise of rail vehicles are usually specified for the standard test situation defined according to ISO 3381 [1] on a free and straight track and on a standard-compliant track. In spite of vehicles such as light rail vehicles and subways operating frequently or exclusively in tunnels, requirements for interior noise when travelling in tunnels are often not specified. This is probably also due to the fact that VDV 154 [2], which is frequently used in mass transit, does not specify any guideline values for interior noise when travelling in tunnels. The lack of guideline values and the associated fact that interior noise is usually not specified for tunnel travel is due to the more complex interaction between vehicle and tunnel geometry. In order to deepen the understanding of the interaction, a computational case study is performed to show the impact of the tunnel geometry and tunnel properties on the interior noise in the train for two different vehicle types.

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[*] ***Corresponding author***: *Alex.Sievi@mbbm-ind.com.*

2. APPROACH AND MODELS

2.1 Why a numerical case study?

The interior noise while driving through a tunnel is not only dependent on the vehicle properties and tunnel properties but also on the track type (slab track/ballasted track) and the acoustical track quality (rail roughness and track decay rate). An experimental investigation of this kind will be limited by the variation of the track type and acoustic track quality. In addition, the parameter space would be significantly limited because the number of available tunnels on a track is usually very limited. In order to investigate the largest possible parameter space and to do so without the disturbing influence of variating track type and quality, this investigation was carried out with the help of computational prediction methods, as they have been used for many years at Müller-BBM for design-related consultancy studies [3]. Some examples of achieved precision of the used prediction method are stated in [4].

2.2 Two-level approach, considered effects

In a first step, the sound pressure level on the outer skin of the vehicle is calculated using a ray-tracing method for the tunnel. In a second step, this sound pressure is used as an excitation input for the interior noise prediction to calculate the interior sound pressure levels.

This approach only considers the effects of airborne sound contributions. Structure-borne noise, noise from auxiliary equipment inside or on the roof of the train and aerodynamic noise are not considered in this investigation. Structure-borne noise contributions do not depend on the tunnel shape and absorptive characteristic of the tunnel. They therefore can be considered as constant additional noise and as background noise from auxiliary equipment. Aerodynamic noise becomes important for high velocities and especially in narrow tunnels. For velocities below approx. 120 to 140 km/h, aerodynamic noise has no important impact on the inside sound pressure. The derived results are therefore especially valid for light rail vehicles and electrical multiple units below these velocities and vehicles where the noise in free field is normally dominated by the rolling noise.

2.3 Simulation of the sound in the tunnel

For the determination of the sound pressure on the outside shell of the vehicle, the cavity ‘tunnel’ (length 160 m) and the train consisting of 4 waggons (20 m each) was simulated with the ray-tracing software Odeon. For simulating the rolling noise of the bogies, omni-directional sound sources were placed at the locations of the wheels beneath the waggons at the position of each wheel. All sound sources were set to the same sound power level with a typical 1/3 octave band spectra for rolling noise.

At first, a tunnel with very low absorption capacity was modelled. For the tunnel walls and the floor, the absorption value was set only to absorption typical values of concrete walls ($\alpha \sim 0.02$ at low frequencies, $\alpha \sim 0.1$ at higher frequencies) and the absorption of the exit portals was set to 1. The absorption of the vehicle and absorption due to scattering effect on installations (cables, rails, sleepers, electric boxes etc.) was neglected. We assume that this model represents the worst case of a tunnel with slab track.

Then, absorption equivalent to ballast was considered for the track surface to absorption values equivalent to ballasted track ($\alpha \sim 0.2$ at low frequencies, $\alpha \sim 0.7$ at higher frequencies). At last, the impact of the sound-absorbing surface on the walls of the tunnels were investigated ($\alpha \sim 0.3$ at low frequencies, $\alpha \sim 0.8$ at higher frequencies). The surface of the train was set to 100 % reflecting.

Two double-track tunnels and four single-track tunnels were investigated in this way (see Figure 1, 2, 3). In order to investigate the closeness of a tunnel wall to the train, one variant was generated with the train placed at a distance of 20 cm from one tunnel wall (see Figure 3).

For simulating the free-field situation on ballasted track, which is taken as baseline for the later displayed sound attenuation, the absorption of the tunnel walls was set to 100 %.

