A Review of Mitigation Measures for Reducing Railway Rolling Noise from an Infrastructure Point of View

Jin Young Yoon* and Sukhoon Pyo†

Abstract

Since increased demands for railway speed and capacity have caused an inevitable increase in railway noise, the noise and vibration pollution for residents living near railway lines are becoming major social problems. Therefore, noise reduction activities are essential to ensure that railways can be recognized as one of the most environmentally friendly means of transportation and to protect people's health. Rolling noise is the main source of noise at speeds below approximately 250 km/h, after traction noise and aerodynamic noise, and infrastructure measures could be effective to abate the rolling noise. This review paper covers various approaches to mitigate rolling noise, focusing on mitigation measures from the perspective of infrastructure. These include noise propagation reduction methods, such as noise barriers, the development and application of sound absorbing materials, such as sound absorbing blocks using porous concrete, and rail vibration and noise control methods using rail dampers and rail pads. It can be concluded, based on the literature review, that the most effective noise control measures are those that mitigate noise at or near the source.

Keywords: Railway noise, Rolling noise, Noise barriers, Sound absorbing concrete, Rail dampers

1. Introduction

1.1 Overview and Motivation

Railways, the most environmentally friendly transportation modes, have long been challenged by the problem of railway noise. Moreover, the railway noise problem is becoming more serious as the speed and capacity of railways increase, and the noise and vibration pollution for residents living near railway lines has become a major social problem as the standard of living rises and quality of life improves. In particular, due to high population densities in some large cities, high-rise residential facilities are often exposed to rail tracks, further exacerbating the problem of railway noise in urban areas. Meanwhile, the current noise barrier system has limited effectiveness for high-rise buildings. In these places, adequate measures should be taken to protect the surroundings from the noise of railway traffic.

Noise reduction activities to protect people's health are very important to ensure that railways continue to be recognized as one of the most environmentally friendly transportation modes. Railway noise can cause adverse health effects in various forms, from noise levels that trigger people's irritation to levels that pose a deadly threat to their health, such as cardiovascular problems and cognitive impairment. Accordingly, the mitigation of railway noise is necessary not just for comfort but also to lessen its negative health effects. Table 1 lists noise exposure levels from roads and railways, based on data provided by Germany, Norway, Sweden and Austria, which indicates that railway noise has a slightly higher noise exposure level than that of road noise.

The scientific approach used to analyze and resolve the railway noise issue can be generally defined at several levels (Zvolenský et al., 2017):

- Theoretical research on the sources and paths of sound propagation
- Simulation and/or numerical modeling of noise fields and their impact on the environment
Experimental research to verify the theory and modelling
The development and application of reduction measures for the design of specified rolling stocks, as well as the construction of railway tracks

Furthermore, railway noise can commonly be classified into three categories: traction noise, rolling noise, and aerodynamic noise. Since rolling noise is the main source of noise at speeds below approximately 250 km/h (Thompson, 2008), various mitigation measures to reduce this type of noise are critically reviewed in this article. Specifically, there are two major approaches for reducing rolling noise: vehicle-related measures and infrastructure-related measures. This review paper focuses on the infrastructure-related measures. In addition, key experimental verification methods are also reviewed.

1.2 Regulations for Railway Noise
To control the railway noise issue, noise regulations have been established in many countries. In Europe, the noise limit values for different types of rolling stocks are specified in Commission Regulation No 1304/2014 to ensure their interoperability within the European Union (EU) member countries. A direct comparison of the noise regulations in the European Railway Agency’s Technical Specifications for Interoperability (TSI) and those in Republic of Korea can be found in Koh et al. (2018). Furthermore, the standards related to railway noise are also set according to the actual conditions of each country (see Table 2).

1.3 Review of Definitions
To clarify some important definitions used in the fields of railway and environmental noise, Table 3 explains some related definitions.

