INTERIOR NOISE REDUCTION APPROACH FOR MONORAIL SYSTEM

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ABSTRACT

This study presents an overview on the possibilities of interior noise reduction for monorail system using passive means. Nine samples out of three materials were subjected for noise test and the performance of each sample was observed. It is found that all of these samples have proved to reduce a significant amount noise at low and high frequencies even though the amount reduced differ from one sample to another. It is also been noticed that this reductions were denominated by means of absorption for some samples such as those from rubber material, and it was dominated by means of reflection for some others such as those from aluminum composite and paper composite. Moreover, from these different acoustic properties of each material, the whereabouts to install every material is different as well. It was suggested that, the rubber material should be installed on the upper floor of the monorail while, the paper composite should be installed under floor, and the aluminum composite should be installed at the outer parts from the monorail such as the apron door, ceiling, etc.

However, despite their promising potential to reduce noise, there were few uncertainties with some samples at certain frequency, for example samples from aluminum composite could not reduce noise at 1250 Hz which denotes that it is not a good practice to use this material at that frequency. However, in terms of ranking, samples from rubber material reduced the largest amount followed by paper composite samples and aluminum composite samples held the last position as the least feasible with an average of 26.46%, 24.69% and 16.05% respectively as for the third sample in every material. This concludes that the passive approach adopted in this study seems to be feasible.

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dB - Decibel

I - Sound intensity level

I_{re} - Reference intensity standardized as 10^{-12} W/m^2

L_p - Sound pressure level

L_w - Sound power level

P_{re} - Reference pressure of 20µ Pa

P - Sound pressure radiated by the source, Pa

U - Volume flow

W_{re} - Reference power 10^{-12} watt

W - Sound power radiated by the source, w

Z - Acoustic impedance

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CHAPTER 1

INTRODUCTION

1.1 Background

Rail transport is perceived as one of the most efficient and environmental friendly means of transport. That is due to its potential of being safer, comfortable, environmental friendly and energy efficient form of transport. These characteristics have led to a considerable expansion of their role in the movement of freight, in long-distance high-speed passenger travel, and also to solve congestion in densely populated areas, in the form of light rail and tramway systems. Railways are therefore entering a new era of higher speeds and higher capacities both for intercity and urban systems and are set to play their part in reducing the environmental burden caused by the steady growth in road transport [1].

Unfortunately, the noise pollution from railways is significant, as several investigations have identified noise and vibrations as key factors to high comfort [2]. Due to this need to improve the quality, comfort level and the environmental requirements of railway transportation system, train operators and manufacturers have become more concerned with noise and vibration reduction in train coaches [3]. This concern arises from two different demands, both having in mind the improvement of passenger comfort. On one hand, from environmental authorities who are interested in reducing the general noise level emitted into the surroundings. On the other hand, is due to the necessity of railway train operators to improve their competitiveness within the passenger transport market by offering more comfortable journeys, but at the same time to produce lighter train coaches. These two trends have led to increasingly sophisticated noise specifications for modern railway trains, including maximum noise levels under conditions such as full-speed running, acceleration, braking, standing, and parking, whether the train is at a ground level, in a tunnel or on a bridge, either in a straight path, or in a curve [3]. As a result, the quality and the ride comfort of the passengers on monorail will not be achieved without mitigating the noise level within the monorail car as minimum as possible in order to satisfy customer needs as well as maintaining low environmental noise.

Besides, as the evolvement of high speed train and less traditional methods of coach construction are now being considered, it is necessary to assess in advance the possible acoustic consequences of any proposed changes. This can hardly be done without a clear understanding of certain basic features of noise field characterization inside and outside railway trains. When these features are understood it becomes possible not only to forecast the effects of changes but also to modify train design. Thus, through the inclusion of advanced means of noise reduction mechanisms, a considerable reduction of the internal sound pressure level inside the train/monorail coach will eventually improve passenger comfort to a satisfactory level [3].

In the normal train, one of the major problems is to prevent noise and vibrations generated by exterior sources, such as the wheel–rail rolling noise and the braking noise. However, unlike the normal train, the major source of noise on the monorail is not from the wheel-rail interaction, nor from the braking system, because it runs on beams. But rather, the source is actually coming mainly from the propulsion system (gearbox). As a result, this study is going to focus on finding ways to reduce noise level on the monorail by identifying different types of materials with low frequency; since the noise type on the monorail is a low frequency noise, and noise absorptive or reflective materials to insulate the interior surfaces of the monorail coach (apron door, under floor and the roof) which will have a considerable noise reduction on the internal noise of the monorail coach.

1.2 Problem statement

Railways are proven to be a sustainable and climate friendly means of transport. However, they do influence the environment. One of the critical effect is the noise they produce. As a result, the interior noise reduction has become one important concern of railway operating environments due to the influence of increased speeds and reduced vehicle weights for energy efficiency. Thus, in order to ensure that the environmentally-friendly aspect of the railways is maintained; the noise level in the monorail has to be in a moderate level that no one would be exposed to noise levels which endanger health and quality of life. Therefore, this study was conducted to mitigate the noise coming into the monorail coach/car using suitable materials to insulate the interior surfaces of the monorail coach/car, and absorbing the noise that already inside the coach interior such the air-conditioning noise or those penetrated to the coach interior through air-born path, or transmitted through the panels of the coach, by installing absorptive materials inside the coach.

1.3 Aim

The purpose of this study is to mitigate the current internal noise level in the monorail coach/car without changing the existing design of the system.

1.4 Objectives

The objectives of this study are:

i. Characterization of noise reduction performance for each material.

ii. Identify the optimum location and the suitable thickness for every material to be installed on the Monorail.

