



THE CORRELATION BETWEEN THE NOISE AND VIBRATION INDUCED BY A BRIDGE MOVEMENT JOINT

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Abstract. This study addresses the research on the noise and vibration correlation of a bridge movement joint. The aim of this research is to assess the noise induced by the vibration of a bridge movement joint without lane closure during the operation period. There are two methods of developing the correlation between the tyre/joint noise and vibration: (i) Direct Sound and Vibration Measurement Method, (ii) Acoustic-Box-in-Vehicle Method. The first one is the measurements of the vibration change at a bridge movement joint and roadside noise change induced when a control vehicle is passing it (this one requires lane closure). The correlation between the vibration change and roadside noise change is plotted according to the measurement data. The second one is the measurements of the structure-borne noise change in an acoustic box installed into the control vehicle and roadside noise change induced. Similarly, the correlation between the structure-borne noise change and roadside noise induced is plotted. It is found that the two correlations are linear and similar to each other, even though the roadside noise is nonlinearly increasing against the control vehicle speed.

Keywords: tyre/joint noise, tyre/joint vibration, traffic noise, bridge movement joint, highway.

1. Introduction

Traffic and other types of road traffic noise have long attracted significant research interest (e.g. Ambrosio *et al.* 2014; Banerjee *et al.* 2014; Bocquier *et al.* 2014; Bueno *et al.* 2014; Dai *et al.* 2014; Kouroussis *et al.* 2014; Li *et al.* 2014; Sygna *et al.* 2014). In Hong Kong, many elevated bridges are built on top of the existing roads to mitigate the traffic congestion. Some of them are less than 50 m away from the buildings. Therefore, noise from the bridges influence the occupants of the buildings. Limited studies are made to study the tyre/joint noise which is caused by the collision between the tyres of the vehicles and the bridge movement joints. On the contrary, more studies (e.g. Braun, Schulze 2007; Hanson, James 2004; Hemmert-Halswick 2007; Spuler *et al.* 2007) are made to study the tyre/road noise which is caused by the collision between the vehicle tyres and the road surface. The documents related to tyre/joint noise are therefore selected as references. In the two

ISO standards, *ISO11819-1:2001 Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise. Statistical Pass-by Method*, and *ISO11819-2:2000 Acoustics – Method for Measuring the Influence of Road Surfaces on Traffic Noise Part 2: Close-Proximity Method*, there are two methods, namely Statistical Pass-by Method and Close-Proximity Method, respectively, for the measurement of tyre/road noise. However, the methods are used in this study because the effective width of a bridge movement joint for measurement is too small comparing with that of the road surface. Moreover, as shown in Fig. 1, two microphones are required to be fixed at one side of the control vehicle (20 cm away from the tyres and 10 cm above pavement level) making them to be damaged easily when the control vehicle runs on inclined sections of a bridge. It is seen that the current methodologies for measuring tyre/road noise are not suitable for measuring tyre/joint noise. Hence, two methodologies of assessing tyre/joint noise are introduced in this paper.

2. Methodology and measurement

Two methodologies are studied:

- i) Direct Sound and Vibration Measurement Methodology and
- ii) Acoustic-Box-in-Vehicle Methodology (Wong *et al.* 2009).

One of the major differences between the two methodologies is the lane closure requirement. Direct Sound and Vibration Measurement Methodology requires lane closure while Acoustic-Box-in-Vehicle Methodology does not. In these two methodologies, the data acquisition system is switched on just before the tyres of the control vehicle collide with the focal bridge movement joint and it is then switched off after passing through it. Data from the sound level meter and that from the accelerometer are synchronized and recorded. That is considered as one set of measurement data. The movement joint measurements are repeated to acquire sets of data for various vehicle speeds and joint locations.

2.1. Direct Sound and Vibration Measurement Methodology

In the proposed methodology, sound and vibration responses are measured on the road surface. With lane closure, the noise and vibration change due to the interaction between the tyres of the control vehicle and bridge movement joint are measured directly on the bridge surface. The measuring instruments are placed on the closed lane while the control vehicle runs on the open lane which is next to the closed lane as shown in Fig. 2. A private car is used as the control vehicle, shown in Fig. 3.

