CONTRIBUTIONS TO CLOSE-PROXIMITY METHOD FOR TYRE/ROAD NOISE MEASUREMENT IN HIGHLY URBANIZED ENVIRONMENT

LAM YAT KEN

M.Phil

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The Hong Kong Polytechnic University

Department of Mechanical Engineering

Contributions to Close-Proximity Method for Tyre/Road Noise Measurement in Highly Urbanized Environment

LAM Yat Ken

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CERTIFICATE OF ORIGINALITY

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________________________ (Signed)

Lam Yat Ken (Name of Student)

ABSTRACT

Notwithstanding decades of governmental and public efforts, traffic noise problem in Hong Kong is still severe. Since the contribution by tyre/road noise is predominant, assessment to it is necessary. Close-Proximity Method is a standard tyre/road noise measurement methodology (ISO/CD 11819-2) that works by towing a trailer installed with test tyres and microphones to travel on a road section to measure the noise emitted. The reliability of its application in highly urbanized city is in doubt because of the severe disturbances to the measurement in real practice. They include the high background traffic noise, the road bumpiness, the substantial variation of temperature and the variation due to road curvature. This study aims to develop a CPX Method suitable for tyre/road noise measurement in highly urbanized city with minimal influence from these disturbances.

The development of the PolyU Mark II CPX Trailer is described in this study. It is equipped with an acoustically treated enclosure for shielding the external disturbing noise with minimized internal reflection. Experiments were conducted to evaluate its acoustic performance against the certification criteria stipulated in ISO/CD 11819-2. The Mark II has passed. The vibration of the microphones installed inside the CPX trailer excited by its travel over road bumpiness induces error to the measurement results. Experimental results indicate the error can lead to a noise level overestimation as much as 3 dB(A). To alleviate such error, a correction method is proposed and illustrated. Tyre/road noise is sensitive to air temperature. ISO/CD 11819-2 suggests temperature correction to alleviate its influence. The correction is optional since temperature constants vary for different road surface types. The correction is however necessary in Hong Kong due to the relatively large temperature variation. Experiment was devised to yield the air and road surface temperature constants of two local common asphalt road surface types. Road surface temperature is found more reliable than air temperature for the correction. The choices of road sections are limited in this highly urbanized city. Sometimes it is inevitable to adopt curved road as test section. Cornering is anticipated to influence tyre/road noise radiation. Study was conducted to assess the curvature effect. Results indicate that the road curvature effect can reach up to 2 dB(A). The minimum critical radii for CPX measurement are yielded for two speeds. The radius is found to be higher for higher vehicle speed.

Through evaluating the levels of influences by the disturbances above and proposals of corrective measures to the errors resulted from them, the present study contributes to the reliability of CPX Method for tyre/road noise measurement in highly urbanized city.

Keywords: Tyre/road noise, Close-Proximity Method, CPX, trailer, urban, certification test, vibration, temperature, road curvature.

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Conference Paper

Lam, Y. K., Leung, R. C. K., and Hung, W. T., 2012. Impact of Microphone Vibration on Tyre/road Noise Measurement with Close-Proximity (CPX) Method. In: HKIOA (The Hong Kong Institute of Acoustics), *The 5th Cross-strait Many Cities Symposium on Acoustics*. Hong Kong, The People's Republic of China 23-24 November 2012. Conference Proceeding, pp.143-147.

Hung, W. T., **Lam, Y. K.**, Leung, R. C. K. and Ng, C. F., 2012. Which Is A Better Metric – Road or Air Temperature – in Assessing Temperature Effects on Tyre/road Noise? In: HKIOA (The Hong Kong Institute of

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CHAPTER 1

INTRODUCTION

In this chapter, the background of traffic noise problem in Hong Kong is introduced. Among various noise sources of traffic noise, tyre/road noise is anticipated to be more and more predominant in the near future so it is taken as the focus of the study. The measurement method adopted in Hong Kong for assessment to tyre/road noise, the Close-Proximity Method (CPX Method), is briefly introduced. Elaboration is made on the limitations of the method. The present study aims to reduce the level of disturbances of the identified limitations of CPX Method so that its measurement accuracy can be enhanced. At last, the structure of the thesis is presented.

1.1 Traffic noise problem in Hong Kong

Hong Kong is a highly urbanized city well-known for its high population. To cope with the massive logistics and population flow everyday, the government has been putting huge effort and resources in developing an ultimately efficient road network. Measures include the construction of numerous highways, flyovers and huge amount of roads. Notwithstanding the high density of population and extraordinary high land price, it is sometimes inevitable to build roads with heavy traffic in the vicinity of residences, schools and even hospitals. The nuisance created by traffic noise grows with the rapid development of road network. Traffic noise is of major concern by Environmental Protection Department (EPD) of HKSAR Government due to its adverse impact to a huge population of over one million people exposed to L_{10} above 70 dB(A) according to the statistics retrieved from website of EPD as shown in Table 1.1 (EPD, 2013). The noise policy adopted by the European Union (1996) states clearly that people are physiologically and psychologically affected by noise in which noise levels above 65 dB(A) are regarded as detrimental to health resulting from tiredness, variations in blood pressure and stress. To minimize these drawbacks, measures to accurately assess and effectively mitigate traffic noise are essential. Sandberg (2001) points out that out of the four main sources of traffic noise, namely engine, exhaust, air intake and tyre/road noises, significant reductions in level from the former ones have been achieved but the tyre/road noise is still dominating at constant speeds. Therefore, assessing and abatement of tyre/road noise play crucial roles in traffic noise control in foreseeable future.

Population Exposed to Traffic Noise > 70dB(A)L10 all Disrticts in Year 2000			
District	District Total Population	People exposed to > 70dB(A)L10	% > 70dB(A)L10
YAU TSIM MONG DISTRICT	276,800	102,700	37.1
KOWLOON CITY DISTRICT	376,200	99,200	26.4
SHAM SHUI PO DISTRICT	345,900	90,200	26.1
TSUEN WAN DISTRICT	272,100	71,100	26.1
WAN CHAI DISTRICT	164,500	40,900	24.9
KWUN TONG DISTRICT	549,700	116,700	21.2
KWAI TSING DISTRICT	470,900	83,600	17.8
TAI PO DISTRICT	308,500	53,800	17.4
WONG TAI SIN DISTRICT	432,300	73,500	17.0
CENTRAL & WESTERN DISTRICT	259,400	40,800	15.7
SHA TIN DISTRICT	621,000	96,500	15.5
EASTERN DISTRICT	608,100	93,900	15.4
NORTH DISTRICT	295,900	42,700	14.4
TUEN MUN DISTRICT	478,600	53,800	11.2
YUEN LONG DISTRICT	444,500	44,100	9.9
SOUTHERN DISTRICT	285,900	17,900	6.3
SAI KUNG DISTRICT	328,700	18,700	5.7
ISLANDS DISTRICT	81,200	<100	<0.1
TOTAL	**6,600,200**	**1,140,100**	**17.3**

Table 1.1 Spatial distribution of traffic noise problem in Hong Kong retrieved from EPD website (EPD, 2013).

1.2 Evolving role of tyre/road noise in sources of traffic noise

To minimize the disturbance to the living of citizens, the Hong Kong Government has formulated a comprehensive plan (EPD, 2006) for tackling road traffic noise with various abatement measures, including retrofitting noise barrier, highway re-surfacing and paving with low-noise road surface material. The most commonly found traffic noise reduction measure is the erection of noise barrier which attenuates noise along its propagation path. Nevertheless, this is not an widely applicable solution for all scenarios. For instance, the structural design of some roads, which are designed and built in earlier time, may not be able to support the additional load of the barrier. There is also concern on the landscape from the residents nearby. In recent years, the Hong Kong Government has been attempting to tackle traffic noise problem at the noise sources including the use of low-noise road surface material which is described as a significant way to reduce tyre/road interaction noise in a government document of mitigation measures against road traffic noise (Legislative Council, 2006). In 2006, the government identified 72 existing road sections and spent HK $80 million for feasibility studies on the sustainability of resurfacing with low-noise material (EPD, 2006). There was also a case of discussion on using low-noise road surface instead of noise barrier to ease traffic noise nuisance to residence at the Hong Kong Legislative Council (2008). The effort and resources allocated demonstrate the crucial role of tyre/road noise as the major traffic noise.

Going back to mid 90s, Iwao and Yamazaki (1996) showed that the noise from the tyre contributes more than 30% of the overall vehicle noise. It is comparable to that from the engine while the exhaust and the air intake share less than 30% and 10% respectively. There has been mutual acknowledgement among researchers (Graf et al., 2002; Iwao and Yamazaki, 1996; Larsson et al., 2002) that tyre/road noise is the dominant traffic noise source at vehicle speed above 50 km/h. As a result of the rapid enhancement of engine design technology and the growing number of electric/hybrid vehicles which emit no/less combustion noise, the contribution of tyre/road noise to overall traffic noise becomes more and more predominant. The European Union (1996) addressed the importance of tyre/road noise in future noise policy for easing traffic noise in 1996. In the following thirteen years, it formulated a tyre labeling system (European Union, 2009) for describing the tyre/road noise performance. This labeling system was enforced in November 2012 for all the new tyre models to be sold in Europe. This stimulated the tyre manufacturers to produce tyres with better noise performance. Currently there are a number of tyre models in the market proclaiming to have good noise performance for instance ZT5 of Avon (2011), Primacy LC of Michelin (2012) and Super E-Spec of Yokohama (2009). Tyre/road noise is drawing more and more attention from the governments around the globe, the tyre manufacturers and the market. From Hong Kong and international perspectives, assessment and abatement of this evolving traffic noise source is of utmost significance.

In 2006, a standard tyre/road noise measurement method, called Close-Proximity Method (CPX Method), was first adopted to explore the influence of road surface material on tyre/road noise by the Hong Kong Polytechnic University (PolyU). For details the work of Hung et al. (2006) is referred. In this method, the tyre/road noise is measured using two microphones installed in a trailer with a test tyre mounted. With the funding support by the Environment and Conservation Fund (Project No. 2007-11), the PolyU Mark I Single-wheeled CPX Trailer was designed and fabricated. It essentially consists of an enclosure, one test tyre on the middle of road lane inside the enclosure and two supporting wheels on the wheel tracks outside the enclosure (Figure 1.1). For further enhancement to the measurement quality and adaptability of the method to Hong Kong environment, the fund has further supported the university to develop the PolyU Mark II Twin-wheeled CPX Trailer (PolyU, 2010) which is the one developed in this study (Figure 1.2). Different from the first generation, the Mark II has two test tyres positioned on the wheel tracks of road lane to monitor the actual tyre/road noise condition of public roads in use. The two test tyres also act as the supporting wheels to avoid noise disturbance from tyres of any additional supporting wheels. In addition to rearranging the test tyre position, this study attempts to further enhance the measurement method by reducing any plausible factors of influence in practice during measurement.

(a)

(b)

Figure 1.1 PolyU Mark I Single-wheeled CPX Trailer. (a) Overview. (b) Single test tyre on centre of lane.

(a)

(b)

Figure 1.2 PolyU Mark II Twin-wheeled CPX Trailer. (a) Overview. (b) Twin test tyres at wheel-track of lane.

1.3 Motivation of present study

Researchers have been studying the influencing factors to tyre/road noise since mid 70s. Along with the evolutions of design and technology of tyres and road surface materials, many researches continue for evaluation of various physical parameters affecting tyre/road noise emission, namely aggregate size, thickness of pavement, tyre rubber hardness, vehicle speed and temperature (Sandberg and Ejsmont, 2002). Recently the noise control community has confirmed that the tyre/road noise will play a relatively more important role than the combustion noise following the evolving trend of electric/hybrid vehicles.

In the early stage of tyre/road noise study, researchers worldwide carried out their works with various measurement methods with tailor-designed instrumental setup for their individual concern on feasibility in practice, target of study, research quality and financial criteria. The large variation in the designs of these tailor-made methods of studies may not provide a comparison on common ground and hinder filling of knowledge gaps in tyre/road noise based on findings by different research groups. In year 2000, the International Organization for Standardization (ISO) formed a research working group to formulate a standard tyre/road noise measurement method named Close-Proximity Method (ISO/CD 11819-2, 2010). The Close-Proximity Method, hereafter abbreviated as CPX Method, measures tyre/road noise emitted by test tyre(s) installed to a trailer travelling on a road section at a reference speed. At least two microphones per test tyre are mounted in the trailer and they are positioned close to and oriented pointing towards the tyre/road contact patch. Details of the setup, data collection and relevant computation are presented in Chapter 2.

CPX Method has the advantage of not requiring road control at the test section and thus no disturbance to normal traffic. It also allows assessing the in-situ condition of the road surface material paved on real roads. CPX Method has been gaining high popularity among various research institutes and government departments worldwide for measurement of tyre/road noise. Different variant models of CPX trailer have been designed (Silent Roads, 2002; Roo et al., 2009; LA2IC, 2013). There is even a consulting company (M+P, 2014) which provides tyre/road noise measurement service with fleet of CPX trailers. To cope with the practical concern on disturbance to the measurement by other noise sources in the traffic, for instance engine and tyre/road noises by vehicles passing by at adjacent lane, these CPX trailers are usually equipped with acoustically-treated enclosures covering up the test tyre(s) and microphones. The treatments include using sound isolation panel to shield external background noise and sound absorption material to minimize internal reflection inside the enclosure. The treatments and the associated acoustic requirements by ISO/CD

11819-2 (2010) are discussed in Section 2.2.4. Although ISO/CD 11819-2 (2010) has already addressed a number of factors which may affect the measurement as discussed above, this study searches for other plausible factors of influence to further improve the measurement accuracy of CPX Method, particularly as well as the credibility of its results for its applications in highly urbanized environment. The levels of influence by vibration-induced error in microphone signal by road bumpiness, temperature effect and road curvature effect on CPX Method are evaluated in this study. These plausible factors of influence to the measurement method are introduced below.

Vibration-induced error in microphone signal

Microphones are rigidly mounted to the CPX trailer to measure the noise emitted by the interaction of the rolling test tyres and the road surface. As the trailer travels on real roads which are usually not perfectly flat and smooth, vibration is imposed from the road to the trailer and transferred to the microphones. Since the measuring mechanism of microphone is by sensing sound pressure fluctuation through vibrational response of the microphone diaphragm, the self-vibration of the microphone may produce erroneous sound pressure signal which is not yielded by the incident noise but the additional vibration-induced relative displacement between the diaphragm and the back plate electrode. Therefore, an erroneous component may exist in the measured tyre/road noise level, especially for measurements done on bumpy road sections. This study attempts to evaluate and correct for this vibration-induced error in CPX Method. A comprehensive study with literature survey, devised experiments, results, analysis and discussion is presented in Chapter 5.

Air temperature effect on measured tyre/road noise level

Bühlmann and Ziegler (2011) and Jabben (2011) have shown that tyre/road noise level decreases when ambient temperature increases. As Hong Kong is located in subtropical region, the variation in temperature at different time or places may have an impact on the noise levels measured. For instance, in evaluation studies of the long-term tyre/road noise performance of a road surface material (Lam et al., 2012; Ho et al., 2013), a set of measurements are conducted over a year. The change in temperature during measurement may induce error to the monitoring result. Another example is that, when assessments are made on two types of road surfaces which are located in different regions and with different levels of sunshine, the comparison between them may be unfair since the one with stronger sunshine tends to give a lowered noise level by the temperature effect. This leads to misleading noise ranking of the road surface materials.

The working group of ISO/CD 11819-2 (2010) addresses the temperature effect on tyre/road noise measurement and attempts to develop a correction formula to compensate for the effect with respect to a reference air temperature of 20 ℃. As the parameter, known as "temperature constant", in the formula is found to vary with different combinations of tyre and road surface, studies on temperature effect could enhance the accuracy of CPX measurement and may also assist the working group.

<u>Road curvature effect on measured tyre/road noise level</u>

According to Sandberg and Ejsmont (2002), there are multiple noise generation mechanisms of tyre/road noise which are categorized into aerodynamically-related and vibration-related ones. To the latter category, an important contribution is the tyre tread vibration caused by its stick-snap motion in which the tread blocks adhere to and then detach from the road surface during a tyre rotation cycle. As a car travels through a road corner, the centripetal force is provided by the friction between the tyre tread blocks and the road surface for changing its original direction. This may interfere with the vibration of the tread blocks and subsequently the structural-borne noise. Tönük and Ünlüsoy (2001) have shown with experiment and finite element modeling that the centripetal force on the tread blocks during cornering can reach up to 3500 N depending on the inflation pressure and angle of wheel turning. It is anticipated that such force will deform the tread blocks and consequently its vibration. The structure-borne noise generation mechanisms (e.g. tread impact, stick-slip and stick-snap) may thus be interfered. In the studies on cornering influence on tyre/road noise by Ejsmont and Sandberg (1988), a set of measurements were conducted on SMA surface for three models of passenger car tyres using Tiresonic Mk1 Trailer. The tested radii of curvature were 60 m and 85 m. Their results show that the tyre/road noise level could be increased by 0 – 2 dB at lower speed (30 km/h), by 0 – 5 dB at the middle speed (50km/h) and by 1 – 7 dB at higher speed (70 km/h). These results clearly illustrate that tyre/road noise is influenced during vehicle cornering and the effect has to be investigated for fair comparison of road surface materials laid on different road sections.

Sometimes it is inevitable to select a curved public road as test section due to the relatively limited choices of roads in a highly urbanized city. The plausible road curvature effect to the measured tyre/road noise level is of concern although ISO/CD 11819-2 (2010) has already made a short note on road curvature as a criteria for selection of road as test section. It is suggested that measurements should not be conducted at road with radius of curvature smaller than 250 m and 500 m for reference speeds of 50 km/h and 80 km/h respectively. As the advice is very brief without further explanation on the recommendations, this study looks into this issue by conducting experiments to investigate the influence by road curvature on the measured noise level with CPX Method.

1.4 Objectives of study

This study aims to further enhance the CPX Method, developed at PolyU, by enhancing the credibility of its measurement of tyre/road noise in urban environment of Hong Kong. Plausible factors of influence to the measurement method are identified and adaptive measures to the issues are proposed and discussed in an attempt to improve the reliability of the measurement results. Parameters of study include vibration, air and road surface temperatures, pavement type, radius of road curvature. Extensive CPX measurements are conducted to achieve the objectives stated.

Tasks executed in this research study are listed below:

i. Reviewing the standard CPX Method for tyre/road noise assessment.

ii. Designing and development of a CPX trailer for conducting measurements in Hong Kong.

iii. Certification of the developed CPX trailer in accordance to ISO/CD 11819-2.

iv. Conduction of on-road measurements with CPX Method and assess its practicability and reliability in urban environment of Hong Kong.

v. Exploration of vibrational effect on the microphones in CPX Method and propose adaptive solutions to the problem.

vi. Development of temperature correction factors for local common road surface materials and evaluation of reliability of corrections with air and road surface temperatures.

vii. Exploration of the relationship between tyre/road noise level and radius of curvature of road section and develop criteria of road curvature for adoption of test section from public roads.

1.5 Structure of thesis

This thesis presents and discusses the research methods and findings for evaluation of four possible factors of influence to Close-Proximity Method for tyre/road noise measurement – background noise disturbance, vibration-induced error in microphone signal, temperature and road curvature effects. Chapter 2 gives a literature review on the current understanding of tyre/road noise generation mechanisms, features and data computation of CPX Method. Chapter 3 introduces the background, the configuration and the features of the PolyU Mark II Twin-wheeled CPX Trailer developed in this study. Chapter 4 presents the devised setups and the measurement results of the three certification tests stipulated by ISO/CD 11819-2 (2010). Chapter 5 concentrates on vibration-induced error in the measured tyre/road noise level with the background theory, the hypothesis involved and analysis on the results from the devised experiments. Chapter 6 is a study on the temperature effect on the tyre/road noise with review on the approaches by researchers worldwide and the devised approach with its results and findings. Chapter 7 presents the study on road curvature effect on tyre/road noise comprising of the test hypothesis, methodology, results and findings. Lastly, Chapter 8 gives overall conclusions to this study.

CHAPTER 2

LITERATURE REVIEW

In this chapter, literature survey is conducted to review the generation and amplification mechanisms of tyre/road noise and the Close-Proximity Method (CPX Method) for measurement of the noise. For the first part, the mechanisms of airborne noises, structure-borne noises and amplification effects by various tyre components are illustrated and discussed. For the second part, features and limitations of the CPX Method are presented with existing CPX configurations worldwide. The signal handling and manipulation in CPX Method and certification of CPX trailer are introduced.

2.1 Generation and amplification of tyre/road interaction noise

Modern vehicle tyre is a complex composite structure and multiple tyre/road interaction noise generation mechanisms are involved when a tyre rolls against the road surface. Sandberg and Ejsmont (2002) have categorized the identified mechanisms of tyre/road interaction noise into two groups, namely the structure-borne and the airborne noises. Kropp et al. (2003), Dai and Lou (2008), Peeters and Kuijpers (2008) also refer them as “vibration-related” and “aerodynamically-related” respectively. Once generated, these noises further then undergo amplification caused by different structures formed by the tyre and road surfaces. Basic knowledge of the structure of modern tyres is essential for an understanding of the generation and amplification of tyre/road interaction noise. It is briefly discussed in the following sections.

2.1.1 Structure of modern tyres

Figure 2.1 illustrates the schematic cross-section of modern vehicle tyres by tyre manufacturer Hankook (2014). The torus-shaped tyre is mounted to the rim of the ring-shaped bead core which acts as a hoop. The formed ring of pipe between internal walls of the tyre and the rim formed a cavity for inflation of air. The carcass refers to the inner layers of fabric ply which supports the air pressure as well as vertical load and absorb shocks. The cords of each layer of fabric ply are in the same direction but may differ between layers. Two common types of fabric ply are applied in the automotive industry – radial ply and bias ply where the cords are in the direction same as and at angle to the circumferential direction respectively (Revzilla, 2014). Figure 2.2 illustrates the direction of cords in radial and bias ply tyres. The belt is used for reinforcing the connection between the carcass and the tread. The external rubber structure of a tyre can generally be divided into three parts, namely the tread, the shoulder and the sidewall. The tread refers to the layer of rubber in contact with the road surface. It provides the friction forces required for vehicle acceleration, braking and cornering. The tread pattern is usually designed to be equipped with channels of cavity between tread rubber blocks, known as grooves, so as to tunnel water out from the tyre/road contact patch on wet surface. That way serves to increase tyre grip and consequently the vehicle safety. Shoulder refers to the thickest portion of rubber between the tread and sidewall. The flexible sidewall is marked with various information of the tyre model for instances trademark of tyre manufacturer, name of the model, tyre size and some other parameters like maximum inflation pressure, date of manufacture and country code.

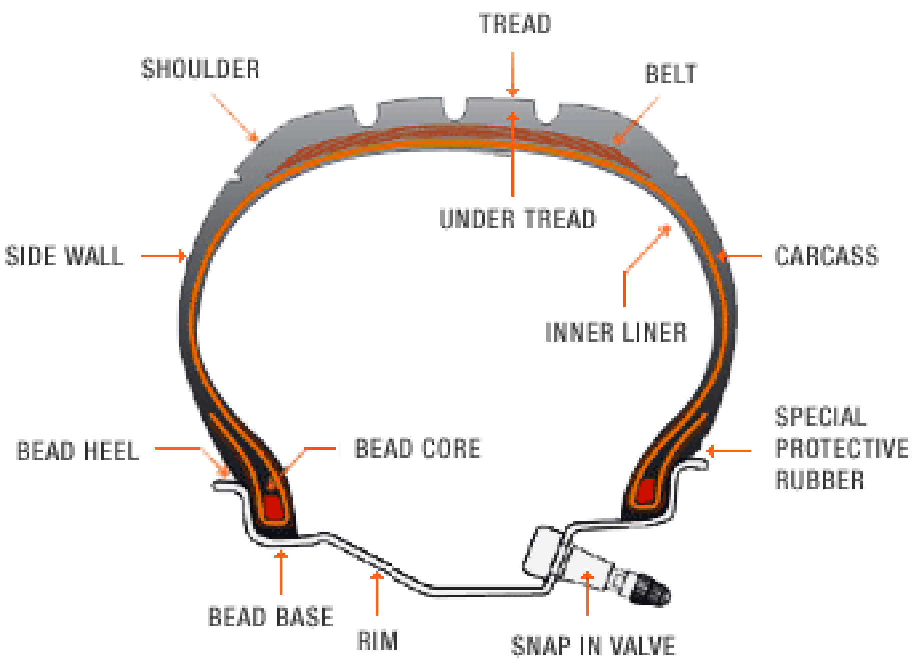


Figure 2.1 Structure of a modern vehicle tyre.

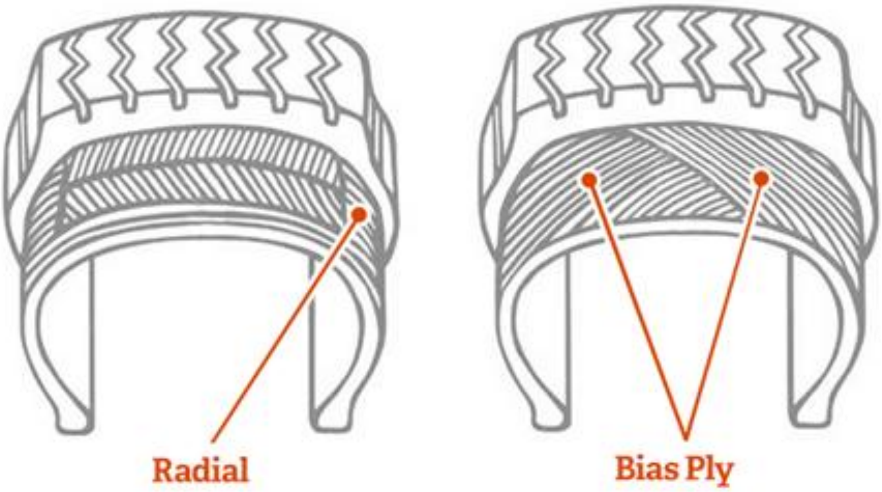


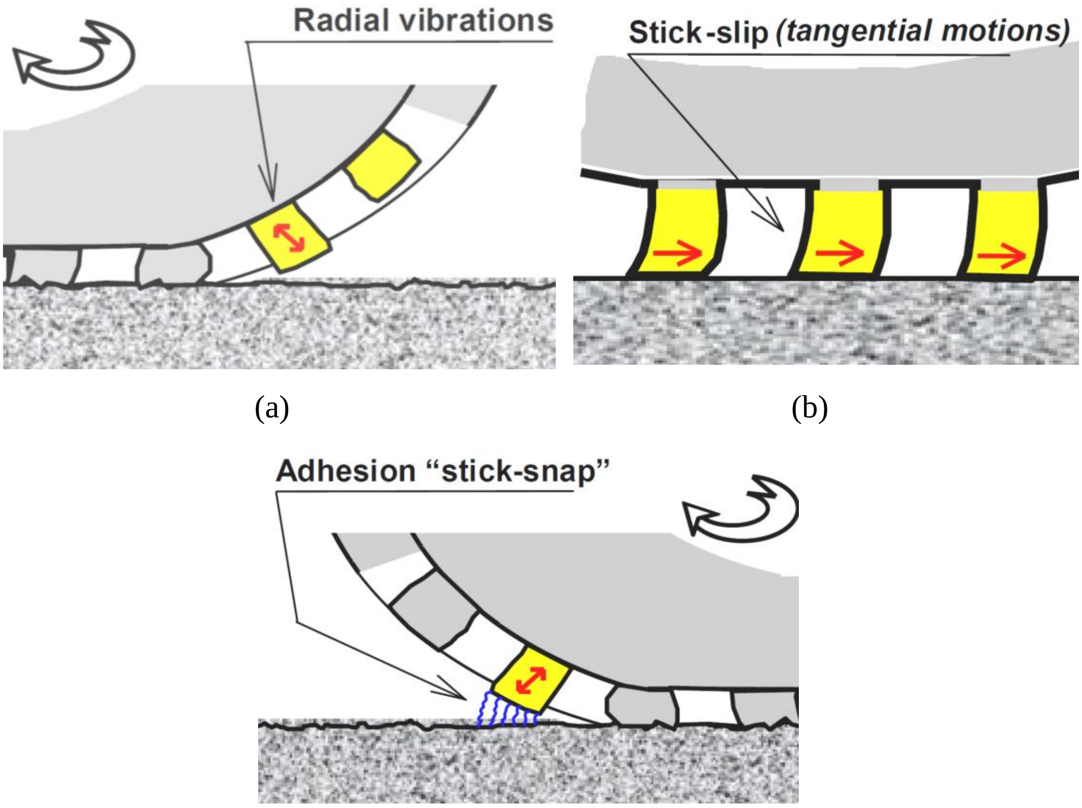
Figure 2.2 Direction of cords of radial and bias ply tyres.

