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BOGIE SKIRTS FOR RAILWAY VEHICLES: EFFECTS ON INTERNAL NOISE

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ABSTRACT
Whereas there are numerous studies on the effect of bogie skirts on the exterior noise emission, the present investigation deals with their effect on the *interior* noise. Scale model experiments are combined with simple analytical models to determine the sound field around the vehicle cross-section in the bogie region due to rolling noise. Different lay-outs of bogie skirts are compared for a wide-body intercity coach. The measurements indicate that the sound field outside the wall is rather complex and the screening effect depend on the rail/wheel source configuration, ballast absorption and frequency. The results are discussed with respect to noise insulation requirements on train walls and floors as well as potential weight savings on the vehicle.

1 - INTRODUCTION
To meet the external noise requirements from trains, bogie skirts are often suggested as a noise control measure. However, such measures also affect the internal noise, as acoustic energy is redistributed from outside the car-body walls to the bogie area. Accordingly, requirements on noise insulation of floors and walls should be redefined to reach the same internal noise levels as for a standard vehicle, keeping an optimum weight distribution of walls and floor. For certain rail vehicles, e.g. when requirements on the wall thickness put a limit on the potential sound insulation, bogie skirts may be beneficial by redistributing the wall-transmitted sound through the floor instead Furthermore, if the sound pressure levels outside car-body walls can be reduced, simpler window solutions can be chosen, saving costs and weight.

2 - ANALYSIS
Due to the complexity of the source configuration, a detailed analysis is rather demanding and beyond the scope of the present work. Instead, a straightforward model involving image monopole sources and diffraction theory is applied. Accordingly, monopole source models for rail and wheel and partially reflecting planes for the ballast and car-body underfloor are assumed. Harmonic excitation is assumed throughout. To account for reflections within the bogie room the method with image sources may be applied [1], as illustrated in Figure 1.
When the ballast absorption α_b is high and results are sought in frequency and spatial average, the image sources may be treated as uncorrelated, and the sound pressure level at the receiver can be written as $L_{p,tot} = \sum \hat{p_i}^2/\hat{p}_{ref}^2$ with $\hat{p^2}_i$ being the squared sound pressure amplitude from source i. Further, we may assume that ground reflection reduces the power of the i^{th} image source according to $W_i = W_0\left(1-\alpha_b\right)^{\text{i}}$, and the total drop in sound pressure level due to the screening of the car-body is thus

$$\Delta L_p = 10\log\left(\sum_i r_i^{-2}\left(1-\alpha_b\right)^i 10^{IL_i/10} / \sum_i r_i^{-2}\left(1-\alpha_b\right)^i\right) \tag{1}$$

where IL_i is the insertion loss of source i due to screening and $r_i^2 = \left(y_{is}-y_r\right)^2 + \left(x_s - x_r\right)^2$. The insertion loss is introduced to describe the sound field outside the wall. It is defined as the difference between the actual sound pressure level at a certain point with the vehicle in place and the level at the same point without the vehicle (i.e. from a monopole source in a free field). However, in the following sections the term insertion loss is also used to denote the difference in sound pressure level for a case with and without bogie skirt. This quantity is an indicator for comparison of the screening effect of the skirts. According to standard Fresnel theory [1] the insertion loss of a screen obstructing the sound from a point source i is given by

$$IL_i = 20\log\frac{\sqrt{2\pi N_i}}{\tanh\sqrt{2\pi N_i}} + 5 \tag{2}$$

where the Fresnel number is $N_i = 2\left(\sqrt{x_s^2+y_s^2}+\sqrt{x_r^2+y_r^2}-r_i\right)/\lambda$ with λ being the wavelength. With the source or receiver close to the barrier, an additional term $20\log\left(\sqrt{x_s^2+x_s^2}+\sqrt{x_r^2+x_r^2}/r_i\right)$ arises due to increased spherical divergence of the field.

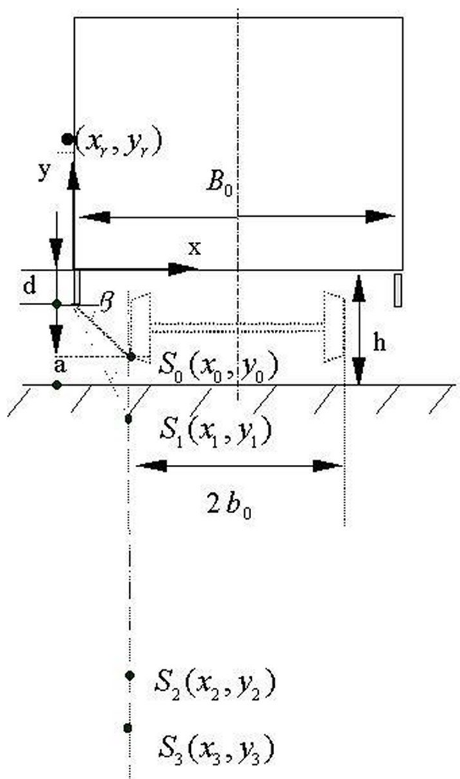


Figure 1: Layout of car-body and bogie-room with image sources indicated.

