Study on Noise Reduction with Paving Different Low Noise Pavement Materials

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Abstract: This paper evaluates the amount of noise reduction when using different pavement materials in two adjacent lanes, where the close-proximity (CPX) method is introduced to analyze the tire/road noise before and after pavement maintenance. We consider four types of pavement materials, including ECA-10, PUC-10, PAC-13, and double-layer porous asphalt pavement (PAC-13+PUC-10), where these materials and their combinations are paved on two adjacent lanes. We measure the tire/road noise with the CPX method using a two-wheel trailer that can install two types of tires in different tests. This study provides some guidelines on controlling traffic noise pollution by using the combination of low noise pavement materials. From the experimental and theoretical results, one can see that the highest amount of noise reduction can be obtained when both the inner and outer lanes use the double-layer porous asphalt pavement. To make a balance between the noise reduction performance and the road maintenance cost, one can have the suboptimal choice, where the inner lane uses PUC-10 and the outer lane uses the double-layer porous asphalt pavement.

Keywords: low noise pavement combinations; tire/road noise; CPX method

1. Introduction

The road traffic noise is significantly influenced by the tire/road noise generated by the vehicle driving on the pavement, especially when the vehicle is operating in good condition. This is because the tire/road noise becomes the dominant noise source of the road traffic noise [1,2]. When studying the amount of noise reduction using a particular low noise pavement material, we often need to measure the road traffic noise level. When different lanes of the highway set up different structures of low noise pavement materials, it is necessary to study the impact of each pavement on the road traffic noise, and thus some guidelines can be given on choosing pavement materials. Generally, we can measure the roadside sound pressure level and/or the tire/road noise to study the effectiveness of pavement materials on reducing the road traffic noise [3].

It is the most popular way to measure the noise pressure level on the side of the road when studying the noise reduction performance of low noise pavements. This is often measured at 7.5 m or 15 m away from the roadside. In general, a measurement microphone is required to quantitatively measure the sound pressure level, while the speed, the model, and the weather conditions are also needed to be written down and recorded. There are three main methods to measure roadside noise. With a low traffic flow, statistical pass-by method (SPB) [4,5] is often used to measure the maximum sound levels of hundreds of individual vehicles when they are passing. In this case, the measurement microphone is placed at a fixed position on the side of the road. Note that hundreds of measurements are necessary so that we can average these sound pressure levels of light vehicles, heavy vehicles, and other vehicle types to get a reliable measurement value at
some standard speed. Control pass-by method (CPB) is similar to SPB, where the only difference is that a specific combination of tires and vehicles is used for CPB. With SPB and CPB, we can compare pavements at different road sections. Because the result is only an “average” value, some errors may be inevitable in evaluating different road surfaces due to that vehicles may be different each time when measuring with SPB and the coupling between specific tires and pavement materials may also be different each time when using CPB [6–8]. Different from SPB and CPB, the third method averages the sound pressure level of a specific vehicle, which is known as the time-average method and uses the continuous flow traffic time-integrated model (CTIM) [9]. In this method, the measurement microphone is set to measure all traffic noise within a fixed period of time, which usually ranges from 5 to 30 min. Note that the recording traffic flow, the vehicle type, and its speed are also needed to be recorded. All the above mentioned methods have to consider the surrounding reflectors and/or other interference factors. As an example, the weather conditions should be written down and recorded, especially when the wind exists that may have a significant influence on the measurement results. Moreover, we also need to eliminate some other interferences, such as aircraft noise, dog barking, and so on. By doing so, the impact of these interferences can be reduced dramatically.

Compared with measuring traffic noise on the side of the road, if one can measure tire/road noise close to the interaction between the tire and the pavement, then the noise reduction performance of low noise pavement can be studied in a better way [7]. Nowadays, there are two often-used methods to measure this tire/road noise, where one is close-proximity (CPX) method [10] and the other is on board sound intensity (OBSI) method [11,12]. CPX is more popular in Europe and has been released as ISO standard 11819-2, while OBSI is developed by General Motors, and it is popular in the United States. Note that both CPX and OBSI place microphones close to the interaction of the tire and pavement to record the measurements of transducers as the vehicle running [13]. Emphasis should be given that there are some obvious differences between these two methods [13,14]. First, CPX uses a microphone to measure the sound pressure level, while OBSI uses a microphone probe to measure the sound intensity, and thus we can study the directionality of the sound when measuring the sound intensity. Second, the microphone of CPX and the microphone probe of OBSI are placed in different relative positions with the interaction of the tire and pavement, which makes the results quite different in the near-field measurement due to the different mechanisms of tire/road noise generation and amplification [15,16]. Third, to reduce the influence of other interferences, CPX usually needs to use an enclosure around the tested tire and microphone, while OBSI generally does not need because it can identify the direction of the sound source [17]. The measurement results of CPX and OBSI are highly correlated with the reference tires used in the test, wherein the reference tires of CPX are specified by ISO 11819-3 [18], and the reference tires of OBSI are specified by ASTM F2493 [19].