2.1.2 Structure-borne noise

The structure-borne noise of tyre/road interaction are radiated from different tyre components, for instance the tyre tread blocks and sidewall, when the tyre rolls on a road surface and are excited to vibrate by road roughness elements which deform the tread and sidewall upon impacting onto and leaving the road surface (Kujipers and Blokland, 2001). The interaction between the tread blocks and the road surface material involves impacting, slipping and snapping. These actions cause the tread blocks to vibrate in both radial and tangential directions to the tyre circumference. The bumpiness of road surface causes repeated deformation of the tyre sidewall in a flexing motion. Kim et al. (1997) states that tyre vibration is a major source of tyre/road noise below 1 kHz.

Vibration of tread blocks

When a tyre is rolling against the road surface, the tyre tread blocks impact onto the road surface. Perisse (2002) states that radial vibration of tread blocks is resulted from their interactions with the road surface material and mainly radiates noises in the low to medium frequency ranges. The noise generation mechanism is illustrated in Figure 2.3a. When the tread blocks reach the tyre/road contact patch, frictional force is imposed onto the tread blocks to push the vehicle forward. This causes the blocks to deform and attain potential energy. As they enter the trailing edge of the patch and are released from the bending by the frictional force as shown in Figure 2.3b, the stored potential energy transforms into kinetic energy in form of vibration that radiates structure-borne noise under the action of stick-slip in which the rubber materials of the tread block exhibit reduction of friction when their relative speeds increase (Kujipers and Bloklan, 2001). Such phenomenon could be explained by the theory of negative friction gradient with speed (You and Hsia, 1995). Robert et al. (2007) describe the stick-slip motion with the analogy of sport shoes squeaking on basketball court. They state when the tread blocks at the tyre/road contact patch are continually deformed and distorted, and the blocks slip periodically, squeaking sound is radiated. In addition, the adhesion of the tyre tread blocks to the road surface also results in vibration of treads. The mechanism involved is termed as stick-snap as shown in Figure 2.3c. Robert et al. (2007) describe this noise generation mechanism with the analogy of a suction cup being detached from a surface. Kujipers and Bloklan (2001) state that it results from the increased adhesive strength when the surface of the tread blocks are sticky and the road surface is very clean. The tyre tread blocks are excited to vibrate when they adhere to the road surface and get detached in a tyre rotation cycle. The vibration of the tread blocks produces structure-borne noise.



(c)

Figure 2.3 Vibration of tread blocks during tyre rolling. (a) Tread impact. (b) Stick-slip action. (c) Stick-snap action. (Images reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

Vibration of sidewall

In addition to the tyre tread blocks, vibration of tyre sidewall is also regarded as one of the sources of tyre/road interaction noise generation. When the vehicle is travelling on real roads, the bumpiness of the road surface causes the tyre to deform repeatedly which causes repeated flexing motion of the sidewall (Figure 2.4). The resultant vibration of this large surface deformation attributes to the radiation of sound. On the other hand, the tread vibrations are transferred to the sidewall which shows a sounding board alike structure (Kujipers and Bloklan, 2001). The transferred vibration thus also constitutes to the radiation of noise from the sidewall.

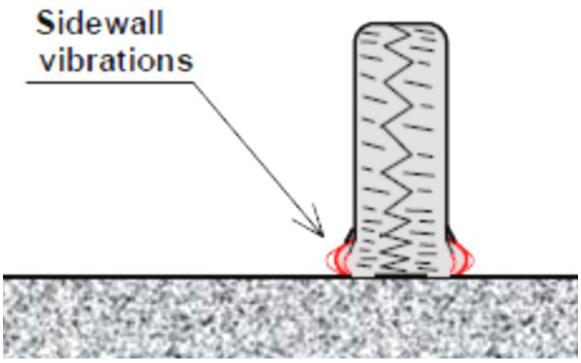


Figure 2.4 Vibration of sidewalls during tyre rolling. (Image reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

2.1.3 Airborne noise

The airborne noise of tyre/road interaction is radiated from the air displacement around the rotating tyre. Instances include pumping of trapped air at the cavities formed between the tread grooves and the road surface, and air turbulence caused by the drag around the rapid spinning tyre/rim configuration. The mechanisms involved are explained below.

Air pumping

When a tyre rolls on the road surface, the air close to the leading edge of the tyre/road contact patch is sucked into the cavities formed between the tread gaps and the road surface (Figure 2.5). The trapped air then enters the compressed volume at the contact patch. As the tyre continues to rotate, the air-filling cavities migrate backward and eventually reach the trailing edge of the contact patch. At this moment of the trapped pressurized air within the cavities is expelled and gives rise to noise radiation (Hayden,1971; Kujipers and Blokland, 2001). Moreover, Hayden (1971) developed an expression indicating that the mean squared sound pressure is directly proportional to the fourth power of the vehicle speed. This continuous process of pressurizing and releasing the air at the patch is referred as air pumping. Sandberg and Ejsmont (2002) regard it as one of the dominating generation mechanisms of tyre/road noise.

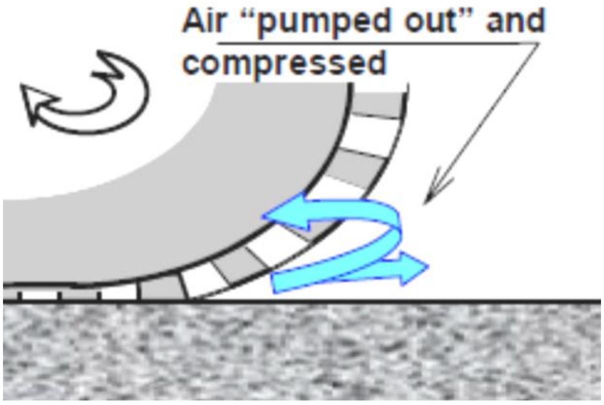


Figure 2.5 Air pumping resulted from pressurizing and releasing air near tyre/road contact patch. (Image reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

Air turbulence

Air drag and turbulence are formed around a spinning wheel. One should note that air is dragged not only around the tyre but also the rim. Sandberg and Ejsmont (2002) compare and consolidate researches worldwide on this noise generation mechanism. They find that the research results indicate consistently that the mechanism has negligible contribution to the overall noise level even when the vehicle speed reaches 100 km/h. This mechanism is usually not considered unless for circumstances when the tyre/road noise is measured at speeds higher than normal allowable highway speeds.

2.1.4 Amplification effects

<u>Horn effect</u>

In the proximity of the leading/trailing edge of the tyre/road contact patch, the tyre and road surface forms a narrow volume of space. On moving away from the patch, this volume becomes larger and forms a wedge or horn alike geometry. Nilsson and Bennerhult (1979) suggest that this exponentially widening geometry resembles the acoustic horn which amplifies the noises generated as mentioned above. The phenomenon is referred as horn effect as shown in Figure 2.6. Theoretical model results from Kropp et al. (2000) show that the amplification effect can reach up to 20 – 25 dB. Graf et al. (2002) also found from experimental results that the effect is responsible for an additional 10 – 20 dB increase in noise level. These findings point out that horn effect can cause significant amplification to the noises generated.

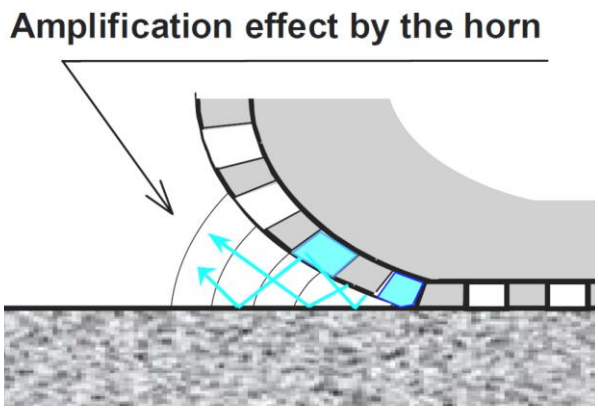


Figure 2.6 Horn effect. (Image reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

Air resonance

Acoustic resonance is resulted when a sound wave enters a volume with its natural frequencies matching that of the incident sound wave. Due to the complex geometries of the tyre and road surface, many closed volumes with different dimensions are formed at their contact patch. Modern tyre pattern designs are usually incorporated with grooves between tread blocks to provide space for water escape to enhance grip and safety in wet condition. Cavities are formed between these tread grooves and the road surface (Figure 2.7). As these cavities reach the trailing edge of the tyre/road contact patch, an opened volume is formed. Robert et al. (2007) make an analogy of this volume to an opened bottle. Helmholtz resonance is possible upon blowing across the top of the bottle. Kropp (1999) states that Helmholtz resonance applies in the case of tyre/road noise where the cavities between the tread grooves and the road surface form volumes with openings. These geometries constitute to the Helmholtz resonators of tyre/road noise.

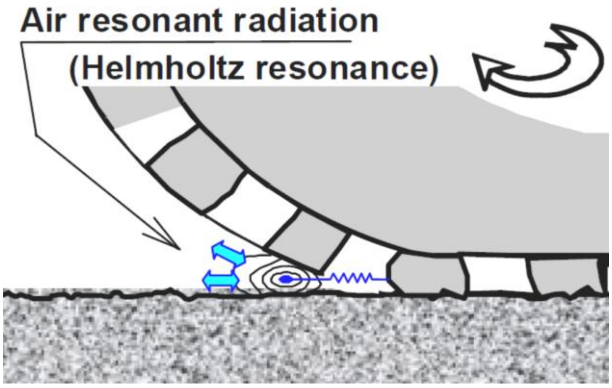


Figure 2.7 Air resonance at the cavities between the tread gaps and the road surface. (Image reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

Belt resonance

Vibrations resulting from road bumpiness imposed to tyre sidewalls and its tread blocks are partly transferred to the tyre belt due to their direct connection. When the vibration frequencies match the mechanical natural frequencies of the tyre belt, it causes the belt to vibrate and resonate (Figure 2.8). Kropp et al. (1998) found that increasing the mass and the bending stiffness of the belt cause substantial reduction in tyres/road noise radiation. They believe that modification to the belt play an important role for abatement of tyre/road noise.

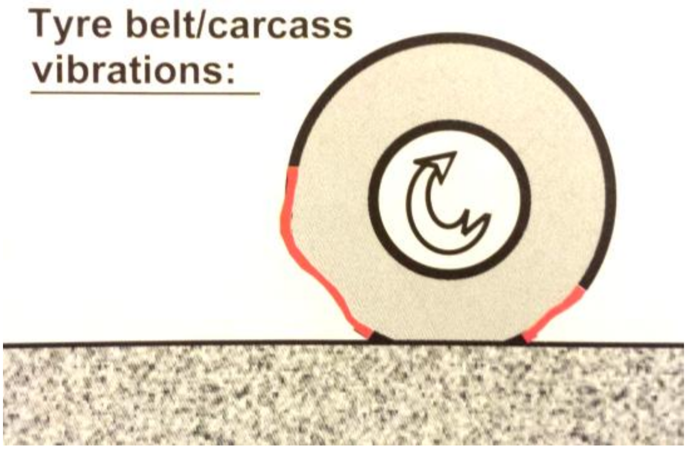


Figure 2.8 Tyre belt resonances. (Image reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

Pipe Resonance

Robert et al. (2007) and NZ Transport Agency (2014) refer to pipe resonance with an analogy of an organ pipe where the noise is amplified at unique frequency related to the length and number of openings of the pipe. As illustrated in Figure 2.9, pipe-alike geometries can be found at the tyre/road contact patch with the tunnel formed between the tread grooves and the road surface. Kujipers and Bloklan (2001) state that this geometry constitutes a system of pipe resonators with resonant frequencies depending on the geometrical properties of the formed pipe but independent of the rotational speed of the tyre.

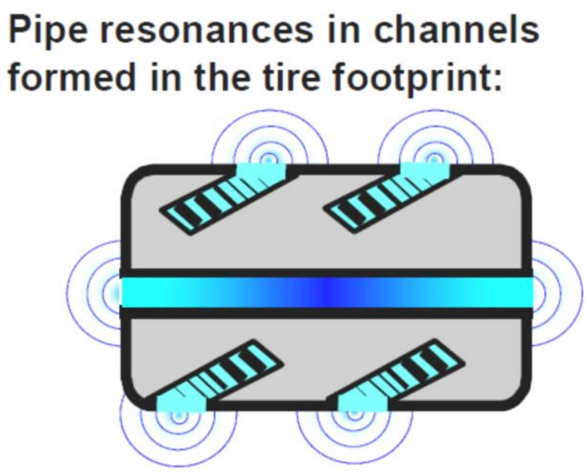


Figure 2.9 Pipe resonances. (Image reproduced from Sandberg, Ejsmont: Tyre/Road Noise Reference Book).

2.1.5 Range of frequency by the noise amplification/generation mechanisms

Although multiple noise amplification/generation mechanisms have been identified, Kropp et al. (2003) states that it is often difficult to have a general answer at which frequencies these mechanisms are dominant due to the vast combinations of tyre and roads. However, Sandberg and Ejsmont (2002) have attempted to consolidate the tyre/road noise researches worldwide and provided the overall approximate ranges of frequency taken by the noise amplification/generation mechanisms. Their summary is plotted in Figure 2.10. The tread vibration related noise generation mechanisms, which are tread impact, stick-slip and stick-snap, jointly spread through from low to high frequency ranges. The vibration of sidewall which is a relatively large surface accounts for the low to medium frequencies. Airborne mechanisms of air pumping and air resonances coincide in the medium frequency range. The amplification mechanisms of belt resonance, horn effect and pipe resonance cover medium-low to medium-high frequency ranges.

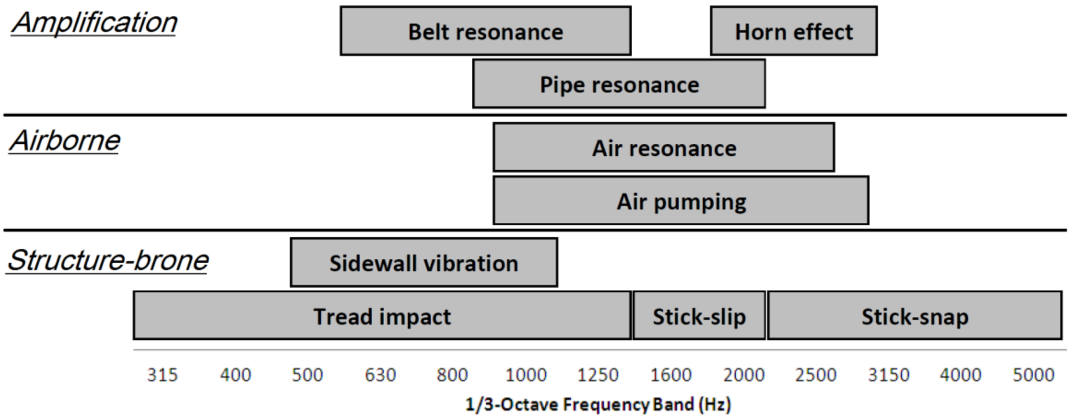


Figure 2.10 Summarized range of frequency by different tyre/road noise amplification/generation mechanisms.

2.2 Close-Proximity Method

Since the aim of this study is to enhance the credibility of the CPX Method for measurement of tyre/road noise, it is essential to have understanding towards the design features of existing CPX configurations worldwide and also the data acquisition and process involved in CPX Method. In this chapter, the common features and general limitations of the method are illustrated and discussed with examples of existing CPX configurations. Following this, the signal handling and manipulation and three certification tests stipulated by ISO/CD 11819-2 (2010) are presented.

2.2.1 Existing CPX configurations

The CPX Method is an international standard measurement method (ISO/CD 11819-2, 2010) developed to assess the tyre/road interaction noise emitted from test tyre(s) travelling at specific reference speed on a real road section or a dedicated test section in a large laboratory. Unlike traditional pass-by method where the microphone is mounted to a tripod and positioned at the road kerb to measure noise from passing by vehicles, the microphones in CPX Method travel with the tyre/road contact patch at its close-proximity. Most of the designs utilize the trailer approach where the test tyre(s) is mounted into a trailer installed with microphones while some of the designs use the non-powered wheel of the vehicle being driven as the test tyre. Specific features and limitations of CPX Method are illustrated and discussed with typical examples of existing CPX configurations worldwide below.

Non-trailer approach without enclosure

Colas (2014) adopts the approach of using the non-powered wheel of the test vehicle as the test tyre as shown in Figure 2.11. From the perspective of conduction of measurement, this approach has an advantage over the trailer method that the configuration has higher flexibility in travelling on narrow roads and thorough tight bends. Moreover, instead of the complex mechanical structure of the trailer, just a simple beam is required for holding the microphones. It is more convenient for the operators to prepare the setup. Nevertheless, in addition to the measuring target of noise from the test tyre, disturbances of engine and tyre/road noises from the vehicles passing by at adjacent lanes are also measured because the measuring microphones are completely exposed to the external environment. Paje et al. (2008) recommends a practice utilizing this setup for a measurement without traffic to ensure that noise results are not disturbed. Obviously, this configuration is not suitable for use in an urban environment, like Hong Kong, in which the road traffic is usually heavy. Figure 2.12 shows a typical traffic condition in peak hour of Hung Hom which is a highly urbanized area of Hong Kong.

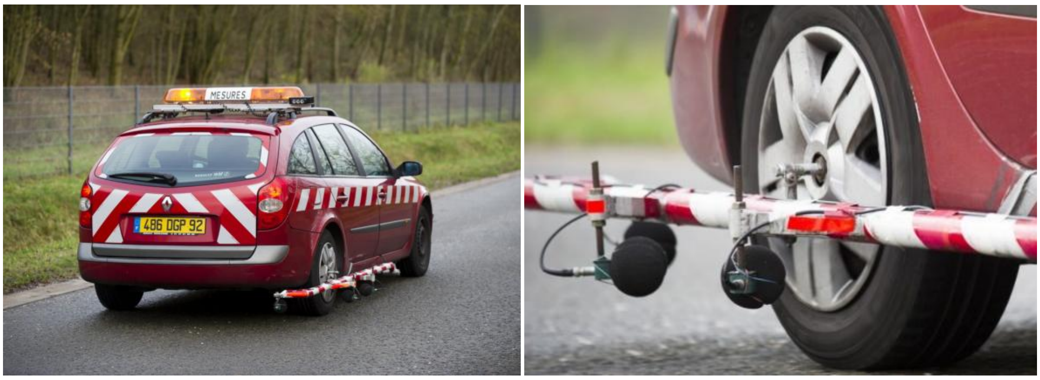


Figure 2.11 CPX configuration by COLAS with tyre of the driven passenger car as the test tyre and without enclosure (retrieved from http://colas.hu/).

Figure 2.12 Typical road traffic condition in peak hour of highly urbanized area of Hong Kong.

Unenclosed trailer approach

SILENTROADS (2008) adopts the unenclosed trailer approach where a light goods vehicle is used to tow the trailer which is installed with test tyres and microphones (Figure 2.13). Having the trailer extending from the test vehicle, the disturbance of its engine and tyre noises is reduced greatly compared to the non-trailer approach. Nonetheless, the measured noise is still contaminated by disturbance from passing by vehicles at adjacent lanes. This method is also not advised for urban environment of Hong Kong.

Figure 2.13 CPX configuration by SILENTROADS, with twin-test tyres at wheel-track of lane and trailer without enclosure (retrieved from http://www.silentroads.nl/).

Enclosed trailer approach

Tiresonic Trailer Series were developed by the Technical University of Gdansk since the 80s. Up to now, 4 generations of the trailers have been constructed (Figure 2.14). These generations share the same design principle with single test tyre at the middle of road lane and additional supporting wheels. The disturbance from external noise sources is shielded and reduced by the enclosure so the signal-to-noise ratio of the measured data is greatly improved. The internal walls of the enclosure of the trailer are usually acoustically treated with sound absorption material so as to minimize the internal reflection. They incorporates supporting wheels to the trailer and position the test tyre at the middle of road lane. The rear supporting wheels are mounted to prevent damage of the enclosure on bumpy roads and during loading on ferries, ramps, etc. However, the tyre/road noise from the front supporting wheels, which are in contact to the road surface anytime, may produce disturbance to the measured noise. Moreover, having the test tyres positioned at the middle of the road lane does not reflect the actual condition of real roads in use because the deterioration and aging of the road surface materials happen mainly at the two wheel-tracks. Figure 2.15 shows the difference in road surface condition between the middle and wheel tracks of a public road. Clear aggregates are observed at the middle while the road surface material on the wheel tracks are washed out.

(a)


MÄTNING
GDN
276D
GNA 0569

(b)


GD 70973
Brüel & Kjær
GD 2256P
PL
MÄTNING

(c)

(d)

Figure 2.14 Tiresonic Trailer Series. (a) Mk.1. (b) Mk.2. (c) Mk3. (d) Mk.4. (Images reproduced from Ejsmont et al. (2014); Ejsmont et al. (2000); Świeczko-Żurek et al. (2014) and LA2IC (2013) respectively).

Figure 2.15 Washed out road surface on wheel-tracks and clear aggregates at middle of road lane.

CoMet CPX Trailer, developed by the consulting company M+P in Netherlands, adopts a twin-wheeler design without additional supporting wheels with the test tyres positioned at the wheel track of road lane. It has been so successful that a fleet of trailers are built to provide consultancy services and they have also sold CoMet CPX trailer to various research institutes and road agencies such as Federal Highway Research Institute (Bundesanstalt für Straβenwesen, BASt) in Germany and one in Flemish Agency for Roads and Traffic, Belgium. This configuration is advised since it has the feature of shielding external noise disturbance and positioning the test tyres on the wheel track which allows assessing the actual tyre/road noise condition of public roads in use.

Figure 2.16 CoMet CPX Trailer by M+P (Photos reproduced from http://www.mplusp.eu/products/measuring-road-noise-go-comet-cpx).

2.2.2 Features and limitations of CPX Method

Following a brief introduction of existing CPX configurations adopted by various research groups or consulting companies, the common features and general limitations of in CPX Method are presented and discussed.

Feature 1 – Minimized noise disturbance

The tyre/road noise measurement method in this study is termed “close-proximity” because the microphones in the trailer are mounted at proximity very close to the tyre/road contact patch in accordance to ISO/CD 11819-2 (2010). They are oriented pointing towards the tyre/road contact patch to ensure that the measured signals are dominated by the noise generated there with minimal background noise disturbance. Figure 2.17 illustrates the position and orientation of the front and rear microphones indicated as M1 and M2 respectively. The CPX trailers are usually fitted with an enclosure to shield the disturbing noise on real roads such as engine noise by vehicles travelling at adjacent lane or the towing vehicle itself. The internal walls of the enclosure are fitted with sound absorption material to minimize internal reflection. The associated requirements for the acoustic treatment to the enclosure are discussed in more details in Section 2.2.4.

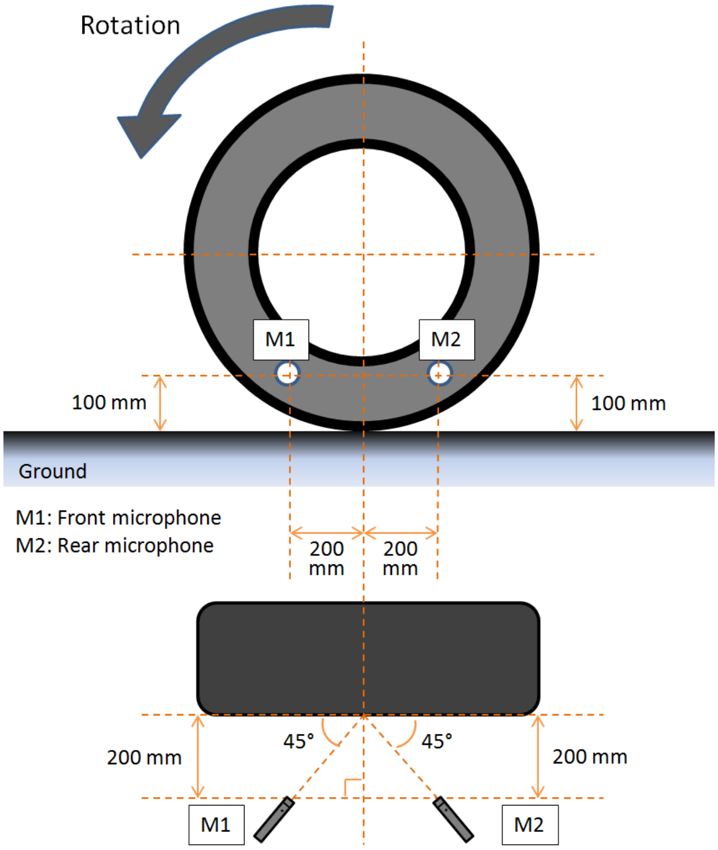


Figure 2.17 Microphones positions in CPX Method.

<u>Feature 2 – Using public roads as test sections without disturbance to traffic</u>

Having the features of creating no disturbance to normal traffic and requiring no dedicated test section in a giant research laboratory, the CPX Method is a practicable and convenient way for researchers to adopt public roads in use as test sections. This also offers an opportunity of assessing the in-situ tyre/road noise performance of public roads which experiences the real traffic condition (Lam et al., 2012; Ho et al. 2013).

Feature 3 – Common Standard Reference Test Tyre

ISO/CD 11819-2 (2010) specifies ***Uniroyal Tigerpaw (225/60R16)*** and ***Avon Supervan AV4 (195-R14C)*** as the reference passenger and heavy vehicle tyres for CPX measurement (Figures 2.18 and 2.19). Considering the fact that the noise from heavy vehicles is yet to be dominated by tyre/road noise and that more than 73% of licensed vehicles in Hong Kong are passenger car from tyre/road noise perspective (Transport Department, 2014), this study therefore focuses on the reference passenger car tyre only. ***Tigerpaw*** is a passenger vehicle tyre manufactured by Uniroyal at the USA. It is also named as ***S****tandard* ***R****eference* ***T****est* ***T****yre* (SRTT). The SRTT is specified to be under static load of 3200 N and inflated to be within 1.9 – 2.1 kPa at cold condition. Any objects stuck to the tyre, usually gravels at the tyre groves, are removed to avoid any plausible influences before conduction of measurement. Due to the strict criteria on the tyre model and properties by ISO/CD 11819-2 (2010), the difference in setup of tyre/noise measurement among research groups is reduced.

(a)

(b)

Figure 2.18 Standard Reference Test Tyre (SRTT) representing passenger car tyres. (a) Side view. (b) Tread pattern.

(a)

(b)

Figure 2.19 Avon Supervan AV4 representing heavy vehicle tyres. (a) Side view. (b) Tread pattern.

General limitation 1 – Vibration to measuring microphones

Although CPX Method allows minimally disturbed in-situ noise measurements on public roads, there are still a number of limitations with the method. The CPX trailer travels on real public roads which are of variety of conditions of road surface. Vibration is imposed to the trailer by road bumpiness and is transferred to the measuring microphones. The sensing mechanism of a microphone is by vibration of its diaphragm (Gayford, 1994), vibration of the microphone may induce error to the measured acoustic signal. In this study, experiments are devised to test for the vibration-induced error to the measurement in Chapter 5.

<u>General limitation 2 – Uncontrollable environmental factor of temperature</u>

Many researches (Kuijpers, 2002; Anfosso-Lédée and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; Jabben, 2011) have consistently shown that tyre/road noise level decreases as air/road/tyre temperatures increase. Owning to such uncontrollable environmental parameter, variation may be added to measurement results across seasons or regions. Although ISO/CD 11819-2 (2010) has addressed such issue by introducing a concept known as “temperature correction” to compensate the influence by temperature, the associated procedure is still not yet mandatory due to variation of correction factors for different road surface types. Temperature effect to the measurement is introduced in Chapter 6 in more details. Air and road surface temperature correction factors for two common local road surface materials are developed with a tailor-devised experiment in this study.