2. Mitigation Measures

2.1 Overview
The basic source of rolling noise is the surface contact that occurs when wheels roll over rails. At the point of contact, irregularities in the running surface of the wheel, as well as lateral and longitudinal vibrations of the rail head, cause the track and vehicle to be oscillate, generating vibrations, which are eventually emitted into the air in the form of noise or propagated through the rail and the wheels (Zvolenský et al., 2017). With the introduction of the high speed railway system, the railway noise issues worsened due to the increase in noise levels, especially the aerodynamic portion, and the adoption of concrete slab tracks. Most countries operating high-speed railways, including Germany and Japan, have adopted concrete slab tracks because of their various advantages; for example, they are more rigid and require less maintenance than conventional ballasted tracks. However, concrete slab tracks are counterproductive in terms of railway noise; field test results have indicated that concrete slab tracks have higher noise levels than that of ballasted tracks due to a reduced connecting impedance for the rail, reduced vibration decay rates along the rail, and reduced absorption (Zhao et al., 2014). Kim et al. (2019) also claimed that noise levels increase when a train passes through a tunnel because the inside of the tunnel is generally made of concrete with a very low rate of sound absorption. For example, the experimental results using a train with the speed of 280 km/h showed that more than 5 dB higher noise level were measured inside the vehicle while a high-speed train running...
through a tunnel compared with before entering the tunnel (Kim et al., 2019).

Various attempts have been made to mitigate the noise of already constructed tracks by using active noise abatement solutions, such as direct design solutions for railway tracks, and passive noise solutions such as noise barriers (Zvolenský et al., 2017). Overall, railway noise mitigation measures can be classified into five major categories: 1) track related measures, 2) reduction of noise propagation (e.g., noise barriers), 3) vehicle related measures, 4) measures at the receiver (e.g., double glazing), and 5) economic measures and regulations (Lakušić and Ahac, 2012; van der Stap and de Vos, 2013). This review paper focuses on the first two primary measures for railway noise reduction, which are closely related to infrastructural solutions: 1) reduction of noise propagation, 2) development and application of sound absorbing materials, and 3) controlling rail vibration and noise using rail dampers and rail pads.

There has been controversy over the measures used to mitigate railway noise. For example, high noise barriers have been challenged by residents due to their visual interference, increasing the pressure for alternative measures to mitigate noise at the source. Also, the replacement of brakes has caused additional financial burdens (de Vos, 2016). In Japan, JR East developed wayside equipment to be installed on top of existing upright sound barriers, utilizing sound diffraction and interference to improve noise mitigation with an approximately 2 dB reduction (Tahara et al., 2010). In addition, Horiuchi et al. (2016) developed

<table>
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<th>Table 3</th>
<th>Explanations of some definitions related to environmental noise (de Vos, 2016)</th>
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<tbody>
<tr>
<td>Definition</td>
<td>Explanation</td>
</tr>
<tr>
<td>decibel, abbreviated as dB</td>
<td>Every step of +10 dB increase sounds to our ears as a doubling of loudness. A doubling of sound production (two similar source instead of one) results in a step increase of only +3 dB</td>
</tr>
<tr>
<td>A-weighting</td>
<td>Weighting of a measured sound, in such a way that the frequencies for which the human hearing is less sensitive (usually the low frequencies) are suppressed and the frequencies where the human ear is more sensitive are emphasized</td>
</tr>
<tr>
<td>Equivalent noise level, abbreviated as $L_{eq}$</td>
<td>The level of an imaginary sound source with an output constant in time, which over a given period emits a sound energy similar to that of the source under concern which emits a output varying in strength over time</td>
</tr>
<tr>
<td>Pass-by noise level</td>
<td>The equivalent level of an entire pass by event</td>
</tr>
<tr>
<td>Maximum level</td>
<td>The highest value of the noise level during a given period where the sound level varies in strength</td>
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<tr>
<td>Day level, abbreviated as $L_{day}$</td>
<td>The equivalent level over a 12 hour period between 7:00 am and 7:00 pm</td>
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<tr>
<td>Night level, abbreviated as $L_{night}$</td>
<td>The equivalent level over an 8 hour period between 11:00 pm and 8:00 pm</td>
</tr>
<tr>
<td>Day-evening-night level</td>
<td>The weighted average of the day level, the evening level + 5 dB penalty and the night level + 10 dB penalty. The weighting takes into account the differences in duration of the day (12 hours), evening (4 hours) and night (8 hours)</td>
</tr>
<tr>
<td>Exposure level</td>
<td>Yearly average value of $L_{den}$, measured or assessed outside in front of the façade, at a height of 4 m above ground. As the exposure relates to incident sound only, 3 dB has to be subtracted from the measured level as this is supposed to be representative for the sound reflected back from the facade</td>
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2.2 Noise Barriers

Noise barriers can be classified according to their shape, their main material, and the sound absorption method used. Table 4 lists the detailed classifications (van der Stap and de Vos, 2013). Morgan et al. (1998) numerically investigated the influence of the shape and the absorbing surface of various track-side railway barriers and concluded that the addition of multiple edges to a barrier led to an insertion loss of up to 3.0 dB. Kim and Kim (2015) proposed a tunnel type of soundproof wall with a partial opening to reduce the railway noise caused by rolling stock running on bridges to minimize the load of the noise barrier to the bridges, based on a numerical analysis. They simulated various types of soundproof facilities, as can be seen in Fig. 1.
a sound absorbing panel using microperforated aluminum for a Shinkansen tunnel entrance hood to dampen noise, achieving total noise decrement of up to approximately 4 dB in near-portal noise levels.