1.4 Scope of study

The scopes of this study are:

i. The noise reduction method would mainly focus on low frequency, fire retardant, light weight, low cost and easy installation materials.
ii. The reduction method would involve variety of different materials.
iii. The technique used should fit the existing design of the monorail coach.
iv. 3D geometrical model or a prototype model will be developed
v. At least 5 dB will be reduced from the existing noise level

1.5 Significance of study

This study is expected to contribute in determining suitable materials to reduce the internal noise in the monorail coach which will have a positive impact on ride comfort of the passengers. In addition, the low noise level obtained from this study will also have a good effect on the environmental noise generated by the monorail. Furthermore, optimal location with suitable thickness to install every material is identified which will give insight to the monorail manufactures on where to install these materials.

1.6 Research limitations

The limitations encountered throughout this study are:

i. Budget
ii. Material availability
iii. Weight
iv. Time

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the theoretical background on previous research related to railway acoustic noise in general and discuss the various sources excite such noise. It also discuss about the countermeasures have been taken by the concerned parties regarding this noise. In addition, application of various means such as active and passive means were adopted in many studies which involved the use of various materials to mitigate such noise was also have given a look.

2.2 Acoustic noise in railway trains

In normal train, there are two noise sources acoustic noise can be produced from; either from inside noise sources like the ventilation or air-conditioning systems, or from outside noise sources like the wheel– rail interaction, the propulsion or hydraulic systems, brakes, compressor and aerodynamics.

However, acoustic noise can reach the coach interior by two different routes: the air-borne path and the structure-borne path. In the airborne path, sound is radiated directly from a source into the surrounding air. This sound is then transmitted through the panels of the coach. Thus, air-borne sound is mainly transmitted, but not exclusively, through the air. In the structure-borne path, vibration from a vibration source is transmitted to and excites the panels of the coach body. These panels then radiate sound to the coach interior. Unfortunately, it is very difficult to split the contribution of each of these noise paths to the overall interior noise in normal operation [3]. Thus, Botto, Sousa & Costa (2004) have adopted in their study a more realistic identification method by means of field tests involving simultaneous measurement of:

i. the interior sound pressure level,
ii. the outside sound pressure level, and
iii. The structural vibration level, i.e. the one that is not caused by the incidence of air-borne sound, for two different running conditions in which the relative proportions of the acoustic and vibration inputs differ [3].

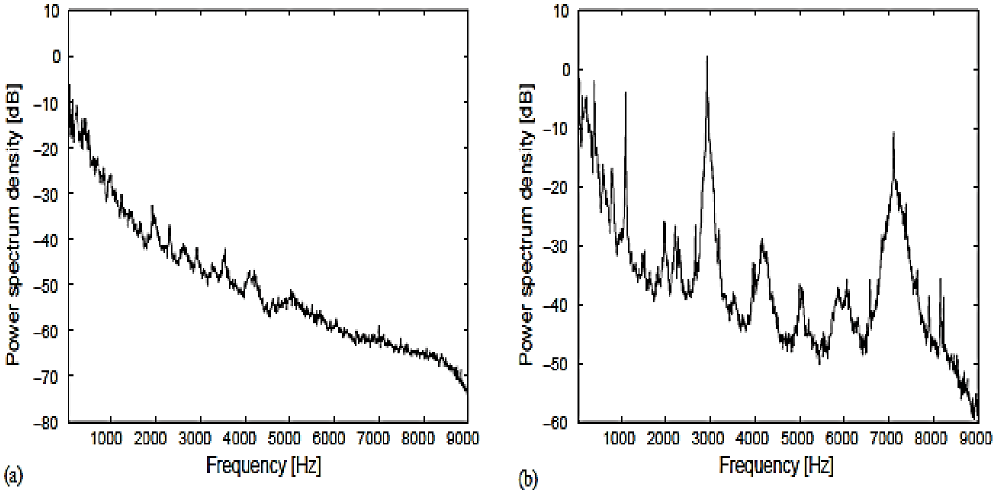


Figure 2.1: power spectrum density of the interior acoustic noise: (a) PSD on a straight path; (b) PSD on a curve [3]

On the other hand, Fan *et al.* (2008) have revealed that, the propulsion system and brakes were identified as the main noise sources responsible for the low frequency noise, while the high frequency noise is due to the wheel/rail interaction as can be seen in Figure 2.1. The same trend is found in the monorail interior noise which is a low frequency noise and the propulsion system is the found to be the main source [2].

However, Fan *et al.* (2008) also have found that one of the major problems is to prevent noise and vibrations generated by exterior sources, e.g. the wheel–rail rolling noise and the braking noise. The interior noise inside a railway coach is composed of air-borne at middle and high frequencies and structure-borne sound below 250 Hz. With a trend towards lighter trains the structure-borne sound will increase. There is a conflict between light weight structures and low levels of noise and vibrations. It has been proven difficult to achieve a satisfactory comfort level without adding mass to the structure. Moreover, they have revealed that Passive damping using viscoelastic materials is simpler to implement and more cost-effective than semi-active and active techniques [2].

In terms of insulation, Botto *et al.* (2004) have declared that, the first attempts that have been made to insulate railway trains against acoustic noise have been based largely on the assumption that most of the noise is rail-wheel-generated and that the highest level occurs beneath the train coach. The result is that current train coach floors have quite high transmission losses at the expenses of heavy thick isolating materials like plywood. Similarly, the latter assumption could be made on monorail system as well but the highest noise is from the propulsion system. However, it is by no means clear that the insulation of other parts of the train coach against airborne sound is equally adequate, nor whether sufficient isolation against structure-borne noise is provided.