The measuring instruments shown in Table 1 are employed to form a data acquisition system. The system consists of a sound level meter with a microphone, an accelerometer, a signal conditioner, and a data acquisition unit. They are used to capture the sound and the vibration responses simultaneously when the control vehicle passing through bridge movement joint.

Three measurements, using the Direct Sound and Vibration Methodology, were carried out on Bridge A on different dates as shown in Table 2 and Fig. 4. The roadside airborne noise change and the vibration change are calculated by the following formulas respectively:

$$\Delta_{air} = 10 \log \frac{\langle P_a^2 \rangle_{avg}}{\langle P_{ref,a}^2 \rangle_{avg}}, \quad (1)$$

where Δ_{air} – airborne noise change; P_a – the sound pressure captured by the roadside microphone just before the control vehicle passing through the joint; $P_{ref,a}$ – the sound pressure captured by the roadside microphone when the control vehicle passing through the joint; $\langle \rangle_{avg}$ – temporal average for the duration when the tyres of the control vehicle passing through the joint

$$\Delta_{vib} = 10 \log \frac{\langle V_r^2 \rangle_{avg}}{\langle V_{ref,r}^2 \rangle_{avg}}, \quad (2)$$

where Δ_{vib} – vibration change; V_r – the vibration captured by the roadside accelerometer just before the control vehicle passing through the joint; $V_{ref,r}$ – the vibration captured by the roadside accelerometer when the control vehicle passing through the joint; $\langle \rangle_{avg}$ – temporal average for

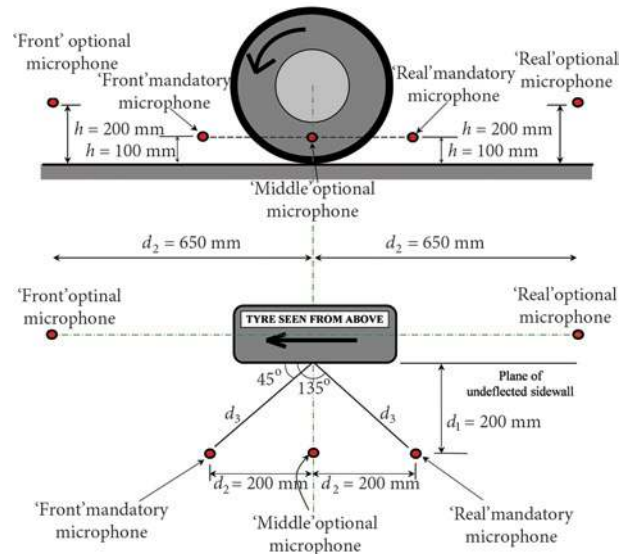


Fig. 1. The suggested positions of the microphones in Close-Proximity Method (photo adapted from ISO 11819-2)

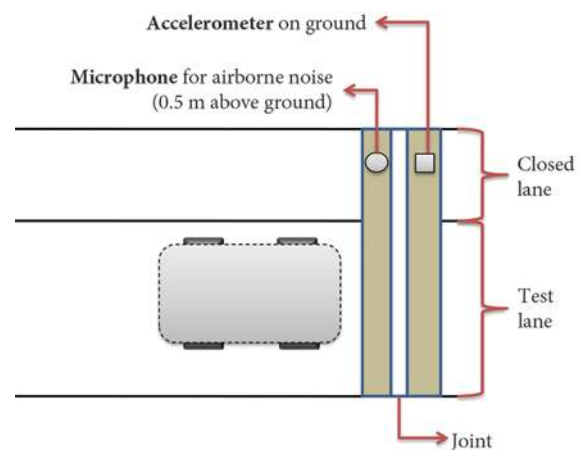


Fig. 2. Schematic setup of Direct Sound and Vibration Measurement Methodology



Fig. 3. The control vehicle

the duration when the tyres of the control vehicle passing through the joint.

