sustainability

Review

State-of-the-Art Review on Sustainable Design and Construction of Quieter Pavements—Part 1: Traffic Noise Measurement and Abatement Techniques

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Abstract: Noise pollution due to highway traffic has drawn the attention of transportation agencies worldwide. Noise pollution is an irritant to residents, especially in urban areas near roads with high traffic volume. In addition to its adverse effects on the quality of life, traffic noise can induce stress that could lead to sleep disturbance and anxiety. Traditionally, noise barrier walls have been used for highways to mitigate traffic noise. However, using barrier walls as a noise abatement measure has proven to be very expensive. In addition to the cost, noise barrier walls are not always effective because they must break the line of sight to work properly, which is not always possible in case of intersections or driveways. Therefore, researchers especially from Europe and USA have been very proactive to reduce the noise at source. A number of research studies show traffic noise can be reduced by using an alternative surface type or changing texture of the pavement while complying with other requirements of sustainability, i.e., safety, structural durability, construction and maintenance costs. This paper presents a comprehensive review of the research conducted on this subject. A review of the tire-pavement noise generation and amplification mechanism, various traffic noise measurement methods and correlation among these methods, in addition to the abatement techniques used by various agencies to reduce pavement noise, is also presented.

Keywords: sustainable design; tire-pavement noise; noise generation mechanism; noise measurement method; noise abatement techniques

1. Introduction

Sound occurs when there is a movement or pressure variations in a fluid medium and is generally all around us, whether it comes from a speaker or the rustlings of leaves due to wind or a car driving by [1]. However, excessive sound may be annoying or objectionable to humans. The unwanted and/or excessive part of sound is termed 'noise', which has a fundamental distinction from the word 'sound'. Noise pollution has become a serious issue in the current world, and therefore many researchers around the globe are actively performing research to find ways of reducing the noise to an acceptable level. Although there are many sources of noise, traffic noise has been shown to contribute as a major source of the total environmental noise [2,3]. Noise generated by traffic is an irritant to nearby residents, especially in critical zones such as hospitals, schools, recreational parks, and neighborhoods near roads with high traffic volume. Traffic noise causes annoyance to humans, which in turn affects the quality of life [4]. In addition to annoyance, it can cause sleeping disturbances and learning disabilities [5]. Furthermore, the relationship between cardiovascular diseases (i.e., hyper tension or ischemia) and exposure to highway traffic noise is also reported [6]. However, traffic noise is not the direct cause of cardiovascular disease, but it contributes in an indirect way which leads to negative cardiovascular outcomes [7]. Noise pollution increases with increase in volume of road traffic, and hence is becoming an important environmental issue throughout the world both in rural and urban areas [2].

Traffic noise level is represented in units of A-weighted decibels (dBA), which is used to quantify the intensity of the pressure differential created by sound according to the perception of the human auditory system [4]. A decibel expresses the ratio of the measured sound pressure level to a standard reference level based on a logarithmic scale. The logarithmic scale is used to represent sound with a manageable range of values. Because the human auditory system is not linear, A-weighting is applied to simulate changes in the ear's sensitivity at different frequencies (pitches). The relationship between sound level (in decibel units) and sound pressure (in Pascal units) along with some examples is shown in Figure 1.

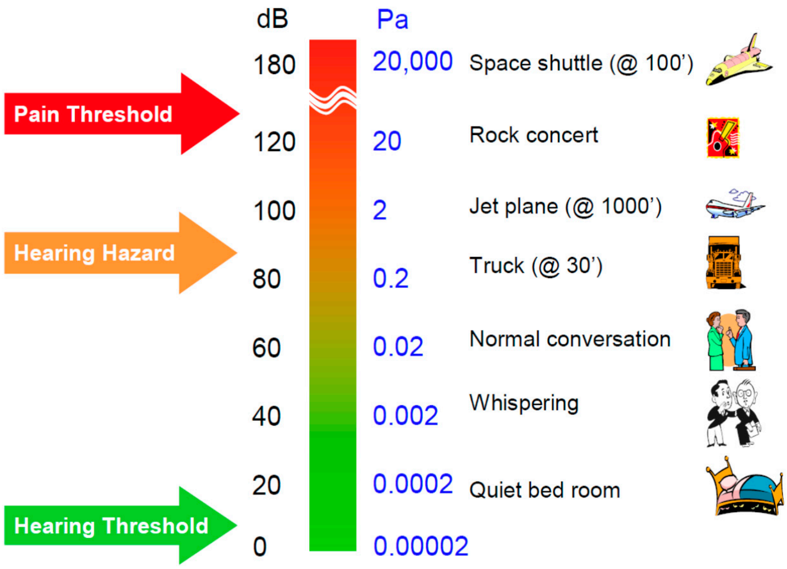


Figure 1. Comparison of sound pressure, sound levels, and common examples (Reproduced with permission from Rasmussen et al.) [1].

Tire-pavement interaction noise is defined as the noise emitted from a rolling tire due to interaction between a tire and pavement surface [3]. When a tire is rolling on a pavement surface, a number of noise generation mechanisms work in conjunction to generate noise. This is further amplified by a number of amplification mechanisms [3]. Tire-pavement interaction is the dominant source of traffic noise, especially vehicles moving at medium to high speed, and therefore researchers are trying to reduce it to an acceptable limit.

A number of noise abatement procedures have been adopted to mitigate traffic noise. However, commonly used noise abatement techniques are proven to be expensive. Therefore, researchers throughout the world tried to use alternative pavement surfaces for mitigating traffic noise at source. Pioneering studies conducted by researchers in Europe and USA demonstrated that constructing a low noise surface is possible by modifying a pavement surface and/or texture [3,8–15]. Further studies [3,12,16,17] also indicated that a low-noise road surface can be built at reasonable construction and maintenance costs without compromising safety, ride quality and sustainability of pavement. There are number of advantages for reducing noise at the source rather than using barrier walls. It can benefit all receivers, including drivers, and also it is less expensive compared to barrier walls. Furthermore, it can be applied all along a road without interruption, including road sections past driveways or through intersections. Therefore, there is an increasing demand for quieter pavement, especially in countries where transportation corridors are close to residential zones. This paper provides a concise but critical review of various mechanisms of tire-pavement noise generation, noise measurement methods, and noise abatement techniques with the aim of providing researchers and practitioners with the knowledge of the latest developments in the field.

2. Noise Regulation Policy

The issue of traffic noise is firstly noticed in Europe which went back to 44 BC. Julius Caesar, the Roman Emperor of that time, established the empire's first noise regulation, "Hence-forward, no wheeled vehicles whatsoever will be allowed within the precincts of the city, from sunrise until the hour before dusk ... Those which shall have entered during the night, and are still within the city at dawn, must halt and stand empty until the appointed hour" [18]. It is, therefore, not a coincidence that Europe has been at the forefront of tackling this issue. All European Union (EU) Member States are required to determine the exposure to environmental noise and take actions to reduce the noise pollution according to the European Directive on the Assessment and Management of Environmental Noise (2002/49/EC). In addition, EU countries are required to produce noise maps for all major transportation corridors such as major roads, rail, airports, and industry (including port areas if appropriate) on a five-year basis effective from June 2007 [19]. Local authorities use these noise maps to identify priorities for actions to reduce the noise level. This information is also provided to the public so they can be aware of the noise level exposure and efforts undertaken to reduce the noise level [19].

In USA, Noise Commission of New York adopted the first noise emission control measure in 1932 [20]. However, proper noise policies were introduced in the 1970's where an important Federal legislation called "The Federal-Aid Highway Act" was adopted for noise control. Under this regulation a section is provided for noise abatement "Title 23 of the United States Code of Federal Regulations Part 772-Procedures for Abatement of Highway Traffic Noise and Construction Noise". This regulation specifies that proper impact assessment of noise to adjacent areas should be conducted for specific types of highway projects using federal funding; the types of projects include: constructing a new highway and physically altering an existing highway (e.g., significantly changing horizontal or vertical alignment, altering the adjacent topography, increasing the number of through traffic lanes, and altering an interchange or toll plaza). If any impacts have been identified by the highway agency, it must incorporate all feasible and reasonable noise abatement procedures in the design of the project [4]. The Federal Highway Administration (FHWA) has selected different sound levels for different categories. For example, for recreational areas, the allowable exterior sound level is 67 dBA (average over worst hour) at a distance of 15 m (50 feet) away from the centerline of the highway. It is to be noted that each U.S. state has its own noise policy with differing requirements, but all must conform to federal regulations and guidance.