Furthermore, the conventional methods of suppressing acoustic noise using passive noise absorbers generally do not work well at low frequencies. This is mainly because at these low frequencies the acoustic wavelength becomes larger when compared to the thickness of a typical acoustic absorber. It is also difficult to stop low frequency sound being transmitted from one space to another unless the intervening barrier is very heavy. Nowadays, in transportation systems, these problems are most of the times difficult to solve using only passive methods since the solutions are very demanding in terms of weight and bulk. Independent of the solution to be adopted (passive, active or both), to reach interior acoustic comfort inside train coaches, a careful analysis is needed towards acoustic noise characterization inside the train coach [3].

2.3 Noise in the environment

One of the most important environmental stress factors for people in industrialized societies is noise with the consequence that they may feel annoyed by various noise sources, although the degree of annoyance differ considerably. Typical environmental noise sources include road traffic, air traffic, rail traffic, industry, noisy neighbors and sports facilities. The distribution of the degree of annoyance is shown in Figure 2.2 and Table 2.1.

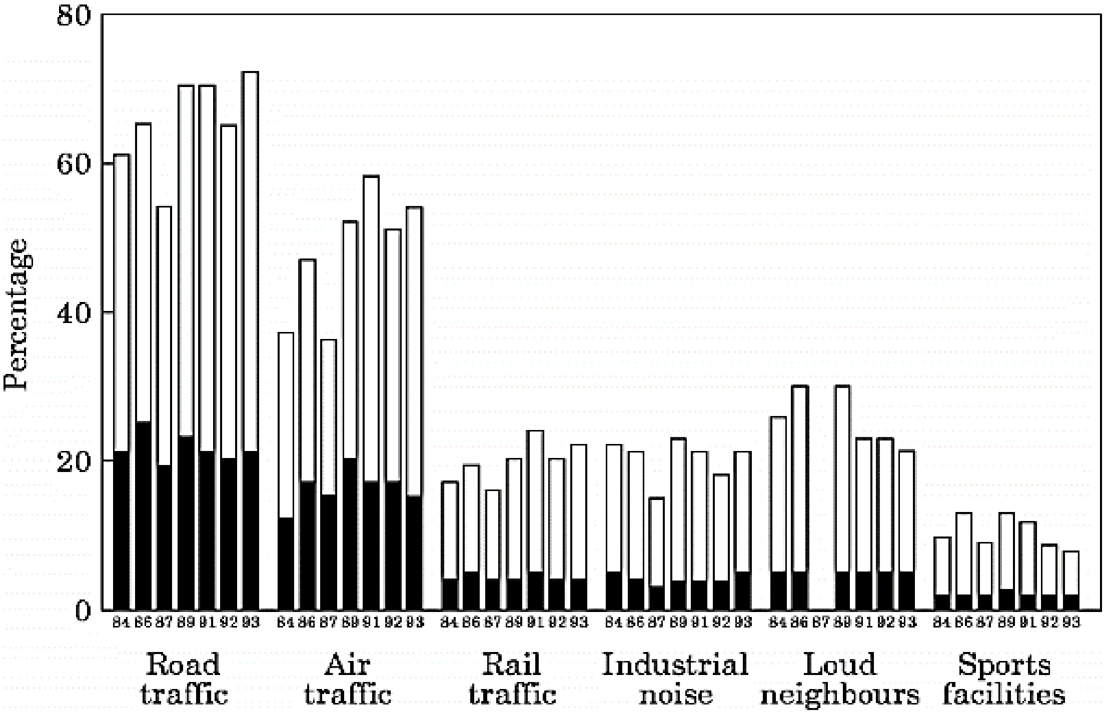


Figure 2.2: The subjective experienced annoyance of the federal German population [7]

■, Highly annoyed; □, annoyed

Table 2.1: Noise annoyance for the population in the old states of Germany [7]

Noise source	**Degree of annoyance**	**Total (%)**	**Annoyance by town size (number of inhabitants)**			
			< 5000	< 20000	<100000	>100000
Road traffic	Strongly annoyed	21	16	19	25	22
	annoyed	51	48	52	48	57
Air traffic	Strongly annoyed	14	14	16	14	11
	annoyed	41	44	42	38	38
Rail traffic	Strongly annoyed	3	2	3	6	3
	annoyed	19	14	25	16	21
Industrial noise	Strongly annoyed	4	3	4	3	4
	annoyed	17	11	18	22	17
Loud neighbors	Strongly annoyed	4	3	5	4	4
	annoyed	17	10	17	18	22
Sports facilities	Strongly annoyed	1	1	1	1	1
	annoyed	6	5	7	5	6

As it is seen in Figure 2.2 and Table 2.1 the most pervading transportation noise source is road traffic, with 21% of the people being highly annoyed, followed by air traffic at 14%, with rail traffic appearing only in third place at 3%. These figures refer to the Federal Republic of Germany for the year 1993. Rail traffic is less annoying, in general, than noise from industry and noisy neighbors (4% highly annoyed) [7, 8].

The same trend is found in a number of studies have been undertaken to contrast road traffic and railway noises through either social surveys or simulated laboratory experiments. Railway noise has been found to be less annoying in many European studies. Proposed explanations for such differential annoyance response include differences in acoustic properties between the two sources, such as frequency characteristics and loudness and regularity and predictability of noise event intervals. The perception people and their attitude towards the two modes of transport may also affect their annoyance to these two individual noise sources. However, a number of Japanese studies showed that railway noise was no less annoying or even more so than road traffic noise, probably due to train-induced vibration, socio-cultural factors and differences in train schedule and average distances of houses to the railway [8, 9].

Moreover, in the study conducted by Kurra, Morimoto & Maekawa (1998) the road and rail difference was confirmed to be greater in urban environments than in rural areas. Berry compared three U.K. surveys including railway and road traffic noises and suggested that the railway noise was not always less annoying than road traffic noise. On the other hand, the regression lines for aircraft and road traffic noise seem to be almost parallel to each other with a 10 dB(A) constant difference for the same annoyance degree, implying higher annoyance from aircraft noise. Cooperet et al. in their Heathrow Airport study, compared the source-specific annoyances expressed on a four-point scale and showed that aircraft noise caused relatively higher annoyance at Leq (outdoor) = 60 dB(A), whilst below this level, road traffic noise caused higher disturbance [10].