Besides using the measurement results of the roadside noise or the tire/road noise, one can also study the noise reduction performance of the pavement by analyzing the variations of the internal noise of the driving vehicle. However, the type and operation condition of the vehicle have a great influence on the measurement results when using this method, especially when considering that there is the big attenuation at high frequencies. Therefore, we usually do not measure the internal noise of the driving vehicle to study the contribution of pavement on noise reduction performance [20,21].

In this paper, to directly measure the sound pressure level of the tire/road noise source, we propose to use CPX, which can also reduce the influence of other interferences on the measurement results simultaneously. A CPX trailer is used to study the noise reduction performance of low noise pavements in each lane of the highway. We also study the noise reduction performance of paving different low noise pavement materials in two adjacent lanes when considering the traffic flow, the vehicle type, and the road capacity. This study can provide some guidelines on controlling traffic noise when considering the economic and environmental benefits for practical applications.
2. Experimental Setup of Testing Lanes

2.1. Pavement Mixtures in Experimental Road Section

The experimental section is located on the Yanjing highway (G1515) in Jiangsu Province, China, which is a two-way, four-lane road. The stake number of this section ranges from K161+300 to K159+100, with a total length of 2.2 km. The original pavement layer is 2.5 cm easy compressed asphalt (ECA-10) dense pavement. The 4.0 cm porous asphalt concert (PAC-13) pavement struck at both ends of this experimental section was laid more than 1km to avoid the blockage of the porous road surface caused by the boundary of dense road surface and the porous road, which may affect the measurement results [22]. According to the requirements of rut detection and road maintenance in this experimental section, the experimental section has different mixture ratios of PAC-13 and porous ultra-thin wearing course (PUC-10), which can be used for porous low noise asphalt pavement. The sieving and compose gradations of PAC-13 and PUC-10 are summarized in Table 1.

Table 1. Gradations of pavement mixture.

| Particle Size (mm) | PAC-13 | PUC-10 |
|--------------------|--------|--------|
| 16                 | 100.0  |        |
| 13.2               | 91.0   | 100    |
| 9.5                | 62.1   | 99.2   |
| 4.75               | 18.1   | 25.3   |
| 2.36               | 10.8   | 12.3   |
| 1.18               | 8.7    | 10.4   |
| 0.6                | 7.5    | 7.9    |
| 0.3                | 6.6    | 6.6    |
| 0.15               | 6.1    | 5.6    |
| 0.075              | 5.4    | 4.8    |
| Else               | 4.8% oil-stone ratio 0.1% polyester doped | 5.0% oil-stone ratio 0.1% polyester doped |

By designing the target mixture ratio of asphalt mixture with PAC-13 on the upper layer, the relevant volume parameters of asphalt mixture can be determined, which are summarized in Table 2. This table also presents the relevant volume parameters of asphalt mixture for PUC-10.

Table 2. Relevant volume parameters of asphalt mixture for PAC-13 and PUC-10.

| Relevant Volume Parameters | PAC-13 | PUC-10 |
|---------------------------|--------|--------|
| Maximum theoretical relative density (g/cm³) | 2.674 | 2.655 |
| Gross volume relative density with volume method (g/cm³) | 2.067 | 2.077 |
| Void ratio with volume method (%) | 22.7 | 21.8 |
| Relative density of gross volume with vacuum method (g/cm³) | 2.142 | 2.105 |
| Void ratio with vacuum method (%) | 19.9 | 20.7 |

Note that all the requirements of engineering standards need to be met, which include the leakage loss, the flying loss, the residual stability, the freeze–thaw splitting strength ratio, the dynamic stability, and the water permeability coefficient of the asphalt mixture, with both PAC-13 and PUC-10 on the upper layers [23].
2.2. Combination of Low Noise Pavements

According to the structure of low noise pavement and implementation of pavement, three types of low noise pavement structures are set up in this experimental section according to lanes and pavement structures, with a total of four types of pavement combination forms, as plotted in Figure 1. They are summarized as follows:

- **Type I**: The laying range is from K159+100 to K159+400, with a total of 300 m in length. Both the inner lane and the outer lane use a 2.5 cm PUC-10. The PUC-10 mainly uses fine particle size aggregates to increase the smoothness of the pavement and thus to reduce the noise generated by tire vibration, and it also has some sound absorption ability at the same time. Due to the thickness issue, compared with PAC-13, the peak frequency of PUC-10 is much higher, while the absorption coefficient of the peak value is slightly lower.

- **Type II**: The laying range is from K159+400 to K159+700, with a total of 300 m in length. The inner lane and the outer lane use a double-layer porous asphalt pavement, where the bottom layer uses 4.5 cm PAC-13 and the top layer uses 2.5 cm PUC-10. The double-layer porous pavement has the noise reduction performance of both single-layer porous asphalt pavement and thin-layer asphalt pavement, which is shown as follows: First, within the effective frequency range, there are two peaks of sound absorption coefficient, so the noise absorption effect is more obvious [24]; Second, the top layer has a fine particle size with a lower value of mean profile depth (MPD), and thus it can reduce the vibration and the noise caused by the contact between the tire and the pavement [25]; Third, the absorption layer of double porous pavement is thicker, and the first effective absorption peak frequency can be lower.

