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Analysis of coast-by noise of heavy truck tires

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ABSTRACT

Heavy truck tires are one of the main sources of road traffic noise. However, the mechanism and propagation of the noise generated by these tires have not been systematically investigated. To determine the noise of heavy truck tires with different structures and patterns, and to analyze the correlation between the indoor tire noise and coast-by tire noise, an integrated tire indoor noise test and a coast-by noise test were designed and successfully implemented. The indoor test was conducted on a drum inside a semi-anechoic chamber to simultaneously measure the near field and far field noise of the tires. The outdoor measurements were carried out using a coast-by test on the new ISO 10844 surface. A formula for quantitative analysis with appropriate corrections was developed to analyze the data with reasonable errors, which can be used to predict the coast-by noise through the indoor tire noise test accurately and effectively. The analysis shows that when trying to build the relationship between indoor and outdoor heavy truck tire noise, care should be taken to differentiate the tires with a load capacity index in excess of 121 and without any dual fitting indication from ordinary tires, due to the specified test procedure.

1. Introduction

It has been well recognized that when the speed of a passenger car or a truck exceeds 60 km/h, the tire noise becomes the dominant source of vehicle noise (Anfosso-Ledee et al., 2000; Heckl, 1986; Herman et al., 2000; Kim et al., 2007; Kropp et al., 2012; Iwao and Yamazaki, 1996; Nilsson et al., 1980; Sandberg and Descornet, 1980). The recent government regulation and code, such as the EU tire labeling law, further brings attention to tire noise behavior and mechanism on specified surface, i.e., ISO 10844 ground (Donavan, 1997, 2005; Donavan and Rymer, 2003; European Union, 2009; ISO, 2011; Landsberger et al., 2001; Sohaney et al., 2012; Moore, 2011; Sandberg, 2012). In order to understand the tire noise generation and propagation mechanism, it should measure both indoor noise in semi-anechoic chamber and coast-by noise in appropriate ways specified by UNECE Regulation 117 (UNECE, 2011) and determine their relationships. Understanding such relationships is very important for tire designers in order to

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screen and improve their products effectively and efficiently (Ge et al., 2002; Lippmann and Reid, 1976; Paje et al., 2007; Woodward et al., 2005). Unfortunately, limited data and analysis can be found in published literature on the quantitative analysis of the relationship between indoor and outdoor tire noise obtained on the road surface specified in ISO 10844 (ISO, 2011), specifically for heavy truck tires (Sandberg, 2005; Sandberg and Ejsmont, 2002).

In this study, an integrated tire indoor noise test and an outdoor coast-by noise test on the new ISO 10844 surface were designed and successfully implemented. The quantitative relationship between indoor near field noise and coast-by noise of heavy truck tires was established for the first time, based on the results obtained in those experiments and point acoustic source tire noise model. In particular, it was found that the proposed quantitative relationship between indoor and coast-by tire noise needed to be modified for wide based tires, and the physics for this modification was given by examining the test procedure of ENECE Regulation 117.

Following the introduction, in the first section, the hybrid indoor test and outdoor coast-by test are designed, including the details of the experimental process. Then the test results and relevant discussions are introduced. Conclusions come in the end.

2. Experimental design

2.1. *The indoor noise test*

The test objects were 4 sets of tires from a domestic supply. The specification of two of the sets of tires was 315/60 R22.5. One set had a block tread pattern (CM335) and the other had a rib pattern (CR966). The other two sets of tires were 385/65 R22.5. One of the sets had a mixed tread pattern (AT557) and the other set had a rib pattern (WSR1). For the sake of convenience, the tires were numbered successively as shown in Fig. 1. To understand the relationship between the indoor near