Table 1. Details of the measuring instruments

Instruments	Manufacturers	Model No.	Error
Sound level meter	Rion	NA28	±0.5 dB
Accelerometer	Kyowa	AQS-2BL	±1%
Signal conditioner	Kyowa	VAQ-500A	±1%
Data acquisition unit	National instrument	NI-9162 NI-9215	±0.02%

Table 2. Details of the measurements carried out on Bridge A

Joint location	Bridge A
	27 April 2008
Date	27 July 2008
	30 November 2008
Joint type	Type A (Fig. 4)
Methodology	Direct Sound and Vibration Measurement Methodology



Fig. 4. The bridge movement joint on Bridge A

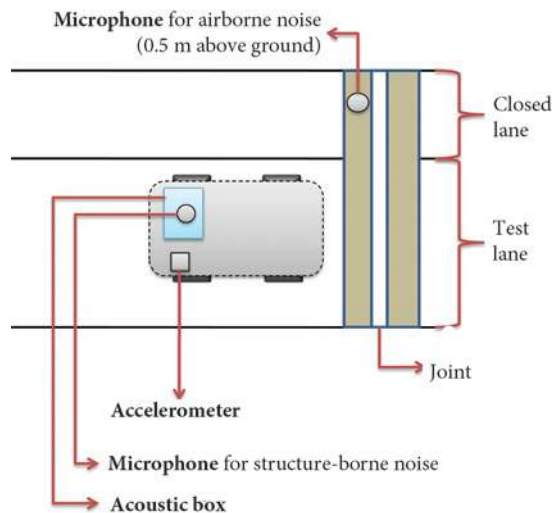


Fig. 5. Setup schematic of Acoustic-Box-in-Vehicle Methodology

2.2. Acoustic-Box-in-Vehicle Methodology

The advantage of the Acoustic-Box-in-Vehicle Methodology is that there is no lane closure requirement. The instruments shown in Table 1 are also employed to form a data acquisition system which is used to capture the sound and vibration responses simultaneously when the control vehicle passing through bridge movement joints. The instruments are placed within the compartment of the control vehicle, as shown in Fig. 5.

The microphone, which is installed in the acoustic box mounted inside the control vehicle, is used to measure the structure-borne noise induced by the tyre/joint interaction. The acoustic box is placed near the rear wheels of the control vehicle. A microphone is placed at the roadside which also captures the sound levels before, during and after the control vehicle passing through a bridge movement joint. In the direct sound and vibration measurement, the tyre/joint noise was found highly correlated to the vibration near the movement joint when the control vehicle passes through it. In the Acoustic-Box-in-Vehicle measurement, the tyre/joint noise was found highly correlated to the structure-borne noise in the acoustic box.

The airborne noise change captured by the roadside microphone is calculated by Eq (1) while the structure-borne noise change captured by the microphone inside the acoustic box is calculated by the following formula:

$$\Delta_{str} = 10 \log \frac{\langle P_s^2 \rangle_{avg}}{\langle P_{ref,s}^2 \rangle_{avg}}, \quad (3)$$

where Δ_{str} – structure-borne noise change; $P_{ref,s}$ – the sound pressure captured by the microphone inside the acoustic box just before the control vehicle passing through the joint; P_s – the sound pressure captured by the microphone inside the acoustic box when the control vehicle passing through the joint; $\langle \rangle_{avg}$ – temporal average for the duration when the tyres of the control vehicle passing through the joint.

Table 3 and Fig. 6 shows that a measurement was carried out on Bridge B to study the relationship between the structure-borne noise change due to the control vehicle running across the joint and the tyre/joint noise induced. Acoustic-Box-in-Vehicle Methodology was used. The measurement was carried out at the non-operational period of Bridge B. No vehicles, except the control vehicle, were allowed to enter the measurement site.

