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State of the art about solutions for tram noise reduction in the framework of the Life SNEAK project

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ABSTRACT

The LIFE SNEAK project, started in September 2021, aims at the reduction of noise in densely populated urban areas where noise and vibrations produced by the tram overlap with noise produced by road traffic.
Applicative measures will be designed and tested in a pilot case of the city of Florence, such as low-noise and vibration surfaces, with life cycle costs comparable to those of traditional surfaces, and measures to reduce tram noise aiming to obtain substantial reductions in noise and annoyance.
Referring to tram noise, in the first phase of the project, specific attention has been dedicated to the state-of-the-art analysis concerning possible measures to perform noise reduction with specific attention to noise due to wheel-rail contact and "squeal noise" phenomena that mainly occur in urban environments close to curves with small radius.
In this paper, the results of the state-of-the-art analysis are presented with particular attention to the use of sound-absorbing panels to be applied on the tram (bogie skirts).

1. TRAM NOISE

Multiple factors must be considered when analysing the noise produced by tramways. This is in general due to the fact that several sources of noise are related to tram vehicles or to the tramway infrastructure operativity. The most significant noise emissions that relate to the transit of tram vehicles, which will be referred to as "tram noise", can be identified in:

- engine noise;
- rolling noise;
- aerodynamic noise;
- stops-related noise (braking, starting);
- curving noise (flanging, squeal).

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On a second level, it is important to consider the tramway infrastructure as a whole, not limiting the analysis to the vehicles; in this context, it is interesting to consider also the emissions caused by the electrical power stations scattered along the lines.

The fundamental parameter influencing the intensity of every tram noise emission is the vehicle speed. As showed in Figure 1, the global noise produced by the tram vehicle is composed by contributions that vary in intensity depending on the vehicle speed. At low speed, engine noise (produced by on-board mechanical and electrical power components) is relevant, while traveling faster than 30 km per hour the rolling noise (and, later, aerodynamic noise) becomes prevalent. The emission area for the engine noise typically coincides with the bogie region for trams that use powered bogies; for this reason, it is difficult to separate completely each factor. Engine noise is typically characterized by well-defined frequency components that directly depend on the engine rotational speed and by the electrical hardware mounted on board.

For rail vehicles, rolling noise that is generated by the wheel-rail interaction principally depends on the speed at which the vehicle travels, since there is a direct proportionality relationship between the sound pressure level and the logarithm of the speed (indicatively, doubling the speed results in an increase in the noise level of about 8-10 dBA). In addition, rolling noise is also linked to the problem of squeal noise (noise generated by tight radius cornering conditions, as later explained).

Rolling noise originates from the unevenness of wheel and rail. This causes a relative motion of the wheel, resulting in high frequency vibrations that are transmitted to both structures and from these are radiated into the air. Rolling noise levels increase with the tram speed (see Fig. 1).

Thus, rolling noise is generated by the interaction of the wheel and rail at their contact area, and both of them radiate significant proportions of the noise. Rolling noise levels increase with increasing train speed. The chapter demonstrates various graphical diagrams of several frequencies to support the aforementioned analysis. It shows that for frequencies where the track has the highest mobility, it is found that the rail vibrates with the highest amplitude. Conversely, the wheel vibrations are greater in the high frequency region where a number of lightly damped modes are present.

Aerodynamic noise becomes significant above 200 km/h [1]. For this reason, trams are not subject to significant aerodynamic noise, due to the limited speed range (see Fig. 2).

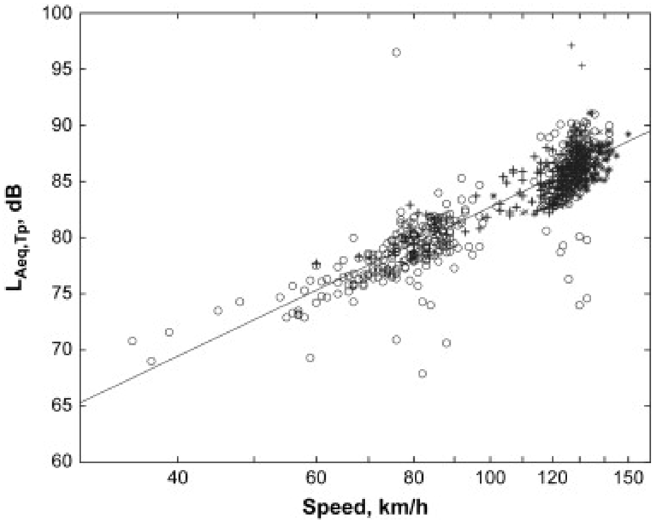

Figure 1: Rolling noise level related to vehicle speed.