However, Knall (1995) compared with other areas of interference, and found that communication is the area in which it is generally agreed that railway noise is at its most annoying. Interference with sleep, on the other hand, was only seldom mentioned, and was not considered as being so serious; furthermore, it is not closely related to the noise level due to railway traffic. In addition to the noise level, non-acoustic factors such as attitude towards the railway, neighborhood environment, sensitivity to noise, etc., also affect the annoyance reaction to railway traffic noise. With the same average noise level, rail traffic noise is less annoying than road traffic noise. The degree of this difference is, however, dependent upon the relevant time period (day or night), upon the absolute level\ and upon the observed annoyance and disturbance variables [7].

While from the Chinese experience, the environmental noise of railway is generated mainly from two groups of sources, i.e. railway line noises and railway station noises. Railway line noise includes the whistling noise of locomotives and train operating noises (composed of rolling noise, traction noise and aerodynamic noise). Railway station noise includes the whistling noise of locomotives in passenger stations, freight stations, operating stations, engineering workshop and train workshop as well as loudspeaker broadcasts in these various places. However, according to a survey of main trunk lines in china whistle noise can occupy 70% of the total energy in A-weighted equivalent continuous sound pressure level at some particular sites near railway stations, alongside some railway line sections in urban regions. This demonstrates that among the existing railway noise sources whistle noise is the most important in China [11].

Moreover, the loudspeaker used for the purpose of communication and operational control at railway stations or railway workshops, has become one of the main source of noise in these areas due to the fact that the A-weighted sound level at 50 m away from the column-type loudspeaker installed at a high place reaches 80–85 dB [11].

2.3.1 Energy environmental advantage of railways

As in Table 2.2, if a comparison is made in terms of passenger-km, trains can offer substantial energy efficiencies over other forms of transport. Furthermore, in terms of their overall contribution to the transport market, trains consume a much lower proportion of the energy budget than their proportional share of the market as in Table 2.3 and Figure 2.3. As examples, in Sweden trains use only 1.8 per cent of the total transport energy to carry 7 per cent of the passenger-km and 38 per cent of the freight tonnes-km; in Japan, with a very high 30 per cent share of the passenger market, trains consume only 7 per cent of the total transport energy.

Moreover, one of the environmental advantage of the train is its ability to run on clean forms of electricity, thus reducing emissions while also conserving hydrocarbon fuels. As shown in Table 2.3, in Switzerland all trains are electric, with 97% of their power coming from renewable hydropower which makes rail energy consumption about 4%

only. While In France, it is 3.8% only, due to the fact that 77% of the railway passenger-km are on electric trains, and the vast majority of the energy for which comes from nuclear power. The case for increasing electrification ratios is therefore very strong on environmental grounds, particularly if the power is generated from non-fossil fuels; however, the short-term economic case is often used to prevent this investment for the future [12].

Table 2.2: Energy efficiency of various forms of transport [12]

Mode	**Efficiency**	
	Passenger-km/MJ-	**kg-km/MJ**
Human on bicycle (mass 60 kg)	18	1100
Human walking	5	300
Intercity train	1.7	100
Boeing 747	0.94	56
Urban bus	0.9	55
Car (4 passengers), long journey	0.7	40
Concorde	0.2	12
Car (1.15 passengers), urban commuting	0.2	12

Table 2.3: Share of energy consumption and transport volumes for rail [12]

Country	**Energy consumption (%)**	**Passenger-km (%)**	**Tonnes-km (%)**
Germany	3.3	6.7	19.4
France	3.8	7.5	25
Sweden	1.8	7	38
Switzerland	4	18	35

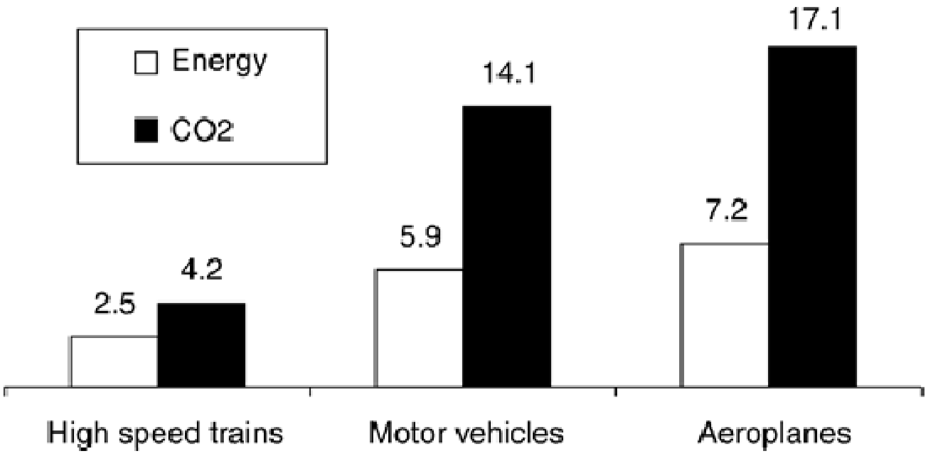


Figure 2.3: Typical comparisons of energy consumption (litres of fuel) and carbon dioxide emissions (kg) for various modes of transport per 100 passenger-km [12]

2.4 Mechanism of noise generation

Railway noise is generated from different sources and it can be categorized as air-born and structure-born noises. Rolling noise is established as originating from structural vibrations of the wheel, rail and sleepers resulting from the combined surface roughness of the wheel and running surfaces. Roughness on wheels can be induced by factors such as the use of tread brakes, especially those made from cast iron [3-5].