<u>General limitation 3 – Adoption of curved public roads as test section</u>

ISO/CD 11819-2 (2010) has stipulated a number of criteria in selection of a test section which includes radius of road curvature. The change of tyre noise is best demonstrated by the tyre squeal when a vehicle is travelling through a tight corner at high speed. To avoid such influence to the measurement, a note has been made by ISO/CD 11819-2 (2010) in which the minimum radii of road curvature for reference speeds of 50 km/h and 80 km/h are 250 m and 500 m respectively. However, measurement on road sections with bends is sometimes inevitable due to the lack of other feasible choices in this urban city. The hypothesis of road curvature effect is presented in more details in Chapter 7. A test for curvature effect on tyre/road noise is conducted in this study.

2.2.3 Signal handling and manipulation

The workflow of CPX signal handling and manipulation is illustrated in Figure 2.20. The individual step is explained in more details in the following sub-sections. To give a brief introduction, at least 200 metres of data have to be collected in total from all runs. If the first two runs differ by more than 0.5 dB(A), two more runs are required. For the data computation, the A-weighted 1/3-octave band levels of each microphone of a segment are energetically summed from centre frequency bands 315 – 5000 Hz. The results between microphones are averaged to calculate the overall tyre/road noise level of a 20-metre segment. Speed correction is applied to the computed level to compensate the deviation of trailer travelling speed from the dedicated reference speed of test. The result of a run is calculated from the mean results of the segments. Finally, the tyre/road noise level representing the test section is computed from the average between runs. Temperature correction to reference air temperature of 20 °C the final result is optional.

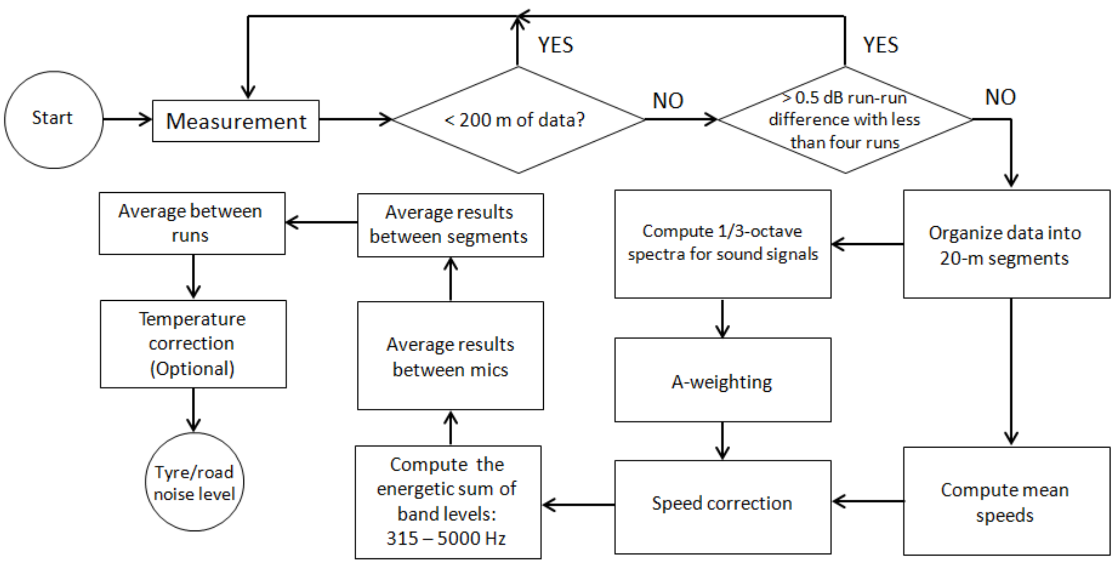


Figure 2.20 Workflow of data collection and computation.

Data collection

To measure the tyre/road noise level of a certain road section with CPX Method, ISO/CD 11819-2 (2010) specifies that at least 200-metre road length of data has to be collected. Each 20 metres of data is regarded as a segment. Data computation is performed to all the segments within the road section, yielding a data point for each. The average of these intermediate results from the segments is regarded as the final result of a run. For sections which already contain more than 200 metres of data in two runs, the measured tyre/road noise level can be accepted if the results by the two runs differ by less than 0.5 dB(A). Otherwise, at least two more runs have to be made. For higher level of confidence, more than four runs are made for the CPX measurements conducted in this study.

Data computation

Upon successful collection of adequate amount of data in accordance to ISO/CD 11819-2 (2010), the A-weighted 1/3-octave noise spectrum of each microphone of a segment of data is computed with exponential averaging mode at fast time constant (0.125 s) for band centre frequencies 315 – 5000 Hz. The band levels are then energetically summed to calculate the overall noise level.

The results yielded from the two microphones are then averaged and speed corrected, yielding the intermediate result of a segment.

Speed correction

In practice, it is difficult to have the towing vehicle travelling at exact constant speed. Deviation from the reference speed is inevitable. To compensate the influence by speed deviation on the measured noise level, speed correction procedure specified by ISO/CD 11819-2 (2010) is implemented according to Equation 2.1.

$$SPL_{V_{ref}} = SPL_{V_{actual}} + B\log\left(\frac{V_{ref}}{V_{actual}}\right) \qquad \text{Equation 2.1}$$

where SPL_{Vref} is the tyre/road noise level in dB(A) at reference speed V_{ref}, $SPL_{Vactual}$ is the tyre/road noise level measured in dB(A) at actual speed V_{actual} and B is a numeric constant termed as speed constant.

Here is an example to illustrate speed correction. The designed test reference speed of a CPX measurement is 50 km/h but the trailer is towed at 55 km/h mean speed at a particular segment. Using the speed constant B of 35, the correction factor to be added to the measured sound pressure level will be $35log(50/55) = –1.5$ dB. This negative correction factor compensates the increase in tyre/road noise level caused by the positive speed deviation of 5 km/h. To be safe, segments with speed deviation from the reference speed by more than ±10 km/h is neglected since the speed correction procedure may not be applicable throughout all speed range.

Temperature correction (optional)

Another correction procedure under proposal in ISO/CD 11819-2 (2010) is for compensation of the temperature influence on the tyre/road noise level in which temperature increase results in drop of tyre/road noise level. The temperature correction constant of –0.03 dB (A)/℃, which is described as conservative, and the reference air temperature of 20 ℃ are suggested. For example if the measurement is conducted at 30 ℃, the resulted correction factor to be added to the measured noise level will be *–0.03 (20 – 30) = + 0.3 dB (A)*.

Although the temperature correction step is not mandatory, the relative large variation in temperature in subtropical region of Hong Kong may have significant impact to measurements conducted across seasons. This study includes an experimental attempt to establish temperature constants for commonly used road surface in Hong Kong in Chapter 6.

2.2.4 Certification

CPX Method is designed for field measurement of tyre/road noise on the real public roads. It is a general fact that environmental disturbances are inevitable in any kinds of field measurement. In the case of tyre/road noise measurement with CPX Method, the main disturbance is the background noise on the road. Example factors of influences include the engine, exhaust and tyre/road noises from vehicles passing-by at adjacent lane. To cope with this issue, CPX trailers worldwide (Roo et al., 2009; M+P, 2014) are usually fitted with an enclosure. The enclosure has to be acoustically treated, not only for shielding the external background noise with rigid panels but also for minimizing the internal reflection with sound absorption material inside. All these measures are important for enhancing the reliability and quality of the tyre/road noise measurement using CPX Method. To ensure that the CPX trailers by research groups worldwide can attain consistent level of reliability, three certification tests have been devised by working group of ISO/CD 11819-2 (2010). The first one is for assessing the internal sound reflection within the enclosure of the trailer. The second one is for testing whether the noise disturbance from the towing vehicle is negligible compared to the tyre/road noise measured. The third one is for assuring that the influencing noise from vehicles passing by at adjacent lane is also negligible. The acoustic design features in response to the certification tests are presented in Section 3.2.1. The actual practice and method of analysis of the tests are illustrated in Chapter 4 for certifying the PolyU Mark II Twin-wheeled CPX trailer utilized in this study.

Certification test 1: Sound reflections against the enclosure and other objects near the microphones

The certification test 1 is to assess the level of influence of sound reflection within the enclosure of the trailer. The reflection could occur from not only the internal walls of the enclosure but also other objects such as the microphone frame and the axle of the trailer. However, the reflections at test tyre and test surface are not the target of test since there will be such reflections even for trailer without enclosure. The experiment is to be conducted in free field environment but the existence of rigid ground is essential for simulation of the road surface in CPX measurement. An artificial noise source is placed near the tyre/road contact patch to simulate emission of tyre/road noise. The analysis is made by comparing the measured noise in cases with and without the enclosure to test out its effect on the measured noise. The difference of 1/3-octave band levels between cases with and without the acoustic enclosure must be within ± 3 dB(A) in 1/3-octave band range of 315 – 5000 Hz.

Certification test 2: Background noise from the towing vehicle itself or its operation

The aim of certification test 2 is to ensure that the noise originating from the towing vehicle contributes negligible disturbance to the measured tyre/road noise level inside the trailer. The analysis is made by comparing the measured noises when the trailer is equipped with test tyres and that without the test tyres. Three reference speeds of 40, 50 and 80 km/h are specified by ISO/CD 11819-2 (2010). The case with test tyre mounted represents the noise from the target of tyre/road interaction along with other disturbing noise from the towing vehicle in normal operation; the case without test tyre indicates solely the disturbing noise. The comparison between the two cases helps checking whether the noise contribution by the towing vehicle is negligible compared to the measured tyre/road noise level in normal CPX measurement. The measured overall A-weighted noise level without test tyre has to be at least 10 dB(A) below than that with tyre mounted. The measured noise difference between cases with and without test tyre must be larger than 4 and 6 dB(A) at 1/3-octave band ranges 315 – 400 Hz and 500 – 5000 Hz respectively.

Certification test 3: Sensitivity to disturbance from other traffic

The third certification test is to ensure that the noise from adjacent passing-by vehicles has negligible influence to the measured tyre/road noise level. Two sets of measurements have to be made. The first one is a normal CPX measurement at reference speed of 80 km/h at road section with dense asphalt concrete road surface. The other measurement is conducted at the same road section but with the trailer parked at road shoulder or any places where the adjacent lane has vehicles passing. After recording of noise from at least 20 passenger cars and 20 heavy vehicles, the 1/3-octave spectra of noise emitted by the noisiest passenger car and heavy vehicles with speed correction to reference speed of 80 km/h are computed. This result is then compared to that from the normal CPX measurement. Compared to the noisiest passenger car and heavy vehicle, the measured tyre/road noise level from normal CPX measurement must be 3 dB and 6 dB higher for 1/3-octave frequency band ranges 315 – 400 Hz and 500 – 5000 Hz respectively.

Concluding remarks of certification test

Upon meeting the requirements of all the three certification tests, the trailer is regarded to have attained adequate performances in shielding external disturbing noise and minimization of internal sound reflection. It is certified to conduct standard CPX measurement. Details of the actual practice and method of analysis of the tests are illustrated in Chapter 4 for certifying the PolyU Mark II Twin-wheeled CPX Trailer utilized in this study.

2.3 Conclusions

In this chapter, literature review on the tyre/road noise generation and amplification mechanisms and the CPX Method for measurement of the noise have been conducted. For the noise, mechanisms of airborne noises, structure-borne noises and amplifications by the different tyre components are presented and discussed. For the CPX Method, features and limitations of it have been illustrated and discussed with examples of existing CPX configurations worldwide. The data collection and manipulation in CPX Method has been introduced.

CHAPTER 3

POLYU MARK II TWIN-WHEELED CPX TRAILER

In this chapter, the background history of evolution from PolyU Mark I Single-wheeled CPX Trailer to Mark II Twin-wheeled CPX Trailer is presented. Comparison between the two generations of trailers is made qualitatively and quantitatively. The design rationale and the features of the Mark II CPX Trailer to tackle challenges in conduction of CPX measurement in this highly urbanized city, Hong Kong, are presented and discussed. Its measurement system with multiple sensory units and a data acquisition device are introduced.

3.1 Evolution from Mark I Single-wheeled CPX Trailer to Mark II Twin-wheeled CPX Trailer

In 2006, through the funding support from the Environment and Conservation Fund, Environmental Protection Department, The HKSAR Government (Project No. 2007-11), the PolyU Mark I Single-wheeled CPX Trailer was designed and fabricated for the measurement of tyre/road interaction noise. It consists of an acoustic enclosure, one test tyre at the middle of road lane inside the enclosure and two supporting wheels at the wheel tracks outside the enclosure (Figure 3.1). In order to further enhance the credibility and the accuracy of the measurements, the PolyU Mark II Twin-wheeled CPX Trailer (Figure 3.2), which is the one utilized in this study, were designed and constructed thanks to the further funding support by the Environment and Conservation Fund in 2010.

(a)

(b)

Figure 3.1 PolyU Mark I Single-wheeled CPX Trailer. (a) Overview. (b) Single test tyre on centre of lane.

(a)

(b)

Figure 3.2 PolyU Mark II Twin-wheeled CPX Trailer. (a) Overview. (b) Twin test tyres at wheel-track of lane.

3.2 Configuration of PolyU Mark II Twin-wheeled CPX Trailer

To inherit the good features of Mark I CPX Trailer, the Mark II is also equipped with an acoustically treated enclosure (Figure 3.2b) for shielding external noisy disturbances and minimizing internal sound reflection. However, some of the design characteristics of Mark I were abandoned due to their limitations observed in its measurements. The first one is to give up the use of additional supporting wheels which plausibly produce disturbing noises to the tyre/road noise measurement inside the enclosure. For Mark II, the two mounted test tyres also act as the supporting wheels so the noise disturbance from the extra tyres is completely eliminated. The second limitation of Mark I is the improper positioning of the test tyre on the middle of the road lane. As the chance for tyres rolling over the road lane middle is relatively much lower than the wheel tracks, the deterioration and aging of the road surface material at the middle are anticipated to be much slower. As such, the tyre/road noise measurement on road sections of public roads by Mark I is not able to reflect the actual performance of the sections. To circumvent such limitation, in the Mark II CPX Trailer the two test tyres are deliberately positioned on the wheel tracks of the road lane where better record and reflect the actual noise performance of public roads in use. To compare the measurement results collected by Mark I and

Mark II, a mass survey is conducted with Standard Reference Test Tyres (SRTT) on over 70 public roads with both pervious and impervious road surfaces from brand new condition to the age of over 10 years. The results are shown in Figure 3.3. Traceable linear trend between the measured tyre/road noise levels obtained by the two trailers can be observed with goodness of fit at 0.7. From Figure 3.3, the noise levels measured by Mark I are generally lower than the corresponding ones by Mark II by 1 to 2 dB(A). This matches with the anticipation of slower deterioration and aging of road surface material at the middle of road lane than that at the two wheel tracks.

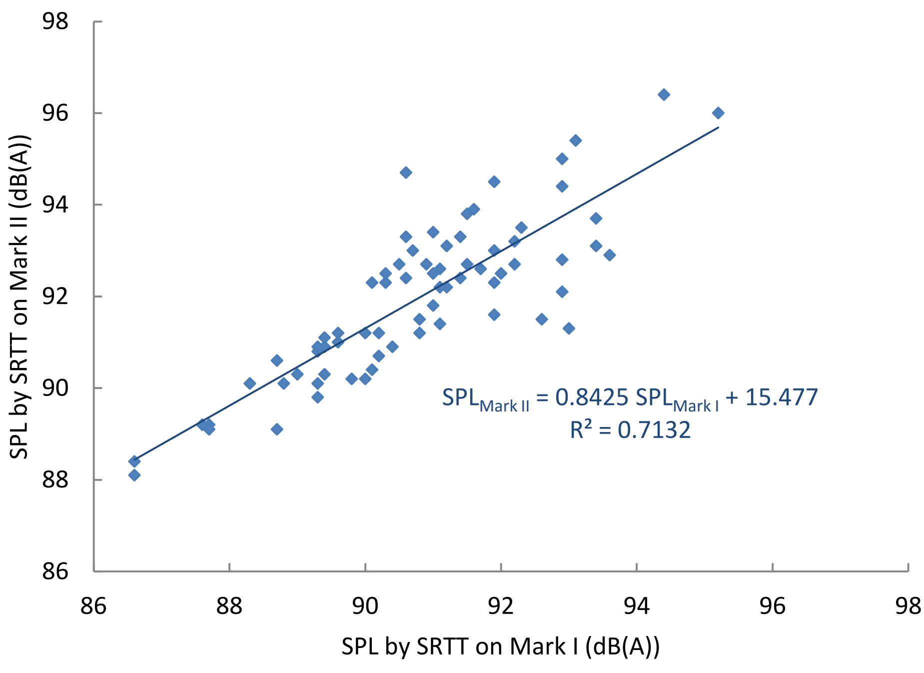


Figure 3.3 Measured Tyre/road Noise Levels by PolyU Mark I Single-wheeled and Mark II Twin-wheeled CPX Trailers.

Special design features are incorporated to Mark II CPX Trailer to tackle the challenges in running CPX measurement in such tough environment of highly urbanized city as Hong Kong. For conduction of researches on different influencing factors to the tyre/road noise, multiple sensory units are deployed to the Mark II CPX configuration. The design features of the trailer and its measurement system are presented as follows.

3.2.1 Design Features

The PolyU Mark II Twin-wheeled CPX Trailer is tailor designed to enhance the quality of tyre/road noise measurement in this tough highly urbanized city environment where noise disturbances caused by heavy traffic persists in the background and road defects causing bumpiness are common on public roads. Special features are deployed to the trailer to tackle these challenges. They include acoustic treatments to its enclosure for minimizing the persisting noise disturbance, and incorporation of suspensions for travelling on bumpy roads, and also a platform for parking the trailer onto the towing vehicle to extend the service life of the test tyres.

Persisting traffic noise disturbances

As the traffic flow rates in urban areas in Hong Kong are usually very high, the enclosed trailer approach as discussed in Section 2.2.1 is adopted for its more effective shielding external noise disturbances such as engine and exhaust noises from passing-by vehicles at adjacent lanes. Acoustic treatments are deployed to the enclosure of the Mark II CPX Trailer to cope with the requirements on internal noise reflection and external noise isolation by ISO/CD 11819-2 (2010) (Section 2.2.4). For further isolation of external noise disturbances, the enclosure of the trailer is equipped with body skirts of low ground clearance, below 100 mm, to minimize the propagation pathways of the external noises into the enclosure (Figure 3.4). Moreover, the walls of the enclosure are embedded with aluminum honey-comb sound isolation panel (Figures 3.5 and 3.6). For minimizing internal noise reflection inside the enclosure, pyramid-shaped sound absorption material is laid on all its internal walls (Figures 3.7 and 3.8). The specification of the noise reduction coefficient of the material is given in Figure 3.9. All these acoustic treatments are implemented in order to enhance the signal-to-noise ratio in field measurements. The requirements on the acoustic performance of the enclosure are evaluated with respect to ISO/CD 11819-2

(2010) and the results of the certification tests conducted in this study are presented and discussed in details in Chapter 4.

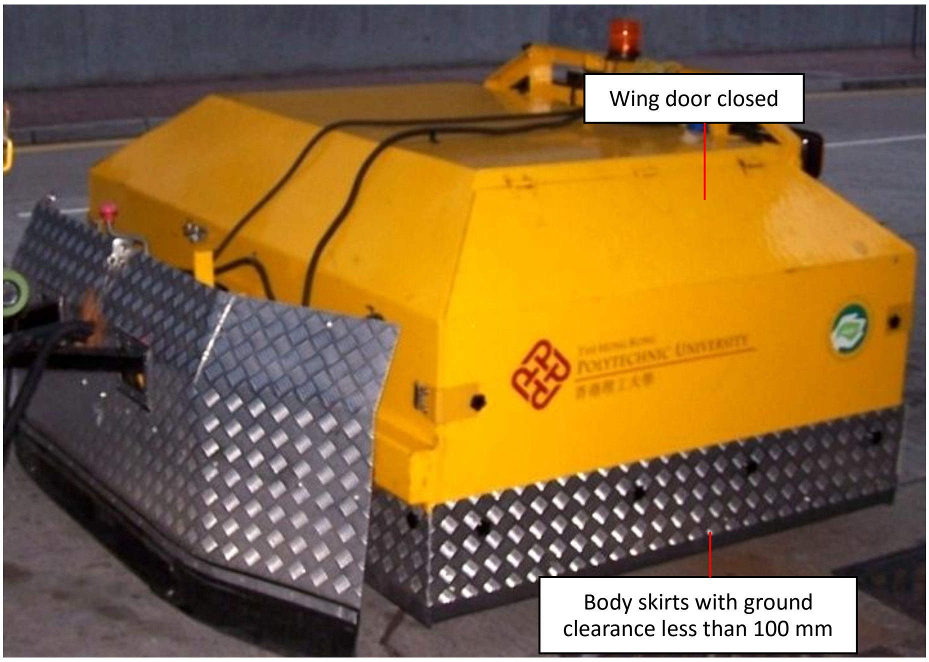


Figure 3.4 External view of the enclosure of the Mark II CPX Trailer with low ground clearance for shielding external noise disturbance.

Figure 3.5 Aluminum honey-comb sound isolation panels embedded in all walls of the enclosure of Mark II CPX Trailer.

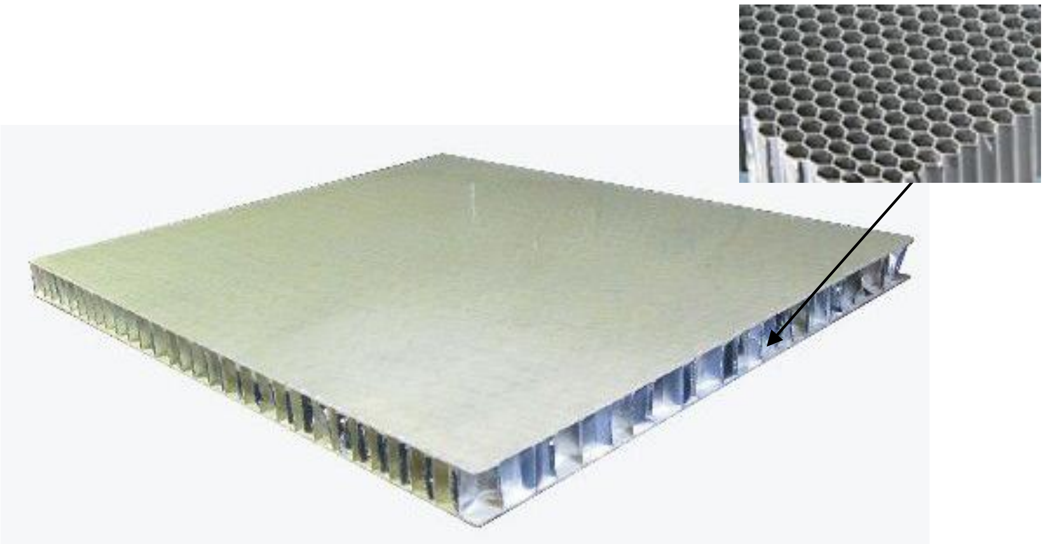


Figure 3.6 Close-up and internal view of the aluminum honey-comb sound isolation panel.

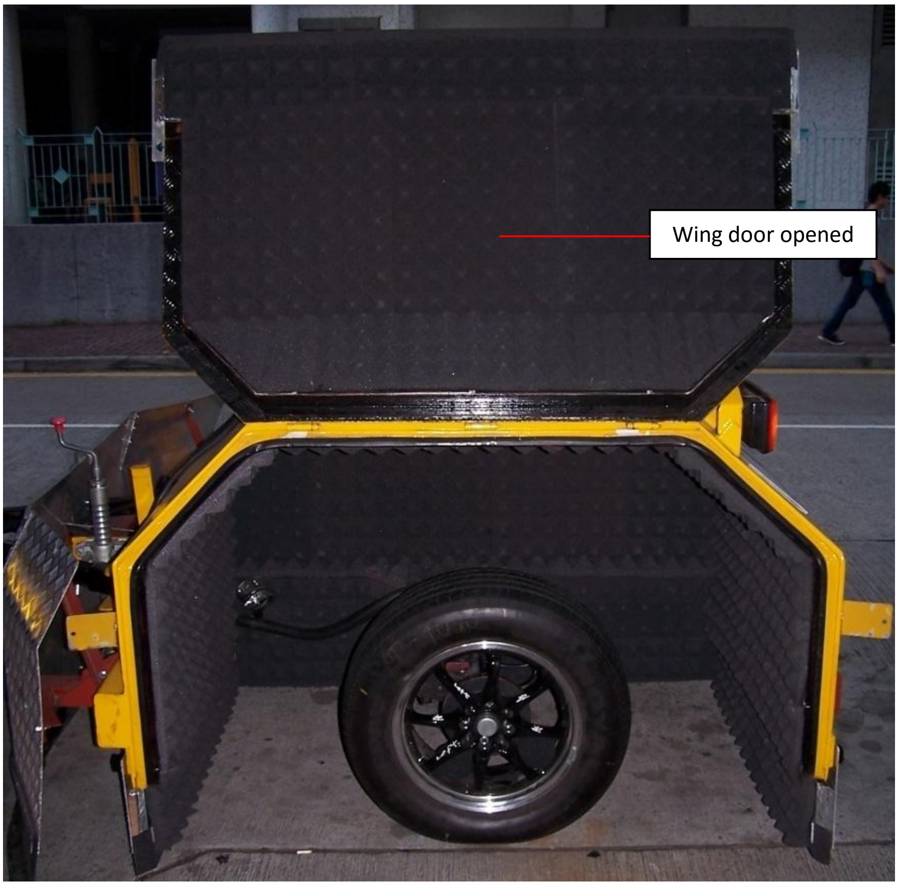


Figure 3.7 Internal view of the enclosure of the Mark II CPX Trailer with sound absorption material on all the internal walls.

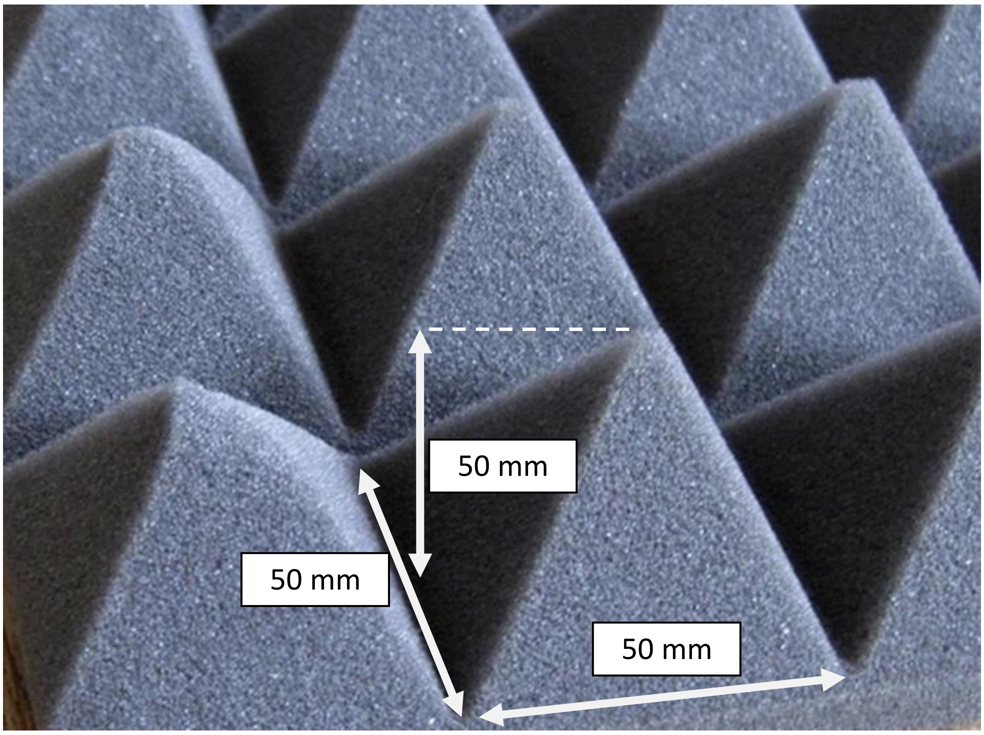


Figure 3.8 Pyramid-shaped sound absorption material on internal walls of the enclosure of Mark II CPX Trailer.