3. Tire-Pavement Noise Generation Mechanisms

Tire-pavement noise generation mechanism has been studied since the 1970's. The mechanism of noise generation and propagation due to tire-pavement interaction is quite complex. Therefore, it is necessary to gain thorough understanding of noise generation mechanisms in order to design low noise road surfaces. When a tire impacts the pavement, some mechanisms create energy which is radiated as sound, and others amplify the sound that is generated from the generation mechanism [3,21,22]. Most of the researchers agreed with the noise generation mechanisms theory but disputed the relative importance of them in generating tire-pavement noise [3]. This is because noise is dependent on both the properties of tire and pavement surfaces and the complex interaction between these two parameters [3]. Generally, noise generation mechanisms can be categorized into two modes: structure borne, directly related to mechanical vibrations of the tires and referred to as source generation mechanism, and air-borne, related to the aerodynamic phenomena and referred to as the sound enhancement mechanism [2,3]. However, a number of mechanisms work in union to generate noise when a tire is rolling across a pavement [3,23]. This following section will describe the tire-pavement noise generation mechanisms.

3.1. Sound Generation Mechanism

3.1.1. Tread Impact

The first sound mechanism occurs when tire tread blocks hitting the pavement cause vibration in the tire carcass as shown in Figure 2. When rolling tire treads travel circumferentially along with the tire, they individually hit the contact patch of pavement hundred times if not thousand times within a second [1–3]. Such vibrations radiate as sound energy and can be a major source of tire-pavement noise. This is analogous to a small rubber hammer impacting the pavement thousand times in a second [1–3]. Tread impact vibration can exist in the radial, tangential or axial direction and generally affect the noise below the 1000 Hz [24,25]. Tire treads vibration mainly affected by surface macrotexture. This noise mechanism is also affected to a lesser extent by the mechanical impedance of pavement [17,26].

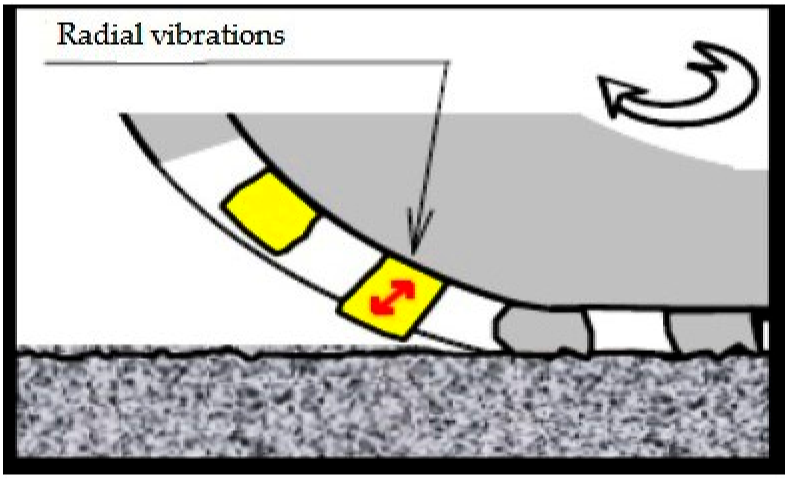
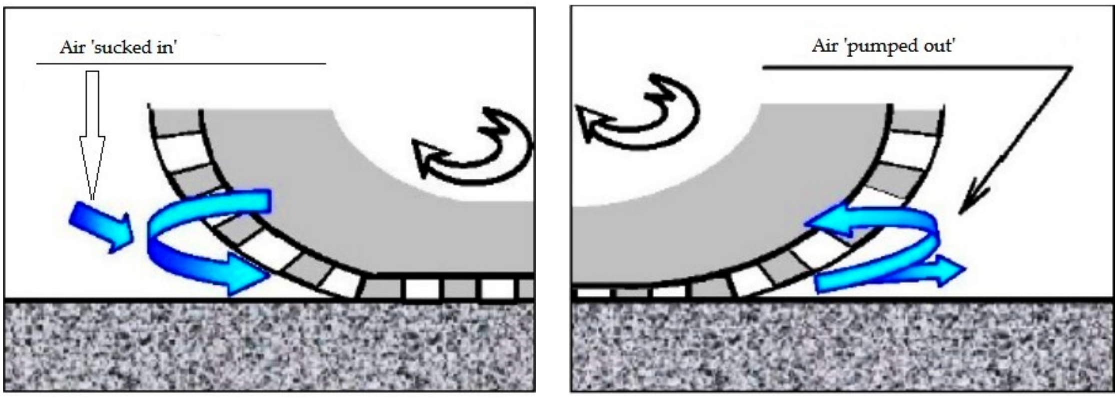


Figure 2. Tire tread block/pavement interaction (Reproduced with permission from Sandberg and Ejsmont) [3].

3.1.2. Air Pumping

The air pumping mechanism occurs when air is pumped or compressed at the contact patch between tire and pavement as shown in Figure 3. A significant void space can be created at the contact patch due to passages and grooves in the tread pattern of the tire. The void spaces between passages and grooves in the tire continuously distort and deform as the vehicle travels on the pavement. The entrapped air in the void spaces compresses and is pumped out as the tire loses contact with the pavement. Consequently, sound is generated aerodynamically due to the air compressing and pumping effect. This is similar to two hands clapping together, where the air is compressed and forced out at the edge of hands, which creates part of the clapping sound [1–3]. Whistle blowing is another example where air is forced outward through a small opening [1]. The air pumping mechanism is influenced by the porosity and macrotexture of pavement; hence, it is the major source of tire-pavement noise as reported in various studies [1–3,17,27,28].Research studies [17,25,26,29] showed that air pumping mechanism is more prominent at frequencies above 1000 Hz (frequency range: 1000–2500 Hz).



(a) (b)

Figure 3. Air pumping mechanism (**a**) entrance; (**b**) exit of the contact patch (Reproduced with permission from Sandberg and Ejsmont) [3].

3.1.3. Stick-Slip

The tread blocks of a tire at the contact patch experience a considerable amount of horizontal forces due to distortion of the tire carcass while rotating on the surface of pavements. During acceleration or braking, these horizontal forces of tire treads are transferred to the pavement. If these horizontal forces are greater than the frictional force of pavement, the tire tread blocks will briefly slip before re-adhering to the pavement [1–3,30]. These events of slipping and re-adhering under each tread block happen thousands of times a second, thus creating high frequency sound. This is analogous to the sound of sneakers squeaking on gymnasium floor or basketball courts. The stick-slip mechanism is shown in Figure 4. Stick-slip mechanism is shown to cause noise in the frequency range (1000 Hz–2500 Hz) and above [28,31]. This noise mechanism is affected by the texture of all wavelengths whether the surface texture is positive or negative. Temperature has also a great influence on this noise mechanism as tire rubber friction changes with temperature [17].

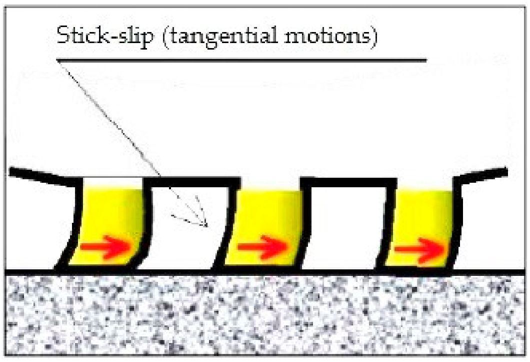


Figure 4. Slip-stick mechanisms of sound under tread blocks (Reproduced with permission from Sandberg and Ejsmont) [3].

3.1.4. Stick-Snap

Sound from the stick-snap mechanism occurs due to adhesion between tire tread blocks and a pavement surface, which is shown in Figure 5. The sticking tread block is released at the trailing edge of the contact patch, thus creating vibration which radiated as sound energy. This phenomenon is similar to a suction cup sticking to a smooth surface [1,3]. Stick-snap mechanism at the trailing edge is shown to affect noise at frequency above 1000 Hz [24]. This noise mechanism is influenced by both microtexture of surface and temperature [17,32]. The adhesion mechanism is reduced in wet condition but increased in dry condition [32].

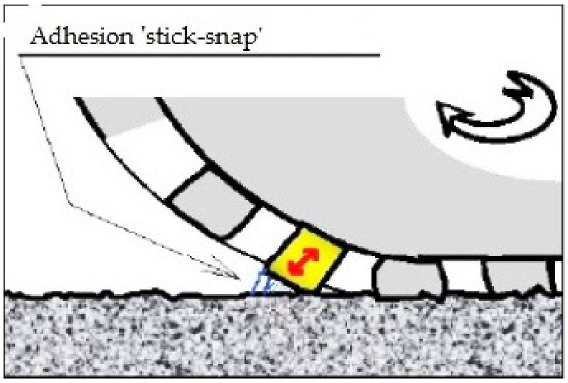


Figure 5. Stick-snap mechanism of sound under tread blocks (Reproduced with permission from Sandberg and Ejsmont) [3].

3.2. Sound Enhancement Mechanism

Noise generated from the source mechanism is not the only noise which directly reaches the human auditory system. There are several amplification mechanisms working in conjunction with the noise source mechanisms that contribute to enhancing tire-pavement interaction noise.