2.2.1. The acoustic box

An acoustic box is designed to measure the structure-borne noise of the control vehicle. Prior work shows that

Table 3. Details of the measurement carried out on Bridge B

Joint Location	Bridge B
Date	19 June 2008
Joint Type	Type B (Fig. 6)
Methodology	Acoustic-Box-in-Vehicle Methodology

the structural vibration of bridge movement joints is less than 500 Hz when the wheels of the control vehicle collide with them. Similar work from Ancich and Brown (2004) also shows that the vibration frequency is below 500 Hz. Therefore, the dimension of the acoustic box is designed as 240×240×240 mm such that the lowest resonance frequency of the acoustic box is higher than the frequency region of interest of the structure-borne noise of bridge movement joints. Acoustic foams are attached on all sides (except the bottom side) in the box to isolate noises from the ambient. Fig. 7 shows the schematic of the acoustic box and Fig. 8 shows the acoustic performance of the acoustic foams. With the absence of acoustic foam at the bottom side of the acoustic box, the microphone is able to capture the structure-borne noise created when the control vehicle collides with bridge movement joints. Moreover, the majority of sound frequency greater than 550 Hz, from other sound disturbances, is blocked.

3. Results and discussion

Figs 9 and 10 show the time histories of the noise and vibration levels. The impulsive noise and vibration responses are observed when the control vehicle passes through the bridge movement joint. Two peaks found in each figure are caused by the front and rear tyres of the control vehicle passing through the joints individually. The peaks due to the roadside noise change, structure-borne noise change and vibration change occur almost simultaneously on the time domain. It is seen that the roadside or structure-borne noise change due to the tyre/joint interaction is highly correlated to the vibration change. Relatively, the pattern of the structure-borne noise change is less similar to that of the vibration change, when compared with that of the roadside noise change.

Fig. 11 shows the tyre/joint noise change measured at the roadside using the Direct Sound and Vibration Measurement Methodology, plotted against the vibration change near the joint. The average control vehicle speed is about 70 km/h. There are three sets of data obtained for different



Fig. 6. The bridge movement joint on Bridge B

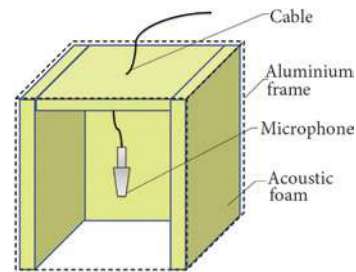


Fig. 7. Schematic of the acoustic box

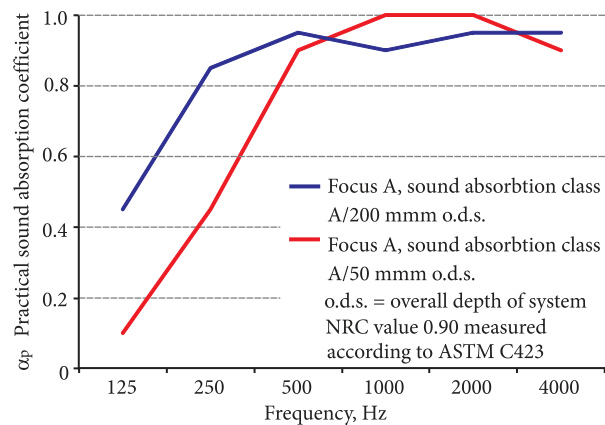


Fig. 8. Acoustic performance of the acoustic foam

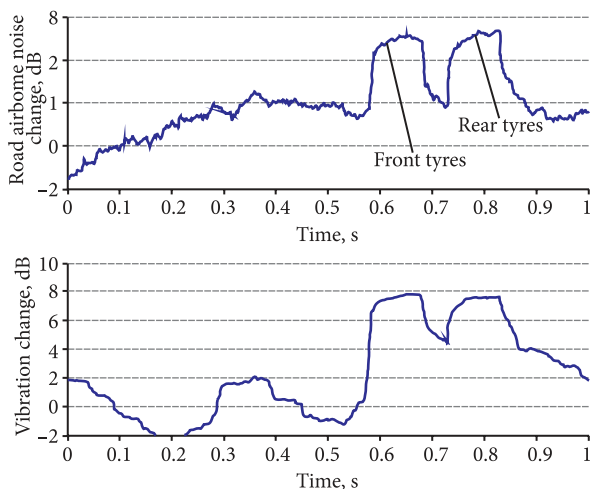


Fig. 9. The raw data captured by Direct Sound and Vibration Measurement Methodology on Bridge A (Joint A2)