However, ground borne vibrations and structure-borne noise mainly occur at low frequencies (< 50 Hz). Frequencies above this are attenuated increasingly rapidly. Vibration disturbance is usually caused by the large vertical dynamic forces between wheels and rails. These forces fluctuate in response to wheel and rail roughness over a wide range of frequencies.

In addition, the wheel squeal originates from frictional instability in curves between the wheel and rail. Stick-slip oscillations (more accurately referred to as roll-slip) excite a wheel resonance; the wheel vibration radiates noise efficiently. In the study conducted by Eadie *et al.* (2004) the accepted model involves top of rail (TOR) frictional instability under lateral creep conditions leading to excitation of out of plane wheel bending oscillations. These are radiated and heard as squeal. The starting point for squeal is lateral creep forces that occur as a bogie goes through a curve and the wheel/rail contact patch becomes saturated with slip (creep saturation). A critical component in all the modeling work is the requirement that beyond the point of creep saturation, further increases in creep levels lead to lower coefficient of friction. This is known as negative friction, referring to the slope of the friction creep curve at saturated creep conditions. In more general tribological terms, this would be equated to changes in sliding velocity, rather than the railroad term creep. This leads to roll-slip oscillations between the wheel and the rail which excite a wheel resonance, and the wheel web radiates the noise [5].

Table 2.4: Frequency range for different types of railway noise [5]

Noise type	**Frequency range (Hz)**
Rolling	30–5000
Flat spots	50–250 (speed dependent)
Ground borne vibrations	4–80
Structure – borne noise	30–200
Top of rail squeal	1000–5000
Flanging noise	5000–10000

However, from the Figure 2.4 shown below it is seen that friction modifiers can reduce overall noise in curves across a wide range of wheel/rail systems.

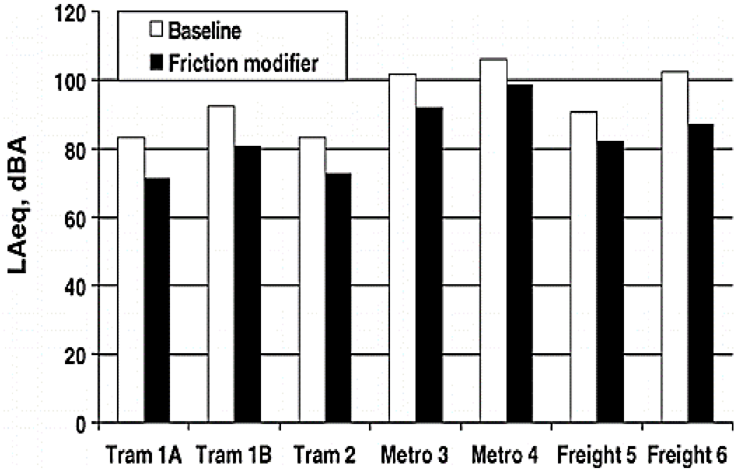


Figure 2.4: Summary of average sound level reductions [5]

This work also shows that in practical railways there is a large variation in absolute sound levels and spectral patterns. These have been characterized across trams, Metro, and heavy haul freight. The results show that:

i. Friction modifiers reduce squeal noise across all systems considered.
ii. Friction modifiers reduce flanging noise in all transit systems tested, but not necessarily in freight, where effective gauge face lubrication may also be required because of the higher lateral and flanging forces, especially in sharper curves.
iii. For systems with highest overall noise levels, the noise tends to be reduced across a broader part of the spectrum with friction modifiers.
iv. In one case, some reduction in low frequency vibration has been observed with friction modifier application [5].

2.5 Noise sources and reduction methods

In the past few years Botto *et al.* (2004) have conducted an experimental study on active noise control and applied to a laboratory railway coach model and concluded that, noise reduction can be achieved by two different methods. The first one consists of using passive means which are based on the absorption and reflection properties of materials, presenting excellent noise cancellation properties for frequencies above 1 kHz. The other method consists of using active means, which can show considerable noise cancellation performance for noise frequencies below1 kHz. The design of active noise cancellation systems are based on the principle of wave interference, where a sound is generated with the same amplitude as the noise source but with an adequate phase shift, in order to cancel the primary noise. This is usually known as active noise control (ANC) [3]. It is worth to mention that the noise reduction mechanism that will be adopted in our study is by using passive means even though the interior noise inside the monorail coach is of low frequency.

Moreover, the first attempts that have been made to insulate railway trains against acoustic noise have been based largely on the assumption that most of the noise is rail-wheel-generated and that the highest level occurs beneath the train coach [3]. However, this phenomenon is not so on the monorail, because firstly, it is not running on rails, and secondly, the internal noise level on monorail is mainly coming from the motor or gearbox, although the highest noise level occurs beneath the monorail coach as well. Therefore, low frequency and high absorptive materials will be used to reduce such noise coming from the motor/gearbox in order to reach interior acoustic comfort inside the monorail coach.

However, Mellet *et al.* (2006) have adopted the classical acoustic measurements method to identify the main sources responsible for the noise radiated by high speed trains and highlight the importance of both the power cars in the overall train noise for speeds above 300km/h. Hence, the power cars become the main contribution in the overall noise emitted by the train set at high speed. These measurements have been used to classify these sources according to their behavior and the speed dependence of their contribution. Three main families have been identified with the aero-acoustic sources:

i. Aero-acoustic sources mainly composed of the bogies, pantograph and its accessories and the front windscreen
ii. Rolling noise source composed of wheels.
iii. Unclassified, which have been added to put unclassifiable sources such as the louvres. Insufficient information is available to discriminate if the noise emitted by these sources is generated by the flow over these louvres or from the cooling fan operation [16] as shown in Table 2.5 below.