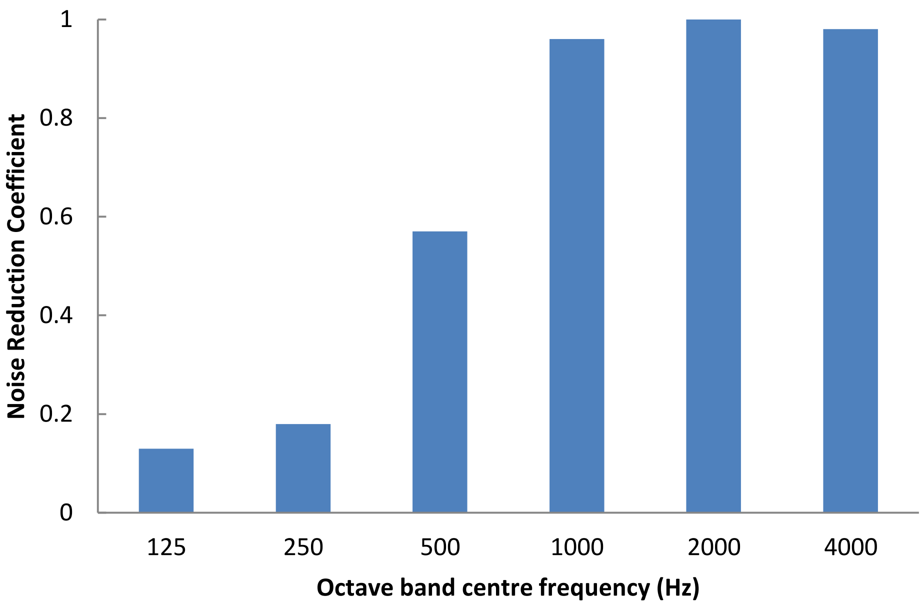


Figure 3.9 Noise reduction coefficient of the pyramid-shaped sound absorption material in specification.

Travelling on bumpy roads

Due to the huge daily population flow relying on public transport (e.g. bus, min-bus, etc.) and inevitable rapid stop-and-go traffic flow patterns in a densely populated urban environment, the public roads in Hong Kong, especially at inner streets, are commonly found with mild to heavy defects (Figure 3.10). Since the measuring CPX microphones are mounted at position only 100 mm above the ground, the road bumpiness caused by the defects often results in damages of various extent to the microphones during tyre/road noise measurement even at a low speed of 50 km/h. From the past experience of measurement with Mark I, about HK $10,000 had to be spent per year for the replacement of damaged microphones due to the impacting of their front caps onto the road surface while the trailer was travelling on bumpy roads. To avoid extra cost arousing from such incident, the Mark II CPX Trailer is equipped with a pair of torsion-type trailer suspensions which provide higher degree of absorption of vibration created by travelling on bumpy roads (Figure 3.11). With such arrangement, the occurrence of microphone damage in the Mark II CPX Trailer is found much reduced.

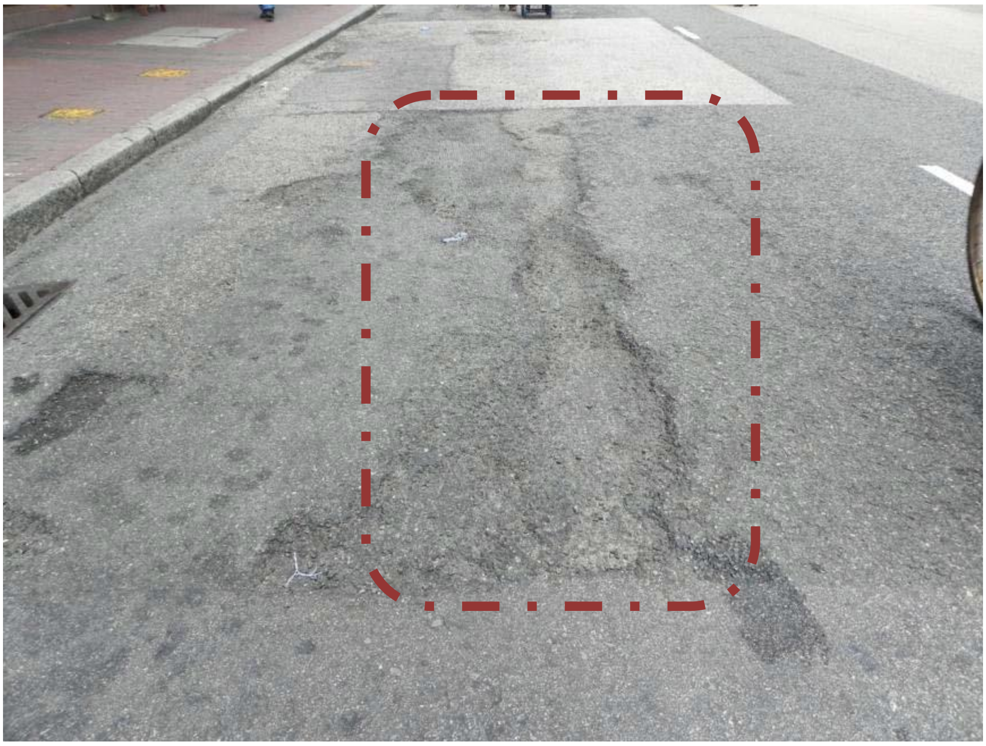


Figure 3.10 Road surface defects of crack and delamination on a public road of Hong Kong.

Figure 3.11 Torsion-type trailer suspensions.

Extended usage life of the test tyres

In this study the Standard Reference Test Tyres (SRTT) are regarded as one of the most precious instruments in the entire configuration. Since Hong Kong resides in subtropical region, the high humidity in the atmosphere as well as the high road surface temperature, especially during summer, are anticipated to boost the aging and wearing of the SRTTs. Furthermore, it takes long time and is costly to ship a SRTT from aboard. In order to better protect from any further unnecessary deterioration of SRTTs during the course of measurement, the trailer is designed to be lifted to fit onto the deck of the towing light goods vehicle when travelling where measurement is not needed (Figure 3.12).

Figure 3.12 CPX trailer parked onto the deck of the towing light goods vehicle.

3.2.2 Sensory units and data acquisition system

The Mark II CPX measurement system is equipped with multiple sensory units for studying the effects of different parameters, such as the microphone vibration, (Chapter 5), the temperature, (Chapter 6), and the road curvature, (Chapter 7), on tyre/road noise measurement. A list of sensory units and devices adopted are listed in Table 3.1. The details and rationales of adoption of each of the units are presented as follows.

Sensory units	**Specifications**	**Measuring target**	**Qty.**
B&K 4189 microphone 	▪ IEC 61672 Class 1 ▪ Free-field type ▪ Prepolarized ▪ Range: 15.2 dB - 146 dB ▪ Frequency: 6.3 Hz – 20kHz	Tyre/road noise	4
B&K 4514 accelerometer 	▪ TEDS – B type ▪ Insulated base ▪ Hermetically sealed ▪ Range: ±50g ▪ Frequency: 1 Hz – 10kHz	Vibration of microphone	4
RS 236-4283 air temperature sensor 	▪ Stainless steel probe ▪ Resistance temperature detector ▪ PT 100, Class B ▪ Range: -50 – 150°C ▪ 500 mm above ground	Ambient temperature	1

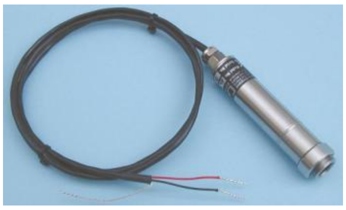
Convir EL301MT-X Road surface temperature sensor 	▪ Infrared type ▪ Non-contact ▪ Stainless steel probe ▪ Range: 0 – 250 ℃ ▪ Pointing at right wheel track	Road surface temperature	1
QSTARZ BT-Q818 eXtreme GPS Receiver 	▪ 51-channel performance tracking ▪ Protocol: NMEA 0183 ▪ Bluetooth ▪ Accuracy: 2.5 m	Route of survey	1
Dawin Speed sensor 	▪ Microwave type ▪ Range: 0 – 400km/h	Vehicle speed	1
Data acquisition system 	▪ National Instrument PXI 1031 ▪ Two items of NI 4472 DAQ Card ▪ 16 IEPE channels ▪ Sampling rate: 102.4 kHz ▪ Sensing range: ±10 V ▪ Resolution: 24-bit	Data from sensory units	1

Table 3.1 Sensory units and data acquisition system of Mark II CPX Trailer.

Microphones

The measurement system is equipped with four B&K Type 4189 Class 1 free-field half-inch microphones (IEC 61672-1, 2002) for detecting the noise from the tyre/road interaction with two installed at each of the two trailer chambers. Their positions and orientations follow the specification given in ISO/CD 11819-2 (2010) as shown earlier in Figure 2.16 in Chapter 2. They are located 100 mm above the ground level and 200 mm from the outward tyre sidewall. Each microphone is oriented pointing towards the tyre/road contact patch of interest. Besides, all microphones are mounted with wind screens so as to eliminate the air flows induced around them when the trailer travels. Since its measuring range covers the anticipated noise level and the interested frequency range of 315 – 5000 Hz defined by ISO/CD 11819-2 (2010) while the cost is adequate, B&K 4189 microphone is adopted to the Mark II Twin-wheeled CPX Trailer.

Accelerometers

Four B&K Type 4514 accelerometers are mounted to the four microphones for monitoring the vibration of microphones. They are adopted to monitor on whether the self vibration of the microphone would induce error in the measured noise signals. The mounting design, the test hypothesis, the experiments conducted and the results are presented and discussed in Chapter 5. Since it is small in size and hermetically sealed, it is adopted for minimized influence to the environment at vicinity to the microphone and to cope with the heat radiation and plausible wetness from the road surface respectively.

<u>Air and road surface temperature sensors</u>

A PT100 Class B air temperature sensor with a measuring range from –50 ℃ to 150 ℃ and an infrared road surface temperature sensor with a measuring range from 0 ℃ to 250 ℃ are adopted for assessing the temperature effects on tyre/road noise measurement (Chapter 6). Their stainless steel probe designs make them resistive to corrosion by humidity, so they are suitable for use in outdoor field measurement on public roads. The air temperature sensor is installed at a position 500 mm above ground level with respect to the specification given in ISO/CD 11819-2 (2010) while the infrared road surface temperature sensor is oriented pointing towards the right wheel track to tell the road surface temperature experienced by the test tyres.

GPS receiver

A QSTARZ eXtreme GPS receiver is associated with the measurement system for tracking the routes of the surveyed road sections. With the availability of its full 51 tracking channels, the receiver offers a very high locating accuracy in which the minimum geographical deviation is as small as only 2.5 m. The tracked route information provides the distance traveled and the variation of road curvature radius of a road section so that the effects of road curvature on tyre/road noise measurement can be studied (Chapter 7). Besides, the receiver is also useful for collation of data collected on a set of connected road sections being surveyed on. It also facilitates the viewing of the measured tyre/road noise information on geographical platform, such as Google Earth, which helps give a clear overview and distributions of the noise on the public roads in different urban regions.

Speed senor

According to ISO standards, the tyre/road noise measurement with CPX Method has to be conducted at specific reference speeds. In practice, variation of driving speed is inevitable during measurement and compensation for the deviation from the reference speed is specified in ISO/CD 11819-2 (2010) via the process of speed correction (Section 2.2.3). Therefore, the actual variation of the vehicle speed needs to be recorded. The traditional approach, which makes use of an encoder mounted to one of the wheels of the vehicle, is not adopted because it produces high measurement errors when the tyre circumference deforms severely while travelling on bumpy roads. The deformation causes significant deviation in the computed linearization from the sensed rotational speed. A better approach is to use an independent non-contact type microwave speed sensor. It also offers convenience in the setup procedure by just attachment of the sensor to the vehicle door using a strong magnet plate. The adopted Dawin Microwave Speed Sensor offers measuring range of 0 – 400 km/h which is well enough for tyre/road measurement with CPX Method.

Data acquisition system

All the sensory units mentioned above are integrated to a centralized data acquisition system (National Instrument PXI 1031) equipped with two NI 4472 data acquisition cards. Altogether it offers 16 IEPE input channels for data acquisition at a high sampling rate of 102.4 kHz. With the acquisition programme development software of LabVIEW, automated streamlined data acquisition and computation programmes can be easily tailor-made for in situ rapid data processing of CPX measurement result.

3.3 Conclusions

The background history of the evolution from the PolyU Mark I Single-wheeled to the Mark II Twin-wheeled CPX Trailer is introduced. Comparison between the two trailers is made qualitatively and quantitatively showing that Mark II better reflects the tyre/road noise performance of public roads by measuring the noise on the wheel tracks. In addition to repositioning of the test tyres, special design features are implemented to the Mark II CPX Trailer to tackle the challenges faced in highly urbanized city. For the persisting traffic noise disturbances at the background, its enclosure is treated with sound absorption material and sound isolation honey-comb panel. The performance of the measures will be evaluated and discussed in Chapter 4. For travelling on bumpy roads which put the microphones at risk damages, Mark II is equipped with a pair of torsion-type trailer suspensions to reduce the cost of microphone replacement. To extend the service life of the precious Standard Reference Test Tyres, the trailer is designed to be lifted and fit to the deck of the towing vehicle. The measurement system with multiple sensory units and centralized data acquisition system is introduced. Their specifications, the rationales of adoption and the purposes of each of the units are presented. In summary, the PolyU Mark II CPX Trailer is an advanced configuration for tyre/road noise measurement in highly urbanized environment. It does not only allow streamlined massive tyre/road noise surveys but also studies on different influencing factors to the noise.

CHAPTER 4

CERTIFICATION OF POLYU MARK II TWIN-WHEELED CPX TRAILER

For any CPX trailer designed for the measurement of tyre/road noise on real roads, noise disturbances from the uncontrolled sources from the surrounding environment are inevitable. To tackle this problem, the PolyU Mark II Twin-wheeled CPX Trailer is designed to be equipped with an acoustic enclosure as just illustrated in Section 3.2.1. Acoustic treatments include the use of sound absorption material and sound isolation panel on the enclosure walls for minimizing internal sound reflection and shielding the disturbing noises from its exterior. As such, three certification tests according to ISO/CD 11819-2 (2010) are devised and performed to evaluate the associated acoustic performance of the enclosure. The first test is for assessing the internal sound reflection within the enclosure. The second test is for testing whether the noisy disturbances from the towing vehicle are negligible to the level of tyre/road noise measured. The third certification test is for assuring the noise disturbances created by vehicles passing by along an adjacent lane is negligible. The three certification tests are conducted on the PolyU Mark II Twin-wheeled CPX Trailer. The measurement results are examined against the test criteria stipulated in ISO/CD 11819-2 (2010). Results indicate that the CPX trailer design passes all of the three tests. The designed setup, the test procedures practiced, and the analysis on the yielded results of each of the three certification tests conducted in this study are presented in the following sections.

4.1 Test 1: Sound reflection against enclosure and other objects near the microphones

The certification test 1 is for assessing the sound reflection by the trailer interior walls within the enclosure and the sound scattering by any other objects such as the mounting frame and cables near the microphones. The principle of the test is to compare the noise levels measured with and without the enclosure so as to note the level of influence by its internal reflection.

4.1.1 Objective and criteria

As the CPX trailer is incorporated with an enclosure, the measured level of tyre/road noise may be influenced by the noise reflection from its internal walls. To assure the reflection does not induce large deviation from the assumption of a free-field environment, the certification test 1 is stipulated by ISO/CD 11819-2 (2010) to assess the internal reflection effect by the enclosure. The acceptance criterion for the certification test 1 is that the difference in the measured band levels from the cases with and without the enclosure must be within ± 3 dB(A) in a 1/3-ocatve centre frequency range 315 – 5000 Hz for each microphone used, i.e.

$$\left|SPL_{f,With\ Enclosure} - SPL_{f,Without\ Enclosure}\right| < 3 \text{ dB(A) for } f\!: \{315, 5000\} \text{ Hz}$$

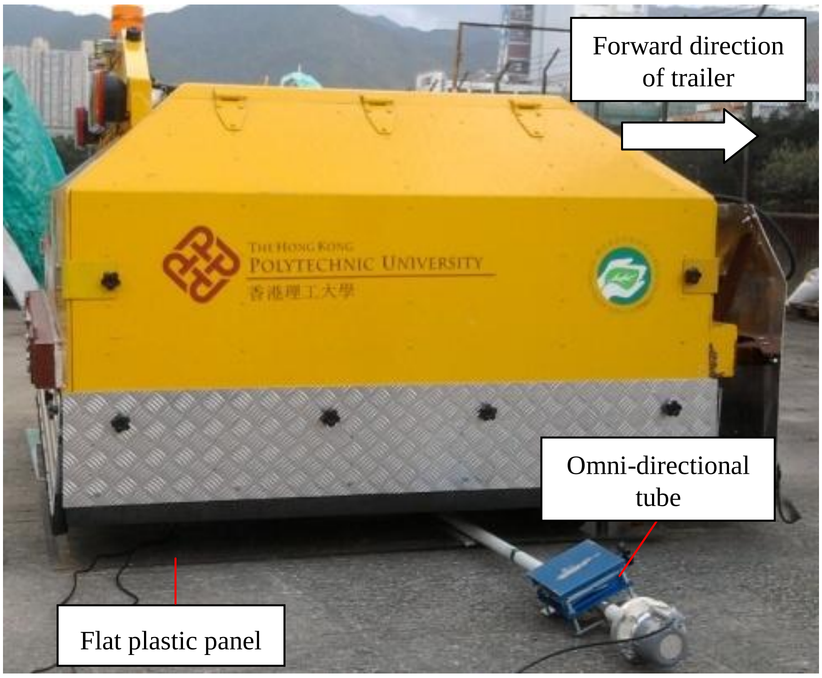
Equation 4.1

where $SPL_{f,\ with\ enclosure}$ and $SPL_{f,\ without\ enclosure}$ denote the A-weighted 1/3-octave band levels measured with and without the enclosure respectively.

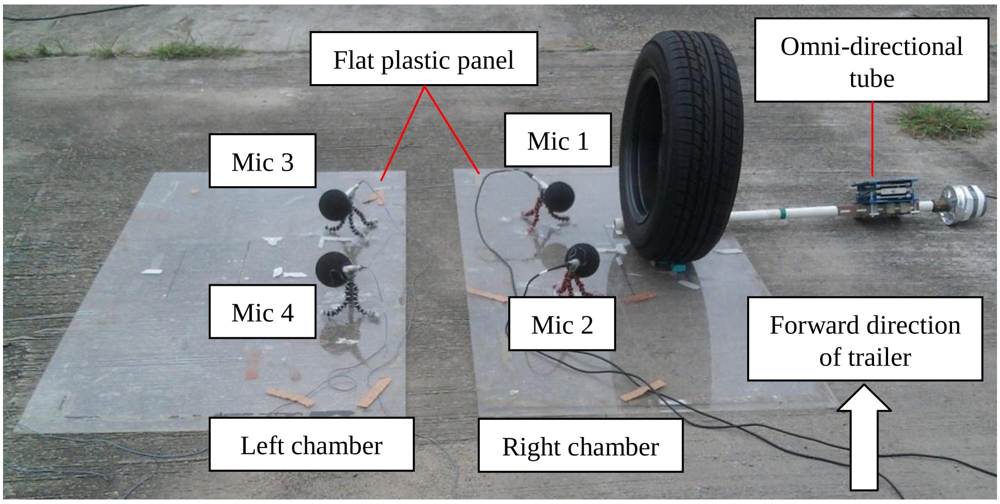
4.1.2 Methodology

4.1.2(i) Setup

The CPX trailer is parked in an open environment in this test. An artificial noise source, fed with white noise, is placed at proximity to the tyre/road contact patch for simulation of tyre/road noise. The setups for cases with (Case A) and without (Case B) the enclosure are shown in Figure 4.1. To ensure the noise could reach as many as the reflecting surfaces within the enclosure, an omni-directional tube (Figure 4.2) is adopted for the test. The directivity patterns of various 1/3-octave bands in the specification are illustrated. In each case, two flat plastic panels are placed under the enclosure chamber. The purpose of placing these panels is to avoid any localized absorption by the ground which may lead to under-estimation of the internal reflection of the enclosure. The four microphones take their usual positions and orientations as specified in ISO/CD 11819-2 (2010).



(a)



(b)

Figure 4.1 Setup of the certification test 1. (a) Case A - WITH acoustic enclosure. (b) Case B - WITHOUT acoustic enclosure

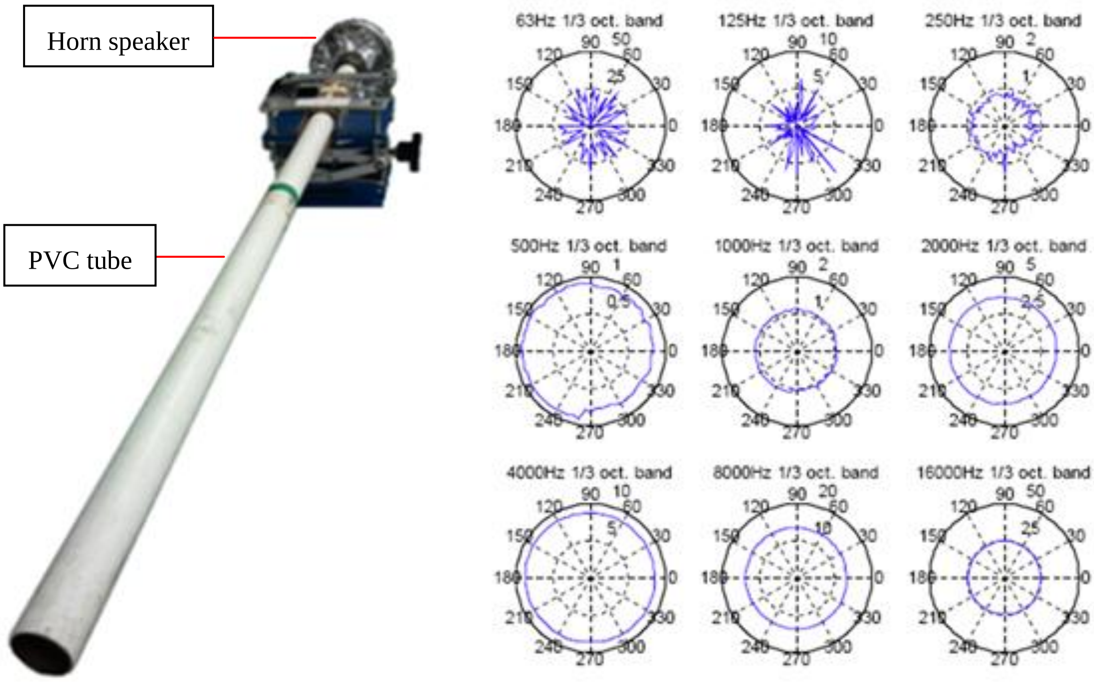


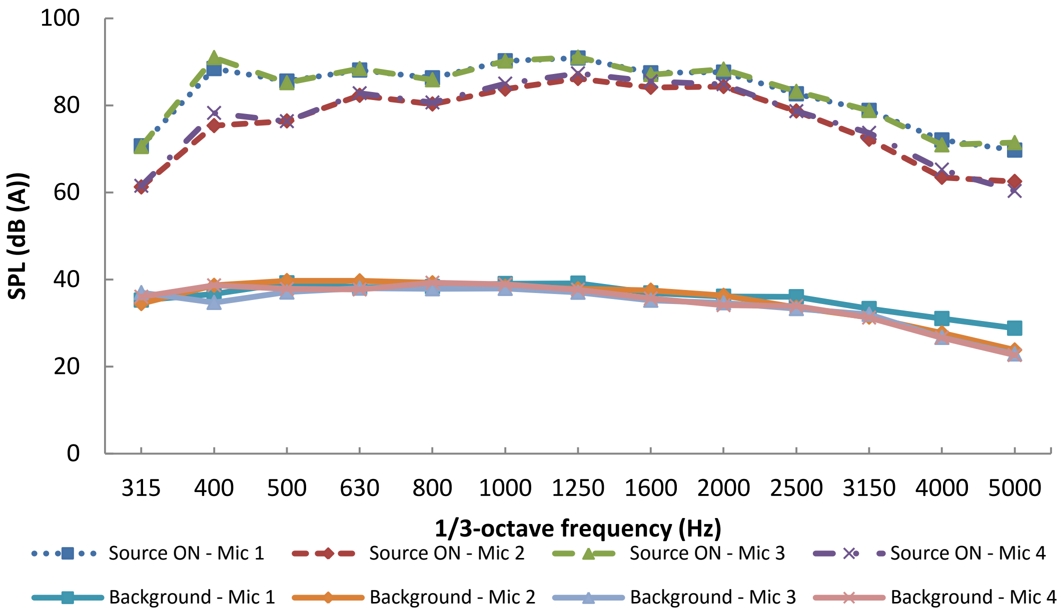
Figure 4.2 The directivity patterns of the artificial noise source for the certification test 1 at different frequency bands.

4.1.2(ii) Procedures

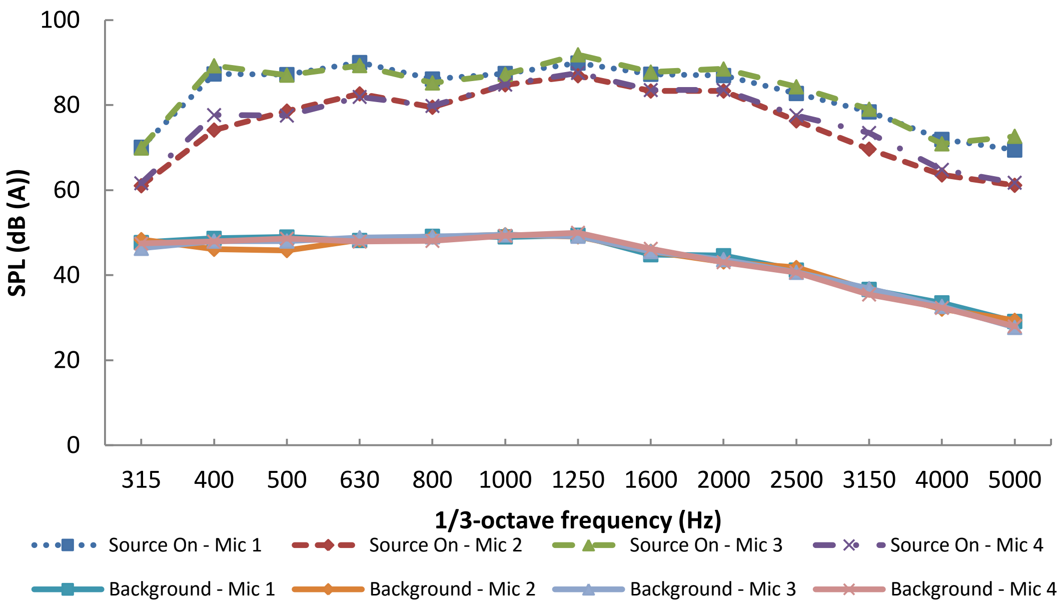
The omni-directional tube is powered on with white noise for a minute for warming up. For the case with the enclosure (Case A), the emitted noise is recorded by the two microphones at the right chamber of the enclosure for one minute. Three runs of measurement are conducted. The trailer is pushed away and the noise source remains on for the next measurement for the case without the enclosure (Case B). To prevent any unnecessary discrepancies between the two cases, the microphones and noise source remain intact but their positions are unchanged. A wheel is then placed onto the plastic panel at the original position of the tyre mounted in the trailer. The noise from the source is recorded by the same two microphones for one minute per run and three runs are made. The procedures above are repeated for the left chamber.

4.1.3 Results and analysis

As the measurement is conducted in an outdoor environment, it is necessary to ascertain whether the background noise disturbance is negligible when compared to the noise levels emitted by the artificial source. Figure 4.3 illustrates the 1/3-octave spectra of the background noise and the noise measured when the noise source is powered on, for cases with and without the enclosure. Mic 1 – 4 denote the four microphones at the front and rear positions of the right and left chambers respectively (Figure 4.1b). It is observed that the background noises measured for both cases are well below than that when the artificial noise source is on, so it is negligible. In the next step the analysis on the influence by the internal reflection of the enclosure can then begin. The 1/3-octave spectra of the measured noise in cases with and without the enclosure are plotted for the four microphones in the two chambers in Figure 4.4. The spectra for the front microphones (Mic 1 and Mic 3) are higher than those of the rear microphones (Mic 2 and Mic 4). This could be explained by the fact that the opening of the artificial source is placed at the leading edge of the tyre/panel contact patch which is closer to the front microphones. For all the microphones, there are no band levels with sharp difference over 3 dB(A) between cases with and without the enclosure.