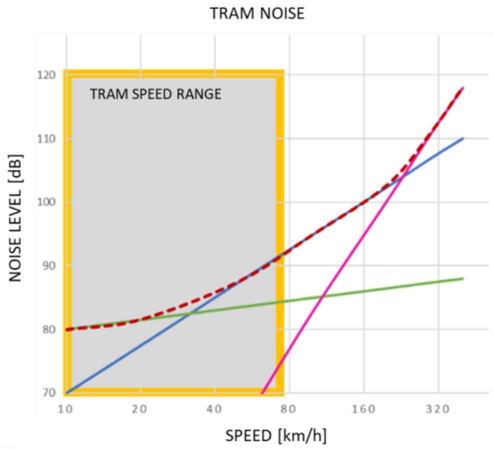

Figure 2: Relationship between the noise generated by a tram and its speed. Green - engine noise; Blue - rolling noise; Fucsia - aerodynamic noise; Dashed Red - Total.

Moreover, additional noise emissions that are not entirely correlated with the vehicle speed must be considered. For such cases, vehicle speed plays an important role but is not the main and only factor influencing noise intensity. Noise produced during stopping and restarting phases falls in this category as well as squeal noise. Such emissions are not continuously produced by the vehicle, but stem in specific conditions.

Stopping and restarting noises depend on the cruising speed of the vehicle but also on its weight and on the type of braking system. This is generally not significant for tram vehicles given their low speed. Squeal noise, on the other hand, is an episodic noise that originates when the vehicle travels in tight corners, due to irregular contacts between the wheels and the tracks. This phenomenon is characterized by high irregularity, small duration and high intensity. Vehicle speed plays a role in the origination of squeal noise but is not the only factor: wheel/track geometries and friction conditions being the major influencing elements.

Due to its complexity and the annoyance caused when compared with other tram noise emissions, the following sub-section is dedicated to the characterization of squeal noise. Subsequent sections of the paper will present solutions to abate and mitigate tram noise emissions currently studied in the literature or implemented in real scenarios.

2. SQUEAL NOISE

Among all the noises produced by tram vehicles, squeal noise is the most disturbing. The phenomenon occurs when tram vehicles travel on a curved path at a speed that exceeds a specific limit. The intensity level and the frequency of the induced vibration can be so high to completely compromise the success of an urban tram project. Concerning squeal frequencies, in literature a quite wide spectral range is reported (0.4-4kHz) [2]. A study carried out by the Universities of Kosice and Bratislava, Slovakia, had shown that the tramway noise in the city of Kosice is significantly characterized by the presence of squeal noise, in curves with a radius of less than 50 m, in the frequency range 400-1000 Hz with a characteristic peak around the frequency of 500 Hz [3]. Preliminary tests carried out on the Florence tramway showed peaks in the 2.5-5kHz range on the most critical points along line 1.

Theoretically, squeal noise stems from three main physical phenomena:

lateral creepage between the wheel tread and the top of the rail head;

wheel flange rubbing on the rail gauge face;

longitudinal creepage of the wheel tread due to differential slip.

Longitudinal differential slip occurs when the wheel's conicity is insufficient to compensate for the difference in distances that the inner and outer wheels must roll in a curved section of track. The outer wheel has more distance to travel and cannot rotate fast enough to compensate, causing it to slip forward longitudinally. Rudd [4], on the other hand, dismisses differential slip as a mechanism for squeal noise, partly due to experimental findings and also to the hypothesis that the excitation forces do not generate noise because they are within the plane of the wheel. Furthermore, while independent wheels eliminate differential slip, they do not eliminate squeal. Since Rudd, the literature has paid little attention to differential (longitudinal) slip as a squeal mechanism.