- **Type III**: The laying range is from K159+700 to K160+700, with a total of 1000 m in length. The inner lane uses a 2.5 cm PUC-10, and the outer lane uses 4.5 cm PAC-13+2.5 cm PUC-10 double-layer asphalt pavement. This combination considers that the inner lane is mainly used for light vehicles, while the outer lane is mainly used for heavy ones. The top layers of the combination use fine particle size aggregates to...
reduce the noise generated by tire vibration [26]. Compared with light vehicles, the tire/road noise generated by heavy vehicles is more dominant at lower frequencies than light vehicles, and the engine noise of heavy vehicles also has more contributes, so double-layer porous asphalt pavements are used in the outer lane. After considering the drainage requirements of road cross-sectional pavement structure, the construction convenience, and the double-layer porous pavement sound absorption capability, the emergency lane also uses double-layer porous asphalt pavement.

- **Type IV:** The laying range is from K160+700 and K161+300, with a total of 600 m in length. Both the inner lane and the outer lane use a single-layer porous asphalt pavement 4.0 cm PAC-13. PAC-13 is the most widely used pavement to mitigate noise in China nowadays, which can reduce traffic noise by absorbing tire/road noise.

From Figure 1, one can get that this paper studies four types of pavement materials. The first one is ECA-10, which is used in the experimental section before road maintenance, and the second and third ones are PUC-10 and PAC-13, respectively. The last one is the combination of PUC-10 and PAC-13. The reason for choosing PAC-13 is that it is one of the most widely used materials for porous asphalt pavement in China because of its efficiency in reducing traffic noise by absorbing the tire/road noise. Compared with PAC-13, PUC-10 can absorb the tire/road noise and reduce the vibration between the tire and the ground simultaneously. Moreover, the peak frequency of PAC-10 in noise absorption is often much higher than that of PAC-13, and thus PUC-10 can be expected to be more suitable to absorb the tire/road noise of light vehicles.

3. **Tire/Road Noise Measurement with CPX**

Before and after road maintenance, we used noise test trailers to measure the influence of tire/road noise with CPX according to ISO 11819-2 to show the effectiveness of different combinations of pavement structures on tire/road noise reduction. All the tests are carried out at one time when the air temperature and humidity are similar [27,28]. The road ECA-10 for pre-maintenance testing has been in use for about 4 years, and the test section of the post-maintenance test has just been laid and the test is carried out with no other vehicles driving in this road section, as shown in Figure 2. According to ISO 11819-2, the tire measuring positions are shown in Figure 3.

![Figure 2. On-site testing: (a) a CPX trailer; (b) the test tire replacement.](image-url)
4. Measurement Results

Because the highway has a 1% to 1.5% cross slope, the sound pressure level results measured by the left and right tires of the trailer are not consistent. According to the measurement results, the sound pressure level of tire/road noise of the tire on the right side of the trailer is usually 1 to 2 dB higher than that on the left side. For every 100 m, we record the left and right tires measurement at positions 1# and 2#, and then calculate the energy average equivalent sound pressure levels. Note that the measurement results need to be corrected to the temperature 20 °C finally [29].

Due to the large differences between light and heavy vehicles in size, width, shore hardness, load, pattern, and axle load, the tire/road noise of the light vehicle and that of the heavy vehicle are quite different. Therefore, when considering the influence of pavement on traffic noise, especially when applying low noise pavement for noise reduction, we have to consider the influence of pavement on tire/road noise for both light and heavy vehicles comprehensively. In this study, we use $L_{CPX:P}$ and $L_{CPX:H}$ to represent the CPX sound pressure level of the light vehicle tire/road noise and that of the heavy vehicle tire/road noise, respectively. The larger the differences of the sound pressure level before and after road maintenance (RM) for each vehicle, the better the noise reduction performance on the pavement maintenance. Note that all the following measurements were performed in the experimental section, as shown in Figure 1.

4.1. Speed of the Trailer at 60 km/h

Figure 4 plots the measurement results with CPX using the trailer at the speed of 60 km/h. For the inner lane, before the pavement maintenance, the road surface is ECA-10, the average equivalent sound pressure level of typical light vehicle tires/road noise is 110.0 dB, while that of the typical heavy vehicle is 112.0 dB, and thus the tire/road noise of heavy vehicles, is about 2 dB higher than that of light vehicles. After the pavement maintenance, both the tire/road noise of light vehicles and that of heavy vehicles have decreased. With 2.5 cm PUC-10, light vehicle tire/road noise has decreased by an average of 0.6 dB and heavy vehicle tire/road noise has decreased by an average of 1.9 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, light vehicle tire/road noise has decreased by an average of 3.5 dB and heavy vehicle tire/road noise has decreased by an average of 5.1 dB. With 2.5 cm PUC-10, light vehicle tire/road noise has decreased by 1.5 dB on average and heavy
vehicle tire/road noise has decreased by 1.5 dB on average. With 4.0 cm PAC-13, light vehicle tire/road noise has decreased by an average of 0.8 dB and heavy vehicle tire/road noise has decreased by an average of 2.0 dB.