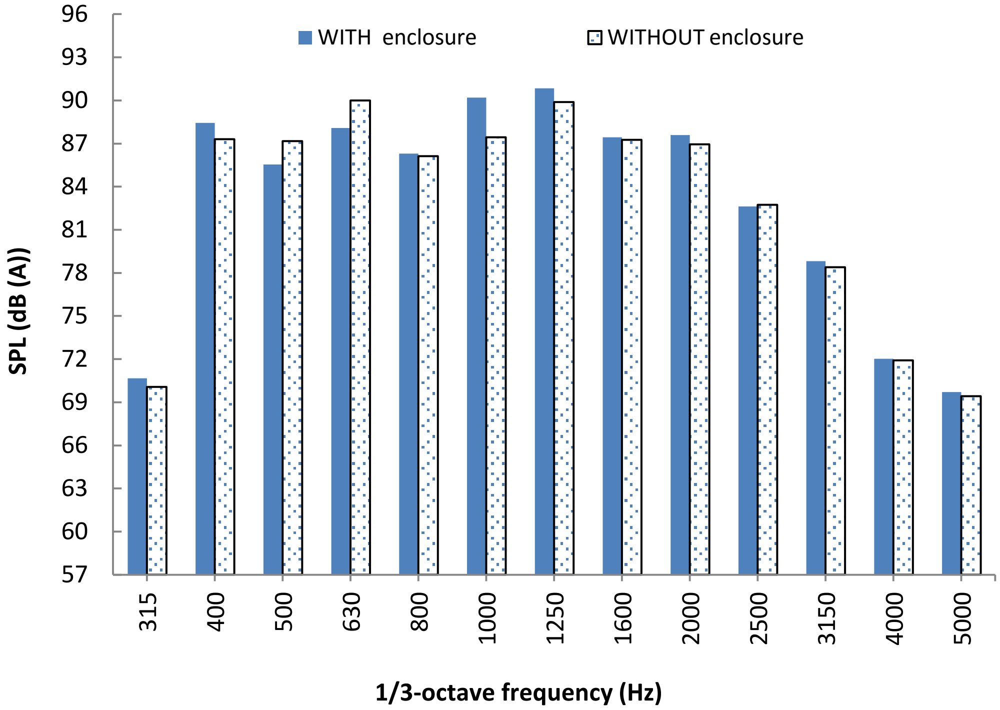


(a)



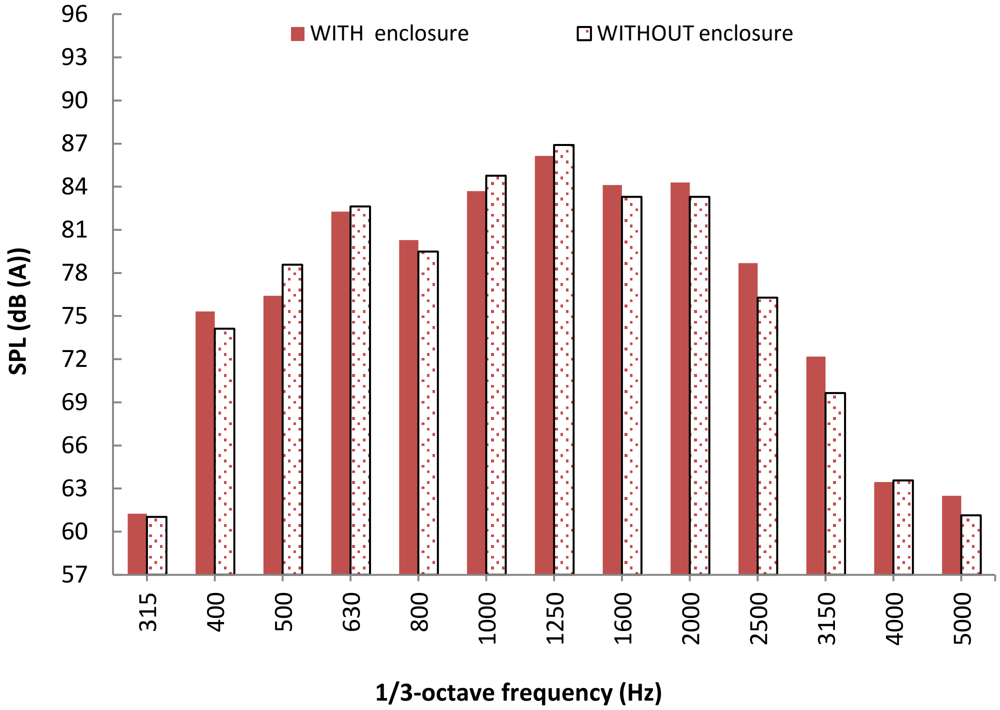
(b)

Figure 4.3 Noise spectra. (a) With acoustic enclosure. (b) Without acoustic enclosure.



96
93
90
87
84
81
78
75
72
69
66
63
60
57
WITH enclosure
WITHOUT enclosure
SPL (dB (A))
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
1/3-octave frequency (Hz)

(a)



96
93
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84
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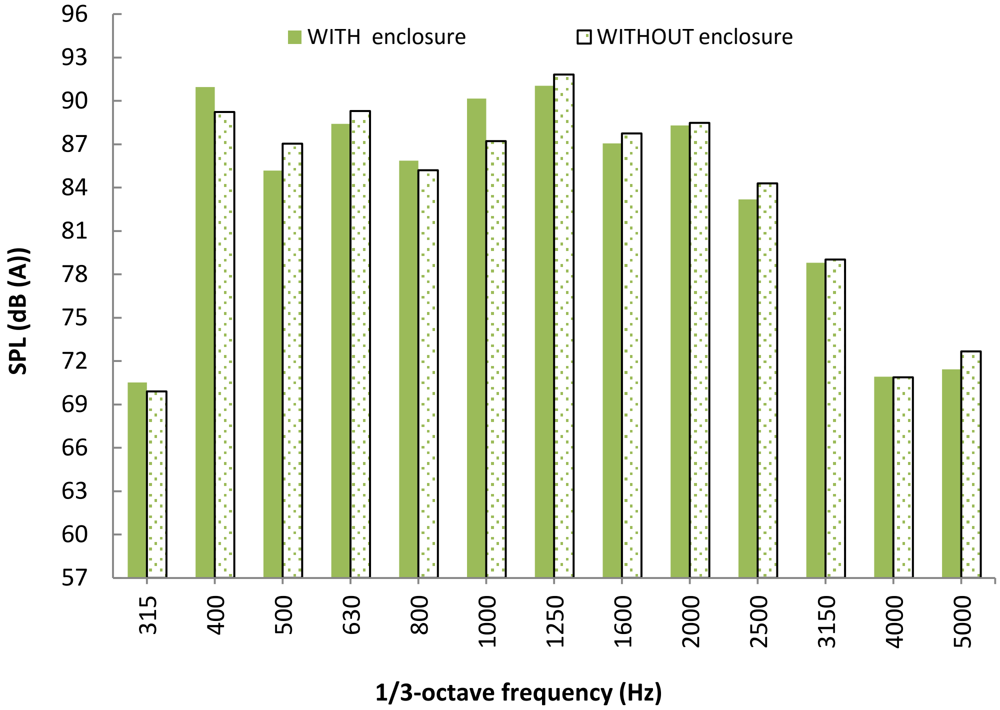
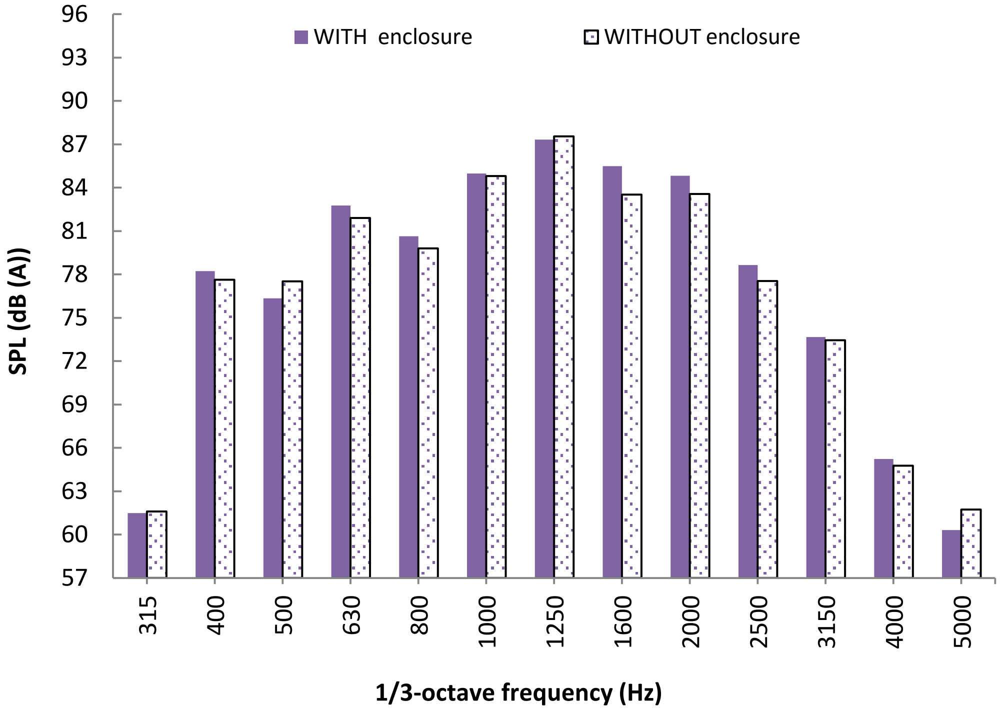
75
72
69
66
63
60
57
WITH enclosure
WITHOUT enclosure
SPL (dB (A))
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
1/3-octave frequency (Hz)

(b)



(c)



(d)

Figure 4.4 Noise spectra measured by the microphones. (a) Mic 1. (b) Mic 2. (c) Mic3. (d) Mic 4.

After checking for any obvious difference in frequency patterns with and without the enclosure, their differences in band levels are examined against the criterion of the certification test 1 stipulated by ISO/CD 11819-2 (2010) (i.e. Equation 4.1). For each microphone, the measured band levels without the enclosure are subtracted from those with the enclosure. The difference in the spectra is illustrated in Figure 4.5. It is observed that the differences in band levels are within ±3 dB. The trailer successfully passes the certification test 1.

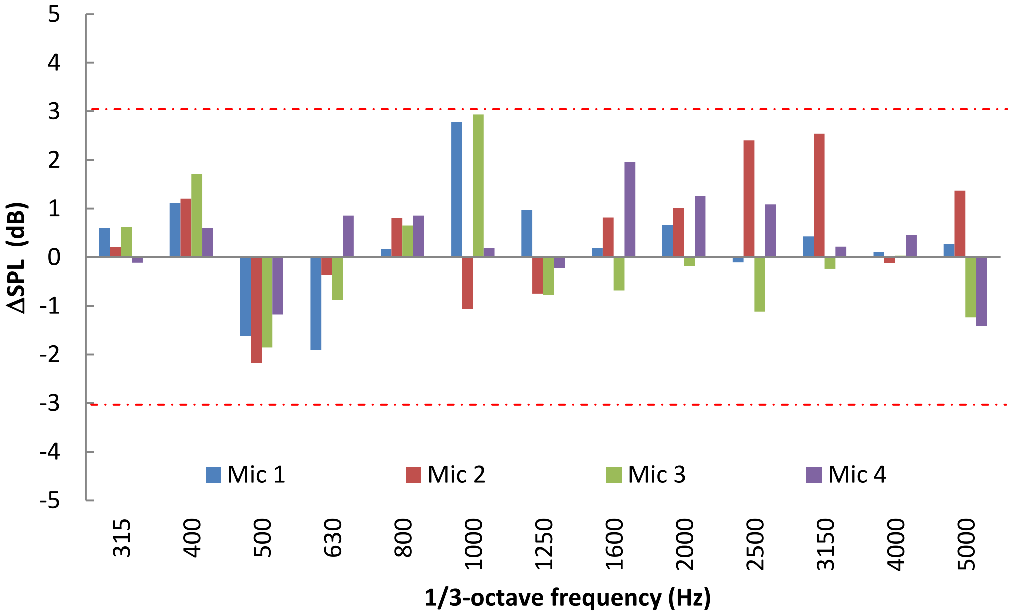


Figure 4.5 Spectral difference with and without the enclosure.

Therefore, it is shown that with the deployment of sound absorption materials all over the internal walls and reflecting surfaces of the enclosure of the PolyU Mark II Twin-wheeled CPX Trailer, the certification test 1 for noise reflection against enclosure and other objects near the microphones is passed.

4.2 Test 2: Background noise from the vehicle itself or its operation

The certification test 2 is for ascertaining the noise disturbances from the towing vehicle such as engine and exhaust noises are negligible to the level of tyre/road noise measured within the enclosure. The principle of the test is to compare the noise levels measured with and without the test tyres to note the level of influence by the disturbing noises from the towing vehicle.

4.2.1 Objective and criteria

Two measurements are conducted on the same road section to note the levels of noise disturbances from the towing vehicle. They are an ordinary CPX measurement equipped with the test tyres and a special measurement without the test tyres. Two criteria for this test are stipulated by ISO/CD 11819-2 (2010). First, the A-weighted overall noise levels measured with the test tyres have to be 10 dB(A) higher than those without the test tyres (i.e. Equation 4.2a). Second, the 1/3-octave band levels for frequency ranges 315 – 400 Hz and 500 – 5000 Hz measured with test tyres in place have to be 4 and 6 dB(A) respectively higher than the corresponding band levels from the measurement without test tyres (i.e.

Equation 4.2b). These two criteria have to be fulfilled for three reference speeds of 40, 50 and 80 km/h.

$$SPL_{with\ tyres} - SPL_{without\ tyres} > 10\ dB(A) \qquad \text{Equation 4.2a}$$

where $SPL_{with\ tyres}$ and $SPL_{without\ tyres}$ denote the A-weighted overall noise levels measured with and without the test tyres respectively.

$$SPL_{f,with\ tyres} - SPL_{f,without\ tyres} > \begin{cases} 4\ \text{dB(A) for } f: \{315, 400\}\ \text{Hz} \\ 6\ \text{dB(A) for } f: \{500, 5000\}\ \text{Hz} \end{cases}$$

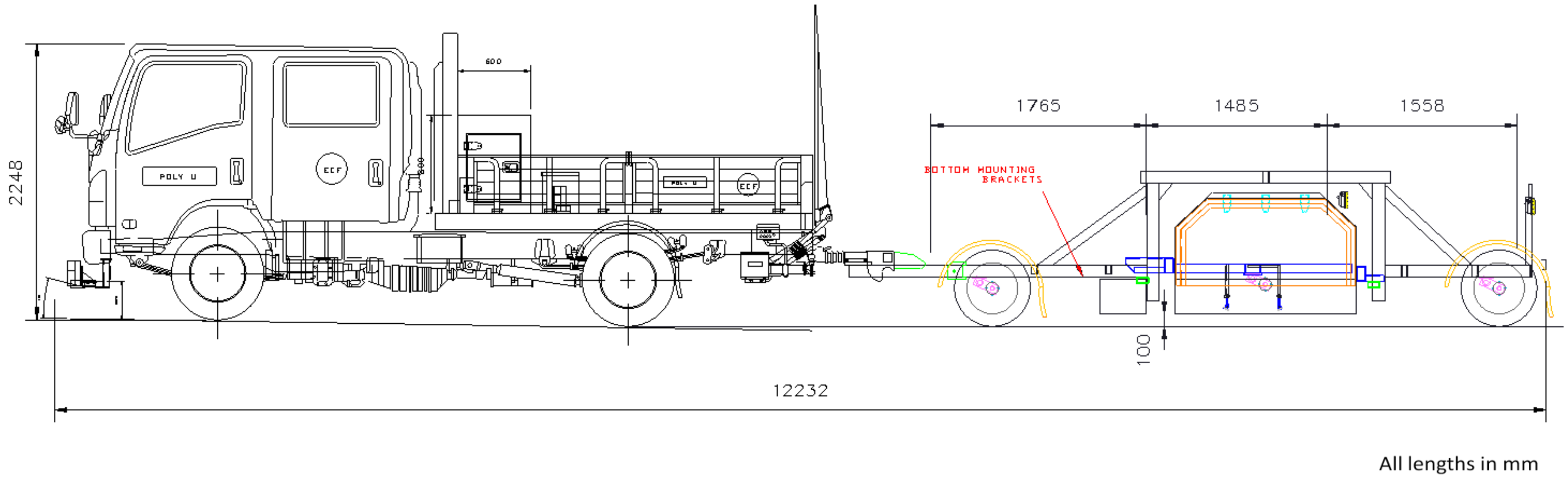
Equation 4.2b

where $SPL_{f,\ with\ tyres}$ and $SPL_{f,\ without\ tyres}$ denote the A-weighted 1/3-octave band levels (dB (A)) measured with and without the test tyres respectively.

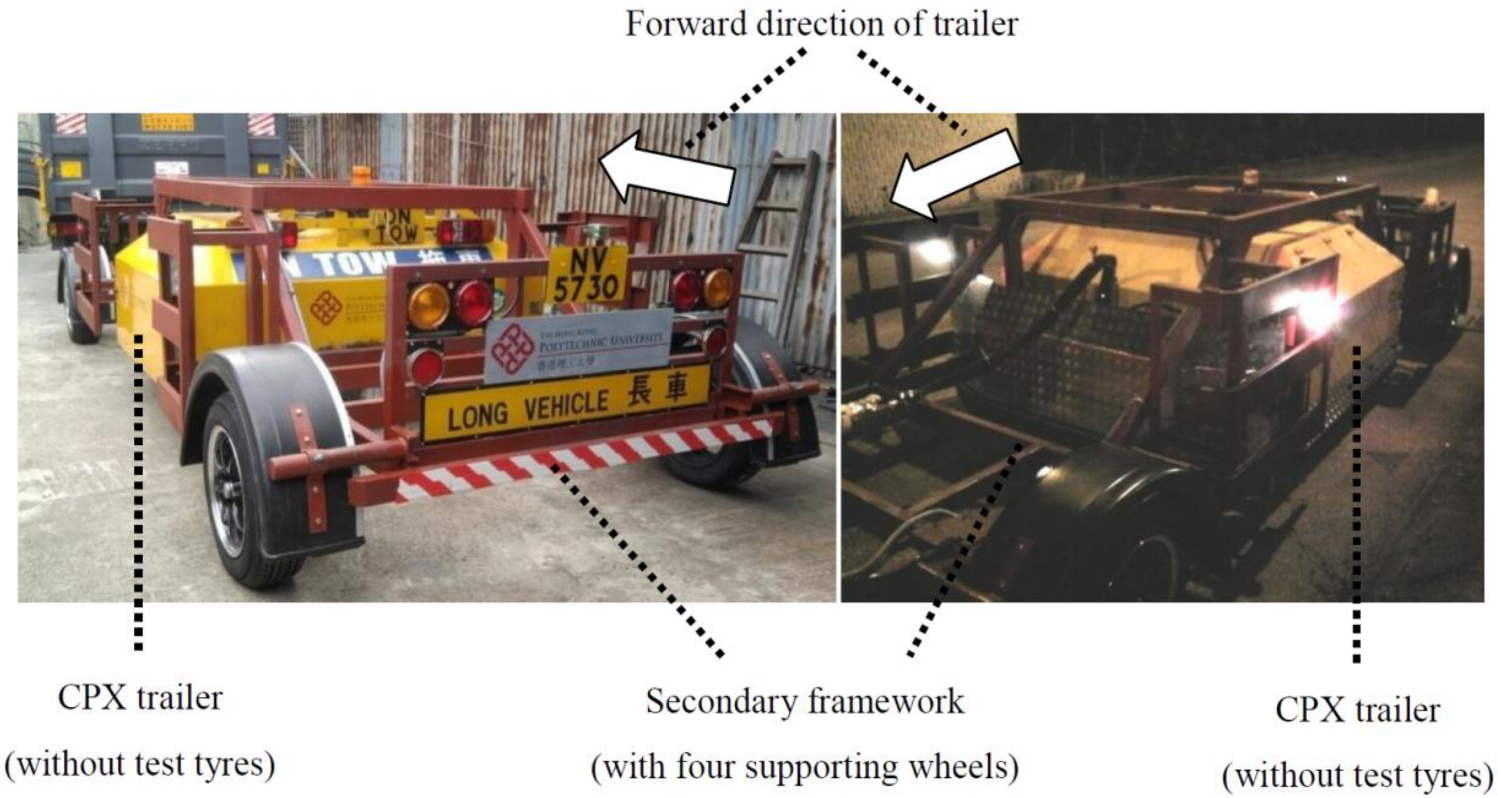
4.2.2 Methodology

4.2.2 (i) Setup

The PolyU Mark II Twin-wheeled CPX Trailer in this study is designed to have only two wheels which are mounted with the test tyres. To conduct the special measurement without the test tyres, it is required to fabricate a secondary framework with supporting wheels in order to hang the CPX trailer above the ground. Figure 4.6 shows the schematic and actual arrangements for mounting the CPX trailer. The secondary framework mounted with the CPX Trailer is towed to conduct measurements on a highway during daybreak with traffic control for minimization of other disturbing noise and safety concern. To have the results on the safe side, a low-noise porous friction course road surface is adopted. Table 4.1 shows the details of the measurement.


2248
600
600
POLY U
ECF
1765
1485
1558
BOTTOM MOUNTING BRACKETS
100
12232
All lengths in mm

(a)



(b)

Figure 4.6 Setup for the certification test 2 for measurement without the test tyres. (a) Schematic. (b) Actual.

Location (Chainage)	**Road Surface**	**Ref. Speed (km/h)**	**Measurements**
Fanling Highway (25.6 – 25.0)	Friction course	40, 50 & 80	***Case A (WITH test tyres)*** Normal CPX measurement
			Case B (WITHOUT test tyres) Removed tyre measurement

Table 4.1 Details of measurement for the certification test 2.

4.2.2 (ii) Procedures

CPX measurement with the test tyres equipped (Case A) is first conducted for the three specified reference speeds 40, 50 and 80 km/h. The trailer is then transferred and mounted to the secondary frame work without the test tyres for the next measurement (Case B). Figure 4.7 shows the process of mounting the framework onto the CPX Trailer using a light crane. The arrangement is then towed to conduct measurement on the same road section for the three speeds. The results from the two measurements are compared and analyzed in the following section.

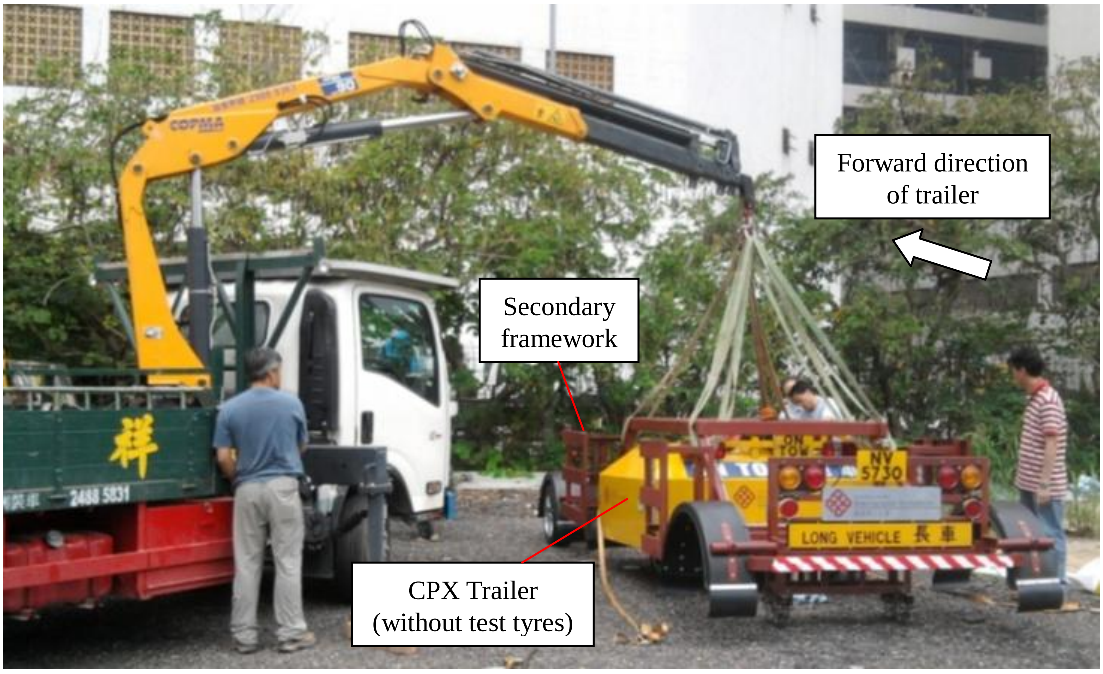


Figure 4.7 Mounting the CPX trailer to the secondary framework.

4.2.3 Results and analysis

The requirement illustrated in Equation 4.2a is first examined. Figure 4.8 shows the noise levels measured from the four microphones in the measurements with (Case A) and without test tyres (Case B) respectively. Notations Mic 1 to Mic 4 take their usual meaning of the four mandatory microphones as in the certification test 1. It is observed that the noise level measured with the test tyres is more than 10 dB(A) higher than that without them. Therefore, the noise level measured in the CPX measurement is well above the noise disturbance from the towing vehicle. The first criterion on the overall A-weighted noise level is fulfilled.