While various research results have consistently reported the effectiveness of noise barriers, side effects should also be considered before their application. For example, Tuler and Kaewunruen (2017) suggested that noise barriers and buried walls are more expensive measures with a higher carbon footprint than other measures and should, therefore, only be used in areas where noise and vibrations are high or where more people live near the train tracks.

### 2.3 Sound Absorbing Materials

Concrete and cement-based materials are the primary materials used for railway infrastructures, including concrete sleepers, concrete slab tracks, and concrete tunnel lining. Many researchers have investigated their acoustic characteristics and how to improve the acoustic performance of cement-based materials (Kang et al., 2008; Zhao et al., 2014; Kim et al., 2018). Therefore, it is important to review the development of concrete with noise absorption capacities. Two major strategies are normally considered for cement-based materials: the enhancement of the materials’ sound absorption capacity and the acoustical design of the surface shape of concrete structures. Even though various surface designs for sound absorbing panels and noise barriers have been proposed and characterized (Ishizuka and Fujiwara, 2004; Jang et al., 2017), this subsection focuses on the materials’ sound absorption characteristics.

### Table 4 Categories of noise barrier (van der Stap and de Vos, 2013)

<table>
<thead>
<tr>
<th>Shapes</th>
<th>Material</th>
<th>Sound Absorption</th>
<th>Type of absorptive material</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. plane, vertical</td>
<td>A. metal</td>
<td>1. no absorption</td>
<td>a. rock or mineral wool</td>
</tr>
<tr>
<td>b. plane, inclined</td>
<td>B. concrete</td>
<td>2. integrated absorption</td>
<td>b. glass wool</td>
</tr>
<tr>
<td>c. plane, curved</td>
<td>C. brick or ceramic</td>
<td>3. additional absorption</td>
<td>c. chip wood</td>
</tr>
<tr>
<td>d. plane, bent</td>
<td>D. wood or board</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. embankment</td>
<td>E. transparent glass or plastic</td>
<td></td>
<td></td>
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### Fig. 1 Classification of soundproof facilities (Kim and Kim, 2015)

![Soundproof walls](image1)

(a) Soundproof walls (b) Soundproof tunnel (c) Soundproof tunnel (closed type) (open type)

As sound waves pass through tortuous pores (also known as continuous voids) inside cement-based materials, the compression and expansion of the air leads to acoustic loss, resulting in sound absorption. Therefore, most of the development of concrete with sound absorption capacities is focused on securing sufficient continuous voids. Most concrete or cement-based materials with higher acoustic absorption capacities are light-weight with relatively low densities. Taking advantage of these benefits, concrete blocks of various shapes have been developed and installed on top of concrete slab tracks. For example, Zhao et al. (2014) developed porous sound-absorbing concrete blocks with a compressive strength of approximately 1.6 MPa and achieved a maximum noise...
reduction of 4.05 dB at a speed of 200 km/h. Fig. 2 shows an example of the installed sound absorbing block at Ulsan station.

In order to adequately evaluate the acoustic characteristics of cement-based materials, two representative measured quantities are commonly used: the sound absorption coefficient and the void ratio, which are described in Section 4.

In addition to cement-based materials, turf tracks (also known as grass tracks, lawn tracks, green tracks, and naturalized tracks) could be a viable solution for light rail systems to reduce urban railway noise. Although turf tracks possess advantages, including improvements in rainwater management and heat island mitigation, this solution also has some inconveniences, such as the need for vegetation maintenance and rail–environment separation; furthermore, additional precautions must be taken to ensure good performance in the long term (Novales and Conles, 2012). Eisenmann et al. (1996) reported that turf tracks led a noise reduction of 7 dB(A) compared with paved or asphalted tracks and that of 2 to 4 dB(A) noise reduction compared with ballasted tracks, depending on the sleeper type.