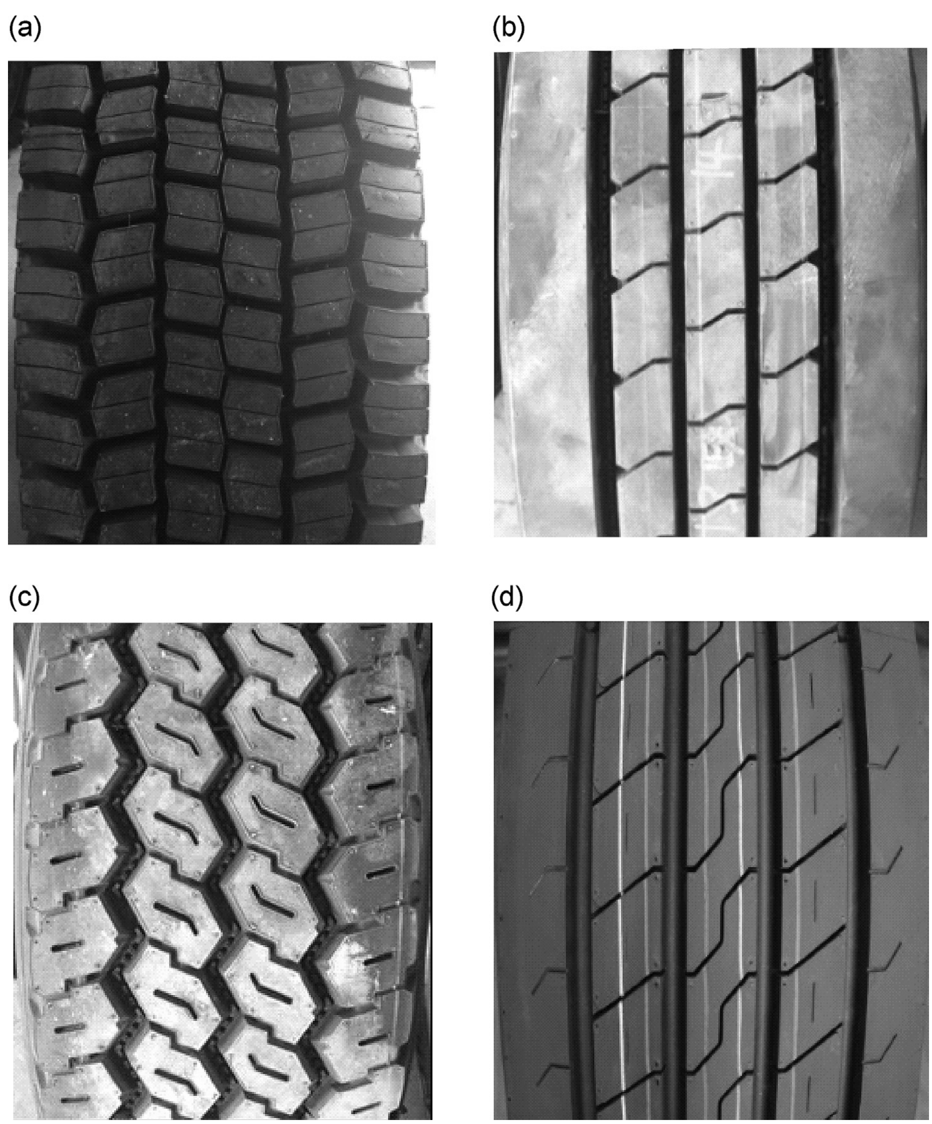

Fig. 1 – Tread pattern of test tires. (a) CM335. (b) CR966. (c) AT557. (d) WSR1.

field noise and the far field noise, the indoor test in this paper performed the measurements for the near field noise and the far field noise simultaneously.

2.1.1. *Equipment and instruments*

The test vehicle was a flat tractor (CA4180P66K2AZ). Test tires were mounted on the right front wheel successively. The load on the test vehicle was adjusted according to the standard. After that, the other devices were installed on proper position successively (Chen, 2014).

To measure the near field noise, 9 microphones were fixed on the right side in a half circle with a defined angular spacing (0°, 30°, 45°, 60°, 90°, 120°, 135°, 150° and 180°) from the back-end to the front end in anticlockwise order (Fig. 2). The radius of the half circle was 1 m and the central point of tire contact area was the center of the circle. In addition, the microphones were positioned 0.1 m above the ground. All microphones were directed at the central point of the tire contact patch.

To measure the far field noise, 5 microphones were mounted in a line on the right side 7.5 m away from the tire and 1.2 m off of the ground to simulate the pass-by noise of tires (Fig. 3). The spacing between the 5 microphones was 2 m.