3.2.1. Horn Effect

The geometry at the tire-pavement contact point is similar to an acoustical horn. A wedge shaped segment of open-air is formed between the pavement and tire near the leading and trailing edge of the contact patch due to the geometry. Multiple sound reflections occur within this wedge shape segment which is similar to the bell of a horn [13,33]. Any noise generated near the horn throat will be enhanced by the horn effect. The horn effect noise mechanism is reduced with increasing porosity and sound absorption properties of the pavement surfaces [34,35]. This mechanism is enhanced at high frequency (frequency range 2000 Hz–3000 Hz) [33].

3.2.2. Helmholtz Resonance

Sound amplification occurs when a trapped volume of air is connected to the outside air via a channel [36]. This amplification mechanism is termed as Helmholtz resonance. This can be best described by equating it by the blowing of air across the top of a soda bottle [1,2]. Blowing air into it is not that loud, however, blowing across the top of the bottle significantly amplifies the sound. This is because air in the neck of the bottle vibrates up and down on the pillow of air inside the bottle, thus amplifying the noise at a frequency unique to that bottle [1]. Air is entrapped in between the tread block and pavement as previously described. When a tire tread block is about to contact the pavement or just lifts off of the pavement, a channel is formed which amplifies the sound. Therefore, Helmholtz resonance and the air pumping mechanism should be considered concurrently in order to properly quantify the noise [37]. Helmholtz resonance can be reduced by using porous or rough textured pavement as noise can move through the voids of pavement surface [17].

3.2.3. Pipe Resonance

When a tire rotates, the sipes of the tire tread are deformed thus forcing air out through these openings. The sound resonance occurs due to opening and closing of sipes while air is transferred through these sipes. This is similar to the mechanism of organ pipe resonance. These resonances are associated with the air pumping mechanism and should therefore be considered concurrently [29,38]. Pipe resonance can be decreased by using porous pavement [39].

3.2.4. Cavity Resonance

The air inside the tire is also excited when a tire comes in contact with the pavement surface. The air inside the tire will also resonate at certain frequencies. This is similar to the ringing sound heard when a balloon filled with air is thumped. This mechanism is more significant for sound inside the car than outside sound [1].

3.2.5. Carcass Vibration

Sidewalls of a tire carcass vibrate when the tire hits the pavement at the contact patch. This vibration wave in the tire carcass amplifies the sound generated by other mechanisms. This is the same way an upside down pie plate would amplify by a vibrating cell phone [1].

4. Noise Measurement Methods

Data collected from the noise measurement systems are usually used to understand the noise generation mechanisms as well as in identifying quieter pavements, thus accurate measurement of tire-pavement interaction noise is critical. This data will also be used in developing and validating traffic noise model (TNM) to predict the future acoustical performance of quieter pavements. Hence, numerous research studies have been devoted to develop accurate tire-pavement interaction noise measurement methods. The types of noise measurement methods can be divided into three broad categories based on the measurement techniques. These include wayside noise measurement methods, measuring noise at source (i.e., onboard measurement methods), and laboratory drum noise measurement methods.

4.1. Wayside Noise Measurement

Wayside measurements involve measuring the traffic noise using microphones that are placed at a certain distance from the center line of the driving lane. Traffic noise from all sources (i.e., power unit noise, tire-pavement interaction noise, aerodynamic noise) is measured for these types of measurements. These include three commonly used methods: Statistical Pass-by (SPB), Controlled Pass-by (CPB), and Continuous-Flow Traffic Time-Integrated Method (CTIM). Similar techniques and measurement set-up are used for these three methods, but there is variation in sample size and data processing. Some other methods such as acceleration pass-by method and coast by (CB) method can also be applied but will not be described in this paper because their measurement technique is essentially similar to the aforementioned three main methods. In addition, their application in highway noise measurement is limited.

4.1.1. Statistical Pass-by Methods

The Statistical Pass-by Method (SPB) utilizes a random sample of typical vehicles selected from a traffic stream under constant or nearly constant speed as described in relevant ISO standard (11819-1) [40]. This method compares traffic noise on different road surfaces for various compositions of road traffic for the purpose of evaluating the acoustic performance of different road surface types. The measurement is done by using a roadside microphone positioned at a defined distance and height from the travel path of a vehicle. The standard specifies that the microphone should be positioned at 7.5 m (25 ft) from the center line of the vehicle travel lane at a height of 1.2 m (4 ft) above the surface. The statistical significant sample size according to the standard should be at least 180 vehicles made up of 100 passenger cars and 80 dual/multi-axel trucks. The maximum sound pressure level is captured for each pass-by event using a sound level meter. The speed and vehicle type of each event is also recorded. The data are used to compute a statistical pass-by index (SPBI) which is used to compare various pavements.

In the USA, the original pass-by method is an FHWA procedure developed by Volpe National Transportation Systems Center [41], where microphone placement is at 15 m (50 ft) from the center line of the vehicle travel path with a height of 1.5 m (5 ft). For purposes of examining the effects of various pavement types in the USA with a wayside procedure, elements from the FHWA method and the ISO SPB method were combined and expanded upon and standardized as AASHTO TP-98 [42]. This method is referred to as the Statistical Isolated Pass-by (SIP) method, which uses the average pavement from a national database [43,44] as a reference in order to compare results. The standard advocates for placement of two microphones, one is at 7.5 m (25 ft) with height of 1.5 m (5ft) and the other one at 15 m (50 ft) with height of 3.7 m (12 ft). If there are any site constraints, either of the defined microphone positions can be used. The standard encourages a sample size of 100 vehicles for each category, with a minimum requirement of 30 vehicles. Figure 6 presents wayside noise measurement apparatus. This method can be used to quantify the performance of different pavement types for each vehicle category. The data for specific vehicle category can be used to develop reference energy mean emission level (REMEL) which can be used in TNM to predict the traffic noise [44]. Traffic noise of various pavement sites with same design but different ages can be measured to predict the acoustical performance with time. However, this process is strictly localized and required large sample size in order to predict long term noise performance.

Figure 6. Wayside pass-by measurement apparatus [14].

The pass-by methods measure all components of vehicle noise alongside the highway, which includes engine, exhaust, aerodynamic and tire-pavement interaction noise. It is therefore not possible to isolate the contribution of a specific component's noise. The result can be varied because this method is based on a random sample for different sites, and hence its measurement is not strictly in a controlled environment. For proper vehicle pass-by measurements, the roadway must be straight and level in the vicinity of measurement site. Presence of an acoustically reflective surface within 30 m (prohibited in the methods) may contribute to the measured noise, thus resulting in erroneous findings. This method is time consuming and expensive but still provides accurate assessment of various pavement effects that could impact neighborhoods adjacent to highways [2].

4.1.2. Controlled Pass-by (CPB) Method

The principle of controlled pass-by methods is similar to the SPB method however with a relatively small sample size, i.e., either a single vehicle or a few selected vehicles. In this method, the noise generated from a single vehicle is measured at a constant speed with the engine running at normal condition for the test speed. In Europe, only France has a national standard that specifies this method (NF S 31-119-2). The main disadvantage of this method is that it cannot be used in highly dense traffic, and is hence used less frequently throughout the world [2,11]. In the USA, Marquette University conducted this type of testing for the Wisconsin Department of Transportation [45].

4.1.3. Continuous Flow Traffic Time Integrated Method (CTIM)

Due to increasing traffic volume on highways, measuring noise by using SPB, SIP, or CPB is difficult. Therefore, FHWA developed the CTIM [46] procedure for measuring noise for continuously flowing traffic. In this method, a microphone is placed at 15 m (50 ft) from the center line of the near vehicle travel path with a height of 3.7 m (12 ft) above the pavement. However, for non-continuous flow traffic, the AASHTO standard recommends the SIP method [42] for wayside noise measurement of single vehicle pass-by's. CTIM is developed to measure the initial noise reduction of a certain pavement site and can be monitored the acoustic performance over time. However, measured data cannot be used for ranking the performance of a pavement as this method is strictly site biased. In addition, the data produced from measurement method cannot be used in TNM for future noise prediction.

4.2. Noise Measurement at Source

Measuring noise at the source (i.e., 'noise near tire') is more accurate than a wayside measurement for isolating the effect of pavements on tire-pavement source noise. Typically, there are two types of measurement techniques used all over the world for noise measurement at the source. These include the Close Proximity (CPX) method for sound pressure level (SPL) measurement and the On-Board Sound Intensity (OBSI) method. A third category, Acoustic Array Technology (AAT) method, is also used for measuring tire-pavement interaction noise. This AAT method is mainly used in a laboratory with few on-road applications and exclusively used in the research domain. Moreover, there is no reported data available to correlate with in-situ measurement data in a highway environment. Therefore, this method will not be elaborated in this paper, but details can be found elsewhere [47].