For the outer lane, before the pavement maintenance, with ECA-10, the average sound pressure level of typical light vehicle tires/road noise is 111.0 dB, while that of the heavy vehicle is 111.2 dB, and thus the tire/road noise level of heavy vehicles is very close to that of light vehicles. After the pavement maintenance, both the tire/road noise of light vehicles and that of heavy vehicles have decreased. With 2.5 cm PUC-10, light vehicle tire/road noise has decreased by an average of 0.9 dB and heavy vehicle tire/road noise has decreased by an average of 2.0 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, light vehicle tire/road noise has decreased by an average of 4.3 dB and heavy vehicle tire/road noise has decreased by an average of 4.1 dB. With 2.5 cm PUC-10, light vehicle tire/road noise has decreased by 3.1 dB on average and heavy vehicle tire/road noise has decreased by
2.2 dB on average. With 4.0 cm PAC-13, light vehicle tire/road noise has decreased by an average of 0.5 dB and heavy vehicle tire/road noise has decreased by an average of 1.3 dB.

Comparing the tire/road noise in the inner lane and that in the outer lane at 60 km/h, with ECA-10, the tire/road noise of heavy vehicles is higher than that of light vehicles. With the use of the road surface, the tire/road noise of heavy vehicles will decrease and be close to light vehicles. For 2.5 cm PUC-10, the average light vehicle tire/road noise is 109.6 dB, and the average heavy vehicle tire/road noise is 110.3 dB, the tire/road noise of heavy vehicle is 0.7 dB higher than that of light vehicle. For 4.5 cm PAC-13 + 2.5 cm PUC-10, the average light vehicle tire/road noise is 108.2 dB, and the average heavy vehicle tire/road noise is 108.4 dB, so the tire/road noise of heavy vehicle is similar to that of light vehicle. For 4.0 cm PAC-13, average tire/road noise of heavy vehicle and that of light vehicle are 109.9 dB. All these results are depicted in Figure 5.

From the experimental results at 60 km/h, one can see that the lowest tire/road noise can be obtained for both light vehicles and heavy vehicles when using the double-layer pavement. Compared with the 4.0 cm PAC-13, for light vehicles, the tire/road noise with 2.5 cm PUC-10 is lower than that with 4.0 cm PAC-13, while for heavy vehicles, the tire/road noise with 2.5 cm PUC-10 is higher than that with 4.0 cm PAC-13. Therefore, at a driving speed of 60 km/h, a combined pavement structure with a 2.5 cm PUC-10 pavement in the inner lane and a 4.0 cm PAC-13 in the outer lane is suggested to obtain a promising noise reduction performance for practical applications.

4.2. Speed of the Trailer at 80 km/h

Figure 6 shows the measurement results with CPX using the trailer at the speed of 80 km/h. For the inner lane, before the pavement maintenance, with ECA-10, the average equivalent sound pressure level of typical light vehicle tire/road surface is 116.7 dB, and that of typical heavy vehicle tire/road surface is 117.5 dB, so the tire/road noise of heavy vehicles is about 0.8 dB higher than that of light vehicles. After the pavement maintenance, both the tire/road noise of light vehicles and that of heavy vehicles have decreased. For the inner lane, with 2.5 cm PUC-10, the light vehicle tire/road noise has decreased by an average of 2.6 dB, and the heavy vehicle tire/road noise has decreased by an average of 1.1 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, the light vehicle tire/road noise has decreased by an average of 2.8 dB, and the heavy vehicle tire/road noise has decreased by an average of 3.8 dB. With 2.5 cm PUC-10, the light vehicle tires/road noise has decreased by an
average of 1.8 dB, and the heavy vehicle tires/road noise has decreased by an average of 0.6 dB. With 4.0 cm PAC-13, the light vehicle tires/road noise has decreased by an average of 0.7 dB, and the heavy vehicle tire/road noise has decreased by an average of 1.1 dB.