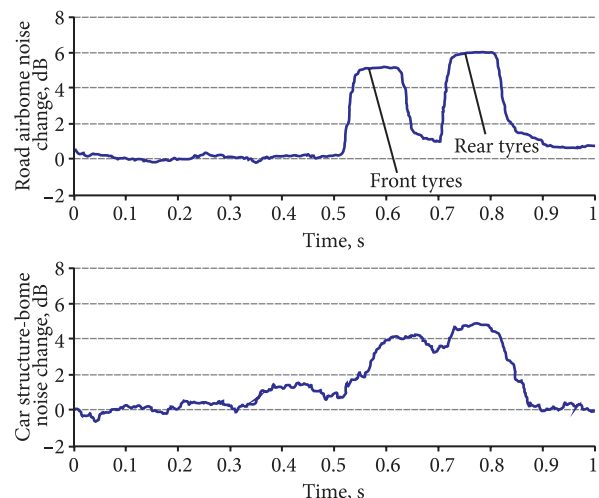


Fig. 10. The raw data captured by Acoustic-Box-in-Vehicle Methodology

joints, and three straight lines fitted for them. Although the slopes of the three lines are different, it is observed that the tyre/joint noise change is linearly increasing against the vibration change. Generally, the vibration change due to the tyre/joint interaction is more sensitive than the noise change. For example, a vibration change of 16.5 dB induces a noise change of 5.5 dB only (the dotted line in Fig. 11).

Fig. 12 shows the tyre/joint noise change measured at the roadside using the Acoustic-Box-in-Vehicle method,

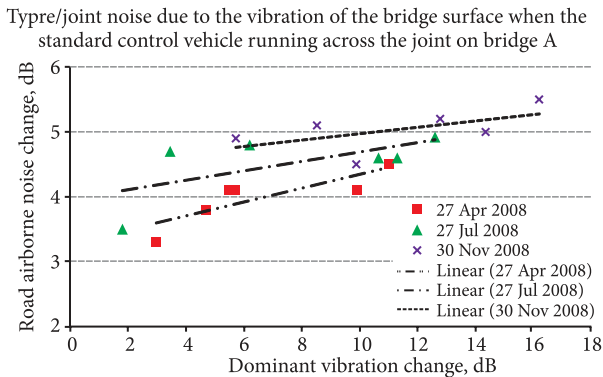


Fig. 11. Road airborne noise change and vibration change on bridge surface (using Direct Sound and Vibration Measurement Methodology)

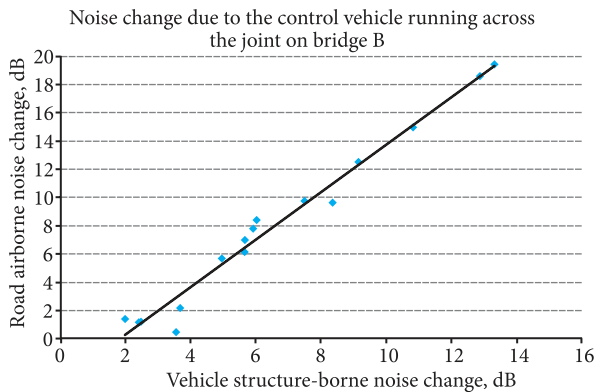


Fig. 12. The noise correlation of the measurement on Bridge B (using Acoustic-Box-in-Vehicle Methodology)