Grassie and Kalousek [5], on the other hand, identify rail corrugation on curves as a possible source of squeal. This is associated with the wheelset's 'axle wind-up' mode, which has a frequency in the range of 50–100 Hz; the corresponding corrugation wavelengths are around 100–200 mm. As a result, while longitudinal differential slip does occur and may cause low frequency stick–slip, it is not thought to be relevant to squeal.

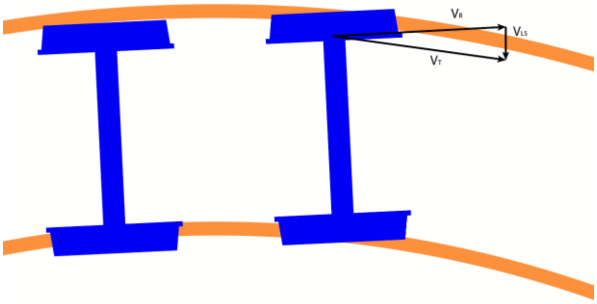

Figure 3: Rolling velocity (V_R), Tangent velocity (V_T) and lateral slip velocity (V_{LS}) in a realistic traveling condition.

Unsteady lateral creepage (Fig 3) is thought to be the main cause of squeal noise among the two remaining mechanisms listed by Rudd, particularly for the leading inner wheel of a bogie. According to observations, the leading inner wheel of a four-wheeled bogie or two-axle vehicle produces the most squeal noise amplitude. Its fundamental frequency corresponds to the wheel's natural frequency. Due to the geometric location, this noise is commonly addressed as “top-of-rail squeal”. Apart from that, squeal noise may also be caused by the contact between the wheel flange and the rail gauge face. Especially in sharp curves, this happens at the leading outer wheel (and possibly the trailing inner wheel). Flange contact, on the other hand, has been shown to partially reduce the likelihood of stick-slip squeal due to lateral slip [6].

3. TRAM NOISE MITIGATION TECHNIQUES

To mitigate tram noise, several strategies and technologies have been developed through the years and can be identified in the literature. As proposed by [7], these can be collected into two main categories: active solutions, that act directly on the noise sources, trying to eliminate the phenomena that cause the emissions, and passive solutions, that operate on the noise transmission paths, dampening the sound pressure waves before reaching the human ear.

Active solutions include devices that are specifically studied and designed to act on a single noise source, hence not introducing mitigating effects for other noise sources. In this category fall solutions that address different phenomena:

- squeal noise, by reducing the friction coefficient at the wheel/rail interface;
- rolling noise, by dissipating vibration in the wheel or in the rail.

Passive solutions consist of physical barriers which are placed in the close proximity of the tram/tramway seat or directly into the bogie area. These solutions evidently involve the need for their integration with respect to the city infrastructure (public road network, residential properties, etc.). Their introduction, beneficially, can bring a reduction of the noise propagated by different sources. This type of solution can be implemented with different modalities:

- sound absorbing barriers along the tramway route;
- sound absorbing road platform;
- on-board barriers.

All there solution will be described in the following sections.

Figure 4: Example of low-height barriers installed in Prague.

3.1 Active solutions

3.1.1 Squeal noise abatement

As previously discussed, squeal noise is attested as the principal contributor in the annoyance caused by a tram vehicle.

It is important to note that radical solutions that entail a dedicated design of the whole tram system but that can guarantee a complete squeal noise abatement do exist. Among these, the use of trams vehicles equipped with steering wheels: this solution imposes high maintenance costs and is not widely used. Similarly, the use of monorail systems eliminates this specific noise source, but even in this case there are several disadvantages for the design and functioning of the whole transportation system, which include high realization and maintenance costs.

Most effective mitigation systems that can be installed retrospectively to abate squeal noise usually rely on the lubrication of the wheel/rail interface, by means of friction modifiers. This solution reduces the generated noise, allowing the wheel to slide more freely on the rail, thus partially limiting or completely preventing the stick-slip mechanism. The introduction of friction modifiers is an operation that can be performed in several ways with limited efforts.