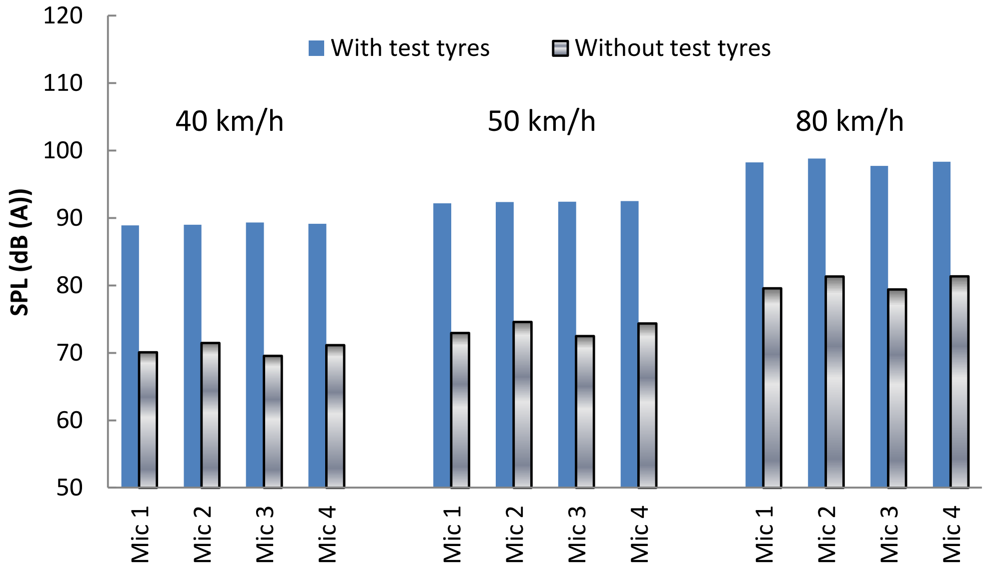
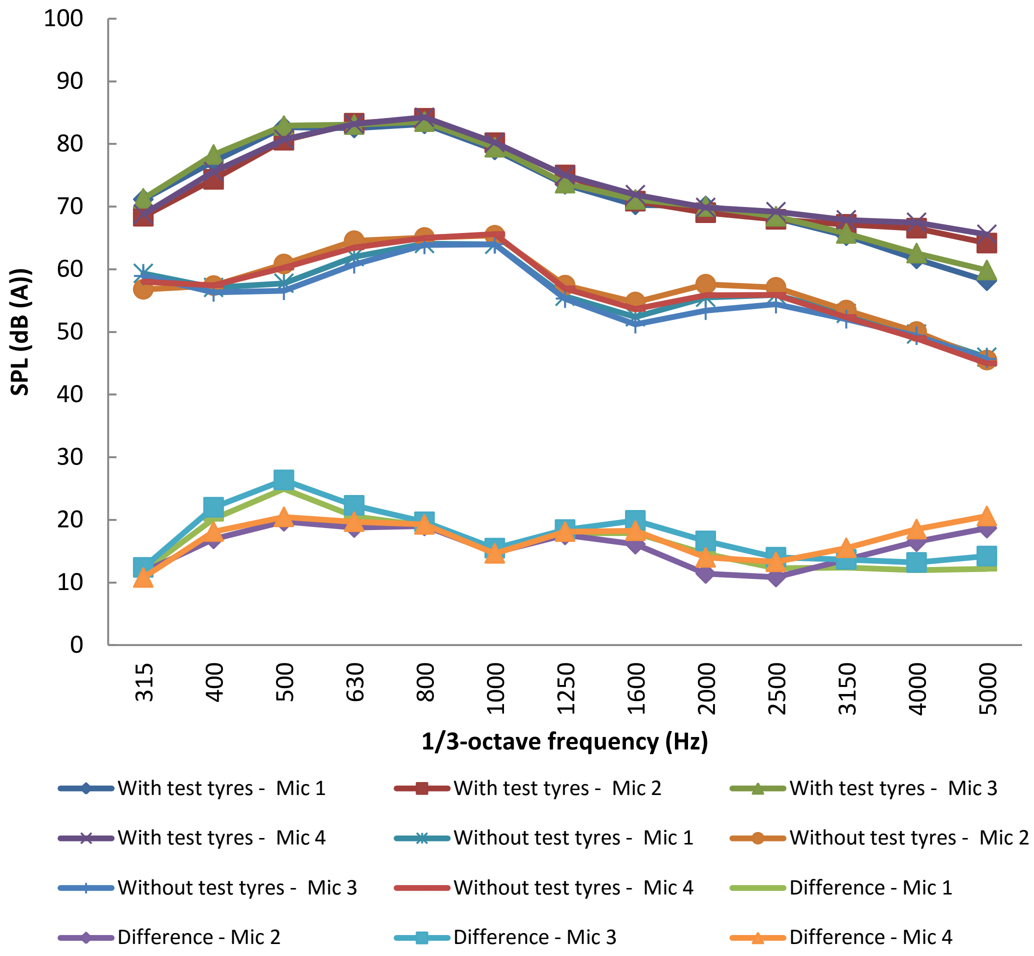


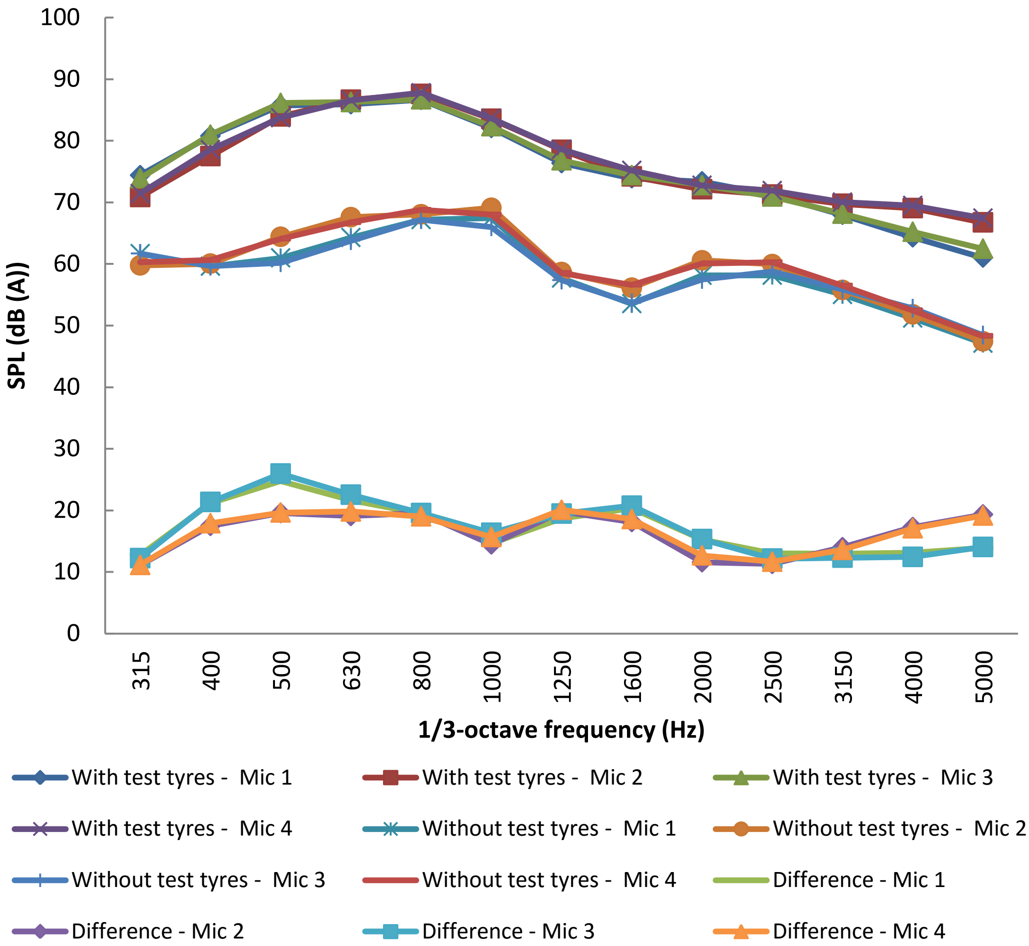
Figure 4.8 Measured noise levels with/without test tyres.

The second criterion of certification test 2 illustrated in Equation 4.2b is then examined. Figure 4.9 show the 1/3-octave noise spectra from the two measurements with and without the test tyres, and their spectral difference at reference speeds 40, 50 and 80 km/h. It is observed that the difference in band levels by subtracting the spectra without the test tyres from those with the test tyres are about 10 dB(A) or above. As such, the enclosure is not only conforming to but well above the second criterion (i.e. Equation 4.2b) instructed by the certification test 2.

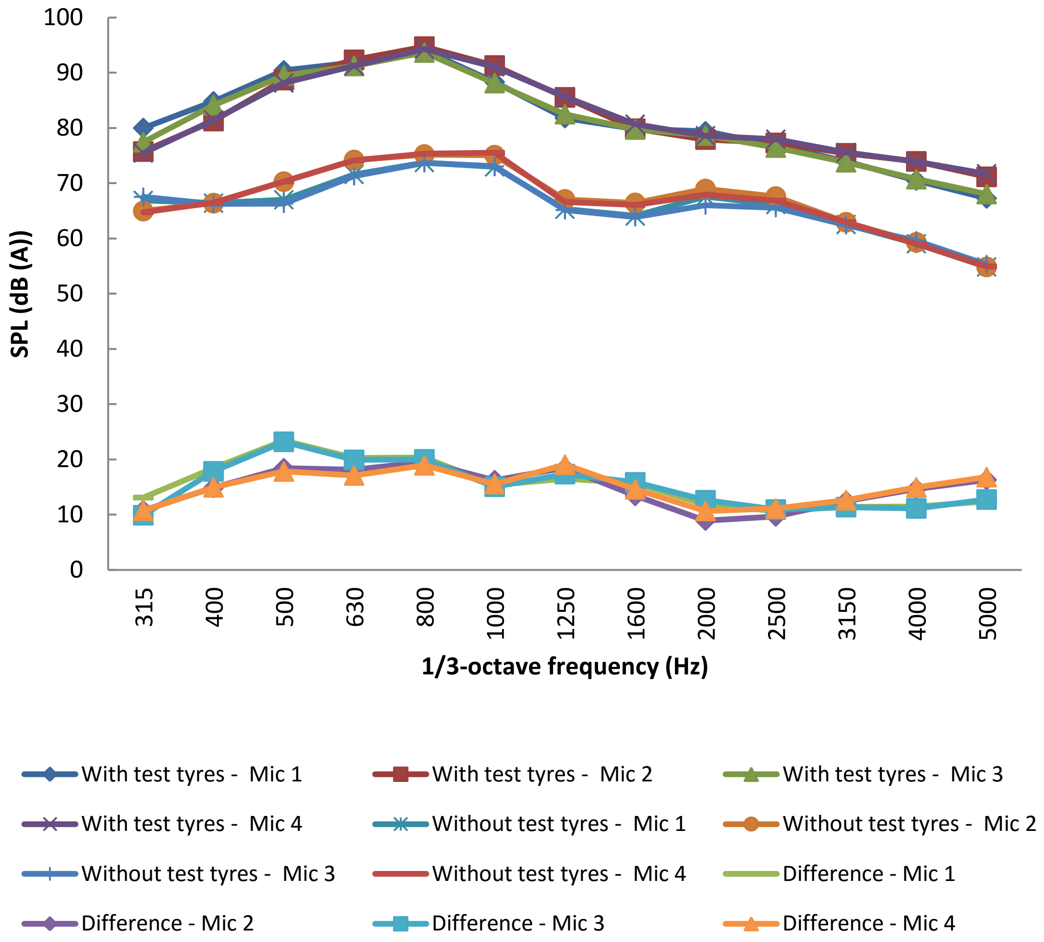


100
90
80
70
60
50
40
30
20
10
0
SPL (dB (A))
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
1/3-octave frequency (Hz)
With test tyres - Mic 1
With test tyres - Mic 2
With test tyres - Mic 3
With test tyres - Mic 4
Without test tyres - Mic 1
Without test tyres - Mic 2
Without test tyres - Mic 3
Without test tyres - Mic 4
Difference - Mic 1
Difference - Mic 2
Difference - Mic 3
Difference - Mic 4

(a)


SPL (dB (A))
100
90
80
70
60
50
40
30
20
10
0
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
1/3-octave frequency (Hz)
With test tyres - Mic 1
With test tyres - Mic 2
With test tyres - Mic 3
With test tyres - Mic 4
Without test tyres - Mic 1
Without test tyres - Mic 2
Without test tyres - Mic 3
Without test tyres - Mic 4
Difference - Mic 1
Difference - Mic 2
Difference - Mic 3
Difference - Mic 4

(b)



(c)

Figure 4.9 Noise spectra in cases with/without test tyres. (a) 40 km/h. (b) 50 km/h. (c) 80 km/h.

Therefore, it is shown that with the deployment of sound isolation panel within the walls of the enclosure, the PolyU Mark II Twin-wheeled CPX Trailer passes the certification test 2 for assessing the noise disturbances from the towing vehicle. Results indicate the disturbances have negligible influence to the tyre/road noise level measured inside the enclosure.

Remark

Notice that the distances between the towing joint and the centre of the test wheel are 1806 mm and 3720 mm in the standard and removed tyre tests respectively (Appendix 1). Their ratio is about 2. If it is conservatively assumed that the all the disturbing noises of the towing vehicle originate at its end, even a 3 dB(A) penalty is added to the results of certification test 2 (Figures 4.8 and 4.9), the criteria stipulated in ISO 11819-2 (2010) are still fulfilled.

4.3 Test 3: Sensitivity to disturbance from other traffic

The certification test 3 is to assess the noise disturbances from the vehicles passing by at adjacent lanes during CPX measurement. The principle of the test is to compare the noise levels measured from two tests on the same road. They are a CPX measurement and a parked measurement with vehicles passing-by the CPX trailer. The levels of influence by the noisiest heavy vehicle and passenger car are compared to the tyre/road noise level measured inside the enclosure.

4.3.1 Objective and criteria

The certification test 3 aims to test whether the noises from the vehicles passing-by at adjacent lanes induce negligible influence to the tyre/road noise measured inside the enclosure. As stipulated by ISO/CD 11819-2 (2010), the trailer is parked at the slow lane for measurement of noise levels by a more than 20 passenger cars and 20 heavy vehicles passing by at the adjacent lane. The noise level from the CPX measurement conducted at reference speed 80 km/h on the same road are compared to those from the noisiest passenger car and heavy vehicle. The criterion of the certification test 3 is that within the 1/3-octave frequency ranges 315 – 400 Hz and 500 – 5000 Hz, the band levels measured from the CPX measurement have to be 3 and 6 dB(A) respectively higher than the corresponding band levels from the noisiest heavy vehicle and passenger car (i.e. Equation 4.3).

$$SPL_{f,CPX} - SPL_{f,noisiest\ car} > \begin{cases} 3\ \text{dB(A) for } f\text{: } \{315, 400\}\ \text{Hz} \\ 6\ \text{dB(A) for } f\text{: } \{500, 5000\}\ \text{Hz} \end{cases}$$

Equation 4.3

where $SPL_{f,CPX}$ and $SPL_{f,\ noisiest\ car}$ are the A-weighted 1/3-octave band levels measured from the CPX measurement and the noisiest heavy vehicle or passenger car respectively.

4.3.2 Methodology

4.3.2 (i) Setup

CPX measurement at reference speed 80 km/h (Case A) and a measurement with the CPX trailer parked at the left lane (Case B) are conducted on the same road section. The details of measurement are shown in Table 4.3. The measured noise levels from the two cases are compared to test whether the noise levels by the passing-by vehicles is negligible compared to the tyre/road noise level measured inside the enclosure.

Location	**Road Surface**	**Ref. Speed (km/h)**	**Measurements**
Cheung Sha Wan Road*	Dense Asphalt Concrete	80	***Case A (Moving)*** Normal CPX measurement
			Case B (Parked) Noise measurement of passing-by vehicles

* Hing Wah Street to Tonkin Street

Table 4.3 Details of measurement for the certification test 3.

4.3.2 (ii) Procedures

CPX measurement at reference speed of 80 km/h (Case A) is first conducted on the road section. The trailer is then parked at the left lane of the road for measurement of noise from the passing by vehicles (Case B) as shown in Figure 4.10. The noise levels by traffic volume of more than 20 passenger cars and 20 heavy vehicles passing by at the adjacent lane are recorded. Meanwhile, the speeds of these vehicles are measured by taking the time of travel in a marked 20-metre segment.

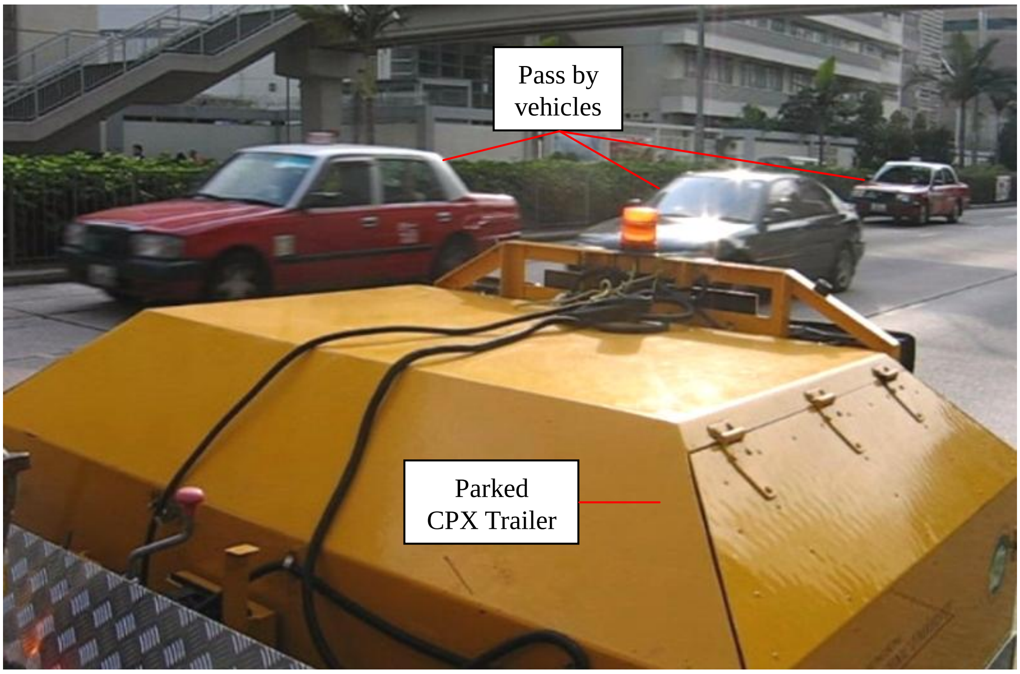
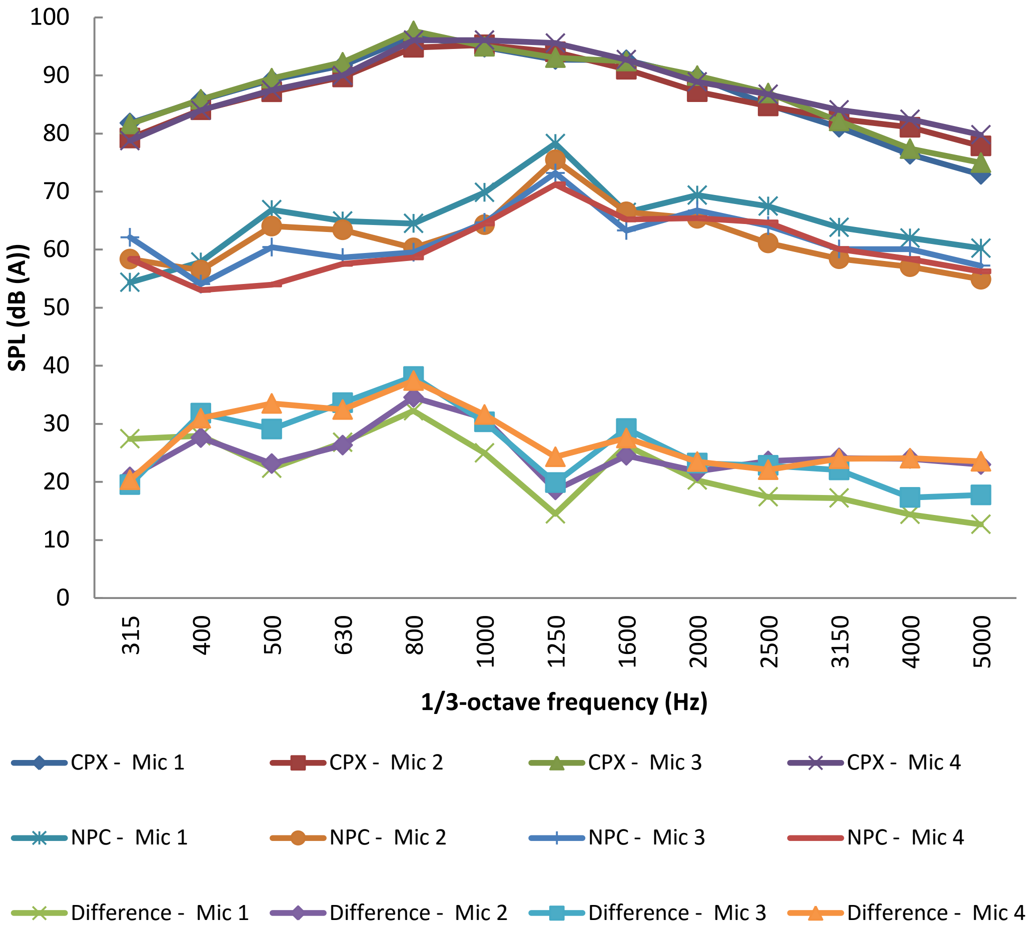


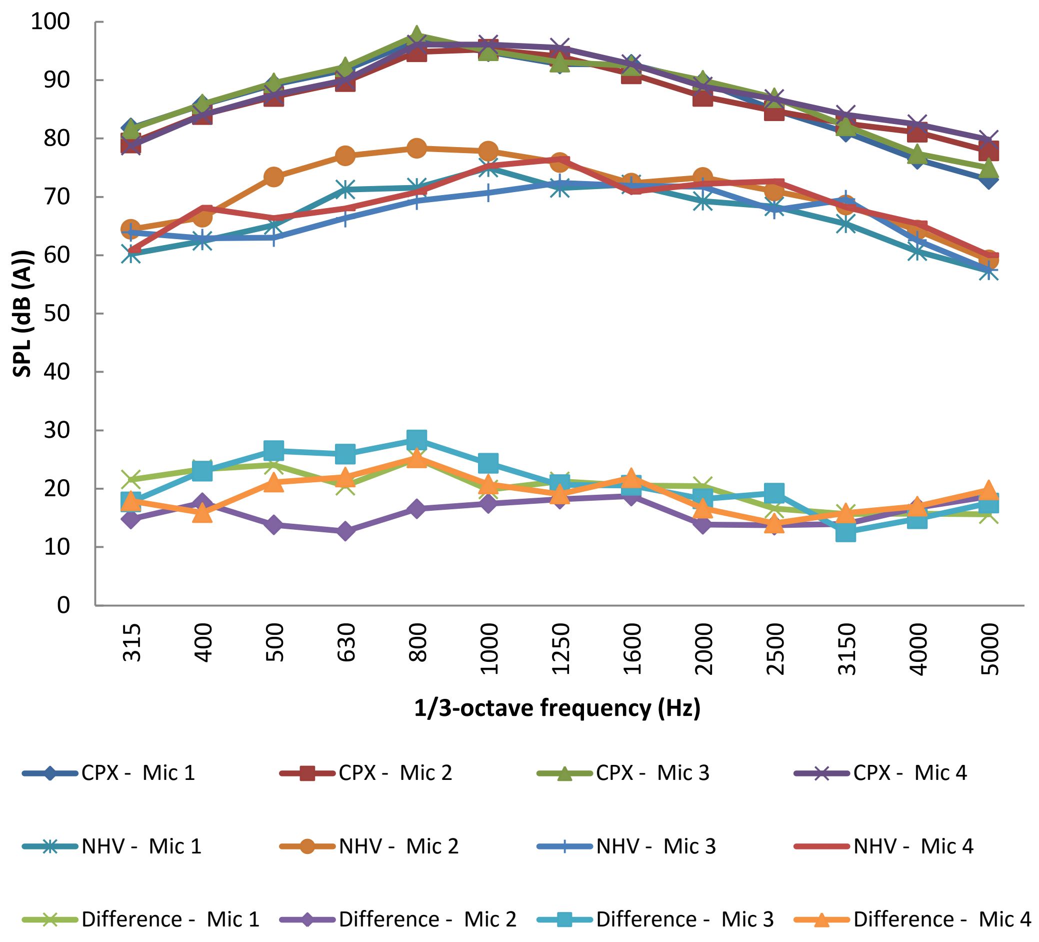
Figure 4.10 Parked measurement for the noise from passing-by vehicles.

4.3.3 Results and analysis

Two pieces of peak noise time history of 0.25-second duration (double of a fast time constant) by the noisiest passenger car and the noisiest heavy vehicle are extracted. Their A-weighted 1/3-octave spectra with correction to reference speed of 80 km/h are computed. The noise spectra of the ordinary CPX measurement, the noisiest passenger car (NPC) and the noisiest heavy vehicle (NHV) passing by, and also their spectral difference are shown in Figure 4.11. Notations Mic 1 to Mic 4 take their usual meaning of the four mandatory microphones as in the certification test 1. From the plots, the spectra measured from the CPX measurement is well above that from the noisiest passenger car/heavy vehicle by more than 10 dB. The criterion of the certification test 3 (i.e. Equation 4.3) is met.


SPL (dB (A))
100
90
80
70
60
50
40
30
20
10
0
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
1/3-octave frequency (Hz)
CPX - Mic 1
CPX - Mic 2
CPX - Mic 3
CPX - Mic 4
NPC - Mic 1
NPC - Mic 2
NPC - Mic 3
NPC - Mic 4
Difference - Mic 1
Difference - Mic 2
Difference - Mic 3
Difference - Mic 4

(a)



(b)

Figure 4.11 Noise spectra from CPX measurement and the passing by car. (a) Noisiest passenger car (NPC). (b) Noisiest heavy vehicle (NHV)

Therefore, it is shown that with the deployment of sound isolation panel, the noise influence from vehicles passing by at adjacent lane is negligible to the tyre/road noise level measured inside the enclosure. The PolyU Mark II Twin-wheeled CPX Trailer passes the certification test 3.

4.4 Conclusions

In this chapter, the three certification tests stipulated by ISO/CD 11819-2 (2010) are conducted. The test criteria, the devised setups and the results are presented and discussed. Upon deployment of the sound absorption material all over the internal walls of the enclosure for minimizing internal sound reflection and embedment of the sound isolation panel within the walls of the enclosure for shielding external noises, results indicate that the PolyU Mark II Twin-wheeled CPX Trailer has passed all the three certification tests instructed for assessing the acoustic performance of the enclosure. The CPX trailer is certified to conduct tyre/road noise measurement in accordance to ISO/CD 11819-2 (2010).

CHAPTER 5

VIBRATION INDUCED ERRROR IN CPX MICROPHONE SIGNAL

For any CPX trailer designed for tyre/road noise measurement on real roads, its movement on bumpy roads inevitably excites the trailer to vibrate. The microphones mounted inside the trailer are then exposed to a background vibration environment. The vibration of microphone may induce error in the measured tyre/road noise level since the sensing mechanism of microphone is based on the vibratory responses of its diaphragm. To evaluate the influence of such vibration-induced error on tyre/road noise measurement, two tests (the laboratory and the trailer on-deck tests) with controlled noise sources and vibration excitation are devised in this study. The results obtained indicate that errors in the measured noise level are produced when the microphone is set to vibrate and they may reach as high as 3 dB(A). The error term is found linearly correlated with the microphone vibration level for five 1/3-octave bands. An attempt to correct these errors is proposed and evaluated in the present study.

5.1 Sensing mechanism of microphone

Sound wave is the fluctuation of air pressure propagating in the ambient atmospheric environment. When it reaches our ears, it is detected and perceived through the vibration it induces to the eardrums. Sound is sensed and measured by a microphone through a similar principle that the fluctuation of air pressure induces vibration of the thin diaphragm at its head. Figure 5.1 shows the key sensing elements of a microphone, namely the light weighted thin flexible diaphragm at the head, the fixed back plate electrode behind the diaphragm and the various electric units such as the electric supply and the resistor. The sensing mechanism of the microphone works in the following principle (Gayford, 1994). As a sound wave is incident to the flexible diaphragm, it is set to vibrate and causes a change of its separation from the back plate electrode. Such change of the relative displacement between the diaphragm and the electrode causes variation in the formed capacitance and produces electric voltage signal. This electric signal is picked up and then computed into the measured noise level by the analyzer.

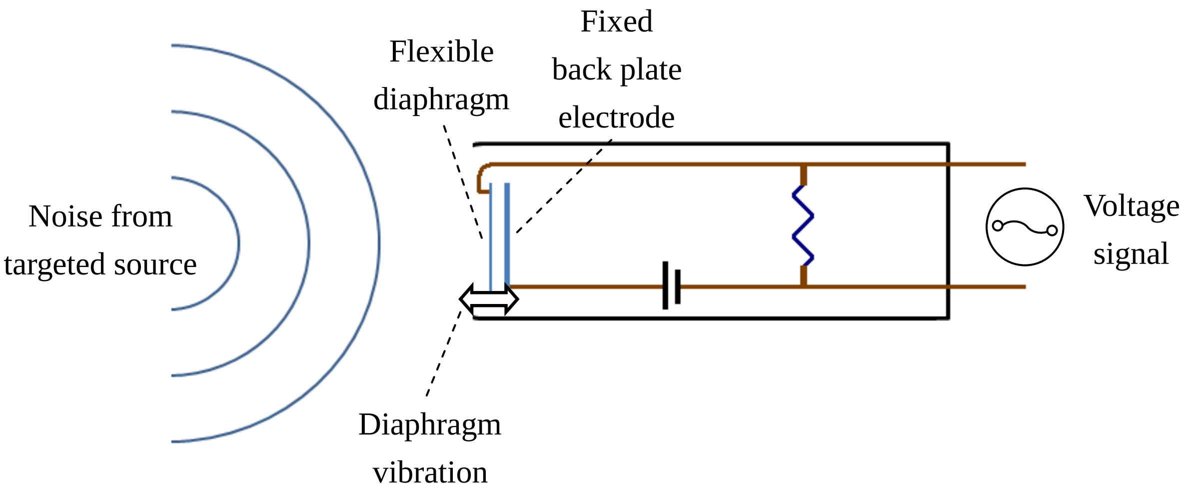


Figure 5.1 Schematic sketch of the working principle of microphone.