For the outer lane, before the pavement maintenance, with the ECA-10, the average equivalent sound pressure level of typical light vehicle tires/road surface is 116.6 dB, and that of typical heavy vehicle tires/road surface is 117.7 dB, so the tire/road noise of heavy vehicles is about 1.1 dB higher than that of light vehicles. After the pavement maintenance, both the tire/road noise of light vehicles and that of heavy vehicles have decreased. For the outer lane, with 2.5 cm PUC-10, the light vehicle tire/road noise has decreased by an average of 2.1 dB, and the heavy vehicle tire/road noise has decreased by an average 1.6 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, the light vehicle tire/road noise has decreased by an average of 2.1 dB, and the heavy vehicle tire/road noise has decreased by an average of 4.1 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, the light vehicle tires/road noise has decreased by an average of 2.8 dB, and the heavy vehicle tire/road noise has decreased by an average
of 4.3 dB. With 4.0 cm PAC-13, the light vehicle tire/road noise has decreased by an average of 1.1 dB, and the tire/road noise of heavy vehicles has decreased by an average of 1.7 dB.

When comparing the tire/road noise measurement results of the inner lane with those of the outer lane at 80 km/h, with the ECA-10, one can see that the tire/road noise of heavy vehicles is higher than that of light vehicles. With 2.5 cm PUC-10, the average tire/road noise level of light vehicle is 114.7 dB, and the average tire/road noise level of heavy vehicle is 116.6 dB, so the tire/road noise of heavy vehicle is 1.9 dB higher than that of light vehicle. With 4.5 cm PAC-13+2.5 cm PUC-10, light vehicle average tire/road noise level is 114.1 dB, and heavy vehicle average tire/road noise level is 113.8 dB, which is very close to light vehicle tire/road noise. With 4.0 cm PAC-13, the average tire/road noise level is 115.7 dB, and the heavy vehicle average tire/road noise level is 115.8 dB. All these results are shown in Figure 7.

![Figure 7. Tire/road noise for different pavements at 80 km/h.](image)

From the experimental results at 80 km/h, one can also see that the tire/road noise of both the light and the heavy vehicles becomes the lowest when using the double-layer pavement, which is the same as the results in subsection 4.1. Compared with 4.0 cm PAC-13 pavement, the average tire/road noise of 2.5 cm PUC-10 is less than 1 dB for light vehicles, and higher than 0.8 dB for heavy vehicles. Therefore, at a driving speed of 80 km/h, using a combined pavement structure with a 2.5 cm PUC-10 pavement in the inner lane and a 4.0 cm PAC-13 in the outer lane, it is an alternative way to obtain a better noise reduction. It is also worth noting that, at an average driving speed of 80 km/h, the light vehicle tire/road noise of 2.5 cm PUC-10 is 114.7 dB, and the light vehicle tire/road noise of 4.5 cm PAC-13+2.5 cm PUC-10 is 114.1 dB, so the influence of two kinds of pavement structure on the tire/road noise of light vehicles is very close. Accordingly, when driving at 80 km/h, one can achieve similar performance of noise reduction to that of two lanes with double-layer pavement, when the inner lane uses 2.5 cm PUC-10 and the outer lane uses 4.5 cm PAC-13+2.5 cm PUC-10. In this way, we still can have a relatively good noise reduction performance, while paving materials and construction costs can be reduced dramatically.

### 4.3. Speed of the Trailer at 100 km/h

Figure 8 shows the measurement results with CPX using the trailer at the speed of 100 km/h. For the inner lane, before the pavement maintenance, with the ECA-10, the average equivalent sound pressure level of typical light vehicle tire/road noise is 121.2 dB,
and that of typical heavy vehicle tire/road noise is 122.5 dB, so the tire/road noise of heavy vehicles is about 1.3 dB higher than that of light vehicles. After the pavement maintenance, both the tire/road noise of light vehicle and that of heavy vehicles have decreased. For the inner lane, with 2.5 cm PUC-10, the tire/road noise of light vehicles has decreased by 0.3 dB on average, and that of heavy vehicles has decreased 1.9 dB. With 4.5 cm PAC-13 + 2.5 cm PUC-10, the light vehicle tire/road noise has decreased by an average of 2.1 dB, and the heavy vehicle tire/road noise has decreased by an average of 4.2 dB. With 2.5 cm PUC-10, the average light tire/road noise has decreased by 1.3 dB, and the heavy vehicle tire/road noise has decreased by 1.2 dB. With 4.0 cm PAC-13, the light vehicle tire/road noise has decreased by 1.0 dB, and the heavy vehicle tire/road noise has decreased by an average of 2.3 dB.

![Figure 8](image-url)

**Figure 8.** Tire/road noise equivalent sound pressure level at 100 km/h before and after road maintenance (RM): inner lane (Upper); outer lane (Lower).

For the outer lane, before the pavement maintenance, with the ECA-10, the average equivalent sound pressure level of typical light vehicle tire/road noise is 121.7 dB, and that of typical heavy vehicle tire/road noise is 122.0 dB. The tire/road noise of heavy
vehicles is similar to that of light vehicles. After the pavement maintenance, the tire/road noise of light and heavy vehicles has decreased. With 2.5 cm PUC-10, the tire/road noise of light vehicles has decreased by an average of 1.7 dB, and that of heavy vehicles has decreased 0.3 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, the light vehicle tire/road noise has decreased by an average of 3.6 dB, and the heavy vehicle tire/road noise has decreased by an average of 3.5 dB. With 4.5 cm PAC-13+2.5 cm PUC-10, the light vehicle tire/road noise has decreased by 3.0 dB on average, and the heavy vehicle tire/road noise has decreased by 3.2 dB. With 4.0 cm PAC-13, the light vehicle tire/road noise has decreased on average at 1.3 dB, and the heavy tire/road noise has decreased by an average of 2.0 dB.