4.2.1. CPX (Trailer) Method

The close proximity method (CPX) was developed in Europe and defined by ISO standard 11819-2 to measure the tire–pavement noise at the source [48]. In this method, a test tire is mounted within a specially designated trailer that is towed by a passenger car. One or more microphones close to the test tire are located to measure the sound pressure level. Microphone positions near the test tire according to the ISO Standard [48] are shown in Figure 7. The microphones are mounted inside an enclosed acoustical chamber to provide screening from winds and other traffic noise. This acoustical chamber is particularly important to isolate the sound from other vehicles. Figures 8 and 9 show the close proximity trailer and testing arrangement. The measurement can be performed along the traffic stream with noise level measured as an average over a certain time interval, usually 4–60 s. This method is relatively simple and minimizes affects from noise generated by other traffic due to the position of microphone inside the enclosed chamber. Hence, a number of studies [1,3,49–51] used this system for measuring tire-pavement noise. However, this method does not take into account the variation of traffic which is normal for continuous traffic. Manufacturing a specially designed CPX trailer is also expensive. In addition, this method is performed with a relatively small set of tires and only one weight is used. The other difficulty of this measurement method is that the data obtained from this measurement system cannot be used directly as an input of a noise prediction model.

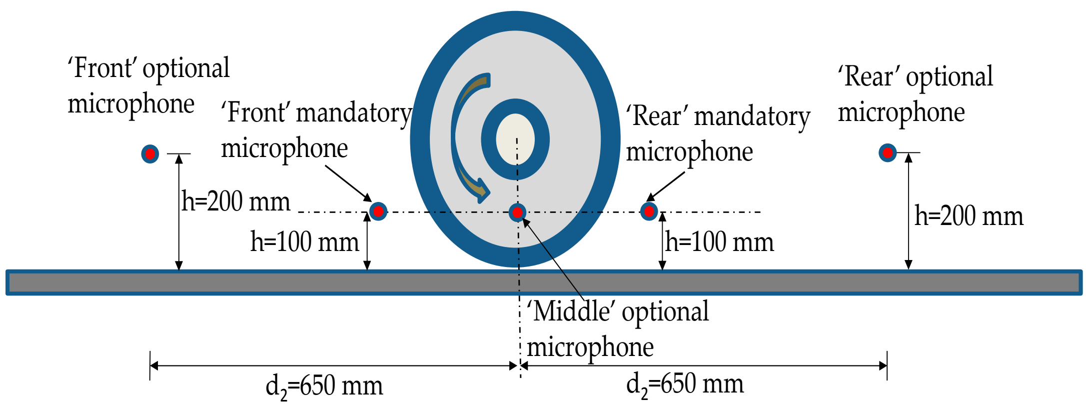


Figure 7. Diagram showing microphone position according to International standards organization (ISO-11819-2) [48].

Figure 8. National Center for Asphalt Technology (NCAT) CPX trailer (Reproduced with permission from Hanson et al.) [11].

Figure 9. NCAT CPX trailer with across door open (Reproduced with permission from Hanson et al.) [11].

4.2.2. OBSI Method

The problems of having nearby traffic sound or sound from other sources such as nearby industry or construction related noise makes it difficult to measure the tire-pavement noise accurately. Although the close proximity method takes steps to minimize contributions from these extraneous noise sources, it is possible they could affect the measured sound level. Therefore, researchers either use specially designed trailers, which are expensive, or tests are performed on the isolated pavement without any nearby traffic, thus creating practical problems. Since the invention of the sound intensity (SI) technique in the 1970's, researchers envisioned this technique for potential use as a tire-pavement interaction noise measurement application. This is because SI is a vector quantity which has the ability to localize noise sources, reject background noise, and detect the propagating energy in the acoustic near field. With these traits, it possible to measure the sound within normal traffic conditions by using SI technique, which is more difficult for the SPL method measurement [52].

The OBSI measured technique was originally developed by General Motors for research purposes in the early 1980's [53]. This method was applied for vehicle development purposes for General Motors industry and documented in the relevant General Motors test procedure [54]. The initial SI probe consisted of two ½-inch microphones spaced 16 mm in a side by side configuration and was fitted with a nose cone pointed in the direction of vehicle travel. Research continued to improve the measurement method, but the measurement approach remained virtually unchanged. Rasmussen [55] showed a new instrumentation system for a SI measurement at the international Tire-Road Conference in 1990. In this new instrumentation system, a face-to-face microphone configuration was placed near the leading and trailing edges of a tire contact patch, although this study did not specify probe location. A 'football' shaped windscreen was used to protect the microphone from the airflow. In this study, time domain approach is first applied for the SI measurement rather than Fast Fourier Transform (FFT). The OBSI protocol was subsequently refined under sponsorship of Caltrans, and is now standardized internationally as Standard AASHTO TP76-13 [56]. The AASHTO Standard [56] specifies two pairs of phase-matched microphones which are placed at both the leading and trailing edges of the tire. If a single pair of microphones is used, then the pair of microphones should be positioned in the leading edge of tire first and complete the valid run. Then the microphones are moved and repositioned to the trailing edge and the procedure repeated. Figure 10 shows the OBSI testing arrangement. The microphones are cabled to the interior of the vehicle where the signals are simultaneously captured on a recorder and processed by a real-time analyzer. Analysis isolates the noise from the tire-pavement interface; noise from other sources such as wind or other vehicles does not intervene.

Figure 10. OBSI testing set-up used at Qatar University.

4.3. Laboratory Drum Method

High precision measurement of noise is difficult for the aforementioned noise measurement methods, in particular for research purposes. Hence, the laboratory drum method is sometimes used for tire-pavement noise level assessment to isolate small differences in noise emission. In this method, a test tire is mounted on a drum (typical diameter 1.5 m–2.5 m). One or more microphones are placed close to the test tire with positioning similar to that of the CPX method. For this testing arrangement, the drum must be equipped with a surface that resembles of actual test surface to get proper data. Such a facility can also be used for testing of durability and friction of pavement [2,57,58]. This method is independent of weather conditions, which is not the case for most of the other field noise measurement testing methods. However, background noise from the drum power unit is always an issue and needs special precautions. Figure 11 represents the view of drum method.

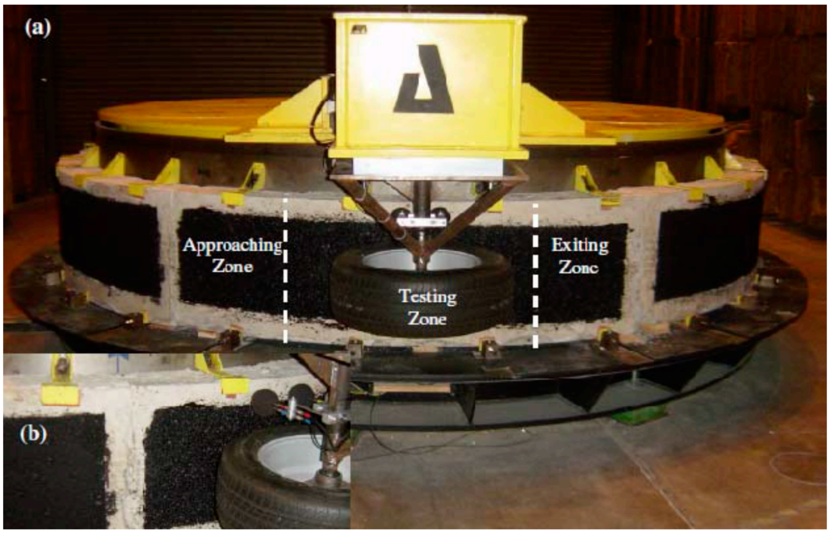


Figure 11. Laboratory tire-pavement testing apparatus (Reproduced with permission from Kowalski) [57].

4.4. Relationship between Source and Wayside Noise Measurements

A number of studies have attempted to find out the relationship between the source and wayside measurement techniques of tire-pavement noise. This is particularly important when only one type of measurement technique is available to any transport authority or research personnel. Many researchers indicated a good relationship between CPX and SPB measurements when considering overall sound pressure levels [3]. The relationship between CPX and SPB measurements was found to be dependent on both microphone position and frequency, but the two methods were shown to give similar rank orders of tires and pavement [59–62].

The first comparative data between pass-by and OBSI is presented by Donavon [63]. Tests were performed on a dense graded asphalt concrete (DGAC) surface with 7 different sets of tires, and the wayside microphone was positioned 7.5 m from the driving lane. Using linear curve fitting, the difference between pass-by and OBSI data was observed to be 24.5 dBA. A similar difference was also observed in a later study [64] where both types of testing were conducted at a test track in the state of California, and again the pass-by measurement position was 7.5 m from the driving lane. They registered that the difference between sound pressure and sound intensity was 23.9 dBA. This study also concluded that pass-by data can be predicted from OBSI data for a variety of pavement types within 0.5 dBA on average. When pass-by measurement was done 15 m from the driving lane, the difference between two measurement methods was 30.4 dBA. This indicates that propagation of noise is also a critical factor. This is in line with findings from the later study by Rasmussen and Sohaney [65], which concluded that the noise difference between the two measurement techniques was 28.2 dBA for the pass-by measurement location of 15 m from the driving lane. A slightly higher offset value between two different types of measurement techniques was observed by a recent study conducted by Florida Department of Transportation [66,67]. Different offset values observed for different researchers are probably due to site geometry, climatic conditions and distance from the center line of road to microphone position. Furthermore, correlation between the pass-by and OBSI methods is also dependent on surface type. For concretes and DGAC surfaces, the relationship appears to be good while a less favorable relationship is overserved for porous asphalt pavement [68]. This is because both the noise generation mechanism and propagation of noise to the pass-by measurement location is affected by porous pavement.