Environmental conditions were semi-anechoic chamber, ambient temperature was 25 °C, and ambient sound level less than 25 dB(A).

2.1.2. *Experimental processes*

The experiments were divided into two parts. One was conducted for background noise and the other was performed with constant speeds.

In the first test, the ambient noise was determined with all of the devices off before the test vehicle was mounted on the drum. The drum was then started and the ambient noise was measured at speeds of 50 km/h, 70 km/h, 90 km/h and 120 km/h. After finishing the first test, the vehicle was fixed on the drum, and the air conditioner and any other components that could produce noise were turned off. The drum was then set to ‘drum drive’ mode, which launched the drum to drive the wheel to rotate at a constant speed. The near field noise and far field noise of the tires at different speeds were measured while the technicians took notes on the speeds of the vehicle and the tires.

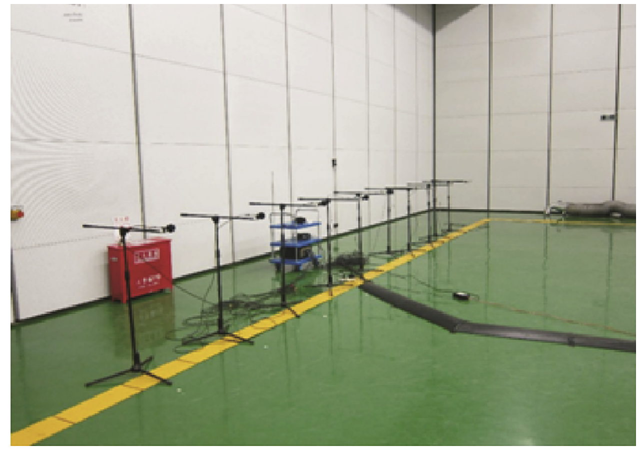

Fig. 3 – Layout of the microphones for measuring the far field noise.

Fig. 2 – Layout of the microphones for measuring the near field noise.

2.2. *The coast-by test*

The test tires for this test were four sets as described above. This experiment was carried out in strict compliance with UNECE Regulation 117 (UNECE, 2011). The main purpose of this experiment was to obtain the coast-by noise of the tires in comparison with the indoor noise to identify a quantitative correlation between the two tests.

2.2.1. *Equipment and instruments*

The test vehicle was a 4 × 2 Dongfeng-Tianjin medium truck chassis, which had a power of 185 hp and a wheelbase of 5 m. To meet the requirements of the measurements, a balance weight was mounted on the test vehicle. In addition, the spray suppression flaps were dismantled according to the standard (UNECE, 2011).

Furthermore, for the sake of shielding the additional noise generated from the test vehicle, a comprehensive acoustic treatment was performed on the vehicle according to the

Fig. 4 – The vehicle used for the coast-by test.

standard (UNECE, 2011), as illustrated in Fig. 4. Additional information about the other devices can be found in the literature (Chen, 2014).

2.2.2. *Experimental processes*

The experiment was conducted on the highway proving ground of the Ministry of Transportation in Beijing. The average air temperature was 30 °C and the wind speed was below 5 m/s. In addition, the ambient sound pressure level was less than 60 dB(A).

The test vehicle entered line A–A′ or B–B′ along a straight line with the transmission disengaged and the engine switched off, as shown in Fig. 5. The center line of the vehicle coincided with that of the test track. Notes of the instantaneous speeds of the vehicle were obtained by using a Vbox mounted in the cab. The largest values for sound pressure level were recorded by the microphones when the truck passed the position of the microphones. The speed of the test truck was 60–80 km/h. For the microphones fixed on both sides, at least 4 measurement replicates were conducted from 70 to 80 km/h. An additional 4 measurement replicates were conducted from 60 to 70 km/h. No less than 8 qualified data sets were obtained. The air and road surface temperature and the velocity of the wind were recorded for each measurement.

3. Results and discussions

3.1. *Indoor near field noise and far field noise*

During the indoor hybrid tests, the near field and far field noise levels of the tires were recorded by microphones. The noise signal collection was imported to LMS test lab, after a certain processing, the overall levels of near field and far field noise with A-weighting were obtained. Besides, the highest sound pressure level of far field noise collected by five microphones was used as indoor coast-by noise in next step. Through such processing, the data of the sound pressure level of tire noise at different speeds were obtained.