5.2 Sensitivity to vibration of microphone

With the nature of sensing sound from the vibration of the diaphragm, the microphone may be sensitive to the vibration itself since this may also induce relative displacement between the flexible diaphragm and the back plate electrode. In fact, previous researches (Rule et al., 1960; Killion, 1975) have shown that the vibration sensitivity of microphone exists and such sensitivity is directly related to the mass per unit area of the diaphragm. There is even a research (Watakabe et al., 2001) utilizing microphone for measuring the vibration of voluntary muscle contractions of human being. It is found that the signal output of the microphone has a linear relationship with the displacement of the muscle. All these researches point out that microphone may produce erroneous noise signal when it is set to vibrate. Such vibrational sensitivity of the microphone may cause significant errors to the measured noise levels in CPX measurement since the microphones mounted at the CPX trailer are inevitably exposed to vibration induced by the road bumpiness.

5.3 Test for vibration induced error in microphone signal

To test the level of influence on the measured tyre/road noise level by the vibration of the microphones, two experiments, one in laboratory and one on road, are devised to evaluate such vibration-induced error in this study. The test principle, the setups, the results and analysis are presented and discussed in the following sections.

5.3.1 Test principle

The test principle of the microphone vibrational influence to the measured noise level is that a vibrating microphone in actual measurement gives a noise level composed of two parts – the noise level given by the targeted noise source and an erroneous noise level induced by its vibration. This latter erroneous component is termed as “vibration-induced error” in this study. The hypothetic relationship between them is expressed in Equation 5.1.

$$SPL_{L_{\ddot{x}}} = SPL_{noise} + E(L_{\ddot{x}}) \qquad \text{Equation 5.1}$$

where $SPL_{L_{\ddot{x}}}$ is the measured noise level in dB(A) under vibration level $L_{\ddot{x}}$ in dB, SPL_{noise} is the noise level by the targeted noise source in dB(A) and $E(L_{\ddot{x}})$ is the vibration-induced error in dB(A) under vibration level $L_{\ddot{x}}$. By rearranging the hypothetic equation, we could define the vibration-induced error by subtraction of the noise level by a known noise source when the microphone is stationary from that when the microphone is vibrated (i.e. Equation 5.2).

$$E(L_{\ddot{x}}) = SPL_{L_{\ddot{x}}} - SPL_{stationary} \qquad \text{Equation 5.2}$$

where $E(L_{\ddot{x}})$ is the vibration induced error in dB(A) under vibration level $L_{\ddot{x}}$ in dB, $SPL_{L_{\ddot{x}}}$ is the measured noise level in dB(A) under vibration level $L_{\ddot{x}}$ and $SPL_{stationary}$ is the measured noise level in dB(A) by the microphone in stationary.

In actual CPX measurement, it is infeasible to compute the vibration-induced error through conduction of control tests with and without vibration of microphone using CPX Method. Therefore, to test out this erroneous component, a different approach has to be devised where the microphone can be kept stationary or set to vibrate in a prescribed manner, with also a controlled noise source. The laboratory test and the trailer on-deck test devised with the concept above and their results are presented and discussed in the following sections.

5.3.2 Laboratory test

To monitor the vibration level of the microphone, an accelerometer-microphone kit is fabricated as shown in Figure 5.2. Other than the plastic microphone holder, all the body parts are made of solid steel. A screw rod is implemented at the top for rigid connection to the frame of the CPX trailer. A flat platform is provided below it for fixing a screw-type accelerometer. An O-ring engaged with cable fastener is used for holding the microphone at the centre hole. The x and y axes in the figure are denoted on a defined imaginary plane containing the accelerometer and microphone.

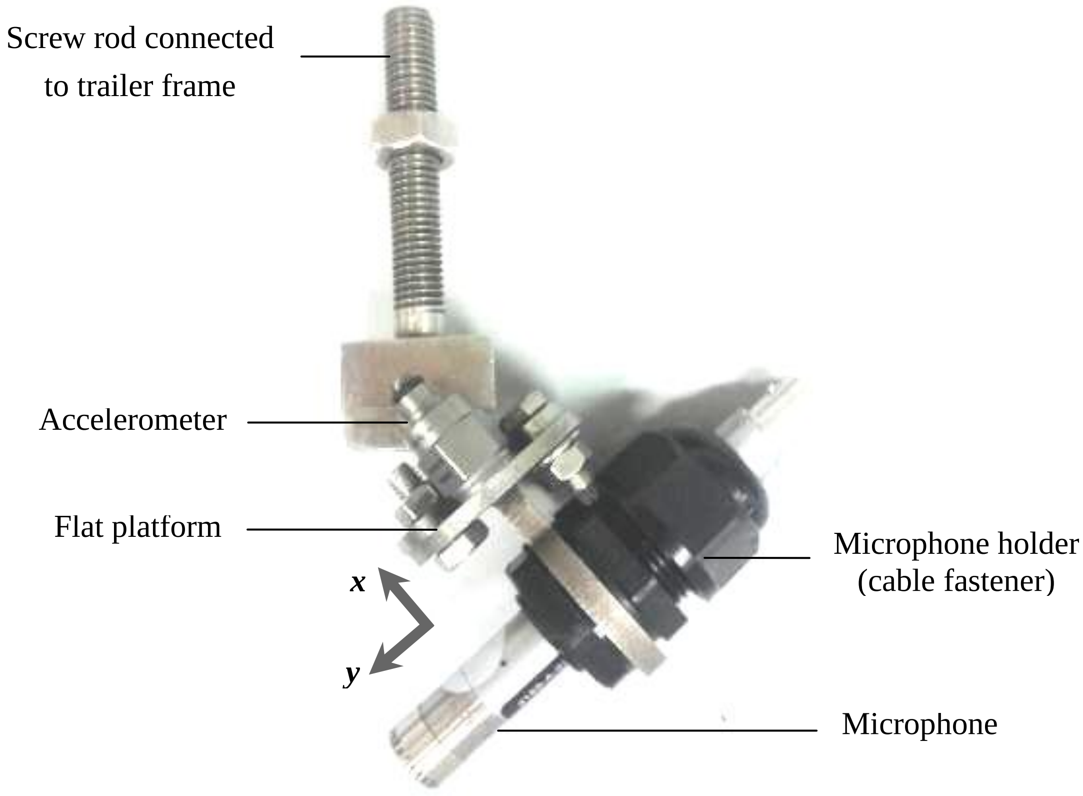
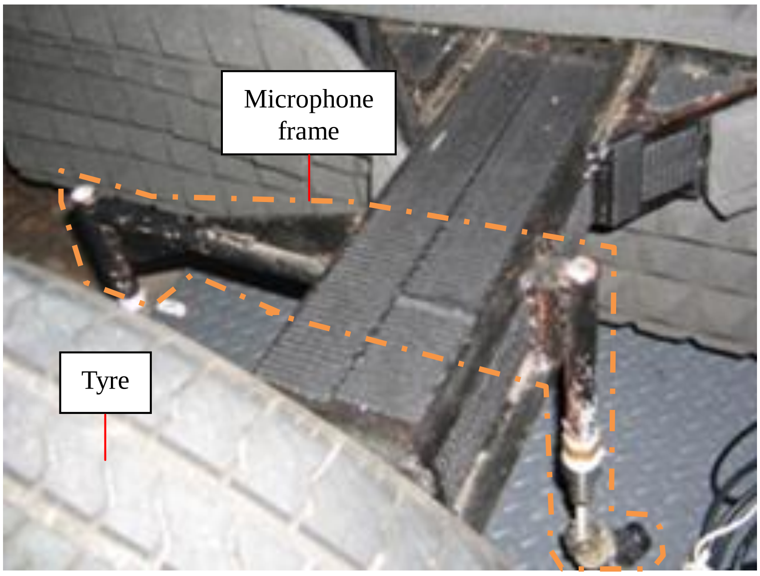


Figure 5.2 Kit set for monitoring microphone vibration.

The laboratory test is equipped with a controlled noise source driven by a speaker and a controlled microphone vibration with a shaker. Since it is impractical to have the bulky CPX trailer placed into the anechoic chamber, the entire microphone mounting frame of the trailer is replicated for the test. Figure 5.3 shows the actual frame in the trailer and the replica. Both the actual frame and the replica utilize the kit shown in Figure 5.2 for mounting the accelerometer and the microphone.



* sound absorption material detached

(a)

(b)

Figure 5.3 Microphone mounting frame. (a) Actual frame in the CPX trailer. (b) Replica frame for laboratory test.

The replica frame is used to simulate the trailer in the laboratory test conducted in anechoic chamber. The set up is shown in Figure 5.4 with the same definition of x and y axes as in Figure 5.2. Vibration is exited to the replica frame at the microphone holder using a shaker connected to a power amplifier fed with sinusoidal signal. The shaker is hung in the air with its axis at horizontal direction using a triangular supporting structure loaded with heavy mass to minimize the return of vibration response. A speaker emitting white noise is adopted as the controlled noise source. Any flat surfaces of the setup are covered with fiber-glass absorption panels to minimize sound reflection there.

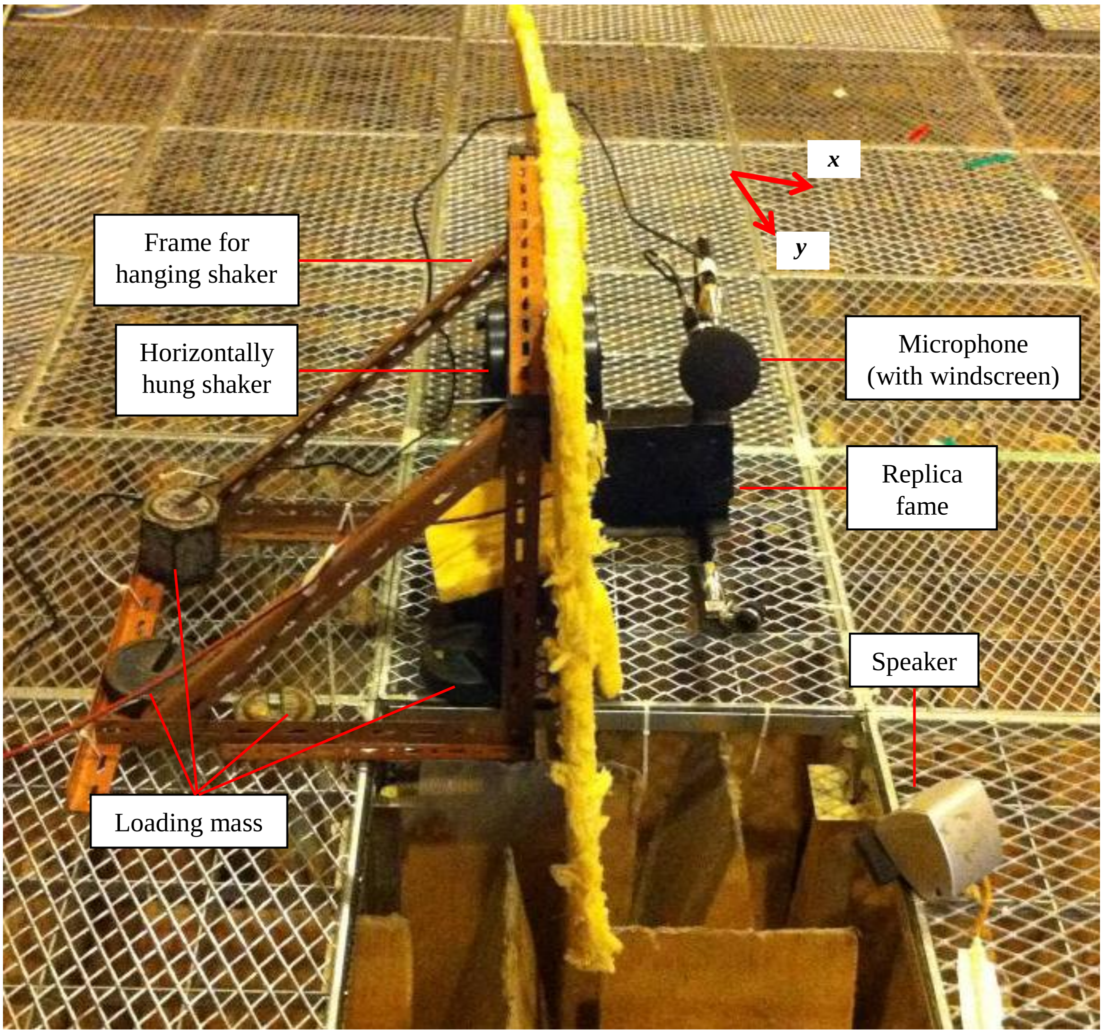
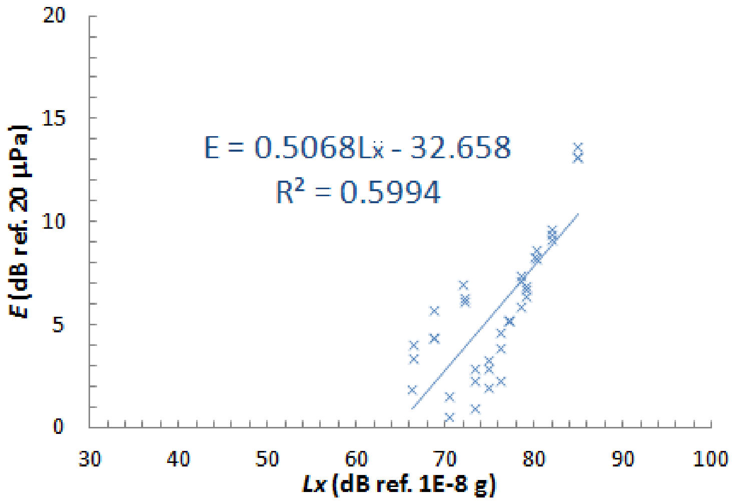


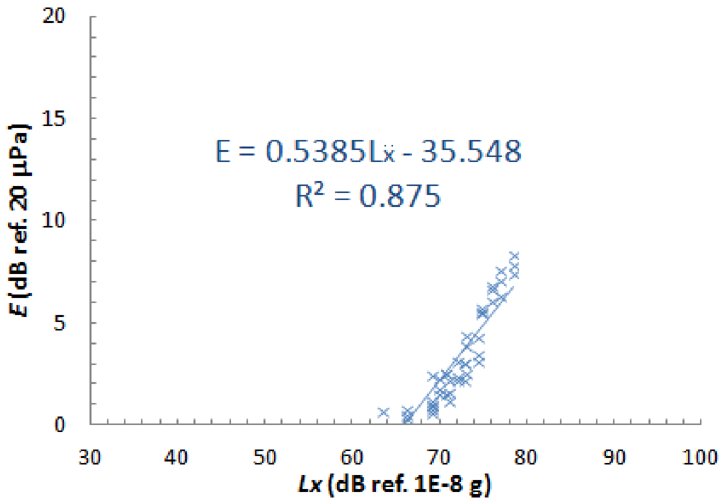
Figure 5.4 Setup of the laboratory test for vibration-induced error.

The speaker is turned on for three minutes for warming up. The noise level with the shaker off is measured for three runs each with 30-second duration. The shaker is powered on with sinusoidal signals at centre frequencies of 1/3-octave bands between 315 and 5000 Hz one by one, which is the tyre/road noise frequency range defined by (ISO/CD 11819-2, 2010). The noise level and the vibration experienced by the shaken microphone are recorded for three runs each with 30-second duration.

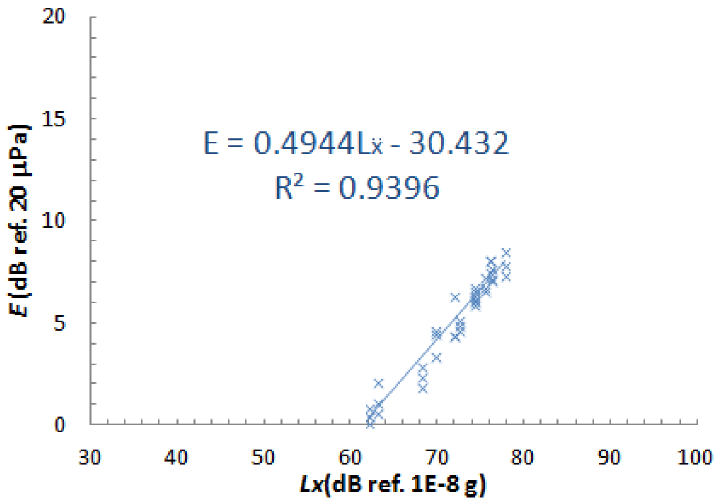
The vibration-induced error in the microphone signal is identified by subtracting the noise level measured by a stationary microphone from that when it is set to vibrate by the shaker. The errors obtained are plotted against the microphone vibration levels for the 1/3-octave frequency bands in Figure 5.5. The reference value for the vibration level is set at 1×10^{-8} g so that all the measured levels will fall on the positive side of the plane for easier viewing. Linear relationships between the two terms are found for five bands with centre frequencies 315, 400, 500, 800 and 1000 Hz. Most of the plots have high goodness of fit at about 0.9. It is observed that when the microphone vibrates, the measured noise level is larger than that measured in stationary condition. This complies with findings from researches elsewhere (Rule et al., 1960; Killion, 1975; Watakabe et al., 2001) that that the microphone is sensitive to its vibration and will produce increased noise level when vibrated. Moreover, it is possible to estimate the vibration-induced error from the vibration level using the linear regression fits. An evaluation study of correction attempt based on compensation of the estimated error is illustrated and discussed in Section 5.4.



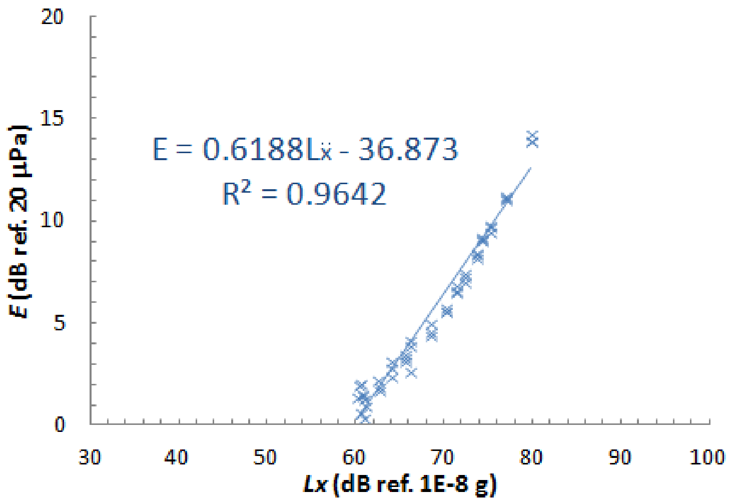
(a) 315 Hz band.



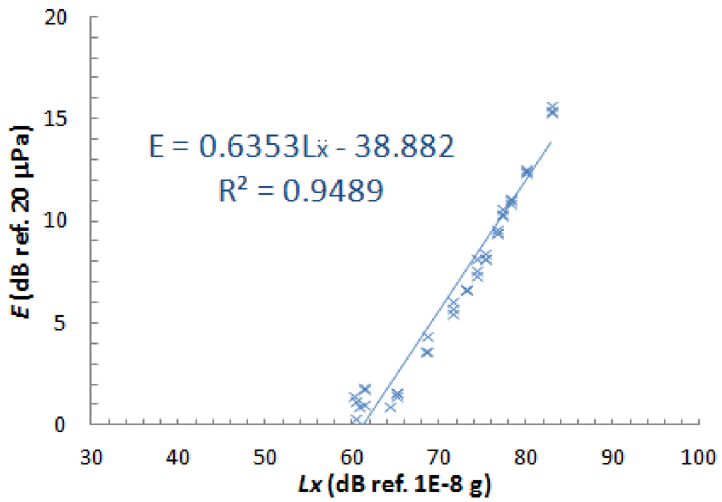
(b) 400 Hz band.



(c) 500 Hz band.



(d) 800 Hz band.



(e) 1000 Hz band.

Figure 5.5 Vibration-induced error and microphone vibration level at 1/3-octave frequency band in laboratory test.

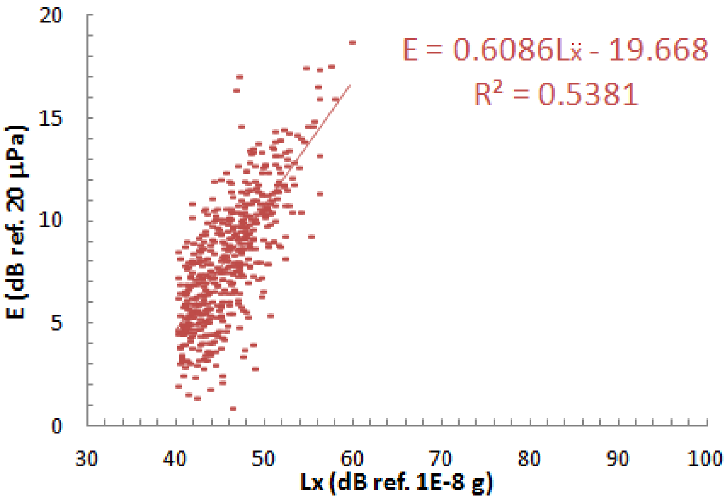
5.3.3 Trailer on-deck test

The principle of the trailer on-deck test is similar to the laboratory test in which the vibration-induced error is found by noting the difference in the noise levels measured when the microphone is excited to vibrate and is stationary. The two tests differ by the environment and the method of vibration excitation imposed to the microphone. To simulate the working environmental of the microphone in CPX measurement, the whole CPX trailer is used in this test. The trailer is fixed onto the deck of the towing vehicle as shown in Figure 5.6. This is done to prevent the tyre from rolling and eliminate the uncontrollable contamination of tyre/road noise created. A speaker emitting white noise is placed near the tyre/deck contact patch as the controlled sound source. The vehicle is then driven to travel on real roads. Vibration excitation to the microphone is provided by the real road bumpiness transmitted to the trailer through the vehicle.

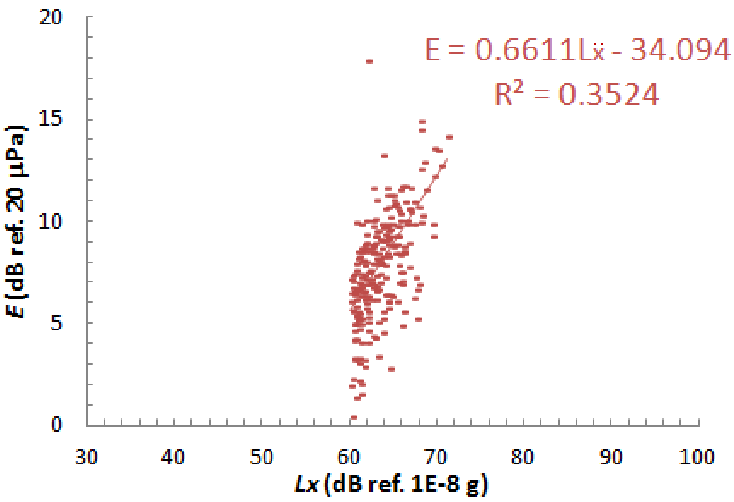
Figure 5.6 Setup of trailer on-deck test for vibration-induced error.

The speaker is turned on for three minutes for warming up. The noise levels with the vehicle parked and travelling are measured for three runs with 30-second duration each. The noise and the vibration experienced by the microphone are recorded.

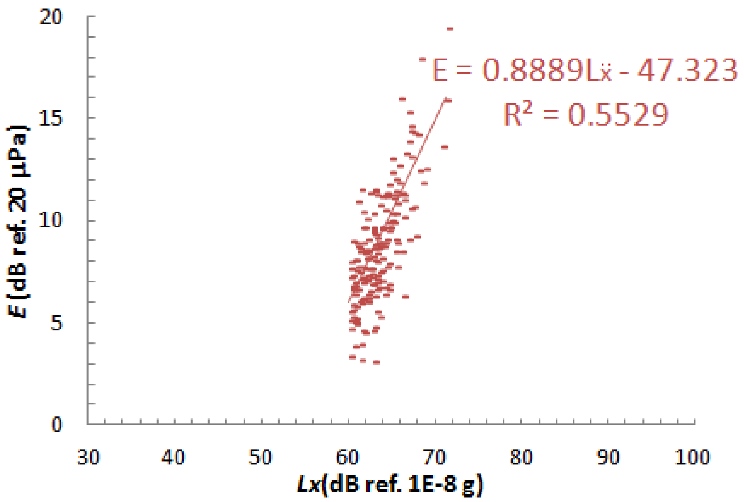
The vibration-induced errors are plotted against the microphone vibration levels (Figure 5.7). Complying with the results in the laboratory test, the error exists in the signal by the vibrated microphone and it increases with the vibration level experienced by the microphone. Same as the laboratory test, linear regression fittings are applied to the data obtained from trailer on-deck test. The average goodness of fit is about 0.5 which is marginally acceptable but weaker than that in the laboratory test due to the relatively noisy background. It is again possible to estimate the error term from the measured microphone vibration level. The results from the laboratory test and the trailer on-deck test are compared in the next section. Besides, an evaluation study of correction attempt is illustrated and discussed in Section 5.4.



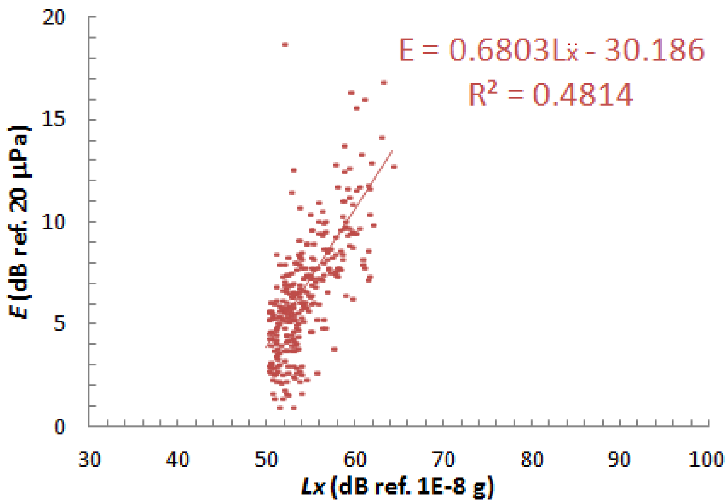
(a) 315 Hz band.



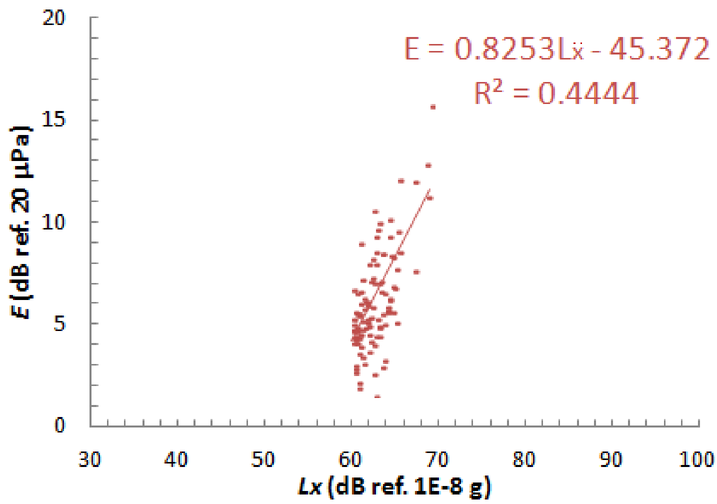
(b) 400 Hz band.



(c) 500 Hz band.



(d) 800 Hz band.



(e) 1000 Hz band.

Figure 5.7 Vibration-induced error and microphone vibration level at

1/3-octave frequency band in trailer on-deck test.

5.3.4 Comparison of laboratory and trailer on-deck tests

The vibration-induced errors obtained from the laboratory and the trailer on-deck tests are compared and discussed in this section. The identified vibration-induced errors against microphone vibration level of both tests are plotted together in Figure 5.8. The common features and differences in the results and findings from the two tests are discussed below.