Researchers also tried to correlate between CPX and OBSI data in order to rank pavement. Studies by [69,70] showed that the difference between sound pressure and sound intensity is ~3 dBA. Donavan and Lodico [71] compared OBSI and CPX noise data based on the noise measurements made at five sites: four asphalt concrete (AC) pavements at the NCAT test track in Auburn, Alabama, and one Portland cement concrete (PCC) pavement in the nearby town of Waverly, Alabama. Reported test data showed that CPX or OBSI source levels could be predicted from the other within a standard deviation of 1.1 dB (Figure 12). Based on their research finding, they encourage the use of the OBSI technique because of practical concerns in the use of a CPX trailer in the continuous flow traffic and the expense of acquiring and maintaining an especially designed CPX trailer. In addition, spectral analysis showed (at 1/3 octave band) that CPX method consistently reduced noise 3 to 4 dBA compared to pass by or OBSI method at low frequency level (below 1000 Hz). This frequency distortion is related to the special acoustical chamber surrounding test tire in CPX method [71].

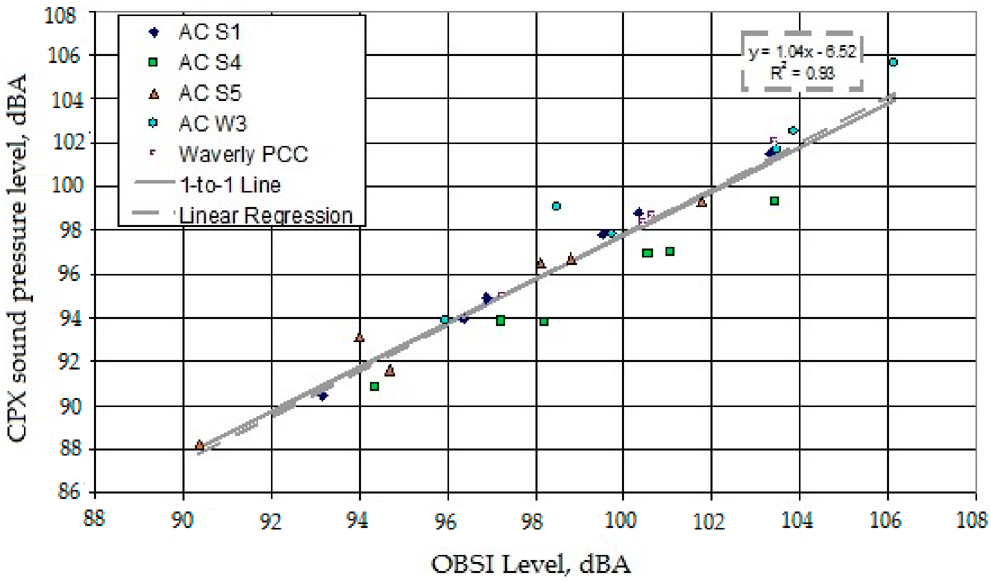


Figure 12. Relationship between OBSI and CPX noise levels (Reproduced with permission from Donavan and Lodico [71].

In order to design and construction of quieter pavements, it is necessary to find a mechanism in which the initial acoustics performances of various pavements can be quantified and then monitored the noise performance over a long time. The data acquired in this process can be used in TNM to predict the future noise level. Of all the noise measurement technique currently available, OBSI is more efficient, economical, accurate and easy to monitor different pavement sections over long time [71,72]. In addition, OBSI data can be incorporated in to the TNM v. 2.5 to predict the future noise [14].

5. Noise Abatement Techniques

Due to increased traffic noise, a number of noise abatement procedures have been adopted by various transport authorities throughout the world. However, FHWA [4] pointed out that there should be a striking balance between particular importance and feasibility. Therefore, it is necessary to perform a multi-criteria pavement analysis before adopting any noise abatement techniques [73–75]. Multi-criteria analysis includes number of factors such as technical feasibility, the unique characteristics of highway generated noise, cost, overall public interest, and aesthetic considerations that should be taken into account before choosing a noise abatement technique [4]. In addition, it is also critical to incorporate sustainability approach in adopting any noise abatement technique so that it is economically viable and environmentally sustainable [74,76]. This section summarizes common traffic noise abatement procedures.

5.1. Noise Barrier Wall

Noise barrier walls are one of the most commonly used mitigating solutions for noise abatement for a highway facility. These are solid obstructions placed between the highway and receivers along the highway. The goal of using a noise barrier is to reduce the noise level between 7 dBA and 10 dBA at the receivers closest to the highway [77]. When a noise barrier wall is placed in between noise source and receiver, it creates an acoustic 'shadow zone' which perceives a reduction of noise level [4,78]. Some part of noise also absorbed by noise barrier wall and some part of it reflected back it across the highway. Still some portion of noise is transmitted and diffracted over barrier wall which reached to the receiver as shown in Figure 13. Generally, the noise reduction of barrier walls depends on the height of the wall and its placement between receiver and source [4,78]. The thickness of barrier walls also plays an important role in noise reduction [78].Barrier wall can be broadly classified in three major categories: earthen berms along the road, solid vertical walls, combination of earthen berm and solid vertical walls [4]. Construction cost of earthen berms along the highway is less expensive and environmental friendly but required large amount of land which is difficult to acquire in this current world. Solid vertical barriers can be constructed of wood, brick, concrete, steel, transparent materials etc. Concrete barrier wall is commonly used in various parts of world due to effectiveness in noise reduction. However, the use of a noise barrier wall causes a number of practical problems. Firstly, construction of a concrete barrier wall is very expensive, i.e., 2.1 million dollar per mile [11,79]. Secondly, reinforced cement concrete structures emitted CO_2 during construction time and throughout its service life [80]. Thirdly, in some locations it is not possible to construct a barrier wall due to driveways or intersection, thus sound tends to diffract around noise barriers walls [65], or due to engineering/construction considerations. Presence of hilly neighborhoods or the height of buildings rising above barrier walls presents further challenges in the effectiveness of a barrier wall [4]. It is also not cost effective when population density is low [4]. Furthermore, concrete noise barriers have very high acoustic reflectivity with limited sound absorption capability, hence adversely affecting passengers and driver comfort [81,82]. It also potentially reflected noise to neighborhoods on the opposite side of the highway. If reflecting noise barriers are placed both sides, theoretically noise can increase up to 6 dBA [78,83,84]. However, if there are any open housing areas, noise can increase theoretically up to 3 dBA. The level of increased noise is still significant as traffic needs to be doubled to increase 3 dBA of noise [78]. Plantation of vegetation in between vertical wall and road can disperse noise before and after reflection from the noise barrier.

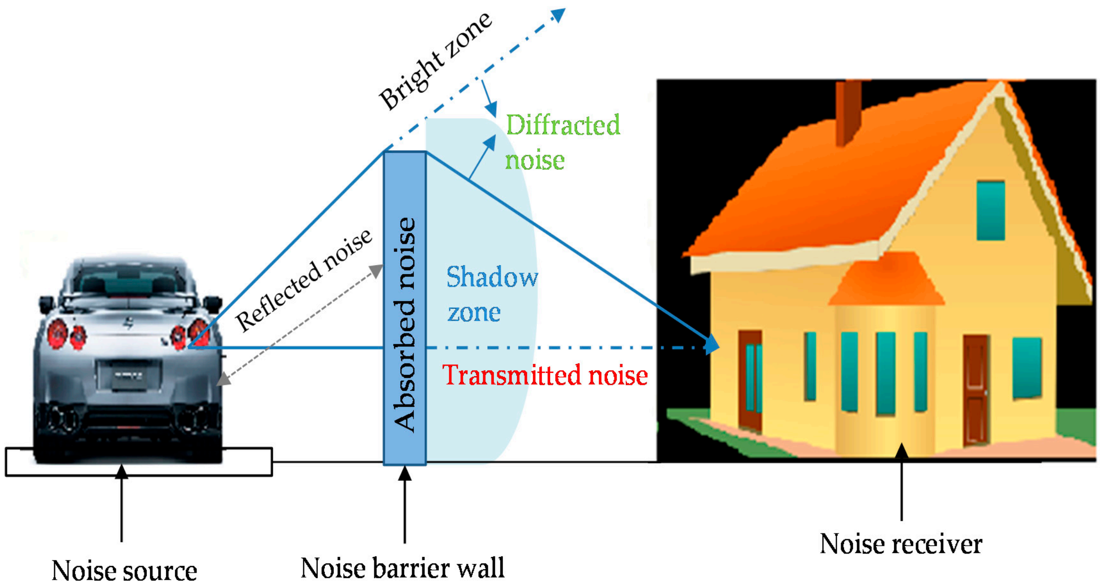


Figure 13. Sketch showing noise distribution due to barrier wall [4].