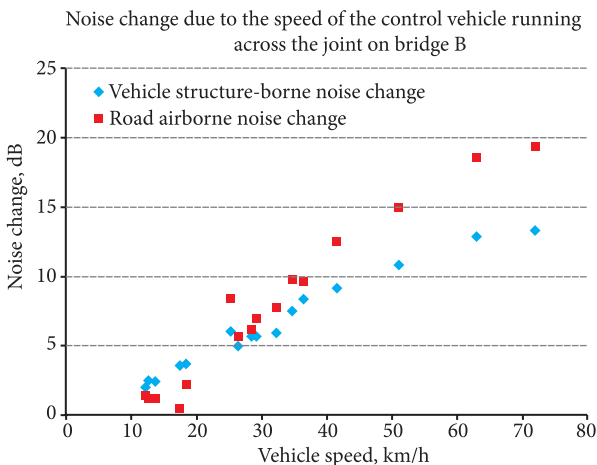


Fig. 13. The speed correlation of the measurement on Bridge B (using Acoustic-Box-in-Vehicle Methodology)

plotted against the structure-borne noise change inside the acoustic box (Wong et al. 2009). Fig. 13 shows the roadside tyre/joint noise change and the structure-borne noise change plotted against the vehicle speed. For the vehicle speed lower than 45 km/h, the relationships between the roadside tyre/joint noise change/structure-borne noise change and the vehicle speed are linear. For the vehicle speed higher than 45 km/h, the relationships are nonlinear that the roadside tyre/joint noise change and the structure-borne noise change are less sensitive to the vehicle speed increase. The control vehicle speed ranges from 13–72 km/h. It is clearly seen that the tyre/joint noise change is linearly increasing against the structure-borne noise change.

Fig. 14 shows the roadside tyre/joint noise change and the structure-borne noise change plotted against the vibration change near the joint. The control vehicle speed ranges from 26–51 km/h. Again, this is clearly observed that the tyre/joint noise change and structure-borne noise change are almost linearly increasing against the vibration change. Hence, the structure-borne noise change is considered as an indicator of the tyre/joint noise and is used to benchmark the noise performance of bridge movement joints.

The results from the Direct Sound and Vibration Measurement Methodology, and the Acoustic-Box-in-Vehicle Methodology show the linear relationships. The first methodology shows that the road airborne noise change linearly increases against the vibration change, even though these two noises are non-linearly increasing against the vehicle speed. The second methodology also shows that the road airborne noise change linearly increases against the vehicle structure-borne noise change. Therefore, the two linear relationships agree with each other.

3.1. Difficulties encountered

As mentioned before, elevated bridges are built on top of the existing roads to mitigate the traffic congestion. Therefore, they also have a high traffic flow and lane closure for measurement will make the traffic congestion get worse. The result shows that the tyre/joint noise, which is the actual noise received by human ears, has a strong correlation with the structure-borne noise change captured by the Acoustic-Box-in-Vehicle Methodology without lane closure. As a result, the noise performance of the bridge

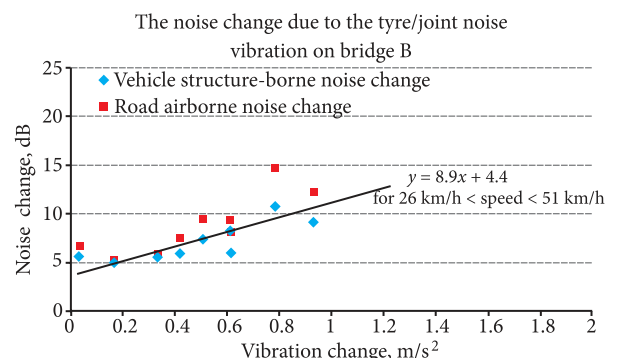


Fig. 14. The tyre/joint noises due to the tyre/joint vibration on Bridge B (using Acoustic-Box-in-Vehicle Methodology)

movement joints is measured in a way which does not affect the traffic flow. In addition, the measurement of tyre/joint noise can be strongly influenced by other sound sources. Therefore, this indirect measurement of tyre/joint noise helps to keep the unwanted sound (such as background noise) away and provides a more accurate result.