Table 2.5: Identification of sources [16]

High speed train	
	Identified sources
Forward power car	First bogie Second bogie Front glass Pantograph recess Wheels Louvers air inlets Louvers air outlets
Middle coaches	Ventilation Wheels Inter-coach gap
Rear power car	Pantograph Last bogie Wheels First bogie Louvers air inlets

2.5.1 Viscoelastic damping materials

Fan *et al.* (2008) have adopted the material damping in their study and concluded that, the material damping is able to extract mechanical or acoustical energy from a vibrating system and convert it into heat, by taking advantage of the viscoelastic damping capacity around the glass transition region. Taking into account the spectral characteristics in internal noise in railway vehicles, three new types of damping materials, such as bitumen-based damping materials, butyl rubber damping materials, and water-based damping coating, are developed for damping treatment of railway carriages to reduce the dominant components of noise within carriages [2]. Similarly, this trend will be adopted in our study as well but by using bitumen-based damping material, cement and acoustic foam.

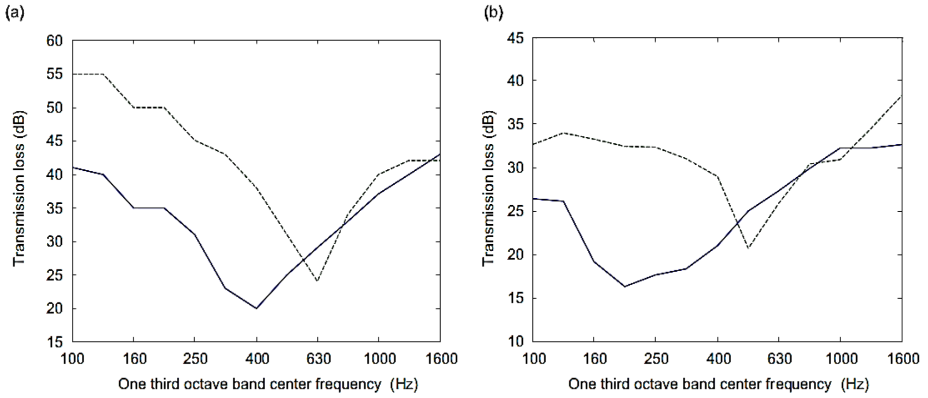
In addition, there is tuned viscoelastic damper (TVD) similar to a dynamic absorber or referred to as tuned mass damper. TVDs are generally applicable to reduce vibration/noise with a single frequency or a narrow band of frequency. Even if they are designed to reduce vibration/noise frequency at a given frequency, several TVDs with different frequency range have a wide band effect. The TVDs are very sensitive to the expected operating temperature range and the glass transition temperature of the viscoelastic material. Any temperature change in the damping material caused by energy dissipation into the internal heating is sufficient to alter the dynamic stiffness. This may lead the TVDs to detune itself. This characteristic of the TVDs makes elastomeric materials for TVDs only used in the rubbery region where slight changes in temperature do not have significant effect on the stiffness [2].

Besides, Fan *et al.* (2008) have also mentioned that the properties of viscoelastic materials are significantly dependent on environmental conditions such as temperature, vibration frequency, pre-load, dynamic load, environmental humidity and so on, therefore, proper surface treatment, dimension and appropriate characteristics of the damping material is of vital importance for the success of viscoelastic material in adding damping to the structure system. However, the new method introduced, which used viscoelastic constraint layers pasted partially on the outside sheeting of the car body. Based on the theoretical evaluation, it was found at the choice of the optimal length and appropriate characteristics lead to the maximum damping. These optimum parameters could give birth to the maximum improvement of riding comfort in a lightweight car body of a high-speed train. The full scale experimental results of Fan *et al.* (2008) showed that the riding comfort level was improved by about 3 dB at 275 km/h [2].

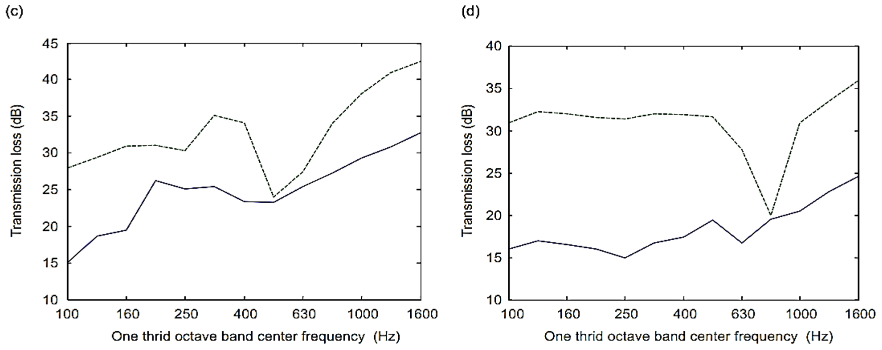
Furthermore, the sound absorption and transmission loss of about 80 samples of three types of damping materials were measured by the method of standing wave separation. The sound transmission loss of the least efficient and the most efficient damping materials among three kinds is illustrated in Figure 2.5. The three types of damping materials of optimal transmission loss and higher loss factor as shown in Figure 2.5(a), (c) and (e), were selected for the survey study. The bitumen-based damping materials in Figure 2.5(a) have higher transmission loss at low frequency than the other two damping materials shown in Figure 2.5(c) and (e). These three types of viscoelastic damping materials using damping treatment method mentioned above have been applied to the luxury sleeper carriage to investigate the optimal reduction effect of damping materials on noise and vibration.