5.2. Vegetation Technique

Planting of trees along the roadside could reduce the traffic noise. The reduction of sound due to vegetation is related to the process of reflection, scattering and absorption of noise. Noise reduction due to vegetation is dependent on the height of the trees and width of the vegetation belt. Generally, noise reduction tends to increase with tree height up to 10–12 m, after; any increase in tree height has an adverse effect on noise reduction. FHWA [4] demonstrated that almost 10 dBA noise reduction can be achieved by providing 61 m (200 ft) dense vegetation. However, from a practical point of view, vegetation that wide is difficult to plant along the road. An effective vegetation belt is also dependent on the location of it between receiver and source. The vegetation belt is more effective when it is placed either relatively close to a noise source or close to the area to be protected. It is less effective when placed midway between the source and receiver. Note that many years are required for vegetation to mature to be effective; hence FHWA does not consider it is as a noise abatement technique. Nevertheless, FHWA still encourages plantation of trees along highways because it provides favorable psychological effects to humans in addition to its environmental benefit. Figure 14 shows noise effectiveness and psychological effects of vegetation.

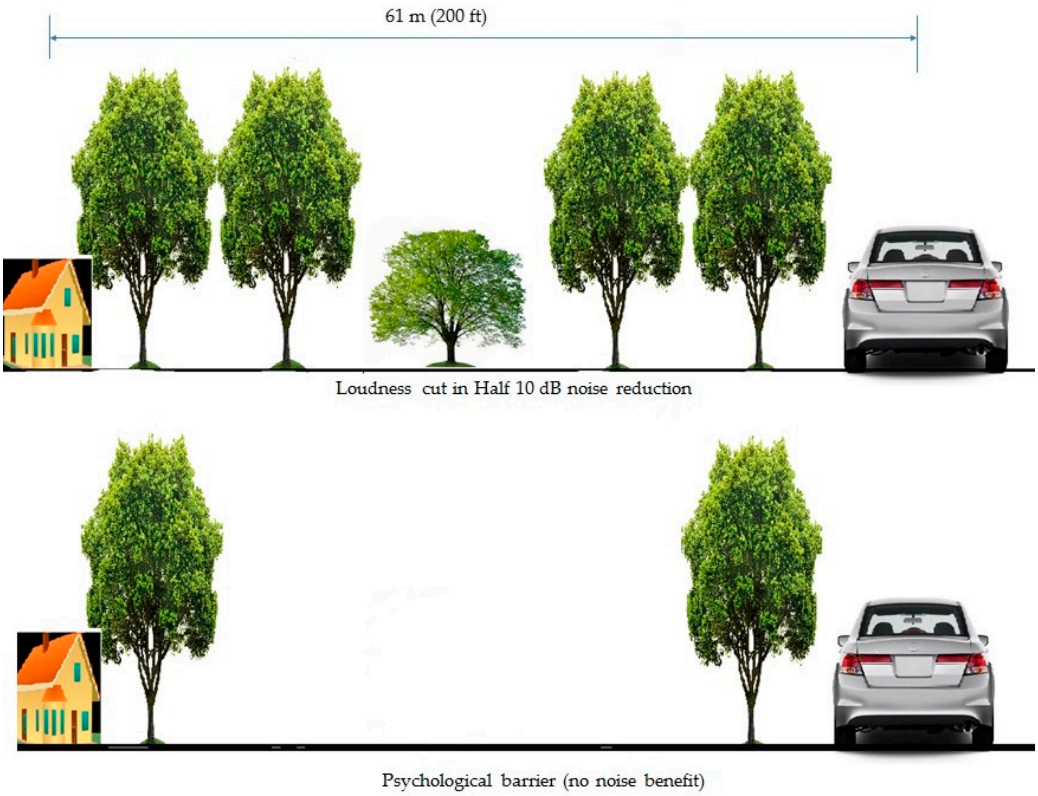


Figure 14. Effectiveness of vegetation [4].

5.3. Private Fencing

Boundary walls or fencing around a house are generally provided for security and privacy reasons. These can provide a visual screen between source and receiver, although they may not provide any noise benefit to inhabitants. Similar to vegetation, these walls or fences may provide psychological relief but should not be considered as a noise abatement procedure [4].

5.4. Buffer Zone

If the distance between the noise source and receiver increases, resulting noise will be reduced at the receiver. Therefore, FHWA [4] sometimes recommends use of a buffer zone as a noise abatement procedure. These zones are underdeveloped, unused open spaces which are used to increase the distance between a highway and nearby neighborhoods. When a state authority purchases land or development rights, in addition to the normal right-of-way, it prohibits any future construction close to the highway. Therefore, any possibility of exposing new dwellings to an excessive noise level from nearby highway traffic is removed. Furthermore, it increases aesthetic beauty of the road which is always desirable for road users. Nonetheless, in this current economic situation, it is very difficult to acquire buffer areas because of excessive expense of land. In addition, in many cases personal land and dwellings close to highway borders already exist, and hence creating buffer zones is often not possible.

5.5. Using Insulating Materials

For public or non-profit organizational structures such as places of worship, schools, hospitals, libraries, etc., sometimes use of insulation materials is considered by highway authorities. Insulating structures is very effective in reducing noise. However, this noise benefit policy is exclusively reserved for public property only. For any private structures, owners are responsible for installing/constructing noise proof insulation. Also, air conditioning is usually required in conjunction with the insulating materials (since proper noise reduction will be achieved only with closed windows); hence the overall cost of the project increases a lot. Therefore, use of insulating materials as a noise abatement method is less practiced by the transport authorities.

5.6. Traffic Management

FHWA [4] suggests that traffic management can be used as an effective method in reducing noise. There are a number of possible ways to use traffic management such as prohibition of trucks using certain streets and roads inside a residential zone, permission of trucks using roads and streets only during the daytime, providing efficient traffic planning to smooth movement of traffic, and reducing the highway speed limit if possible (but this requires an approximate 20 mph decrease of speed to be effective). Most transport authorities in the world are using traffic management as a noise abatement measure because of its effectiveness, as well as it being inexpensive.

5.7. Modifying Surface or Mixture Properties

Researchers in Europe showed that a modified pavement surface or mixture type has the potential to be used as a noise abatement measure for highways [3]. Therefore, a large number of pavement surfaces have been constructed using modified mixture or surface properties, especially in Europe. Generally, these surfaces were constructed by using three major techniques to reduce tire-pavement noise [3,85]. Firstly, the surface textures of these pavements are optimized, i.e., constructed smooth surface which reduced dynamic deflection of the tire due to texture impact. However, there should be a striking balance between two conflicting properties, i.e., surface smoothness and friction. Secondly, these pavements should be constructed having higher air voids so that air can move through the interconnecting voids and minimize 'horn effect' mechanism. Thirdly, tire-pavement noise can be reduced by constructing softer pavement similar to the stiffness tire so that some of the tire deflection can be minimized. Nevertheless, Sandberg and Mioduszewski [85] pointed out that first two construction methods are incompatible as smooth surface will not normally provide high porosity surface. Researchers suggested that these two conflicting properties of the pavement surface can be achieved by providing smooth and flat surface in the top and rest of the pavement surface can be constructed having enough air voids and connected pores that directed downwards into the pavement layers [85]. The following paragraphs discuss some of the most commonly used modified mixture /surface types as quieter pavement.

5.7.1. Porous Asphalt Surface/Mixture

Porous mixture has been used in the asphalt pavement industry since the 1960's. This is because porous asphalt increases skid resistance in wet conditions as well as strengthens resistance to fatigue and rutting [3]. In addition, porous surfaces drain the rain water efficiently thus reducing splash and spray behind the car [86]. Noise beneficial properties of porous asphalt were discovered in the mid-1980's. Researchers observed that porosity plays an important role in generation and propagation of highway noise, in particular for asphalt pavement. Generally, DGA and porous asphalt is differentiated by porosity. If the porosity of asphalt pavement is less than 10% then it is termed a DGA surface. However, the commonly used porous surface referred to as an open-graded friction course (OGFC) must have in excess of 15% air void [3]. Furthermore, European authorities recommend in excess of 20% air voids to be considered as a noise beneficial porous pavement [10]. A number of researchers [3,11,64,87,88] specified that an OGFC surface reduces noise significantly (3 dBA to 5 dBA) compared to a DGA surface. The air trapped between the tire and the pavement surface moves to void space available within the porous surface, thus reducing the 'horn effect' of noise amplification. Additionally, it provides increased sound absorption capability, which in turn reduces noise [3,11]. However, the air voids should be inter-connected to be able to damp the noise [3]. Furthermore, use of an OGFC surface has proved to be problematic because dirt and dust from the environment can enter into the void spaces thus clogging the surface. At wet condition, these pores are 'self-cleansed' under high speed passing wheel [89]. The process of clogging accelerated on the road of less important especially, at lower vehicle speeds, the pores of the surface are consistently filled up by fine particles due to passing wheel. This is because there are no adequate facilities to cleaning the surface. This reduces noise benefit of these surfaces. Early study by Bendtsen [90] demonstrated initial noise reduction of around 4 dBA by using a porous surface compared to a DGA surfaces. However, researchers observed noise reduction of 1 dBA after 7 years in comparison with a DGA surface. Sandberg [89] reviewed the experience of porous surfaces around the world and concluded noise benefit of porous surface diminished at a rate of 1 dBA per year in relation to DGA surface. The rate of noise reduction increases at low speeds and especially in areas where there is a large amount of dirt in the vicinity. In addition, these surfaces are at least 50% more expensive in comparison with DGA surface over life-cycle. Figure 15 shows the surface texture of porous and dense asphalt surfaces.