The accuracy of the used ray-tracing method for determining the sound pressure level on the train’s outer surface in the tunnel is demonstrated in [4].

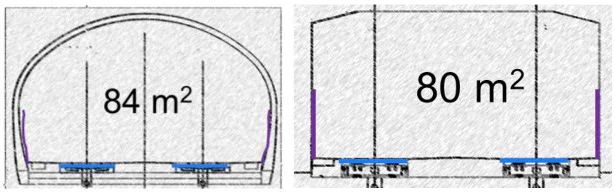

Figure 1. Double-track tunnels, blue/purple: sound-absorbing material on the track/walls.

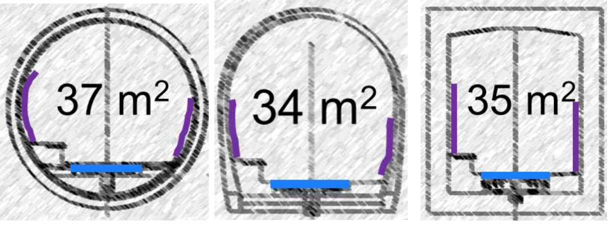

Figure 2. Three single-track tunnels, different shape, blue/purple: sound-absorbing material on the track/walls.

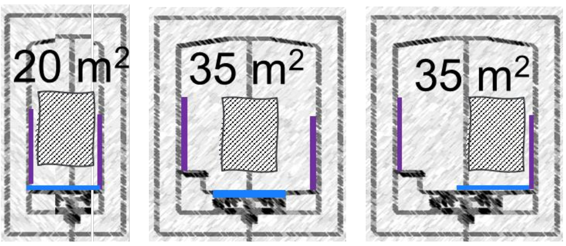

Figure 3. Smaller single-track tunnel (left), impact of the closeness of the tunnel wall to the train: variation of the vehicle position in the tunnel (middle/right), blue/purple: sound-absorbing material on the track/walls.

2.4 Simulation of the sound in the vehicle

The sound power contribution of the air-borne sound source via the train's surface areas is determined with the outside sound pressure and the transmission loss R of the surface areas assuming random incidence of the waves and statistic room acoustics for the vehicle interior. A simplified model of a passenger area was created consisting of the surface area's floor, the lower side walls, windows, the sides beside and above the windows and the roof. The dimensions of the surface areas were taken from a typical subway. Transmission losses of two light rail vehicles were used in order to investigate the impact of the variation of the transmission loss over the vehicle areas. The used transmission loss values are stated in Table 1. For vehicle no. 1, the floor has the highest transmission loss compared to the other surface areas. For vehicle no. 2, the roof and the lower side walls have the highest transmission losses. The used sound transmission losses were determined by in-situ measurement technique directly on the trains. Since all input parameters of predicting the inside sound pressure are based on experimental results, the determined sound pressure should represent the real values of the simplified train section quite well. We assume a similar accuracy of the prediction model as presented in [5]. To study exclusively the influence of the sound insulation of the different trains, the geometry of investigated passenger area and reverberation time of the segment has been set constant for both trains.

Table 1. Considered R_w-values.

Train's surface area	Vehicle no. 1	Vehicle no. 2	Surface area
Floor	36 dB	33 dB	9.2 m^2
lower sides	32 dB	35 dB	7.2 m^2
upper sides	35 dB	35 dB	4.2 m^2
windows	33 dB	33 dB	4.8 m^2
Roof	31 dB	37 dB	11.0 m^2

The cross-section of the vehicle was about 7.2 m^2. The calculations were performed in third-octave bands from 50 Hz to 5 kHz.

3. RESULTS

3.1 Exterior sound pressure attenuation

In Figure 4, the predicted sound pressure level in a tunnel using the ray-tracing method is displayed as a colour plot.

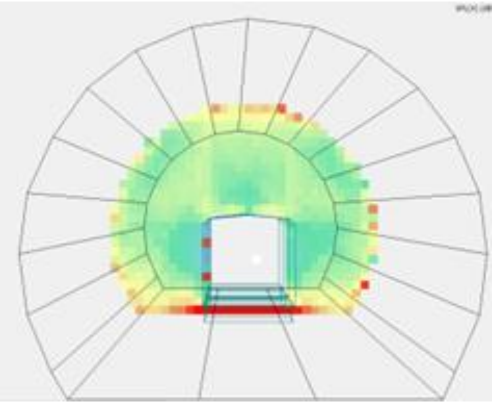

Figure 4. Predicted sound pressure levels in the tunnel.