However, Bitumen based and butyl rubber damping sheet were designed to isolate the transmission of vibration from the bogie frame to the car floor and attenuate the vibration of the wall panel of car body. Water-based damping compound of synthetic resin and fillers is suitable to spray onto the whole internal surfaces of the car body to prevent the transmission of rolling noise through car body [2].

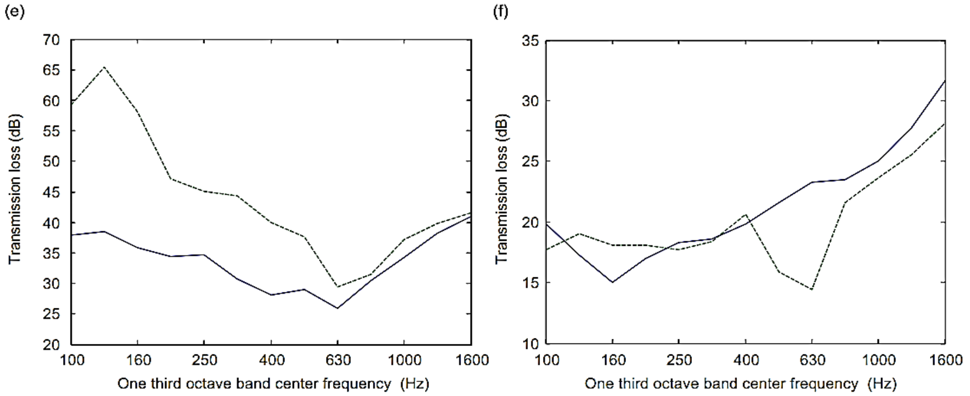
These three types of damping materials were installed on two carriages C1 and C2. The entire installation of damping materials on the carriage C1 is shown in Figure 2.6. The two sleeper carriages C1 and C2 were, respectively, equipped with 3.0 mm thickness of bitumen-based damping sheet and butyl rubber damping sheet on the inner surface of corrugated steel panel under the car floor, the upper surface of the floor panel and the side wall 484 mm high above the floor surface, as shown in Figure 2.6 and Figure 2.7(a). Furthermore, as shown in Figure 2.7(b), the water-based damping compound was sprayed onto the whole wall surface of the carriage C1 to replace the sprayed common damping material on the normal sleeper carriage C3.



(a) the best efficient bitumen-based damping material, (b) the least efficient bitumen-based damping material; (–) bitumen-based damping sheet with thickness of 2.5 mm; (- - -) the laminate consisting of 1.2 mm thick steel sheet and 2.5 mm thick bitumen-based damping sheet



(c) the best efficient butyl rubber damping material; (d) the least efficient butyl rubber damping material; (–) 3 mm thick butyl rubber damping sheet; (- - -) the laminate consisting of 1.2 mm thick steel sheet and 3 mm thick butyl rubber damping sheet.



(e) The most efficient water-based damping coatings; (f) the least efficient water-based damping coatings; (–) 2.4 mm thick water-based damping coating; (- - -) the laminate consisting of 1.2 mm thick steel sheet and 2.4 mm thick water-based damping coating

Figure 2.5: Sound transmission loss in one-third octave bands [2]

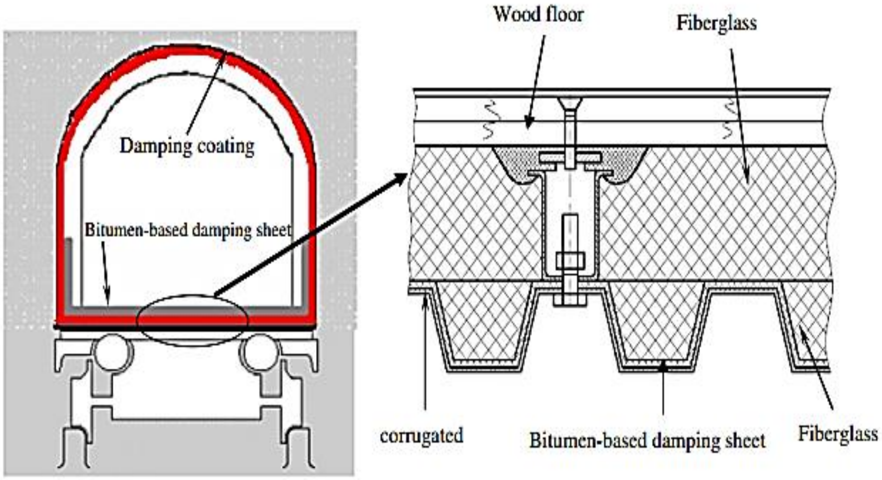


Figure 2.6: Schematic diagram of installation of water-based coatings on the whole internal car body and bitumen-based damping sheet on the sidewall and floor panel in the carriage C1 [2]

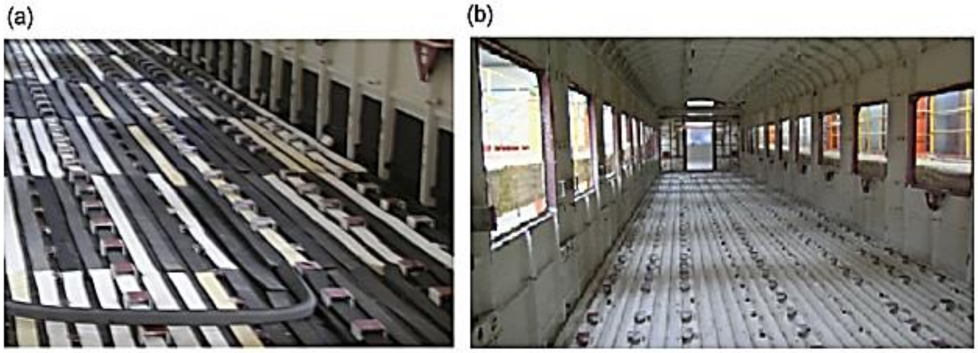


Figure 2.7: The damping treatment of the car body: (a) the equipment of damping sheets on the corrugated steel panel and side wall of the car body and (b) the car body sprayed with water-based damping coating [2]