(**a**) (**b**)

Figure 15. Surface texture of (**a**) porous asphalt; (**b**) dense asphalt (Reproduced with permission from European Asphalt Pavement Association (EAPA)) [87].

5.7.2. Double Layer Porous Surface

In Europe, the concept of two layer drainage pavements is introduced to counter the problem of clogging in porous pavement [91]. Figure 16 shows a diagram of this concept. In this pavement system, the top layer is filled with finer mixes (with 1/4 inch maximum aggregate size) whereas the bottom layer is filled with a thick highly porous mixture (with 5/6 inch maximum aggregate size) for acoustic absorption [89,92]. Sandberg [89] demonstrated at high speed the initial noise reduction of newly constructed double layer porous is up to 6–7 dBA compared to a DGA or SMA 0/11 mm surface for the mix traffic. The noise reduction of double layer porous surface is due to the combination of two mechanisms. Firstly, small aggregates at the top layer produced smooth surface which minimizes the texture impact of tires. Secondly, the thicker underneath layer consists of coarse aggregate which has higher void content thus increases sound absorption. Therefore, air pumping underneath the tire suppressed as the air can pass through the inter-connected voids in the pavement. In addition, the top surface filters out the clogging particles; hence acoustical performance is maintained for a longer period of time [91,93]. Nevertheless, noise benefit of these surfaces diminished with age albeit at a slow rate [89]. Furthermore, double layer porous surface is expensive compared to single layer porous surface or conventional DGA surface and generally have less life cycle due to problem of raveling of aggregates from the top layer [92].

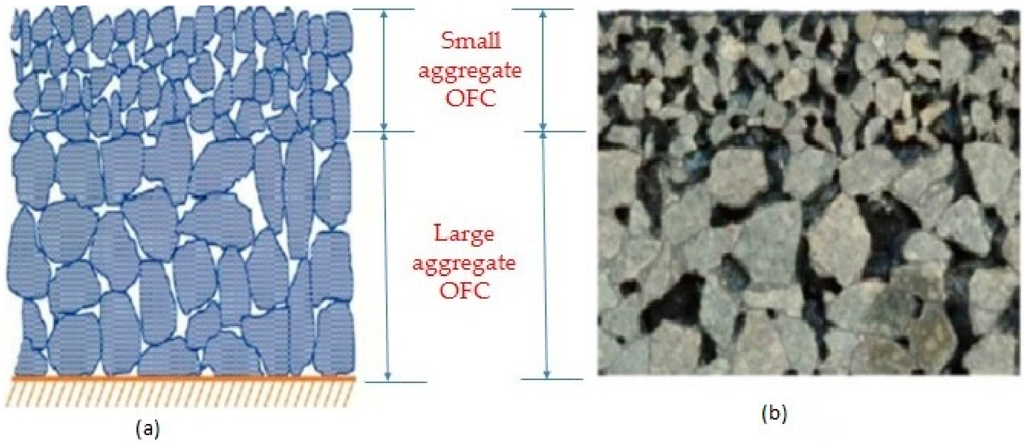


Figure 16. Double layer concept (**a**) schematic diagram; (**b**) cross section of real pavement [93].

5.7.3. Thin Asphalt Layer

A thin asphalt layer (TAL) is a gap graded high quality aggregate asphaltic mixture with layer thickness varying from 10 mm to 30 mm depending on the nominal maximum size of aggregates (approximately 12 mm or smaller) [87,94]. In these mixtures, moderate percentages of sand and modified polymer binder content are also added. The air void content of these mixtures varies from 15% to 25%. Noise benefit of TAL surfaces from various references are summarized in Table 1. Much of the information is extracted from the Sandberg et al. [94] in addition with latest references. Initial noise reduction of TAL surfaces varied between 0.9 and 6.9 dBA for passenger car depending on the maximum aggregate size and surface type. For multi-axle truck, the initial noise reduction of TAL surfaces is less significant compared to passenger car. In the beginning of constructing TAL, road engineers have serious conservation of using lower nominal size aggregate as it is assumed that it will compromise the skid resistance to an unacceptable level. However, Bendtsen and Raaberg [95] demonstrated from the French study that these thin layers have actually increased macrotexture which in turn has better skid resistance compared to conventional pavements. Furthermore, open textured TAL is virtually 'self-cleansing' due to passing wheel thus minimizes the problems of clogging of pores due to environmental effects, which is an issue with most of the other porous surfaces [8,10,85,89]. In addition, TAL is less expensive for in-service pavement maintenance cost and has a low initial construction cost; it is therefore widely used for roads with heavy traffic in Europe [87]. However, as observed for other porous surfaces, noise benefits of TAL surfaces decrease with age. Recently, Vuye et al. [96] performed both SPB and CPX noise testing on various TAL sections of Belgium at different pavement aging time. Researchers registered noise benefit of these TAL sections diminished at a rate of 0.02–0.14 dBA/month and 0.05–0.20 dBA/month for SPB and CPX method, respectively. The diminishing of noise benefit with pavement age is also consistent with the experience of other European countries [97–99]. Noise benefit of these TAL surfaces diminished due to raveling of aggregates under heavy traffic [94,96]. Therefore, it is very difficult to use these TAL surfaces at places where heavy vehicles exert high shear forces on the surface layers.

Table 1. Summary of noise reduction by using TAL surfaces.

Reference Used	Reference Pavement	Pavement	Maximum Aggregate Size (mm) of TAL	Air Void (%)	Noise Test Reference Condition	Noise Reduction Compared to Reference Pavement (dB)	
						Passenger Car	Multi-Axle Trucks
Vuye et al. [96]	SMA-10 - 10 mm maximum aggregate size; - air void content 7%	Test Section 2	4	25	- Test Reference Speed—80 km/h - Test Reference temperature—20 °C - CPX method - All the pavement surfaces are 5 month old	6.9	3.6
		Test Section 3	4	25		5.9	3.2
		Test Section 4	6.3	11		5.7	2.7
		Test Section 6	6.3	15		5.8	4.2
		Test Section 7	6.3	11		4.6	3.5
		Test Section 8	6.3	11		3.7	3.0
		Test Section 9	6.3	11		3.3	2.5
		Test Section 10	8	14		1.3	1.3
Thompson et al. [100]	DAC - 11 mm maximum aggregate size	OGAC 6	6	-	- Test Reference Speed—50 km/h - Test Reference Temperature—20 °C	4.3	-
		SMA-a-6 *	6 *	3.4		1.3	-
		SMA-b-6 *	6 *	5.7		0.9	-
		SMA-6	6	15.3		3.2	-
		SMA-4	4	8.8		1.6	-
		SMA-4 *	4 *	10.2		3.0	-
		SMA-6 * (opt)	6 *	13.9		3.7	-
Bendtsen and Raaberg [101]	AC - with 10 mm maximum aggregate size	Type-1	6	-	- Test Reference Speed For car—90 km/h For multi-axle trucks—80 km/h	2.7	1.9
		Type-2	6	Higher air void than type-1		3.7	3.1
Bendtsen and Raaberg [101]	AC - with 14 mm maximum aggregate size	Type-1	6	-	- Test Reference Speed For car—90 km/h For multi-axle trucks—80 km/h	4.2	3.0
		Type-2	6	Higher air void than type-1		5.2	4.2

* In these mixes small portion of 8 mm size aggregate added to obtain more open texture surface; "-" No data available.

5.7.4. Stone Mastic Asphalt (SMA)

The porosity of a SMA surface is similar to a porous surface (20% porosity). It is a gap-graded mixture with an aggregate skeleton of relatively coarse aggregates filled with mastic of bitumen, filler, and fine aggregate [87]. The layer thickness varies depending on the nominal aggregate size, which generally varies between 15 mm (SMA 0/6 mm) and 45 mm (SMA 0/16 mm). The SMA surface was initially developed in Germany in the mid 1960's in order to have high resistance for studded tires. Later it was found that these surfaces have a number of other benefits and are hence used for heavily trafficked roads in Europe. These surfaces offer high durability, excellent resistance to rutting and comfortable riding characteristics. In addition, a study in Europe [102] showed that SMA pavements with a maximum aggregate size of 11 mm (0/11 mm) or less (0/6 mm) reduced noise 2–3 dBA in comparison with a DGA surface. This is because SMA has a relatively open surface texture that reduces the air pumping mechanism, resulting in less noise [9]. Research conducted in Finland showed that SMA surface with 5 mm aggregate size showed an initial noise reduction of 3 dBA and 5 dBA at vehicle speed of 50 km/h and 80 km/h, respectively in comparison with original pavement [103]. However, after one year, noise increased significantly due to the wear on SMA surface. SMA surface is generally more expensive compared to conventional DGA surface because of higher binder content and high quality aggregates.