Based on the calculated sound pressure levels on the surface areas of the train (floor, lower side walls, windows, upper side walls and roof), the level attenuations were calculated using the underfloor sound pressure of the free-field situation with ballasted track as baseline. The determined level attenuations are displayed for both sides of the train in Figure 5.

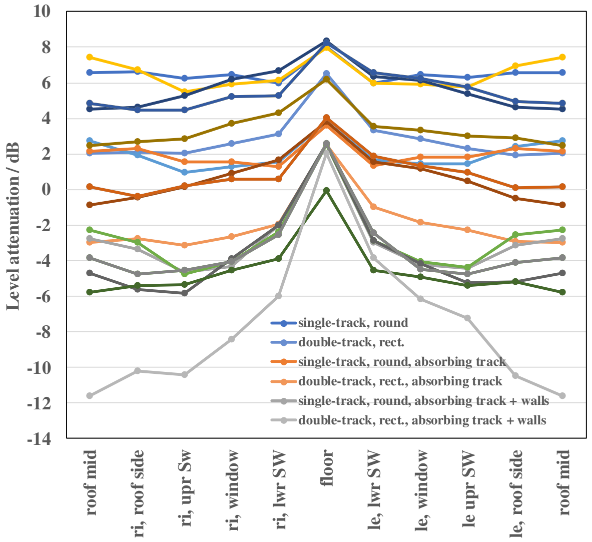

Figure 5. Averaged level attenuation compared to free-field on ballasted track for the different tunnels on the surface areas of the train for the frequency band 400 Hz to 1250 Hz.

The number of measurement data with sound pressure on the outside train's surface areas while running normal operation are very rare. In Figure 6, the level attenuation for a comparable case is displayed for a very narrow tunnel together with calculated values in this investigation. The measured level attenuation is referenced to the sound pressure in the vicinity of the bogie and not to the free-field situation on ballasted track. Figure 6 shows that the general attenuation from the floor to the sides and the side roof areas are quite similar.

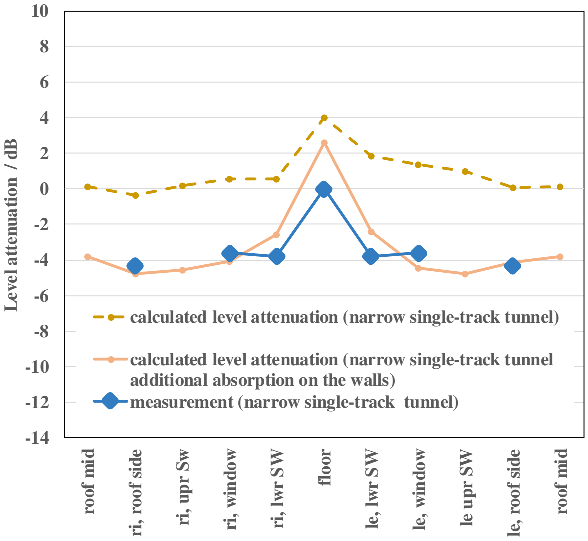

Figure 6. Comparison of measured vs. calculated level attenuations in dB for the frequency band 400 Hz to 1250 Hz.

3.2 Impact of the tunnel

The following Tables 2 and 3 show the determined levels in the interior of the segments for the two different vehicle types for all tunnel geometries and tunnel configurations. The level increase compared to driving on the open track is marked in color. The average increase is + 7.9 dB with a variance σ = ± 3.5 dB for all cases.

Vehicle No. 1 has 2.6 dB higher values in average than vehicle No. 2. Consequently, vehicle No. 1 reacts more strongly, which is due to the higher transmission loss of the floor compared to the other surface areas of this train. Trains with acoustically weak floors are less prone to high-level increase.

Narrow tunnels lead to higher level increases than large tunnels.

Table 2. Impact of the tunnel on the interior noise level in vehicle no. 1.