To determine the correlation between the near field noise and far field noise, a comparative analysis of the data was conducted. The most significant positive correlation was between the near field noise collected by the microphone at 60° and the far field noise, as shown in Fig. 6. The correlation coefficient was 0.9795.

Based on the test data above, it can be concluded that there was a quantitative relationship between the indoor near field noise and the far field noise. To determine this relationship, the indoor test data was further analyzed. Because a certain degree of attenuation occurred when the near-field noise passed to the far-field, it was assumed that the attenuation of the tire noise was in line with the attenuation law of a point acoustic source according to Eq. (1).

$$L_{r_2} - L_{r_1} = 20\lg(r_1/r_2) \tag{1}$$

where r_1 and r_2 denote distances, L_{r_1} is the sound pressure levels of the noise recorded at position r_1 from the point acoustic source, L_{r_2} is the sound pressure level of the noise recorded at position r_2 from the point acoustic source.

In Table 1, *N* and *F* denote the sound pressure levels for indoor near field noise and far field noise, respectively. ABS (absolute errors) is the deviation between the SPL (sound pressure level) of the actual far field noise and the SPL of the calculated far field noise with the attenuation law of a point acoustic source. In addition, the unit is dB(A).

It can be found that the average relative error is less than 1% and the absolute error is no more than 1 dB(A).

3.2. *The outdoor coast-by noise*

In this section, the SPL data for the coast-by noise of the 4 sets of tires were processed as specified in UNECE Regulation 117 (Table 2).

The data in Table 2 were obtained after processing as specified in UNECE Regulation 117. The reference speed was

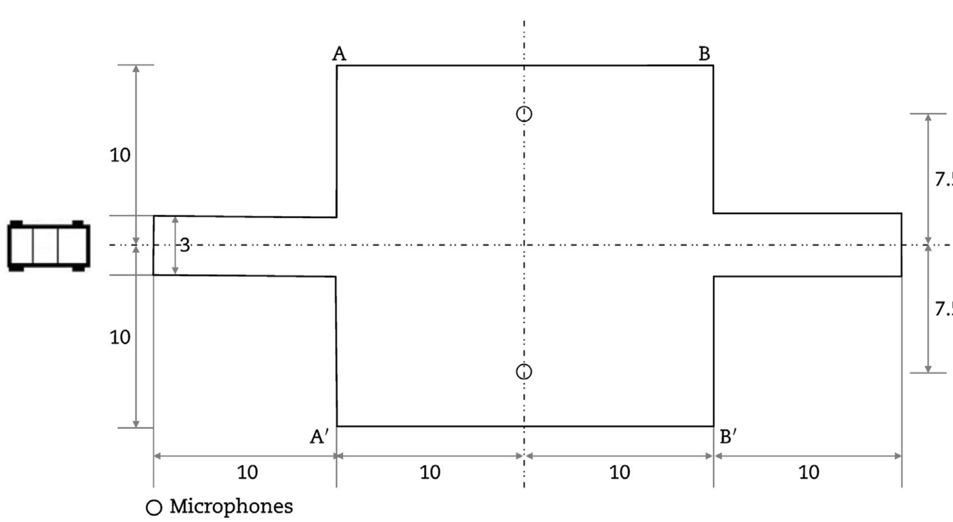

Fig. 5 – The principle diagram of the coast-by method (unit: m).