Satisfactory results are generally observed in literature. The main distinction that can be performed in this area is between systems that are mounted on board the vehicle and devices that are positioned in the track proximity, in correspondence with a tight corner that is susceptible to squeal-related issues.

On-board squeal noise mitigation systems can be installed directly on the axles of the vehicles or on the bogies. Two friction modifiers typologies can be used:

- solid friction modifiers;
- liquid friction modifiers (water-based - WFM - or oil-based - OFM).

In case of solid friction modifiers, the dispenser consists of a graphite stick which is positioned directly in contact with the wheel and the lubricant is applied by rubbing the surface of interest (see Fig. 5). Due to the low number of components, the overall system requires only basic maintenance and its cost is relatively low. For these reasons solid friction modifiers are generally preferred and more diffused. Unfortunately, their effectiveness on the squeal noise mitigation is limited.

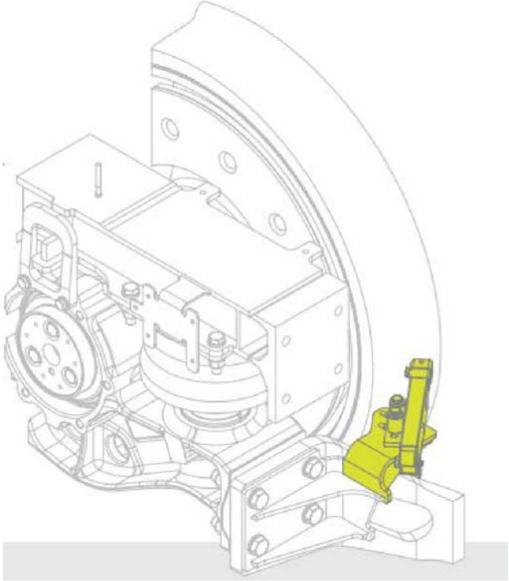

Figure 5: Kelsan® LCF (Low Coefficient of Friction) Solid Stick wheel flange lubrication system developed for railway.

In case of liquid friction modifiers, the bogie is equipped with a hydraulic system that applies water-based or oil-based friction modifier (WFM/OFM) to the wheel, thus eliminating the negative slope of friction creepage curve (see Fig. 6). A suitable feeding rate can be found depending on the properties of the lubricating fluid, noise severity and the conditions of the track. Both OFM and WFM were reported to be very effective on the reduction of the squeal noise, with a noise reduction up to 12 dB [8]. In [9], a squeal noise reduction of 30% up to 47% after the introduction of liquid friction modifier is reported, but squeal noise still partially exists.

More recent studies confirm that the introduction of friction modifiers only limits but doesn’t completely eliminate the squeal phenomenon [10].

If liquid lubricants are generally considered to be more effective than solid ones, on the other hand they require the design/implementation/managing of a relatively complex system (dispenser, tank, ducts).

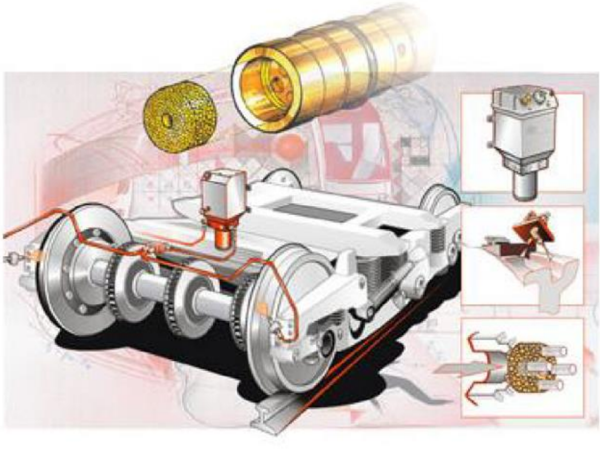

Figure 6: On-board liquid lubricant system – Bekalube.

The same considerations about friction modifiers are still valid in the case of off-board systems (see Fig. 7-8). For obvious reasons, in this case friction modifiers are only liquid. The system is fairly similar to the on-board one. In this case, the friction modifier is applied on the top of the rail (TOR solutions). Another difference is that in this case the liquid is not dispensed continuously but only at the tram passage. In general, their effect is comparable with on-board liquid friction modifier systems [11, 12].