Tunnel	Tunnel shape	concret tunnel	concret tun. + ballast	concret tun. + ballast + absorbing walls	level increase due to the tunnel / dB		
Situation		**A-weighted sound pressure level / dB**					
Free-fieled on ballasted track		**71**					
Single-track tunnel*	round	85	81	77	**+ 14.5**	**+ 10.4**	**+ 6.1**
	oval	85	81	77	**+ 14.3**	**+ 10.3**	**+ 6.2**
	rectangular	85	80	76	**+ 14.1**	**+ 9.5**	**+ 5.7**
Single-track tunnel***	rectangular	85	81	77	**+ 14.6**	**+ 10.1**	**+ 6.0**
Double-track tunnel**	oval	82	77	75	**+ 11.3**	**+ 6.8**	**+ 4.4**
	rectangular	81	77	74	**+ 10.9**	**+ 6.9**	**+ 3.9**

* $A \approx 30\ m^2$, ** $A \approx 80\ m^2$, *** $A \approx 20\ m^2$

Table 3. Impact of the tunnel on the interior noise level in vehicle no. 2.

Tunnel	Tunnel shape	concret tunnel	concret tun. + ballast	concret tun. + ballast + absorbing walls	level increase due to the tunnel / dB		
Situation		**A-weighted sound pressure level / dB**					
Free-fieled on ballasted track		**71**					
Single-track tunnel*	round	82	78	75	**+ 11.3**	**+ 7.0**	**+ 4.0**
	oval	82	78	75	**+ 11.1**	**+ 7.0**	**+ 4.0**
	rectangular	82	78	75	**+ 11.3**	**+ 6.6**	**+ 3.8**
Single-track tunnel***	rectangular	83	78	75	**+ 11.6**	**+ 7.1**	**+ 3.9**
Double-track tunnel**	oval	80	75	73	**+ 8.6**	**+ 3.8**	**+ 1.9**
	rectangular	79	75	74	**+ 8.6**	**+ 4.5**	**+ 2.7**

* $A \approx 30\ m^2$, ** $A \approx 80\ m^2$, *** $A \approx 20\ m^2$

3.3 Impact of the tunnel absorption

The previously determined levels were used to determine the influence of tunnel absorption. For this purpose, level differences for the configurations with ballasted track were determined for all tunnels and vehicles (Table 4 and 5) with the following conclusion:

- The absorption in the tunnel is of very great impact, especially when the tunnel has very low absorptive capacity.
- The variation between the different tunnel absorption is between + 4,8 dB (oval double-track tunnel, vehicle 2) to - 4.3 dB (round single-track tunnel, vehicle 1).
- The average impact is + 4.4 dB with σ = ± 0,3 dB (without absorbing track) and - 3.1 dB with σ = ± 0,8 dB (with absorbing walls).

Table 4. Impact of the tunnel absorption for vehicle no. 1, brown: tunnel without absorbing track, green: additional absorbing tunnel walls.

		level increase compared to the tunnel with ballast / dB		
Single-track tunnel*	round	**+ 4.1**		**- 4.3**
	oval	**+ 4.0**		**- 4.1**
	rectangular	**+ 4.6**		**- 3.8**
Single-track tunnel***	rectangular	**+ 4.5**		**- 4.1**
Double-track tunnel**	oval	**+ 4.5**		**- 2.4**
	rectangular	**+ 4.0**		**- 3.0**

* $A \approx 30\ m^2$, ** $A \approx 80\ m^2$, *** $A \approx 20\ m^2$

Table 5. Impact of the tunnel absorption for vehicle no. 2 brown: tunnel without absorbing track, green: additional absorbing tunnel walls.

		level increase compared to the tunnel with ballast / dB		
Single-track tunnel*	round	**+ 4.3**		**- 3.0**
	oval	**+ 4.1**		**- 3.0**
	rectangular	**+ 4.7**		**- 2.8**
Single-track tunnel***	rectangular	**+ 4.5**		**- 3.2**
Double-track tunnel**	oval	**+ 4.8**		**- 1.9**
	rectangular	**+ 4.1**		**- 1.8**

* $A \approx 30\ m^2$, ** $A \approx 80\ m^2$, *** $A \approx 20\ m^2$

3.4 Impact of the tunnel shape, position of the train in the tunnel and the tunnel's cross-section area

For determining the impact of the tunnel shape, position of the train in the tunnel and the tunnel's cross-section area, level differences between the different cases were calculated which are displayed in the Table 6 and 7. The results are:

- The tunnel shape has an influence on the sound pressure level inside the segment.
- In general, round/oval tunnels seem to be more critical than rectangular tunnels. In the most critical case the inside sound pressure rises by 0.9 dB from rectangular to round tunnel.