When comparing the tire/road noise measurement results of the inner lane with that of the outer lane at 100 km/h, with the ECA-10, one can see that the tire/road noise of heavy vehicles is higher than that of light vehicles. With 2.5 cm PUC-10, the average tire/road noise level of light vehicles is 120.5 dB, and that of heavy vehicles is 121.4 dB, so the tire/road noise of heavy vehicles is 0.9 dB higher than that of light vehicles. With 4.5 cm PAC-13+2.5 cm PUC-10, the light vehicle average tire/road noise is 118.7 dB, and the heavy vehicle tire/road noise level is 118.6 dB, which has nearly the same value. With 4.0 cm PAC-13, the average tire/road noise is 119.7 dB, and the heavy vehicle tire/road noise is 119.9 dB, which can be seen in Figure 9.

![Figure 9. Tire/road noise for different pavements at 100 km/h.](image)

From the experimental results at 100 km/h, one can see that both the tire/road noise of the light and heavy vehicles becomes the lowest when using the double-layer pavement among these four kinds of pavement materials. Compared with 4.0 cm PAC-13, for light vehicles, the 2.5 cm PUC-10 road noise is 0.8 dB higher, while for heavy vehicles, 2.5 cm PUC-10 road noise is 1.5 dB higher. Therefore, at a driving speed of 100 km/h, the noise reduction performance of 4.0 cm PAC-13 is much better than that of 2.5 cm PUC-10.

5. Analysis of Noise Reduction Performance of Composite Pavement

According to the above measurement results, it is obvious that $L_{CPX:P}$ and $L_{CPX:H}$ are quite different, where $L_{CPX:H}$ is generally much larger than $L_{CPX:P}$. In this study, we use $L_{CPX}$ to represent the CPX sound pressure level for both the light and heavy vehicles, which can evaluate the comprehensive influence of pavement on tire/road noise. The
results presented in this section are quite different from Section 4, where the analysis results using $L_{\text{CPX}}$ are given in this section, while the measurement results including $L_{\text{CPX}:P}$ and $L_{\text{CPX}:H}$ are presented in Section 4. From Figures 4, 6 and 8, one can see that the tire/road noise equivalent sound pressure levels have some variations, even for the same type of pavement materials. This comes from the measurement deviation. To reduce this problem, we need to increase the number of measurement points and/or increase the number of measurements, and thus we can smooth these measurement results to obtain more reliable quantitative results. As mentioned above, we measure three times for each lane and the distance of two adjacent measurement points is about 100 m. By doing so, for each type of pavement, we have at least night measurement results at a specific speed of vehicle. The arithmetic mean of $L_{\text{CPX}:P}$ and $L_{\text{CPX}:H}$ is performed to obtain $L_{\text{CPX}}$ [30], which can be given by:

$$L_{\text{CPX}} = 0.5L_{\text{CPX}:P} + 0.5L_{\text{CPX}:H}$$

(1)

where (1) can be regarded as the highway having 80% volume of light vehicles and 20% volume of heavy vehicles with an average speed of 80 km/h, or having 75% volume of light vehicles with an average speed of 115 km/h and 25% volume of heavy vehicles with an average speed of 85 km/h.

However, for practical applications, the percentage of light and heavy vehicles changes over time even at the same section, and the percentage of vehicle types in different driving lanes is also quite different [2]. Therefore, using the arithmetic average value of $L_{\text{CPX}:P}$ and $L_{\text{CPX}:H}$ may not evaluate accurately the influence of this road section on traffic noise. For these reasons, we assume that the number of lanes is $n$, with $i$ the lane index, and the traffic volume per lane is denoted by $v_i$, the percentage of light vehicles and that of heavy vehicles per lane are $p_i$ and $h_i$, respectively, with $p_i + h_i = 1$, the noise influence between different lanes can be calculated according to the energy average. Accordingly, we can calculate the CPX sound pressure level with different lane pavement combinations, which can be given by:

$$L_{\text{CPX}} = 10\log_{10}\left(\frac{\sum_{i=1}^{n} \left( \frac{v_i}{v} \left( p_i L_{\text{CPX}:P,i} + h_i L_{\text{CPX}:H,i} \right) \right)}{\sum_{i=1}^{n} v_i} \right)$$

(2)

where $v = \sum_{i=1}^{n} v_i$ represents total traffic volume.

At different speeds, such as 60 km/h, 80 km/h, and 100 km/h, the values of the tire/road noise sound pressure level for typical light vehicles and heavy vehicles have been shown in Figures 4–9. We use Equation (2) to calculate the influence of pavement on traffic noise when different pavement structures are combined.