Additionally, Koller et al. (2012) used a high-performance damping material in two different ways to effectively reduce railway noise: first, it was applied as a rail noise-reduction system to reduce rolling noise directly from the rails, and, second, it was applied on the surface of the web within a railway bridge structure to reduce structure noise, which led to a noise decrement of up to 4 dB.

2.4 Rail dampers and Rail pads

A rail damper (also known as a rail vibration absorber) is a passive element attached to both sides of the rail web, which reduces the airborne noise caused by the rail vibration. Fig. 3 shows the placement of a rail damper. Rail dampers reduce the noise radiated by the rails by improving the rail’s ability to decay the noise-inducing vibrations resulting from the rolling contact between the wheel and the rail (Parker and Weber, 2010). In principle, a rail damper is designed to work on the system of vibration absorption at frequencies with the greatest noise levels (e.g., in the case of frequencies that are characteristic for most of the noise generated, the rail damper is the most efficient) (Zvolensky et al., 2017). Generally, rail dampers have various exclusive advantages; for example, they can be installed after construction, while the rails are operational. Furthermore, they do not need any maintenance, they do not require any restrictions on track maintenance, and they do not interfere with the overall appearance of the track (Bavlna et al., 2015).

Several types of rail dampers with different shape and structures are already commercially available (e.g., models manufactured by Vossloh, KamPa International Inc., Schrey & Veit GmbH (S&V), and Trelleborg Group). Parker and Weber (2010) conducted a field trial using a commercial rail damper on a section of the standard Australian ballast track, which effectively reduced the noise levels by approximately 1.5 dB(A), and they claimed that rail dampers could be a cost effective noise mitigation measure on tracks with lower rail pad stiffness. Jang and Ryue (2017) numerically analyzed the noise reduction performance of rail dampers, as can be seen in Fig. 3. They claimed that the proposed dynamic absorber could reduce rail noise by about 2–5 dB based on the simulation (Jang and Ryue, 2017).

It should be noted, however, that the efficiency of the rail dampers mostly depends on the characteristics of the rail pads, as reported in cases in Germany, the Czech Republic, and the Netherlands (de Vos, 2016). Vincent et al. (1996) conducted theoretical research on reducing railway rolling noise by optimizing the stiffness and damping of rail pads and insisted that optimized noise reduction could be achieved through the simultaneous optimization of several track components, including the rail damper and the rail pad.

In addition, it has been revealed that the application of rail dampers poses some challenges, such as expensive unit costs, increased maintenance costs, safety issues (occurring when rail dampers are loosening from the rail or due to excessive rail corrugation), and impact on rail roughness growth (de Vos, 2016). Therefore, it is recommended to considered the advantages and disadvantages of rail dampers and rail pads before their actual application.

3. Experimental Evaluation

3.1 Sound Absorption Coefficient Test Methods

Various test methods and standards are available for the quantitative evaluation of the sound absorption of materi-
als and systems. The sound absorption of a material depends on the incident sound orientation conditions, such as vertical and random propagations. Therefore, sound absorption coefficient test methods are generally categorized based on wave propagations. The reflection method and impedance tube methods, such as the standing wave ratio method and the transfer function method, are effective in measuring vertical propagations; whereas, the reverberation method is effective in measuring random propagations.

The standing wave ratio method is used to determine the sound absorption coefficient, the reflection factor, the surface impedance, or the admittance of materials and objects by evaluating the standing wave pattern of a plane wave in a tube, and it is suitable for parameter studies and the design of sound absorbers because only small-sized specimens are used for the test (ISO, 1996). The transfer-function method is intended to provide an alternative, and, generally, a much faster measurement technique than that of the standing wave ratio method, in which plane waves are generated in a tube by a noise source, and the decomposition of the interference field is achieved by the measurement of acoustic pressures at two fixed locations using wall-mounted microphones or an in-tube traversing microphone (ISO, 1998). The reflection method is an in situ test method based on an acoustic impulse response measurement of the material surface. Fig. 4 shows the schematics and test set-up of the method. The advantages of the in situ method are the ability to measure the normal incident acoustic absorption coefficient of any planar surface as installed or in situ and a quick testing time of less than a minute (ISO, 2002; Londhe et al., 2009; Kim et al., 2018).

The reverberation room method is intended to measure the sound absorption coefficient of acoustical materials used as wall or ceiling treatments or the equivalent sound absorption area of objects, such as furniture, persons, or space absorbers, in a reverberation room (ISO, 2003). The reverberation method is a popular method as it can measure the sound absorption rate for random sound incidents, but it has some disadvantages; for example, it is difficult to install and it requires a relatively large-sized specimen.