The differences between on-board and off-board solutions are principally related to the layout of the systems and to their proneness to be implemented in an existing scenario. The introduction of on-board solutions post-operam is typically difficult due to the limited space in the bogie region; accordingly, they shall be conceived from early design phases. Solid friction modifier systems, on the other hand, are more flexible under this point of view and offer less limitation for what concerns post-operam updates. On the other hand, since tram lines often intersect urban roads and other civil structures, off-board systems may constitute obstacles.

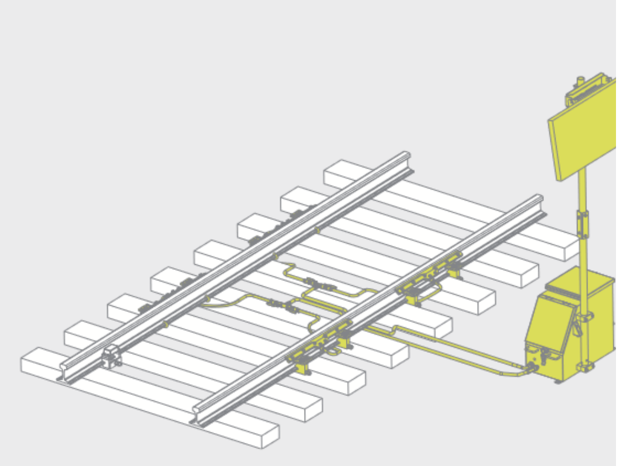
Figure 7: LBFoster KELTRACK® TOR friction modifier.


Figure 8: RS Clare & Co. TOR friction modifier.

3.1.2 Rolling noise vibration dampers

The purpose of this kind of dampers is to reduce the rail vibrations as the train passes and consequently the transmitted noise, hence they have effect on both squeal (very limited) and rolling noise. The main advantage of these systems is that they can also be installed after the construction of the infrastructure, in most critical points. Several studies related to post operam evaluation, measured a noise reduction up to 3-5dB(A) after the installation of energy absorbers at the base of the tramway rails [2, 7, 13–15].

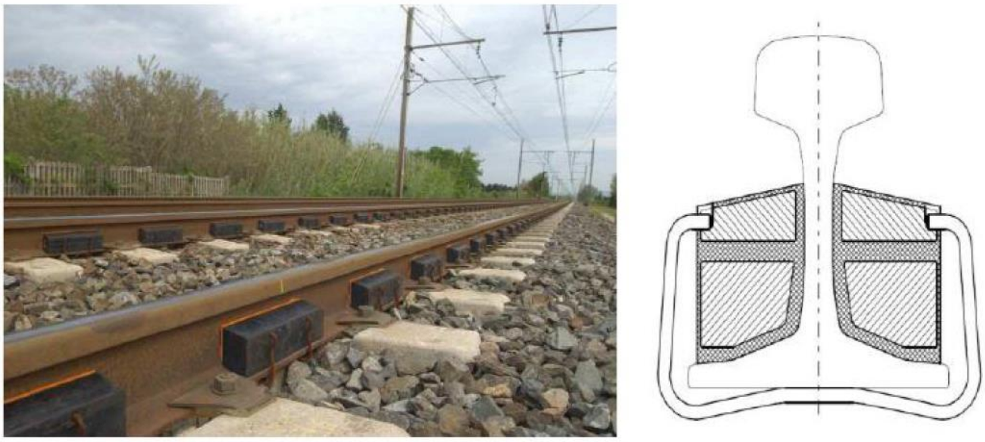
Figure 9: Absorbers tested on a railway by Vossloh company [16].

A similar system, tested on various tram infrastructures, for example in Athens in 2009 [32] within the QCity project, and now present in almost all infrastructures, is based on the use of continuous elastomers at the base of the tracks that are able to dampen vibrations as vehicles pass by and also partially contain squeal noise. As said, this system, implemented and revised for better performance, is now present on most of the tramway systems in urban areas.