We assume that there is a highway section having 2 lanes, and the capacity of the outer lane is about 80% of that of the inner lane, which means $v_1/v = 5/9$ for the inner lane and $v_O/v = 4/9$ for the outer lane [31]. We further assume that all heavy vehicles drive in the outer lane, which means $p_O = 0$ and $h_O = 1$. More light vehicles drive in the inner lane, in which the ratio of light vehicles and heavy vehicles is 6:1, and thus $p_I = 6/7$ and $h_I = 1/7$. When the vehicles on the same lane have the same speed, with the above assumptions, Equation (2) can be further reduced to

$$L_{\text{CPX}} = 10\log_{10}\left(\frac{5}{9} \left( \frac{6}{7} 10^{\frac{L_{\text{CPX}:P,I}}{10}} + \frac{1}{7} 10^{\frac{L_{\text{CPX}:H,I}}{10}} \right) + \frac{4}{9} \left( 10^{\frac{L_{\text{CPX}:H,O}}{10}} \right) \right)$$

(3)

where $L_{\text{CPX}:P,I}$ and $L_{\text{CPX}:H,I}$ represent the CPX sound pressure level for the light and heavy vehicles in the inner lane, respectively. $L_{\text{CPX}:H,O}$ indicates the CPX sound pressure level for the heavy vehicles in the outer lane. Note that the outer lane only has heavy vehicles running and both light and heavy vehicles run in the inner lane when using (3), which coincides with the fact.

With Equation (3), we can calculate combinations of road surfaces at the same speed of the inner and outer lanes, and compare the noise reduction performance of different
combinations with the test results of the inner and outer lanes with the original ECA pavement, where the results are summarized in Table 3 and Figure 10.

**Table 3.** $L_{CPX}$ of composite pavement at the same speed in two nearby lanes.

| Speed | Inner Lane          | Outer Lane          | $L_{CPX}$ (dB) | NR (dB) |
|-------|---------------------|---------------------|----------------|---------|
| 60 km/h | 2.5 cm PUC-10       | 2.5 cm PUC-10       | 110.0          | 1.2     |
|       | 2.5 cm PUC-10       | 4.0 cm PAC-13       | 109.8          | 1.4     |
|       | 2.5 cm PUC-10       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 109.2 | 2.0     |
|       | 4.0 cm PAC-13       | 4.0 cm PAC-13       | 109.8          | 1.4     |
|       | 4.0 cm PAC-13       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 109.2 | 2.0     |
|       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 108.4 | 2.8     |
|       | 2.5 cm ECA-10 (Inside) | 2.5 cm ECA-10 (Outside) | 108.4 | 2.8     |
| 80 km/h | 2.5 cm PUC-10       | 2.5 cm PUC-10       | 115.8          | 1.4     |
|       | 2.5 cm PUC-10       | 4.0 cm PAC-13       | 115.4          | 1.8     |
|       | 2.5 cm PUC-10       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 114.5 | 2.7     |
|       | 4.0 cm PAC-13       | 4.0 cm PAC-13       | 115.8          | 2.7     |
|       | 4.5 cm PAC-13       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 115.0 | 2.3     |
|       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 113.9 | 3.3     |
|       | 2.5 cm ECA-10 (Inside) | 2.5 cm ECA-10 (Outside) | 115.8 | 1.4     |
| 100 km/h | 2.5 cm PUC-10       | 2.5 cm PUC-10       | 121.0          | 0.7     |
|       | 2.5 cm PUC-10       | 4.0 cm PAC-13       | 120.3          | 1.4     |
|       | 2.5 cm PUC-10       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 119.8 | 1.8     |
|       | 4.0 cm PAC-13       | 4.0 cm PAC-13       | 120.3          | 1.4     |
|       | 4.5 cm PAC-13       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 119.8 | 1.8     |
|       | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 119.8 | 1.8     |
|       | 2.5 cm ECA-10 (Inside) | 2.5 cm ECA-10 (Outside) | 121.7 | 1.4     |

**Figure 10.** Noise reduction effect of composite pavement at same speeds.
From Table 3 and Figure 10, one can get that the best noise performance can be obtained when the inner and outer lanes are adopted by double-layered porous asphalt pavements. However, when we need to take raw materials and construction costs into account, we can choose some more economical choices with the help of these experimental results. For example, when the average speed of traffic flow of the road section is 80 km/h, the combination of the inner lane road surface of 2.5 cm PUC-10 and the outer lane road surface of 4.5 cm PAC-13+2.5 cm PUC-10 is also a suboptimal choice. Compared with the total use of double-layer, noise reduction decreases by only about 0.6 dB. With the percentage of light vehicles increases, compared with double-decker road surface combination, the sacrificial amount of noise reduction will further decrease. With these results, one can avoid choosing some of the worst combinations.