- The position of the train inside the tunnel, respectively the closeness of the train to a wall, also increases the levels inside the train slightly.
- The tunnel's cross-section area is of more importance. With a cross-section area of 1/4 of the original cross-section (80 m^2) the level in the interior increases by 2.2 dB to 3.7 dB. Tunnels with less absorption are more prone for higher level increases.

Table 6. Impact of the tunnel shape, train's position and cross-section area on the interior noise level in vehicle no. 1.

	dB		
	concret tunnel	**concret tun. + ballast**	**concret tun. + ballast + absorbing**
impact of the tunnel's shape			
oval vs rectangular/ single-track	**+ 0.2**	**+ 0.8**	**+ 0.5**
round vs rectangular/ double-track	**+ 0.4**	**+ 0.9**	**+ 0.4**
oval vs rectangular/ double-track	**+ 0.4**	**- 0.1**	**+ 0.5**
impact of the location of the train in the tunnel			
Single-track tunnel**/ train 20 cm near one wall	**+ 0.1**	**+ 0.4**	**+ 0.3**
impact of the tunnel's cross section area			
35 m^2 vs 80 m^2/ oval	**+ 3.0**	**+ 3.5**	**+ 2.0**
35 m^2 vs 80 m^2/ rectangual	**+ 3.2**	**+ 2.6**	**+ 1.8**
20 m^2 vs 80 m^2/ rectangual	**+ 3.7**	**+ 3.3**	**+ 2.2**

** $A \approx 30\ m^2$, ** $A \approx 80\ m^2$, *** $A \approx 20\ m^2$*

Table 7. Impact of the tunnel shape, train's position and cross-section area on the interior noise level in vehicle no. 2.

	dB		
	concret tunnel	**concret tun. + ballast**	**concret tun. + ballast + absorbing**
impact of the tunnel's shape			
oval vs rectangular/ single-track	**- 0.1**	**+ 0.4**	**+ 0.1**
round vs rectangular/ double-track	**+ 0.0**	**+ 0.5**	**+ 0.1**
oval vs rectangular/ double-track	**+ 0.1**	**- 0.7**	**- 0.9**
impact of the location of the train in the tunnel			
Single-track tunnel**/ train 20 cm near one wall	**+ 0.0**	**+ 0.3**	**+ 0.1**
impact of the tunnel's cross section area			
35 m^2 vs 80 m^2/ oval	**+ 2.5**	**+ 3.2**	**+ 2.0**
35 m^2 vs 80 m^2/ rectangual	**+ 2.7**	**+ 2.1**	**+ 1.1**
20 m^2 vs 80 m^2/ rectangual	**+ 3.0**	**+ 2.6**	**+ 1.2**

** $A \approx 30\ m^2$, ** $A \approx 80\ m^2$, *** $A \approx 20\ m^2$*

4. SUMMARY

Based on the case study a ranking of the influencing parameter can be derived:

- Absorption characteristic of the tunnel: Especially in tunnels with hard tunnel walls, the effect of the ballast and additional absorption can be of high impact. The average influence of tunnel absorption is + 4.4 dB with $\sigma = \pm 0.3$ dB for the case where the tunnel has no absorbing track and - 3.1 dB with $\sigma = \pm 0.8$ dB for a tunnel with a ballasted track that has more absorption surfaces than a raw concrete tube.
- Trains' transmission loss characteristics: Vehicle no. 1 shows 2.6 dB higher inside sound pressure levels than vehicle no. 2. Vehicles with acoustically weak floor areas are less prone to high level increase.
- Tunnel cross-section area: The size of the tunnel section area is the third relevant parameter. The smaller the cross-section area of the tunnel the higher the inside sound pressure level. By reduction of the cross-section area to 1/4 of the original cross-section (80 m^2), the level in the interior increases by 2.2 dB to 3.7 dB.
- The dependency of the tunnel shape and the closeness of the train to the next tunnel wall is weak (<1 dB).

5. REFERENCES

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