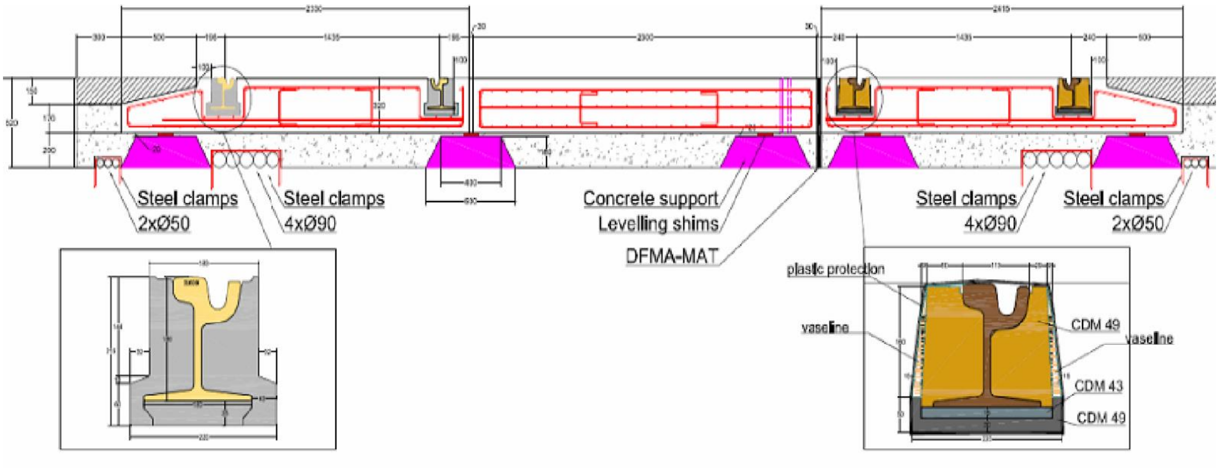

Figure 10: Typical absorbers tested within Qcity project activities [16].

3.2 Passive solutions

3.2.1 Absorbers along the tramway route

In the field of passive solutions, the type of noise barriers often used in the railway sector find little room for application in the tramway sector. This is a consequence of two factors: i) the barriers would be an oversized intervention since the noise generated by trams is much less significant than that of a rail vehicle; ii) tram lines are located in urban centers where the presence of houses close to the road and frequent intersections with the public road system (road, bicycle, pedestrian) would not allow an easy installation.

For this reason many studies, projects and applications are moving towards low-height noise barriers [13] that, thanks to their conformation, are tailored to address the noise produced by the wheel/rail contact, emitted a few centimeters above the ground. The efficiency of this type of device depends on the shape of the cross-section and on the acoustic properties of the surface treatment. Sound absorbing coating is often used to improve performance by preventing the phenomenon of multi-reflection, however unlike high barriers, given the small surface area treated, such coatings can be very expensive in reference to the acoustic benefit.

The results achieved with this type of technique vary significantly depending on the application characteristics and on the type of measures used to validate the solution; attenuation levels are generally significant: the literature reports values varying from 3-5 dB(A) [17] to 7 to 11 dB(A) [18]. Effective solutions can be obtained by studying custom barrier shapes and configurations, tailored to address the specific noise profile measured: as an example, [19] documents an improvement of 10-14 dB(A) between the use of straight and semi-circular barriers (Fig. 11). On this topic, numerical results, obtained from an acoustic study carried out by the Universities of Paris and Pennsylvania [20], have shown a significant improvement obtained in the mid/high frequency range (typical of squeal noise) through the study of different configurations with comparable encumbrances. The improvement is due to the dispersion of the incident acoustic energy upwards, thus reducing the direct energy reaching the shadow zone.

As previously mentioned, the development of more effective solutions characterized by bigger absorption volumes is hindered by the context of application. Modular solutions, studied to be easily dismantled in case of need (Fig. 12), for example for infrastructure maintenance or for the passage of emergency vehicles, were developed in [17] to solve this issue.

Figure 11: Circular profile used in Czech Republic (interchecplus.cz) for a railway solution.

Figure 12: Example of low-height modular barriers installed in Prague.