In general, light vehicles tend to be faster than heavy vehicles, and thus the average speed of the inner lane is much higher than that of the outer lane. In this case, we can also study the noise reduction performance by using this method. Three scenarios are considered, where one is the average speed of the inner lane 80 km/h and the outer lane 60 km/h, another is the average speed of the inner lane 100 km/h and the outer lane 80 km/h, the other is the average speed of the inner lane 100 km/h and the outer lane 60 km/h. The theoretical results are summarized in Table 4 and Figure 11.

In these cases, when the inner and outer lanes are both double-layered porous asphalt pavement, the road CPX sound pressure level is the lowest and one can obtain the best noise reduction. We can also find that the inner lane using 4.0 cm PAC-13 can obtain a better noise reduction performance than that using 2.5 cm PUC-10. When considering the cost of double-layer porous asphalt pavement and construction difficulty, one can also use the single-layer porous asphalt pavement suboptimally.

| Speed Inner Lane | Outer Lane | $L_{CPX}$ (dB) | NR (dB) |
|------------------|------------|----------------|---------|
| **Inside 80 km/h** | 2.5 cm PUC-10 | 2.5 cm PUC-10 | 113.5 | 1.6 |
| **Outside 60 km/h** | 2.5 cm PUC-10 | 4.0 cm PAC-13 | 113.4 | 1.7 |
| 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 113.2 | 2.0 |
| 4.0 cm PAC-13 | 4.0 cm PAC-13 | 114.0 | 1.2 |
| 4.0 cm PAC-13 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 113.8 | 1.4 |
| 4.5 cm PAC-13 + 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 112.4 | 2.8 |
| 2.5 cm ECA-10 (Inside) | 2.5 cm ECA-10 (Outside) | 115.1 | — |
| **Inside 100 km/h** | 2.5 cm PUC-10 | 2.5 cm PUC-10 | 119.3 | 0.9 |
| **Outside 80 km/h** | 2.5 cm PUC-10 | 4.0 cm PAC-13 | 119.1 | 1.0 |
| 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 118.8 | 1.4 |
| 4.0 cm PAC-13 | 4.0 cm PAC-13 | 118.4 | 1.7 |
| 4.0 cm PAC-13 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 118.0 | 2.1 |
| 4.5 cm PAC-13 + 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 117.1 | 3.0 |
| 2.5 cm ECA-10 (Inside) | 2.5 cm ECA-10 (Outside) | 120.1 | — |
| **Inside 100 km/h** | 2.5 cm PUC-10 | 2.5 cm PUC-10 | 118.4 | 0.8 |
| **Outside 60 km/h** | 2.5 cm PUC-10 | 4.0 cm PAC-13 | 118.4 | 0.8 |
| 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 118.3 | 0.9 |
| 4.0 cm PAC-13 | 4.0 cm PAC-13 | 117.5 | 1.7 |
| 4.0 cm PAC-13 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 117.4 | 1.8 |
| 4.5 cm PAC-13 + 2.5 cm PUC-10 | 4.5 cm PAC-13 + 2.5 cm PUC-10 | 116.4 | 2.7 |
| 2.5 cm ECA-10 (Inside) | 2.5 cm ECA-10 (Outside) | 119.2 | — |
C1: Inside 2.5cm PUC-10 + Outside 2.5cm PUC-10
C2: Inside 2.5cm PUC-10 + Outside 4.0cm PAC-13
C3: Inside 2.5cm PUC-10 + 4.5cm PAC-13 + Outside 2.5cm PUC-10
C4: Inside 4.0cm PAC-13 + Outside 4.0cm PAC-13
C5: Inside 4.0cm PAC-13+4.5cm PAC-13 + Outside 2.5cm PAC-10
C6: Inside 4.5cm PAC-13+2.5cm PUC-10 + Outside 4.5cm PAC-13+2.5cm PUC-10

Figure 11: Noise reduction effect of composite pavement at same speeds.

6. Conclusions

In this paper, a combination method of low noise pavement is given when considering both vehicle speed and different lane traffic flow characteristics. According to the traffic flow and capacity of the road section, we use the CPX method and study the CPX sound level of combinations of pavement at different speeds. From this study, one can see that the tire/road noise of heavy vehicles is higher than that of light vehicles with ECA-10. Compared with other pavement combinations, the double-layer porous pavement on both the inner and outer lanes has the best noise reduction performance on the tire/road noise of light and heavy vehicles. One contribution of this paper is that one can also use the measurement and analysis method in this paper to evaluate and/or choose other, more economical, low noise pavement combinations. For example, when the average speed of a road section is only limited to 80 km/h, one can consider to pave the 2.5 cm PUC-10 in the inner lane and the double-layer asphalt pavement in the outer lane (4.5 cm PAC-13+2.5 cm PUC-10). When the average speed is limited to 100 km/h, the inner lane using 4.0 PAC-13 can obtain a relatively good noise reduction performance. This study can also provide some guidelines on limiting the speed of vehicles to reduce the tire/road noise in some noise-sensitive areas.

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