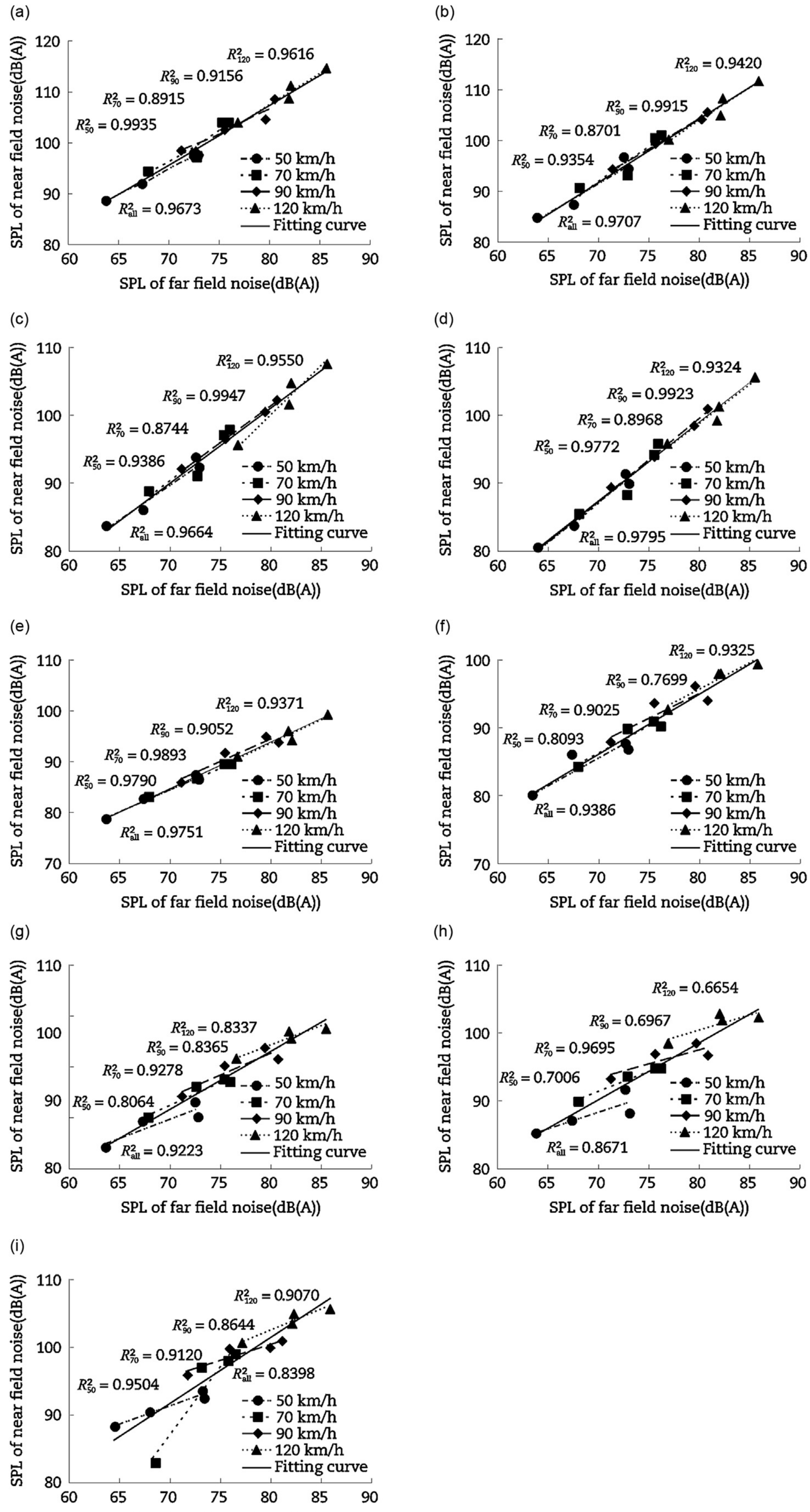

Fig. 6 – Correlation between the near field noise and the far field noise for the 4 sets of tires. (a) 0°. (b) 30°. (c) 45°. (d) 60°. (e) 90°. (f) 120°. (g) 135°. (h) 150°. (i) 180°.

Table 1 – Quantitative relationship between the SPL of the near field noise collected by the microphone at 60° and the SPL of the far field noise.