Before conducting a measurement, the instruments are setup on the bridge surface within a particular area. Hence, lane closure is necessary in order to make sure the safety of the technicians setting up the measurement (Fig. 15). The application of lane closure must be submitted to a relevant authority for approval at least 3 months in advance. As lane closure creates a traffic bottleneck nearby and affects traffic flow and safety (Abukauskas *et al.* 2013; Lazda, Smirnovs 2014), there may also be a rejection or questioning by the authority. Besides, measurements can be interrupted by adverse weather and a new application of lane closure is then required to be submitted again. This incurs extra cost and interrupts the continuity of the measurements.

Sometimes the control vehicle and other vehicles pass a bridge movement joint at the same time. If the bridge consists of more than one lane and other vehicles run in parallel to the control vehicle passing the joint used in the measurement, the tyre/joint noise which is created by the control vehicle are not distinguished from those by other vehicles.

There are other noise sources in the measurements. For instance, some vehicles with poor maintenance radiate high engine noise which is captured by the microphone. Loads on some trucks would also induce noises due to vibration.

Ideally, the control vehicle speed should be constant in the Direct Sound and Vibration Measurement Method. The control vehicle has to accelerate to a particular speed, then runs with the constant speed, and crosses the joint. However, the road condition may not allow the control vehicle to do so.

In Fig. 16, it is seen that the position of the control vehicle running on the test lane shifts slightly in each run. Hence, the position that the tyres pass the joint is also different in each run. Since the conditions of a joint at different positions may not be the same (especially for aged joints), an average value of tyre/joint noise obtained from several runs is taken.

4. Conclusion

The two methodologies, (i) Direct Sound and Vibration Measurement Methodology, and (ii) Acoustic-Box-in-Vehicle Methodology, of developing correlation between the tyre/joint noise and vibration have been presented. In the first methodology, the correlation between the vibration change and roadside noise change is plotted according to the measurement data. In the second methodology, the correlation between the structure-borne noise change and roadside noise induced is plotted. It is found that the two correlations are linear and similar to each other, even though the roadside noise is non-linearly increasing against the control vehicle speed. Therefore, the Acoustic-Box-in-Vehicle Methodology and the structure-borne noise change measurement are suitable for measuring the



Fig. 15. Lane closure. Contractors are placing traffic cones to close the lane

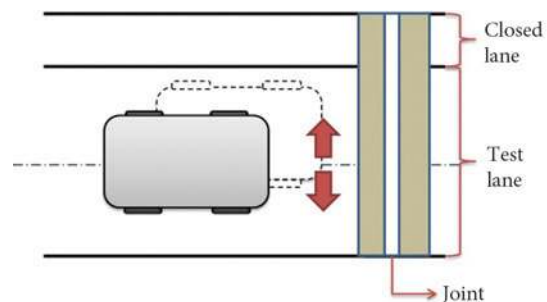


Fig. 16. The position of the control vehicle shifts slightly in each run

noise performance of bridge movement joints. Besides, the proposed measurement method does not require lane closures, thus avoiding any effects on the traffic flow.

References

- Abukauskas, N.; Sivilevičius, H.; Puodžiukas, V.; Lingytė, I. 2013. Road Safety Improvement on at-Grade Intersections, *The Baltic Journal of Road and Bridge Engineering* 8(3): 212–219. <http://dx.doi.org/10.3846/bjrbe.2013.27>
- Ambrosio, L.; Iglesias, L.; Pascual, V.; Pedrero, A.; Rodriguez, M.; Diaz, C.; Gimenez, M. D. 2014. A Nonlinear Mixed Model for the Assessment of Traffic Noise Levels in Urban Areas, *Stochastic Environment Research and Risk Assessment* 28(5): 1085–1098. <http://dx.doi.org/10.1007/s00477-013-0805-z>
- Ancich, E. J.; Brown S. C. 2004. Engineering Methods of Noise Control for Modular Bridge Expansion Joints, *Acoustics Australia* 32(3): 101–107.
- Banerjee, D.; Das, P. P.; Foujdar, A. 2014. Association between Road Traffic Noise and Prevalence of Coronary Heart Disease, *Environmental Monitoring and Assessment* 186(5): 2885–2893. <http://dx.doi.org/10.1007/s10661-013-3587-3>
- Bocquier, A.; Cortaredona, S.; Boutin, C.; David, A.; Bigot, A.; Sciortino, V.; Nauleau, S.; Gaudart, J.; Giorgi, R.; Verger, P. 2014. Is Exposure to Night-Time Traffic Noise a Risk Factor for Purchase of Anxiolytic-Hypnotic Medication? A Cohort Study, *European Journal of Public Health* 24(2): 298–303. <http://dx.doi.org/10.1093/eurpub/ckt117>
- Braun, J.; Schulze T. 2007. Road Bridge Expansion Joints - Reduction of the Overrolling Noise Caused of Vehicles During Crossing the Expansion Joint, in *IABSE Symposium Weimar 2007. Improving Infrastructure Worldwide*. September 19–21, 2007, Weimar, Germany, 77–86.