5.7.5. Asphalt Rubber Friction Course (ARFC)

An ARFC surface was first developed in Arizona to resist cracking, and is now also used to counter traffic noise. In this surface, the binder is mixed with crumb rubber (granules 0.5–2.0 mm). The proportion of crumb rubber is 10% weight of total binder content which is generally twice of polymer modifier used in a porous asphalt surface [89]. Mixing of crumb rubber with bitumen is conducted in 'wet process' rather than 'dry process'. Figure 17 presents a typical view of an ARFC surface. Arizona Department of Transportation (ADOT) placed an ARFC surface on the existing PCC surface and conducted noise study on it by using OBSI testing method [104]. Test results showed that 7 dBA of noise reduction of ARFC surface compared to existing PCC surface. Sandberg [89] explained noise reduction of ARFC surface is due to combination of number of factors. Firstly, the surface texture of ARFC has negative profile due to small maximum aggregate size as Bendtsen et al. [105] demonstrated negative pavement texture generates low noise due to minimum tire tread vibration (Figure 18). Secondly, ARFC surface has lower stiffness due to excess amount of binder and rubber content hence, the impact between tire tread and pavement becomes less which reduces noise. In addition, Sotil et al. [106] demonstrated hysteresis losses due to vibration of visco-elastic materials, i.e., asphalt rubber mix reduces noise. Furthermore, Ripke et al. [107] stated that the open texture of an ARFC surface developed from the mix of aggregate size reduces the air pumping noise mechanism. Recently, Tehrani [108] performed a review of rubberized HMA surfaces used for noise abatement technique and summarized that addition of rubber decreases noise level about 2 to 3 dBA compared to a HMA surface and 4.5 to 6 dBA compared to a PCC surface. Researchers explained that addition of rubber to pavement mix tends to shift the frequency of noise to the lower frequency which is close to tire noise. Therefore, rubber does not resonate at high frequency thus limits the amplification of noise mechanism which in turn generates less noise. However, as observed for other modified surface or mixture, noise benefit of crumb rubber bitumen is also diminished with time [107,108].

Figure 17. ARFC surface on Arizona Freeway [107].

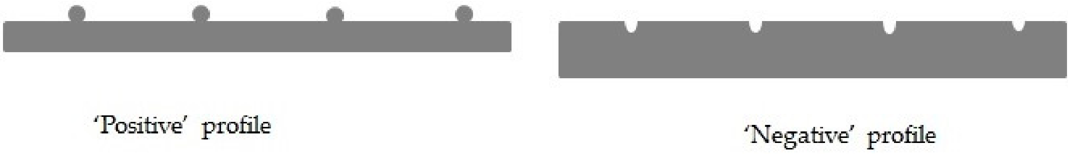


Figure 18. Sketch of pavements with "positive" and "negative" profile of the surface texture [105].

5.7.6. Diamond Grinding Concrete

Diamond grinding is a concrete restoration technique in which the surface is ground by small sawblades to create a narrow and fine longitudinally grooved surface [109]. Diamond grinding of either fresh or old pavements provides smooth surface and enhance frictions consequently reduces noise. Initial noise reduction after grinding the surface is about 1–2 dBA compared to a DGA surface and 3–5 dBA in relation to a transverse tinned concrete surface [89,109]. Diamond grinding pavement is quite durable except it is susceptible to wear from studded tire especially in winter. However, the initial noise benefits of this surface decreases due to polishing of aggregates [89,109].

5.7.7. Exposed Aggregate Cement Concrete (EACC)

In this type of concrete, aggregates are exposed to the environment as the mortar is extracted before hardening. This pavement was initially developed to provide high skidding resistance. However, a number of research studies [89,110,111] showed that noise benefit of EACC surface is similar to SMA or thin asphalt surfaces. Further studies [110,111] presented that EACC surfaces are durable for almost 20–30 years and have same noise reduction potential for almost for the entire life cycle. However, good quality aggregates are required to the full thickness of EACC surface for proper functioning which resulting increased construction cost.

5.7.8. Poroelastic Road Surface (PERS)

PERS is a wearing course made of rubber granulates combined with binder. Under the European Union sponsored project SILVIA, a number of PERS surfaces have been constructed, and noise data were collected by using the CPX method [111]. Results showed a significant amount of noise reduction by using a PERS surface. Noise reduction mechanism of PERS is due to the combination of a number of factors. A well-constructed PERS has very smooth surface texture which produces less impact to the tire. In addition, PERS usually have very high air void content (30%–35%) which effectively minimize the air pumping mechanism. A significant portion of noise is also absorbed by PERS due to high air void content [112]. This idea was adopted by Japanese researchers and used for block pavements as shown in Figure 19. OBSI noise testing was performed on these pavements and test result showed initial reduction of 7–9 dBA compared to a conventional DGA 0/16 surface [113]. Temperature has showed great influence on the acoustic performance of PERS surface. Test results showed 0.142 dBA increase of noise for per 1 °C decrease of temperature which indicated colder weather gives noisier PERS due to expansion of joints [113]. PERS was developed a long time ago in Sweden, but these surfaces did not gain popularity due to durability issues as well as high construction cost.

Figure 19. Two types of PERS mounted on interlocking blocks tested in Japan [107].

5.7.9. Enhanced Porosity Concrete (EPC)

A high porosity concrete surface has been developed recently in Europe and USA to reduce pavement noise. EPC is a gap graded material with minimum or limiting sand particles in the matrix. It is reported that up to 25% to 30% air void content of the matrix can be possible without any structural problems, which suggests it is less prone to clogging in comparison with conventional porous pavement because dirt takes more time to fill the higher amount of pores inside the pavement [16]. For an EPC surface, noise is reduced by a combination of low generation and high absorption of noise [114,115]. Tests conducted on an EPC pavement in Europe have shown that noise can be reduced as much as 10 dBA compared to a normal concrete surface [114,116]. For better performance of EPC surface, it is needed to be tightly controlled mix design and placement of materials. In addition, repairing of EPC surface is a challenge due to bonding.

The aforementioned discussion showed modified mixture/surface type reduced initial pavement noise significantly in comparison to a conventional pavement surface. However, this initial noise benefit of all of these modified surface/mixture type (except for EACC) is diminished with pavement aging. This is the main reason of FHWA's reluctance to accept these modified mixture/surface types as a noise abatement technique [4]. Furthermore, durability is an issue for most of the surface except for SMA and EACC surface. In addition, all of these surfaces are expensive compared to conventional pavement surfaces. This calls for further research for these modified surfaces in order to be recognized as an effective noise abatement technique. However, from the current state of knowledge, Donavan et al. [72] recommended replaced or treated of quieter pavement at faster rate compare to normal pavement to maintain acoustic performance of pavement. This may increase the maintenance cost of the quieter pavements in comparison to conventional pavements but it is still viable option due to its effectiveness to entire length of highway as oppose to the commonly used barrier walls.

6. Conclusions

An overview of tire-pavement noise generation mechanism and noise abatement techniques has been presented in this paper. The following conclusions can be drawn based on the literature review presented in this paper:

- Tire-pavement noise is generated due to a combination of noise generation and amplification mechanisms. Different combinations of generation and amplification mechanisms of noise may be dominant for different surfaces and conditions. Therefore, it is difficult to develop one single strategy which can be used to reduce the tire-pavement noise efficiently. Furthermore, some of these mechanisms are directly related to the safety, durability, and cost of pavement, which adds further challenges in mitigating noise.
- Tire-pavement noise measurement systems are reported widely in literature. Currently, there are three general methods used throughout the world, which include Pass-by methods, the CPX method, and the OBSI method. However, researchers encourage the use of the OBSI because of its efficient and precise monitoring of pavement noise. Noise prediction of quieter pavement can be performed by using OBSI when combined with TNM.
- There are a number of noise abatement techniques adopted by various transport authorities all over the world. Of them, noise barrier wall is used frequently by various highway agencies due to its effectiveness of initial noise reduction and acoustic performance over time. However, noise barrier wall is only a local solution and cannot be extended to the entire length of the road due to its high construction cost.
- European transport authorities recognize that modifying the pavement surface type has the potential to be a cost effective and practically viable noise abatement technique. However, FHWA is still reluctant to accept modifying pavement surface type as a noise abatement technique because the issues with cost, durability, maintenance and sustainability of noise benefit of these surfaces.
- More research is required for the sustainability of the modified surface before using as noise mitigation technique. However, these surfaces can be used as a noise mitigation technique with additional maintenance in accordance with conventional pavement maintenance scheduling. This may lead to overall cost of pavement construction and maintenance but it is still a viable option as noise benefit can be provided to the entire length of highway.

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