2.1 - Bogie room noise

The sound field in the bogie room may at high frequencies be assumed to be diffuse and any change in average wall absorption is related to the far-field sound pressure level as,

$$\Delta L_p = 10\log\left(\left(1-\Delta\bar{\alpha}\right)/\Delta\bar{\alpha}\right) \tag{3}$$

where $\Delta\bar{\alpha} = \sum\alpha_i/\sum S_i\alpha_i$ with S_i and α_i being surface area and absorption coefficient of the i $^{\text{th}}$ cavity wall element. With data for the geometry together with the absorption of ballast, under-floor and skirts, estimates of the increase of noise level due to the skirts can thus be obtained at high frequencies.

3 - MEASUREMENTS

For the experiments a 1:4 scale model of a wide body intercity train was built in particle board. The key dimensions (in fullscale size) with notation as in Figure 1 are: body width $B_0 = 3.0$ m, wheel-set width $2b_0 = 1.6$ m, underfloor height $h = 1.5$ m. The model, shown in Figure 3, includes simplified but acoustically relevant components of bogie, wheels, car-body and 2.5 meters of track. The skirts were mounted on the side-walls in different vertical positions to let the skirt depth d vary. The hard ground/board was covered with 5 mm thick foam to represent ballast absorption. Laboratory measured absorption coefficients are presented in Figure 2 (re-scaled to full scale frequency). Note that real life ballast absorption is reported to be in the range $0.4 < \alpha_B < 0.8$, flat over the audio range, so the present ground absorption may be too low at low frequencies. Thinner foam was placed underneath the car-body floor but the skirts were left untreated.

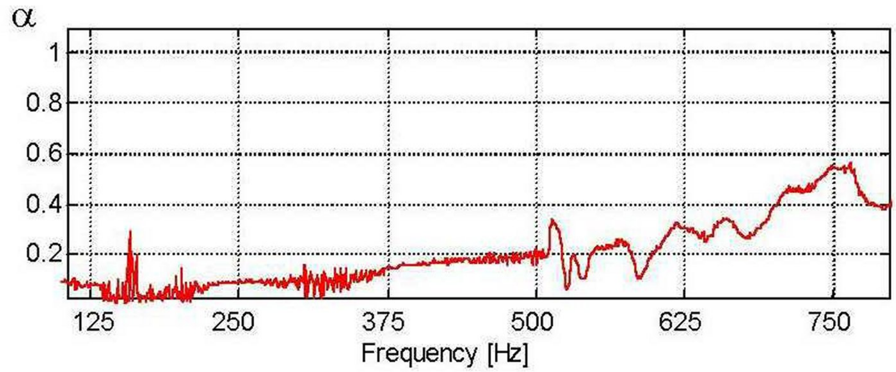


Figure 2: Measured absorption of ballast mat.

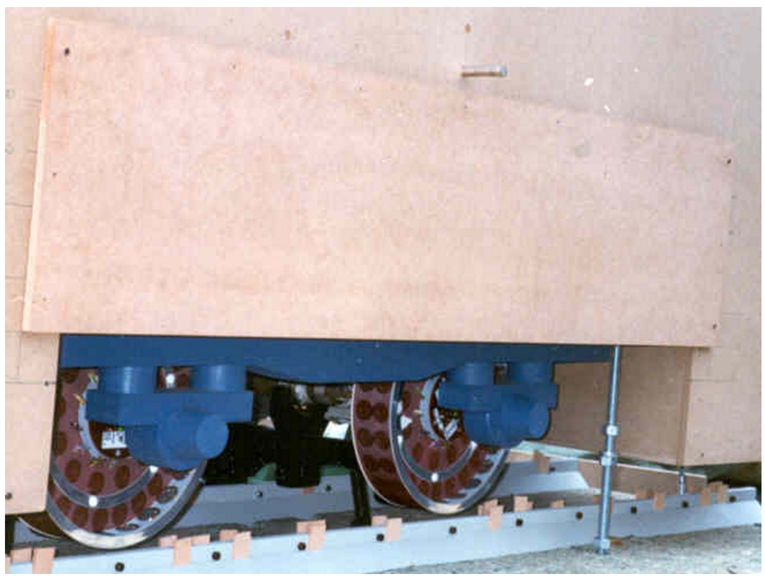
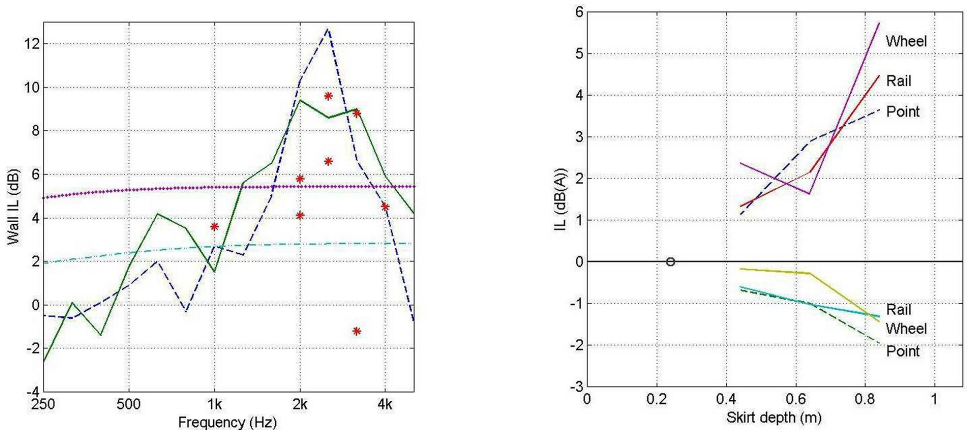