Specification (tread pattern)	50 km/h				70 km/h				90 km/h				120 km/h			
	N	F	(N-F-20lg7.5)/F (%)	ABS	N	F	(N-F-20lg7.5)/F (%)	ABS	N	F	(N-F-20lg7.5)/F (%)	ABS	N	F	(N-F-20lg7.5)/F (%)	ABS
315/60 (CM335)	83.8	67.4	−1.63	−1.10	88.2	72.8	−2.89	−2.10	93.5	75.6	0.53	0.40	98.4	82.0	−1.34	−1.10
315/60 (CR966)	80.8	63.8	−0.79	−0.50	85.5	68.0	0.00	0.00	89.0	71.3	0.28	0.20	95.1	76.9	0.91	0.70
385/65 (AT557)	89.7	73.0	−1.10	−0.80	95.3	76.1	2.30	1.75	100.0	81.0	1.90	1.54	104.6	85.8	1.51	1.30
385/65 (WSR1)	90.9	72.7	0.96	0.70	93.7	75.5	0.93	0.70	97.6	79.7	0.50	0.40	100.5	82.2	0.97	0.80
Average	86.3	69.2	−0.64	−0.44	90.7	73.7	0.08	0.06	95.0	76.9	0.80	0.62	99.7	81.7	0.51	0.42

Table 2 – Sound pressure level for the outdoor coast-by noise of the tires.

No.	Tread pattern	SPL (dB(A))
1	CM335	74
2	CR966	70
3	AT557	74
4	WSR1	73

70 km/h. The values for the sound pressure level should be reduced by 1 dB(A) and rounded down to the nearest lower whole values. To investigate the correlation between the indoor far field noise and the coast-by noise, the experimental data for the indoor far field noise should also be corrected in a reasonable manner before comparison. As shown in Table 3, the correlation between the SPL of the tire indoor far field noise and the SPL of outdoor coast-by noise can be revealed explicitly only after the corresponding corrections.

The correction method should be elucidated by the analysis of the indoor and outdoor tests of the 4 sets of tires with different specifications. As shown in Fig. 2, the tire noise in the indoor test was generated only by one rotating tire, while 4 tires mounted on the truck all produced the noise shown in Fig. 4. For tires CM335 and CR966, the 4 tires mounted on the vehicle were identical during tests. It was assumed that the sound pressure level generated by the 4 identical tires was the same and that the microphone on one side was affected only by the two tires on the same side. The superposition formula of independent acoustic source can be described as follow

$$p_{\text{tot}}^2 = \sum_{i=1}^{n} p_i^2 \tag{2}$$

where p_i is the sound pressure of acoustic source numbered as i, p_{tot} is the sound pressure that results from the superposition of several independent acoustic sources, n is the number of independent acoustic sources.

Thus, after superposition of the two independent acoustic sources, the overall sound pressure level can be determined according to the following equation.

$$L_p = 10\lg\left(\sum_{i=1}^{2} 10^{0.1L_i}\right) = 10\lg 2 + L_i = L_i + 3 \tag{3}$$

where L_p is the overall sound pressure level after superposition of the two independent acoustic sources, L_i is the sound pressure level of the acoustic source.

Accordingly, the sound pressure level of the outdoor coast-by noise should theoretically be 3 dB(A) more than that of indoor far field noise. Based on this, 3 dB(A) was added to the sound pressure level of the indoor far field noise. However, there were no corrections for tires AT557 and WSR1. Because of the regulations specified in UNECE Regulation 117, during the coast-by noise test for the tires with a load capacity index in excess of 121 and without any dual fitting indication (wide base tires), only two test tires were mounted on the rear axle, while two low-noise tires were fixed on the front axle. Consequently, it was assumed that the coast-by noise of the wide base tires was only affected by one of the two rear test

Table 3 – Contrast between the indoor far field noise and the outdoor coast-by noise of the tires at a velocity of 70 km/h (unit: dB(A)).

Specification (tread pattern)	SPL of indoor far field noise (SPL_1)	SPL of indoor far field noise after correction (SPL_2)	SPL of outdoor coast-by noise (SPL_3)	Deviation (SPL_1-SPL_3)	Deviation after correction (SPL_2-SPL_3)
315/60 (CM335)	71	74	74	−3	0
315/60 (CR966)	67	70	70	−3	0
385/65 (AT557)	75	75	74	1	1
385/65 (WSR1)	74	74	73	1	1