### 3.2 Evaluation of Concrete Porosity

An overview of the techniques for analyzing the pore structure of cement-based material is provided in Fig. 5. The pores of cement-based materials are classified as micropores (<100 nm), mesopores (100 nm–10 μm), and macropores (10 μm–10 mm); specifically, gel pores (<10 nm), capillary pores (10 nm–10 μm), entrained air (40–300 μm), and entrapped air (1–4 mm) (Gong et al., 2014; Shah and Bishnoi, 2018). Since porosity and large-sized pores negatively affect the strength of cement-based materials (Mehta and Monteiro, 2013), several techniques have been developed for characterizing pore structures. The most convenient and popular method is the water saturation test, which consists of immersion and boiling, following ASTM C642 (ASTM, 2013). Compared to that test, the vacuum saturation method provides a more accurate volume of water permeable voids by removing remaining the air and fluid in specimens, following ASTM C1202 (ASTM, 2019). It should be noted that the size of a water permeable pore is estimated as one that is larger than 100 nm (Nguyen et al., 2014; Cnudde et al., 2009). In addition, mercury intrusion porosimetry (MIP) has been used to estimate pore size distribution and total porosity, which are determined by the amount of intruded mercury at each pressure step and the total intruded volume, respectively, using the Washburn equation (Cnudde et al., 2009; Stroeven et al. 2010). Even though some drawbacks have been suggested regarding pore size errors when determining pore throat diameter (the so-called ink bottle effect), the
assumed cylindrical shape of a pore, and pore connectivity, MIP still has a great capacity to conduct comparative assessments of porosity between cement-based materials (Diamond, 2000). Gas pycnometer is generally applied as a pressure equalization principle to measure the exact volume of the solid phase (Ma, 2014). It should also be noted that helium is preferable for this technique due to its nearly ideal gas behavior (Semel and Lados, 2006). The measured pycnometric volume is also applicable to determine the total, open, and closed porosity of solids or powders (Semel and Lados, 2006; Tracz, 2016; Liu et al., 2011).

Recently, non-destructive tests of nuclear magnetic resonance (NMR) and X-ray computed tomography (X-ray CT) have been introduced to characterize the pore structure of cement-based materials. The high resolution of NMR allows for the detection of the pore sizes from 0.2 nm to 1 mm in diameter, which is a broader range than can be detected by conventional methods (Rifai et al., 2018). Meanwhile, X-ray CT provides a 3D visualized internal microstructure. Even though X-ray CT can detect pores larger than 10 μm due to its comparatively low resolution, 3D pore structure information provides total porosity, pore size distribution, and pore orientation (du Plessis et al., 2016). Some previous studies showed reasonably complementary data on the pore structure analysis of cement-based materials by combining X-ray CT with the MIP or NMR techniques (Cnudde et al., 2009; Rifai et al., 2018).

### 4. Conclusion

In recent years, the importance of controlling the noise caused by the operation of railways, the main means of public transportation, has continuously increased due to improvements in quality of life. Various attempts have been made to mitigate the noise of already constructed tracks and/or new construction projects. Since there is controversy over the developed measures, several mitigation measures have been reviewed in this paper, especially infrastructure measures for the abatement of rolling noise, including the reduction method for noise propagation, the development and application of sound absorbing materials, and rail vibration and noise control methods. In addition, key experimental verification methods have also been reviewed. Based on a critical review of the literature on various aspects of railway noise mitigation measures, some important conclusions can be summarized as follows:

1) Even though it is well-known that noise reduction measures at both the track and the vehicle sources are more cost-effective, noise barriers are continuously being installed due to their effectiveness, especially in dense urban areas. Therefore, it is rational to conclude that mitigation measures at sources should be applied along with the noise barriers to reduce the required dimensions of the barriers, which will eventually lead to cost savings.

2) Turf tracks are a competitive solution for urban light rail tracks since they could enhance the city landscape, increase the acceptance of the network by citizens, and improve light rail operation in several respects.

3) The most appropriate mitigation measure should be determined on a case-by-case basis, and life-cycle assessments would be helpful to analyze the economic costs of different methods (Tuler and Kaewunruen, 2017).

4) For various railway environments, the maximum limit permitted by the standard could be exceeded by just a few decibels, so a variety of methods should be developed and applied for small noise reductions (Zvolenský et al., 2017).

### References

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