Figure 3: Scale model used in experiments.

The measurements were made outdoors. Three different excitations were used: (1) a point source at the position of a wheel/rail contact, (2) a realistic rail radiation accomplished by an "acoustic loudspeaker rail" with adjustable vertical and horizontal slots, (3) a realistic wheel radiation using specially designed rotating acoustic source wheels fitted with 84 small loudspeakers on the disc and rim as seen in Figure 4. The loudspeakers are controllable in a way that the radiation from individual structural modes can be imitated. A microphone was placed outside the side wall at $x_r = -0.2$ m, $y_r = 1.0$ m, as shown in Figure 3. A second microphone was placed inside the bogie room. For the point and rail sources, measurements were made using a swept sine signal within each 1/3-octave bands (chirp). For the wheel source, pure sine excitation was used due to the modal character of the wheel radiation. Wheel eigenfrequencies and mode shapes were first calculated with FEM and a selection of wheel modes at their corresponding model-scale frequencies were used for the excitation.
For each measurement, 45 averages were taken. With the "no skirt" configuration as reference, corresponding to $d = 0.24$ m, insertion loss spectra for a skirt depth of $d = 0.84$ m are presented in Figure 4(a) for the three different kinds of excitation. The markers for the wheel excitation here indicate individual wheel modes and have been located in pertinent 1/3-octave bands. Two curves representing different point source positions in the analytical model, wheel/rail contact and wheel centre, are included.
Assuming a spectral content of the source, an overall IL can be calculated from the measured 1/3-octave IL-values. This has been performed using 1/3-octave sound power spectra calculated by the TWINS



(a): Insertion loss spectra for skirt depth $d = 0.84$ m and different source types.

(b): Overall A-weighted insertion loss for different source types as functions of skirt depth d (reference: d=0.24 m).

Figure 4: Calculated: rail ($a = 0.3$ m, dash-dot & light green); wheel ($a = 0.9$ m, dotted & light green); Experiment: rail (continuous & light green); point (dashed & light blue); wheel modes (*).

rolling noise software [3] for a similar vehicle at 200 km/h for the different skirt depths tested. From Figure 4(b) it is clear that the overall sound pressure level drops outside the wall with increasing skirt depth whereas the level increases in the bogie instead. This increase would be reduced if the skirts were treated with absorbents. Note also that the effects on interior noise are not as strong as those outside the wall, as low frequency noise, which is less effectively screened, dominates the transmission into the car-body.

4 - DISCUSSION OF MODELING

The measured results are shown to be in the same range as those from simple analytical models. However, at low frequencies calculated insertion losses are greater than those measured due to insufficiencies in the applied model; one reason is that the source is too close to the train floor. In addition, the low frequency absorption of the clad surface representing the ballast was too low as compared to field conditions resulting in a pronounced modal behavior of the bogie cavity which may be unrealistic. As low frequency noise dominates the transmission into the car-body and as prediction tools are eagerly desired in the train-building community, it is concluded that better calculation models are of interest, possibly by applying BEM [4,5], or more refined analytical models. A general complication is the modeling of the wheel/rail source, which is rather dependent on the lay-out of the track-wheel system.

5 - SUMMARY

Bogie-skirts are often suggested as a measure to reduce exterior noise. Here, the effects of such measures on the internal noise are analysed and discussed. Results from an experimental investigation indicate that bogie-skirts may have significant influence on the distribution of the sound pressure outside car-bodies for trains and accordingly on the interior noise.

From model experiments with bogie skirts it is concluded that the decrease of A-weighted sound level outside the train-wall is greater than the corresponding increase in the bogie room. This observation indicate a potential for overall weight-savings using bogie skirts. In addition, the wall thickness may be reduced, offering more spacious interiors.

Knowledge of the insertion loss of skirts can be used to optimize the requirements for transmission losses set on windows, doors and bellows, components that normally dominate noise transmission through train walls. As these components are generally expensive, bogie skirts may also have a positive effect on the overall costs for noise isolation on trains.

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