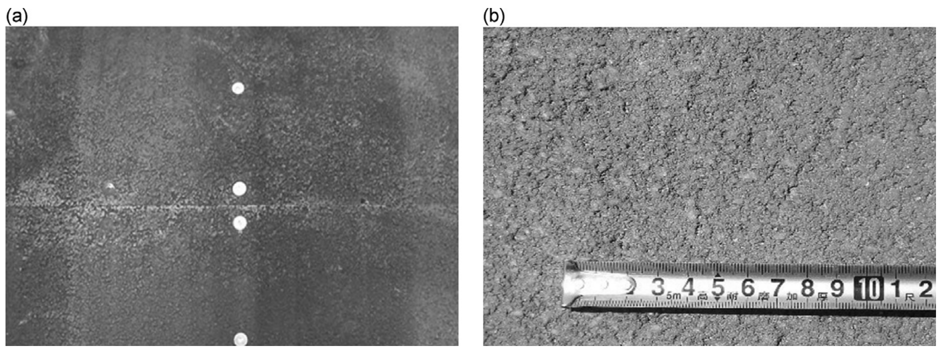

Fig. 7 – Contrast between the surface of the drum and the surface of the road in accordance with ISO 10844. (a) Surface of the drum. (b) Surface of the road.

tires. Thus, there was no correction needed for the sound pressure level of the indoor far field noise.

As shown in Table 3, the maximum error between the sound pressure level of the coast-by noise and that of the indoor far field noise after correction was 1 dB(A). For tires CM335 and CR966, the sound pressure level of the indoor far field noise was equal to that of the coast-by noise, while for the two other larger tires, the error was 1 dB(A). However, the sound pressure levels of the indoor far field noise generated by the two tires were higher than those of the outdoor coast-by noise. The most probable reason for this phenomenon is that there are differences between the sound generation mechanisms of the wide base tires and the medium heavy truck tires. For wide base tires, the contact area between the tire and the road is larger than normal area, which enhances the air pumping noise and also causes stick-slip and stick-snap noises. The air pumping noise and friction-induced noise are the main sources of noise for the wide base tires. Because the air pumping noise and friction-induced noise occur more easily on smooth surfaces and the surface of the drum is much smoother than the road surface used in the test (Fig. 7), the sound pressure level of the indoor far field noise caused by the drum surface is higher than that by the proving ground for wide base tires.

To determine the quantitative relationship between the indoor near field noise and the coast-by noise (Table 4), a contrast analysis was performed between the near field noise obtained by the microphone at 60° when the speed was 70 km/h and the outdoor coast-by noise. In Table 4, *N* denotes the sound pressure level for the indoor near field noise and *O* denotes the sound pressure level for the outdoor coast-by noise. In addition, the sound pressure levels for the indoor far field noise were reduced by 1 dB(A) and rounded down to the nearest lower whole value according to UNECE Regulation 117 (UNECE, 2011).

Table 4 – Quantitative relationship between the indoor near field noise collected by the microphone at 60° and the outdoor coast-by noise at a velocity of 70 km/h (unit: dB(A)).

Specification (tread pattern)	*N*	*O*	Deviation (*N*-20lg7.5)-*O*	Deviation after correction (*N*-20lg7.5)-*O*
315/60 (CM335)	88.2	74	−5	−2
315/60 (CR966)	85.5	70	−3	0
385/65 (AT557)	95.3	74	2	2
385/65 (WSR1)	93.7	73	2	2

As shown in Table 4, the relationship between the SPL of the near field noise collected by the microphone at 60° and a speed of 70 km/h, and the SPL of the coast-by noise complied with the attenuation law of a point acoustic source well. The maximum error after correction was no more than 2 dB(A). Given the randomness of the tests and the small amount of data, the errors were reasonable.

4. Conclusions

This work mainly focuses on the analysis of coast-by noise of heavy truck tires. The quantitative relationship between indoor near field noise and coast-by noise of heavy truck tires was established for the first time with the maximum error less than 1 dB(A), according to carefully designed tire indoor/outdoor noise tests and point acoustic source tire noise model.

An integrated tire indoor noise test and an outdoor coast-by noise test on the new ISO 10844 surface were designed and successfully implemented.

Last but not least, it was found that the proposed quantitative relationship between indoor and coast-by tire noise needed to be modified for wide based tires, and the physics for this modification was given by examining the test procedure of UNECE Regulation 117.

Acknowledgments

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