2.5.2 Rolling noise

Rolling noise is caused by structural vibrations of the wheel, rail and sleepers induced by the combined surface roughness of the wheel and rail running surfaces. It also transmits vibrations to other parts of the train. Therefore, in the recent years the main focus of research into rolling noise has been the application of theoretical models to the design of low noise wheels and tracks. Furthermore, Thompson *et al*. (1995) have further clarified that, when a railway wheel rolls on straight or slightly curved track in the absence of discontinuities, a broadband noise is emitted which is known as rolling noise. Theoretical models for this rolling noise have been substantially developed by them [13]. They added that rolling noise is generated by surface irregularities (roughness) on the wheel and/or rail running surface. These roughnesses introduce a relative vibration between the wheel and the rail, the consequent wheel and rail vibrations radiating noise [1, 4, 13, 14].

Moreover, as in Figure 2.8, the roughness induces a vertical relative displacement between the wheel and rail or in the Hertzian contact spring, the motion of each depending on the relative amplitudes (and phases) of their receptances. The local contact defections are represented by a linearized incremental stiffness, which is valid only for relatively small amplitudes, but allows the model to be implemented in the frequency domain [13].

In contrast, this trend is not so in monorail system, because it does not run on rails and thus the main source of noise is from the propulsion system.

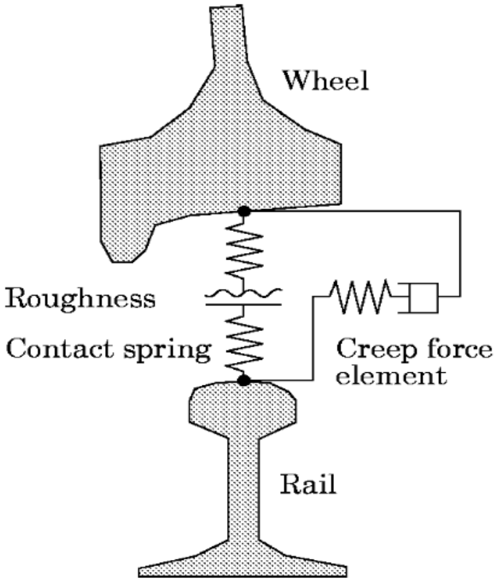


Figure 2.8: Details of the wheel-railed interaction [13]

2.5.2.1 Wheel design

The shape of the wheel also has turned out to have significant effect on the noise generated by the wheel-rail interface. Optimized wheel designs using theoretical models have been considered for some time. However, in the OFWHAT project an optimized wheel shape was designed and implemented that had a thick web and diameter of 860 mm. This was predicted to reduce the wheel component by 4 dB although in field tests only 1 dB reduction was measured. The design was, in any case, unsuitable for application in tread-braked vehicles. In Silent Freight, optimized wheel shapes were again studied. In this case, the thermo-mechanical requirements of tread braking had to be taken into account, which imposed a further constraint. Two 860 mm diameter wheels were produced, each predicted to reduce the wheel noise by 3 dB; experimental results showed modest reductions. However, for a disc-braked wheel, the potential of shape optimization is much greater than for a tread-braked wheel.

Wheel shape optimization was attempted on a TGV in France as well, producing 4–5 dB less noise in the frequency range above 1.6 kHz where the wheel is expected to dominate. A small (640 mm diameter) straight-webbed design has been shown to produce as much as 18 dB reduction in wheel noise compared with a conventional wheel, although the track component of noise can increase slightly due to a shift in the contact filter effect [4]. The other main area in which wheel noise reductions are sought is in added damping. More recently such damping treatments have also been used in attempts to reduce rolling noise. A reductions of 3–4 dB was predicted in the wheel component of noise.

An alternative method of adding damping is a tuned absorber system. Absorbers of various designs have been used on railway wheels for many years in Germany with success. Applications elsewhere have been less successful. Simple tuned absorbers were used in the OFWHAT project and achieved a 4 dB reduction, while in the Silent Freight project reductions of up to 7 dB were found in combination with optimized wheels. A wheel cover, which shielded the wheel web, was also studied in Silent Freight. This, in combination with the optimized wheel design, also reduced the wheel noise by about 8 dB. Table 2.6 summarizes the main results obtained in the combined final tests of the

Silent Freight and Silent Track projects. The first column of results indicates the reduction in the wheel component of noise compared to the reference wheel and the first row similarly the reduction in track component of noise. The remaining figures are reductions in overall noise due to the various combinations of measures [4]. However, all of these optimization techniques are not applicable in the monorail system due to some reasons mentioned earlier.

Table 2.6: Measured noise reduction obtained for various wheel and track treatments in Silent Freight and Silent Track projects to nearest whole dB [4]

	Wheel noise reduction	Stiffer pads	Reference track + absorbers	Stiffer pads + absorbers	New track	New track+ absorbers
Track noise reduction	-	2	6	5	3	7
Perforated wheel with ring damper	4	2	6	4	2	6
Optimized wheel with shields	8	3	7	5	4	8
Optimized wheel with tuned absorbers	7	3	7	6	4	8

2.5.2.2 Wheel dynamics

It is also found that the wheel dynamics also has an effect on the vibration created and that will increase the total amount of noise produced. A railway wheel is a very lightly damped resonant body, which can be characterized readily by its normal modes. Axial modes are categorized by the number of nodal diameters (*n*) and the number of nodal circles (*m)* radial modes are also important and are categorized by the number of nodal diameters. However, from the simulation model developed by Thompson *et al*. (1995) it is found to

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