Beside the study of effective configurations and shapes at the macro level, several studies focus on the development and testing of advanced materials attenuating specific frequency bands. Such materials, consisting of a series of micro-perforated porous layers, can be used as surface treatment. In [19] the use of a frequency-optimized structure is estimated to convey an additional 8 dB(A) attenuation.

3.2.2 Sound absorbing road platform

One of the areas that allow the installation of sound-absorbing materials with limited constraints is the base of the roadway and generally all horizontal surfaces in the proximity of the railroad. One of the solutions proposed and tested (Dublin light rail line [21]) is related to the use of sound-absorbing mats (see Fig. 13). The results of the monitoring have shown reductions in levels of up to 3-4 dB(A), compared to a traditional sound reflecting pavement.

Also the use of a special mix of plant material (grass, low plants, etc.) on the tramway showed a reduction of about 2-4 dB(A) [22]. In other case studies [13], the roadway was covered with special sound-absorbing panels made of wood or recycled material placed between the rails and laterally to them, obtaining similar performances. This gain, in terms of reduction of noise levels measured at the roadside, is evidently less significant w.r.t. other solutions, but this type of installation can be performed practically in every scenario, as there are no external elements to be considered.

Figure 13: Sound absorbing barriers in Dublin light rail line [21].

3.2.3 On board barriers

An alternative solution to reduce the diffusion of squeal, engine and rolling noise in the surrounding area involves the application of sound barriers directly on the vehicle. In this way, the mitigating device follows the noise source; accordingly, positive effects can be obtained across the entire railway without the need of installing kilometers of barriers. On the other hand, these devices need to comply with several constraints imposed by the vehicle and by its operating conditions: ground clearances, lateral margins, dynamic stresses imposed on the structure. Typically, they are designed to cover the area of the wheel/brakes; in the most straightforward design, they introduce a reflective barrier in front of emitting sources; more advanced solutions introduce absorbing materials. The efficiency of absorbing barriers has been largely discussed in several studies. In [23], it is reported that an absorptive barrier is typically 3-4 dB(A) more effective than a reflective one. In [24], it is assessed that a standard bogie cover (i.e. a laminate cover, principally adopted to prevent the direct accessibility to tram wheels for safety reasons) is not effective in reducing noise, since it can become a secondary source of noise. In the same study, the behavior of a cover enriched with acoustic functions - through the application of a polymer damping material with mineral fillers - has been studied. Applied to three different tram vehicles, it allowed significant sound attenuation (5–15 dB(A) depending on the frequency range - mainly in the range of 630–1600 Hz).

A potential improvement to bogie absorbing covers is bogie skirts. These are acoustical barriers attached to the sides of a car (or a bogie cover) and extending down as far as possible to block the direct line-of-sight from the truck, wheels, and undercar equipment to the wayside. In [25], three different types of skirts (see Figure 10) have been tested in combination with three different types of barriers, to mitigate locomotive noise. In this study, a preliminary test on a 1:4 scale model estimated a 3dB(A) reduction of noise levels. In [26], it is reported that the adoption of bogie shrouds together with low height barriers comports an expected wheel noise reduction of 8-10dB(A). Despite the benefits, some documents report that the implementation of skirts may lead to a more complicated maintenance, with slightly higher costs. In addition, in [23] it is reported that the effectiveness of vehicle skirts in reducing wheel/rail noise is limited because of restrictions on how far down the edge the skirt can extend. In Europe, vehicle clearance specifications limit the lowest point of the bogie to be located above the top edge of the rails by the amount of travel of the spring system plus the height of the wheel treads - i.e., about 13 cm - still leaving a part of the wheel and the whole rail exposed.

4. CONCLUSIONS

Several valid solutions can be taken under consideration to mitigate tram noise. As discussed in the paper, the seek for the most effective solution is a task that is usually deflected towards the development of a viable solution given the existing application constraints. This is the result of the typical noise management process, which is usually initiated post-operam, when a negative situation is identified. When integrated from the early design phases, active solutions seem like the most effective approach to avoid possible problems, especially considering the occurrence of squeal noise. Conversely, passive approaches (specifically low-height barriers which usually result as the most effective mitigating solution) are easier to implement post-operam and tackle different noise sources simultaneously.

5. ACKNOWLEDGMENTS

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