- Bueno, M.; Luong, J.; Teran, F.; Vinuela, U.; Paje, S. E. 2014. Macrotexture Influence on Vibrational Mechanisms of the Tyre-Road Noise of an Asphalt Rubber Pavement, *International Journal of Pavement Engineering* 15(7): 606–613. <http://dx.doi.org/10.1080/10298436.2013.790547>
- Dai, B. L.; He, Y. L.; Mu, F. H.; Xu, N.; Wu, Z. 2014. Development of a Traffic Noise Prediction Model on Inland Waterway of China Using the FHWA, *Science of the Total Environment* (482–483): 480–485. <http://dx.doi.org/10.1016/j.scitotenv.2013.06.019>
- Hanson, D. I.; James, R. S. 2004. *Colorado Dot Tire/Pavement Noise Study*. Research Report CDOT-DTD-R-2004-5. Dept of Transportation Research, USA. 29 p.
- Hemmert-Halswick, A. 2007. Expansion Joints for Road Bridges – Requirements and Reality-Durability and Noise, in *IABSE Symposium Weimar 2007. Improving Infrastructure Worldwide*. September 19–21, 2007, Weimar, Germany.
- Kouroussis, G.; Pauwels, N.; Brux, P.; Conti, C.; Verlinden, O. 2014. A Numerical Analysis of the Influence of Tram Characteristics and Rail Profile on Railway Traffic Ground-Borne Noise And Vibration in the Brussels Region, *Science of the Total Environment* (482–483): 452–460. <http://dx.doi.org/10.1016/j.scitotenv.2013.05.083>
- Lazda, Z.; Smirnovs, J. 2014. Application of Design Speed for Urban Road and Street Network, *The Baltic Journal of Road and Bridge Engineering* 9(1): 26–30. <http://dx.doi.org/10.3846/bjrbe.2014.04>
- Li, M. L.; van Keulen, W.; van de Ven, M.; Molenaar, A.; Tang, G. Q. 2014. Investigation on Material Properties and Surface Characteristics Related to Tyre-Road Noise for Thin Layer Surfacing, *Construction and Building Materials* 59: 62–71. <http://dx.doi.org/10.1016/j.conbuildmat.2014.02.050>
- Spuler, T.; Moor, G.; Urich, B. 2007. Expansion Joints with Noise Reduction – will Recent Developments Become Widespread Across Europe? in *IABSE Symposium Weimar 2007. Improving Infrastructure Worldwide*. September 19–21, 2007, Weimar, Germany, 506–513.
- Sygna, K.; Aasvang, G. M.; Aamodt, G.; Oftedal, B.; Krog, N. H. 2014. Road Traffic Noise, Sleep and Mental Health, *Environmental Research* 131: 17–24. <http://dx.doi.org/10.1016/j.envres.2014.02.010>
- Wong, K. W.; Leung, A. Y. T.; Lee, R. Y. Y.; Wong, J. C. K.; Yiu, E. C. Y.; Lo, Y.; Lam, P. H. F. 2009. A New Methodology of Measuring Tyre/Joint Noise in Hong Kong, in *The 4th Symposium on Environmental Vibration, “Environment Vibrations, Prediction, Monitoring, Mitigation and Evaluation”*, vol. 1, 599–604.

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