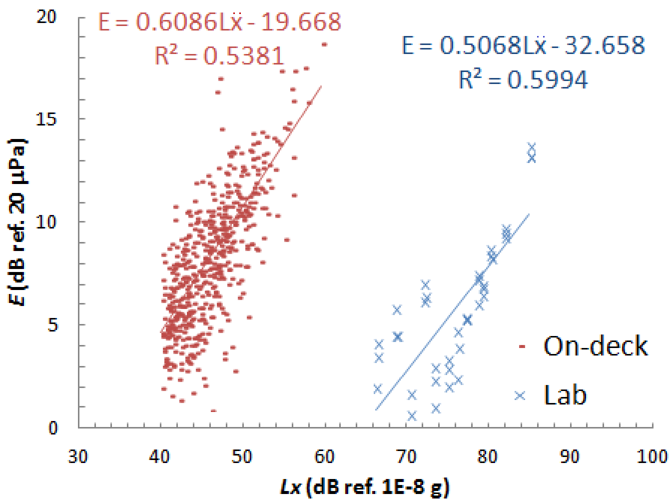
<u>Relationship between the error and the vibration level</u>

For both the laboratory test and the trailer on-deck test, it is observed from Figure 5.8 that a vibrating microphone produces an erroneous component in its measured noise level. The level of error can reach up to 20 dB(A) deviation in the band level in extreme cases. Since vibration excitation to the microphones inside the CPX trailer due to bumpiness of real roads is inevitable, it is not a surprise to see that the measured tyre/road noise level may be overestimated. The evaluation study of correction attempt in Section 5.4 shows that the overestimation can reach as much as 3 dB(A).

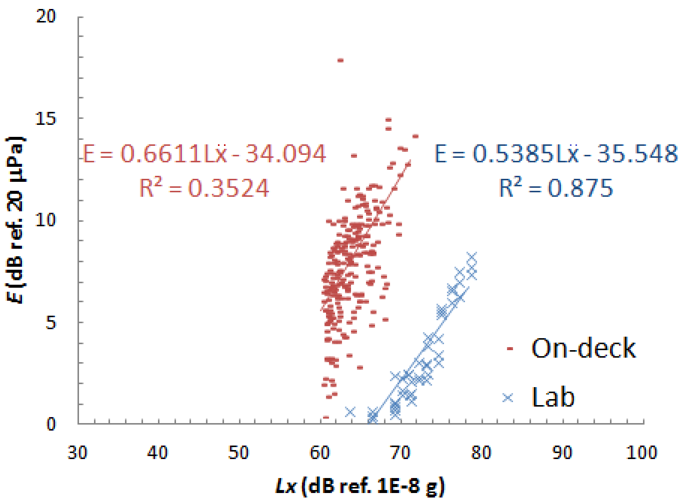
It is observed from Figure 5.8 that the vibration-induced error increases linearly with the microphone vibration level. The correlations between the two parameters appear to be stronger in the laboratory test. This can be explained by the fact that in the laboratory there is a well controlled background acoustic environment with minimized noise disturbance while the trailer on-deck test is carried out in an outdoor environment where noise influence from the surrounding exists (e.g. noise event by other mechanical parts of the vehicle when vibrated by road bumpiness). The additional noise event is a possible explanation to the data obtained from the trailer on-deck tests being on the left to that of the laboratory test.

Slope of the error to the vibration level

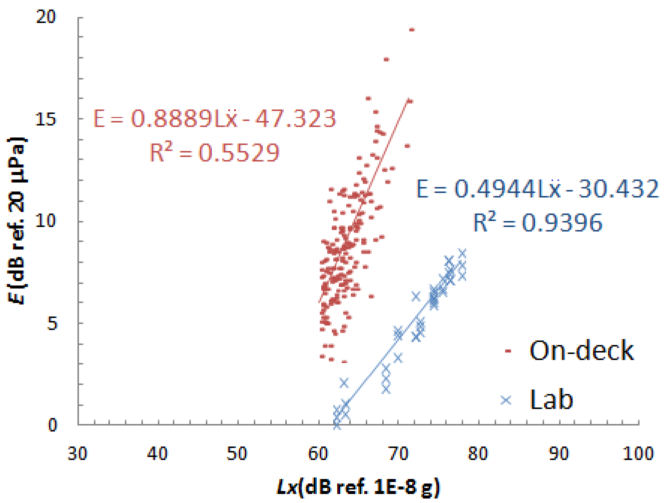
The slope of the vibration-induced error against the microphone vibration level is of particular importance that it represents the sensitivity to vibrational influence of the CPX microphones. The slopes obtained from the laboratory and the trailer on-deck tests are plotted in Figure 5.9. For most of the bands, the slopes obtained from the two tests are close and differ by only about 0.1 out of 0.6. This inspires confidence to the results obtained. The slopes obtained from the trailer on-deck test are all larger than those from the laboratory test. This could be explained that the road bumpiness in the trailer on-deck test may result in additional noise events by vibration of other mechanical components of the trailer or the whole vehicle (e.g. body parts of the trailer and metal fences of the deck) while the laboratory test has minimized number of such unrelated items. It explains for the data from the trailer on-deck test being shifted left to the laboratory test in Figure 5.8. The exceptionally large slope for band with centre frequency 500 Hz from trailer on-deck test may also be attributed to the same reason.



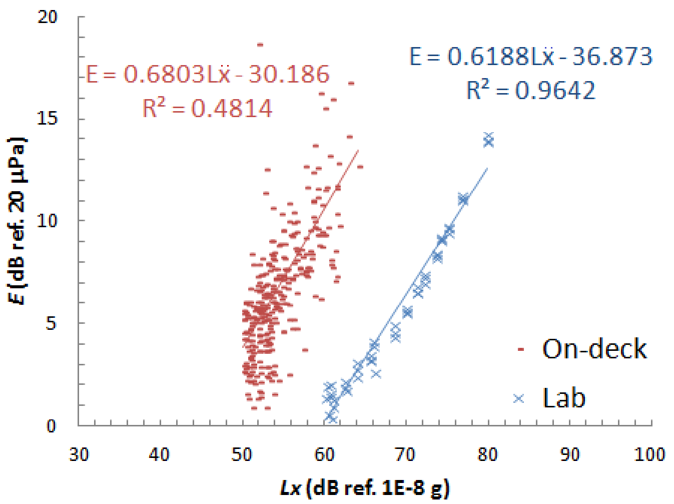
(a) 315 Hz band.



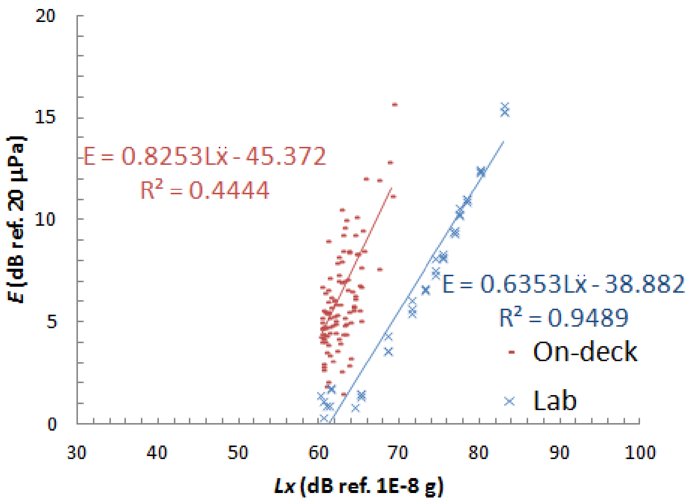
(b) 400 Hz band.



(c) 500 Hz band.



(d) 800 Hz band.



(e) 1000 Hz band.

Figure 5.8 Vibration-induced error and vibration level in microphone signal at 1/3-octave frequency band.

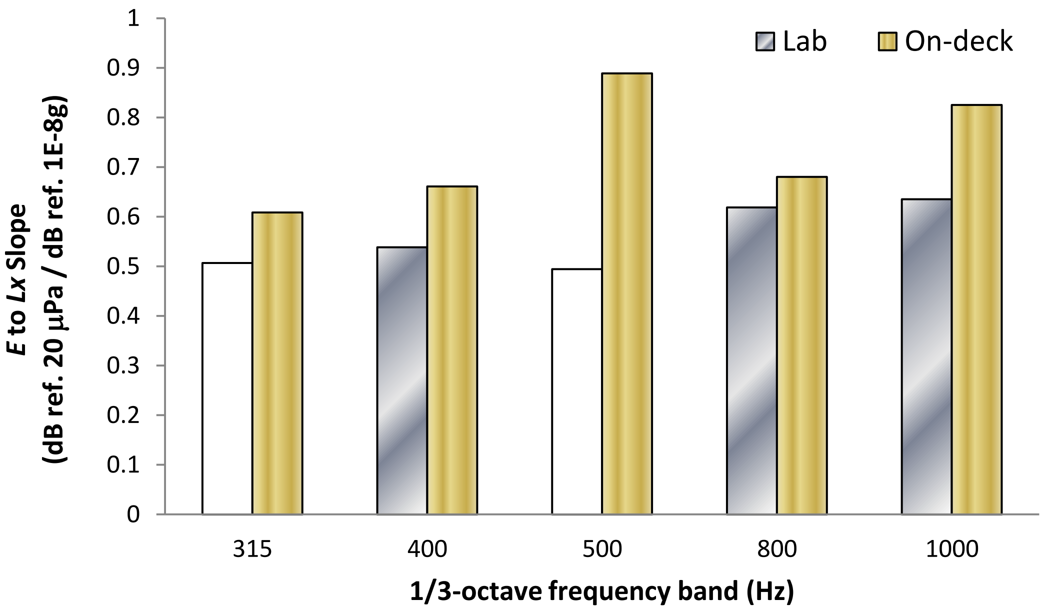


Figure 5.9 Slope of vibration-induced error to microphone vibration level.

5.4 Evaluation of correction attempt with case study

Based on the results given in Section 5.3, an attempt to correct the vibration-induced error in tyre/road noise measurement is given here using the principle of compensation of the error term estimated from the measured microphone vibration level. The error-vibration level regression fits Figure 5.8 are summarized in Table 5.1. The application of the correction is illustrated with a CPX measurement conducted at 70 km/h on a dense asphalt concrete surface. The background details of the evaluation study are shown in Table 5.2.

1/3-octave centre frequency (Hz)	**Laboratory test**		**Trailer on-deck test**	
	Regression fit	R^2	**Regression fit**	R^2
315	$E(L_{\ddot{x}}) = 0.5068L_{\ddot{x}} - 32.658$	0.60	$E(L_{\ddot{x}}) = 0.6086L_{\ddot{x}} - 19.668$	0.54
400	$E(L_{\ddot{x}}) = 0.5385L_{\ddot{x}} - 35.548$	0.88	$E(L_{\ddot{x}}) = 0.6611L_{\ddot{x}} - 34.094$	0.35
500	$E(L_{\ddot{x}}) = 0.4944L_{\ddot{x}} - 30.432$	0.94	$E(L_{\ddot{x}}) = 0.8889L_{\ddot{x}} - 47.323$	0.55
800	$E(L_{\ddot{x}}) = 0.6188L_{\ddot{x}} - 36.873$	0.96	$E(L_{\ddot{x}}) = 0.6803L_{\ddot{x}} - 30.186$	0.48
1000	$E(L_{\ddot{x}}) = 0.6353L_{\ddot{x}} - 38.882$	0.95	$E(L_{\ddot{x}}) = 0.8253L_{\ddot{x}} - 45.372$	0.44

Table 5.1 Regression lines of vibration-induced error against microphone vibration level.

Location	**Road Surface**	**Ref. Speed (km/h)**	**Measurement Type**	**Tyre**	**Remarks**
Cheung Sha Wan Road*	Dense Asphalt	70	CPX measurement	***S**tandard **R**eference*	Microphone vibration

Concrete	***T**est **T**yre* (SRTT)	monitored

* Hing Wah Street to Tonkin Street

Table 5.2 Background details of the case study for vibration correction attempt.

Step 1: Computing the 1/3-octave spectrum of the microphone vibration

The 1/3-octave spectrum of the measured microphone vibration is computed using fast time constant (Figure 5.10). The numerical values for each band levels are noted for the next step of estimation of the level of vibration-induced error.

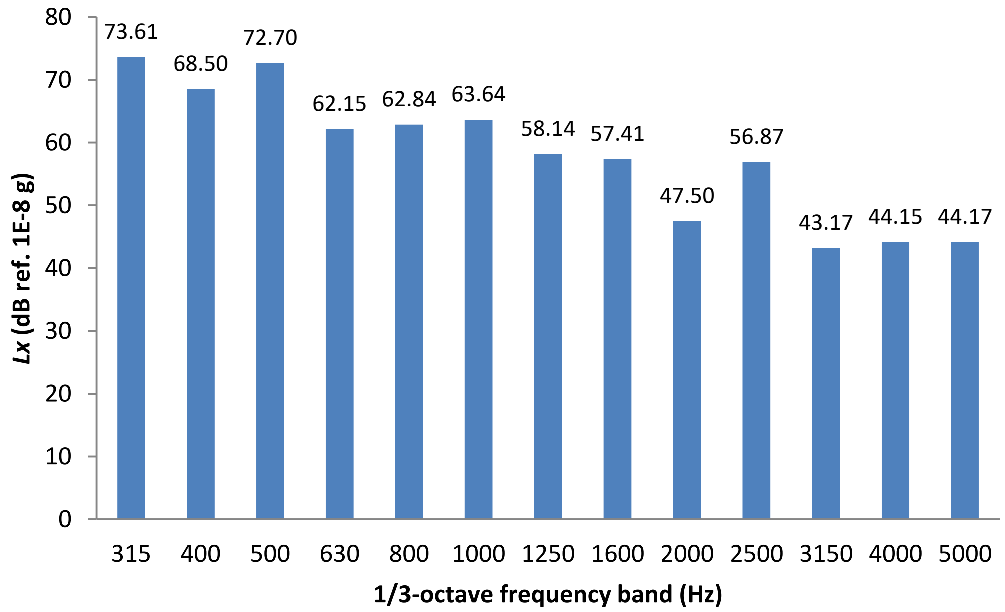


Figure 5.10 Spectrum of microphone vibration in a CPX measurement.

Step 2: Estimation of vibration-induced error

The measured microphone vibration level is substituted into the regression fits in Table 5.1 to estimate the vibration-induced error. The error computation for band 315 Hz using the corresponding fit from the laboratory test is illustrated below as an example. The same is repeated for other bands. Notice that only positive error yielded is accepted since the vibration-induced error is found to be positive from Figure 5.8.

$$E_{315,lab}(73.61) = 0.5068 \times 73.61 - 32.658$$

$$= 4.65\ dB$$

Step 3: Compensation of vibration-induced error for the measured tyre/road noise spectrum

The estimated vibration-induced error is compensated by subtraction of it from the measured tyre/road noise band level as illustrated below.

$$SPL_{corrcted,315} = SPL_{measured,315} - E_{315,lab}$$

$$= 81.62 - 4.65$$

$$= 76.97 \quad dB$$

The original and the corrected spectra of this case study are shown in Figure 5.11. The noise spectra corrected with the fits yielded from laboratory and trailer on-deck tests have similar pattern in which dips exist at 500 Hz and 800 Hz. The overall tyre/road noise levels for the original and the corrected results from the laboratory and the trailer on-deck tests are 101.6, 100.5 and 98.3 dB(A) respectively. The registered noise level reductions after corrections range from about 1 dB(A) and even up to 3 dB(A). The vibration induced error on the measured tyre/road noise level is significant.

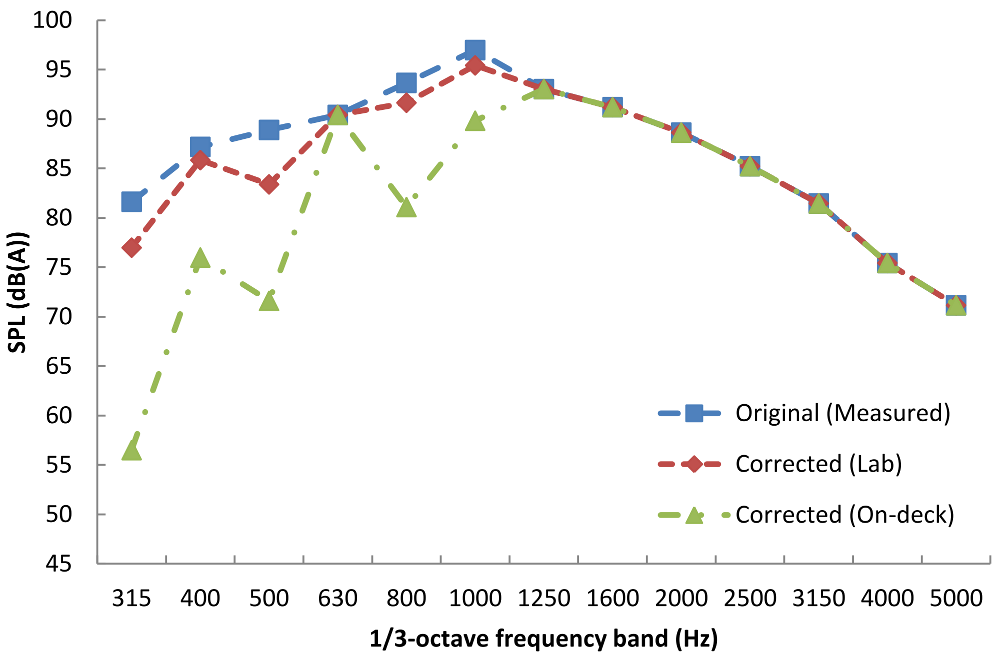


Figure 5.11 Tyre/road noise spectra before/after correction for vibration induced error.

Recommendation for the choices of original/corrected results

Up to this stage, one may ask which one of the three tyre/road noise levels should be adopted – original, "lab-corrected" or "trailer on-deck-corrected". Analysis is made on the features of each of the three results. The adoption guidelines devised by the author and the rationale involved are summarized in Table 5.3.

Tyre/road Noise Level	**Suggested Application**	**Rationale**
Original	Assessment to road sections all in flat and smooth conditions (e.g. newly paved).	With smooth road surfaces, unfairness to road sections susceptible to vibration-induced error (bumpy roads) is avoided when comparing the tyre/road noise performance of individual road surface materials.

Lab-corrected	Assessment at low speed (e.g. below 50 km/h) on road sections with pavements already in use but not heavily defected (e.g. mild crack and raveling).	Trailers equipped with suspensions are rarely shocked when travelling on roads with mild defects. The lab-corrected result is better than the original one by reducing the vibration influence on the measuring microphone.
Trailer on-deck-corrected	Assessment to road sections with heavy defects in the pavement (e.g. potholes and delamination).	Heavy pavement defects induce strong vibration to the CPX trailer. As in the trailer on-deck test, the road bumpiness not only causes vibration-induced error but also additional noise events by vibration of other mechanical components of the CPX configuration.

Table 5.3 Rationale for adoption of original or corrected tyre/road levels.

5.5 Conclusions

The sensing mechanism and vibrational sensitivity of microphone are briefed in this chapter. The laboratory and the trailer on-deck tests are developed to test and evaluate the vibration-induced errors in real tyre/road noise measurement. It is found that a microphone produces this additional erroneous component when it is set to vibrate. The magnitude of this error is found linearly correlated with the microphone vibration level for five 1/3-octave bands of interest in tyre/road interaction noise. An attempt to correct for this error is illustrated with a case study using the regression fits of the vibration level against the error obtained from the two tests. Results indicate that the vibration effect can cause an over-estimation of the measured tyre/road noise level by as much as 3 dB(A). Recommendations on adopting the original and the two corrected tyre/road noise level results are given for different applications of CPX Method.

CHAPTER 6

TEMPERATURE EFFECT ON TYRE/ROAD NOISE

Tyre/road noise measurement with CPX Method on public roads is influenced by the uncontrollable temperature of the surrounding environment. ISO/CD 11819-2 (2010) suggests the optional temperature correction process to compensate the effect on the measured noise level. Since Hong Kong is located in subtropical region, the change in temperature may induce significant influence to the measured noise level. Temperature correction is therefore necessary for tyre/road noise surveys with relatively long duration. The temperature constant involved in the correction process varies for different combinations of tyre and road surface. A single-day test is devised and conducted with SRTT on two local common road surface types. Their air and road surface temperature constants are yielded. Moreover, the reliabilities of correction with air and road surface temperatures are compared.

6.1 Tyre/road noise level and temperature

Temperature is anticipated to be an influencing factor to the tyre/road noise level due to the thermoplastic properties of the tyre rubber. Jabben (2011) gave a hypothesis that the higher stiffness of the tyres at lower temperatures tends to induce a stronger tyre/road impact and consequently higher tyre vibration and thus tyre/road noise level. Further studies (Kuijpers, 2002; Anfosso-Lédée and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; Jabben, 2011) consistently show that the tyre/road noise level decreases linearly with air and road surface temperatures. The relationship between the noise level and the temperature can be expressed as follows (i.e. Equation 6.1).

$$SPL = mT + C \qquad \text{Equation 6.1}$$

where SPL is the tyre/road noise level in dB(A), m is the slope of tyre/road noise level against temperature in dB(A)/°C, T is the temperature in °C and C is a numeric constant.

Since the relationship of the tyre/road noise level with the temperature is found, the level of temperature effect can be estimated. Furthermore, it is possible to develop and apply temperature correction to the measured noise level through compensating the effect to a reference temperature. ISO/CD 11819-2 (2010) specifies a reference air temperature of 20 °C as illustrated in the correction formula below (i.e. Equation 6.2). The estimated level of temperature effect is computed by multiplying the deviation from the reference temperature with a temperature constant *a* which is dependent on the combination of tyre model and road surface type. This estimated level of temperature effect is then subtracted from the measured noise level to yield the estimated noise level at 20 ℃. Temperature correction is optional in ISO/CD 11819-2 (2010). However, the relatively large variation in temperature in Hong Kong may have significant influence to the measured tyre/road noise level. It is therefore necessary to determine the temperature constants for the local common road surface types to ensure reliable measurement results.

$$SPL_{20°C} = SPL_T - a(T - 20) \qquad \text{Equation 6.2}$$

where $SPL_{20℃}$ is the corrected tyre/road noise level in dB(A) to reference air temperature of 20 ℃, SPL_T is the measured tyre/road noise level in dB(A) at temperature T in ℃ and a is air temperature constant in dB(A)/℃.

6.2 Test for temperature effect on tyre/road noise

In this section, a literature survey on the approaches to test for the temperature effect on the tyre/road noise level is conducted and the adopted single-day test method in this study are presented and evaluated. Comparison on the reliabilities of air and road surface temperatures for temperature correction is also made. The temperature constants for two common types of asphalt surface in Hong Kong, wearing course (WC) and stone mastic asphalt (SMA), are yielded.

6.2.1 Methodology

To evaluate the temperature effect on the tyre/road noise level, the approach of parametric test with variation in temperature by natural weather is commonly adopted by the research groups (Kuijpers, 2002; Anfosso-Lédée and Pichaud, 2007; Bühlmann and Ziegler, 2011; Jabben, 2011). They have devised different approaches to vary the temperature which can generally be categorized into two. The first utilizes the climatic temperature variation through the four seasons and the second makes use of the temperature variation from daytime to nighttime in a single day. Their test methods and findings are presented and discussed below.

6.2.1 (i) Approaches by researchers elsewhere

Seasonal temperature variation

Anfosso-Lédée and Pichaud (2007) have the approach with a set of controlled pass-by measurements on public roads using two models of Michelin tyres for the four seasons in Bouguenais, France. It is assumed that the aging of the road surfaces is negligible and their properties are stable due to the small traffic and the adoption of old surfaces as test sections. Large variations in air and road surface temperatures of 5 – 30 ℃ and 0 – 50 ℃ respectively are registered. It is found that the measured noise levels decreases with air and road surface temperatures linearly. The yielded air and road surface temperature constants are –0.10 dB(A)/℃ and –0.06 dB(A)/℃ respectively. Similar to this approach in terms of duration, Jabben (2011) conducts a one-year scaled survey with a set of nighttime pass-by measurements at a motorway in Netherlands. The noise events by 8750 random passenger cars and trucks are recorded. The air temperature ranges from 3 – 18 ℃. It is also found that the measured noise level decreases with air temperature and a linear regression is established between the two parameters. Air temperature constant of –0.03 dB(A)/℃ is yielded. Although both of the two approaches discussed above demonstrate the advantage of large variation of the temperatures, which is favorable for parametric test, the unwanted discrepancies in condition of the road surface and the test tyres may induce uncertainty in the test results. The seasonal approach using public roads are not adopted in this study since the high traffic flow in this urbanized city is anticipated to cause rapid aging and wearing of the road surface which increases the measured tyre/road noise level. The yielded temperature constants may therefore be interfered.

A similar but better approach is devised by Kuijpers (2002). He conducts a set of controlled pass-by measurements for 10 months with 20 tyre models on 3 especially built asphalts test sections at an old airstrip in Sperenberg, Germany. It is therefore expected that the properties of the road surface materials are more stable than those in the approaches by Anfosso-Lédée and Pichaud (2007) and Jabben (2011). Large variations in air and road surface temperatures of 0 – 35 °C and 3 – 50 °C are achieved respectively. The air and road surface temperature constants vary for different tyre/road combinations and their values range by –0.13 to –0.04 dB(A)/°C and –0.13 to –0.02 dB(A)/°C respectively. This approach has the advantage of maximized variation of temperatures and minimized discrepancies in condition of the road surfaces. Nevertheless, such resources and facility for paving the preserved road sections are not available locally. This approach is hardly feasible for this study.

Day-to-night temperature variation

Bühlmann and Ziegler (2011) have the approach of repetitive CPX measurements from morning to afternoon within a single day in late summer in Switzerland. Large variations in air and road surface temperatures of 10 to 30 °C and 8 to 50 °C are reached respectively. Air temperature constant for standard reference test tyres (SRTT) on dense surface is found to be –0.1 dB(A)/°C but road surface temperature constant is not provided. This single-day approach has a particular advantage over the seasonal ones discussed above that the measurements are completed within a short period of time so change in conditions of the test tyres and the road surface are minimized. The practicability of this method highly depends on the climate of the test site. For the case here in Hong Kong, achieving temperature variation within a day in summer is feasible since it is located in the subtropical region. The devised experimental approach in this study and the results and findings are presented and discussed in the following sections.

6.2.1 (ii) Devised single-day test

As discussed in the sections above, the researchers have devised various experimental approaches to achieve variation in temperature for evaluating its effect on the tyre/road noise level. Upon balancing the pros and cons of their approaches, the test devised in this study is to compare the noise levels measured with CPX Method using SRTT in daytime and nighttime within a single day in summer in Hong Kong. Air and road surface temperatures are monitored along. Specifications of the two temperature sensory units have been introduced earlier in Table 3.1 of Chapter 3. To determine temperature constants suitable for local use, two types of road surface material commonly found in Hong Kong are selected. They are stone mastic asphalt (SMA) and wearing course (WC). Four road sections are assigned for each. The measurement details are shown in Table 6.1. Before conducting the measurement, the test tyres are warmed up by towing the trailer for over 3 km. At least eight runs are made for each road section. The setup of the CPX arrangement remains intact during the time gap between the daytime and the nighttime measurements to prevent any unnecessary discrepancies of the setup. In the following section, the ability to reveal temperature effect by the devised single-day test method is evaluated.

Road Index	**Road Name**	**Road Surface Type**	**Ref. Speed (km/h)**
SMA1	Hung Hom Road	Stone Mastic Asphalt (SMA)	50
SMA2	Chuk Yuen Road		
SMA3	Clear Water Bay Road		
SMA4	Wang Lok Street		
WC1	Hoi Fai Road	Wearing Course (WC)	
WC2	Tin Ying Road		
WC3	Fuk Wang Street		
WC4	Castle Peak Road [Tam Mei]		

Table 6.1 Road sections for test on temperature effect on tyre/road noise.

6.2.2 Results and findings

6.2.2 (i) Evaluation of single-day test method

The ranges of air and road surface temperatures measured from the eight road sections are shown in Figures 6.1 and 6.2 respectively. The variations of air and road surface temperatures for the sections range from 0.5 to 3 ℃ and 5 to 15 ℃ respectively. Notice that these two sets of values should not be compared directly as they represent two different physical parameters. At this stage, it is hard to judge whether the devised test method can reveal temperature effect based on these values. Instead, the judgment should have its basis on whether any specific trend between the noise levels and the temperatures is observable.

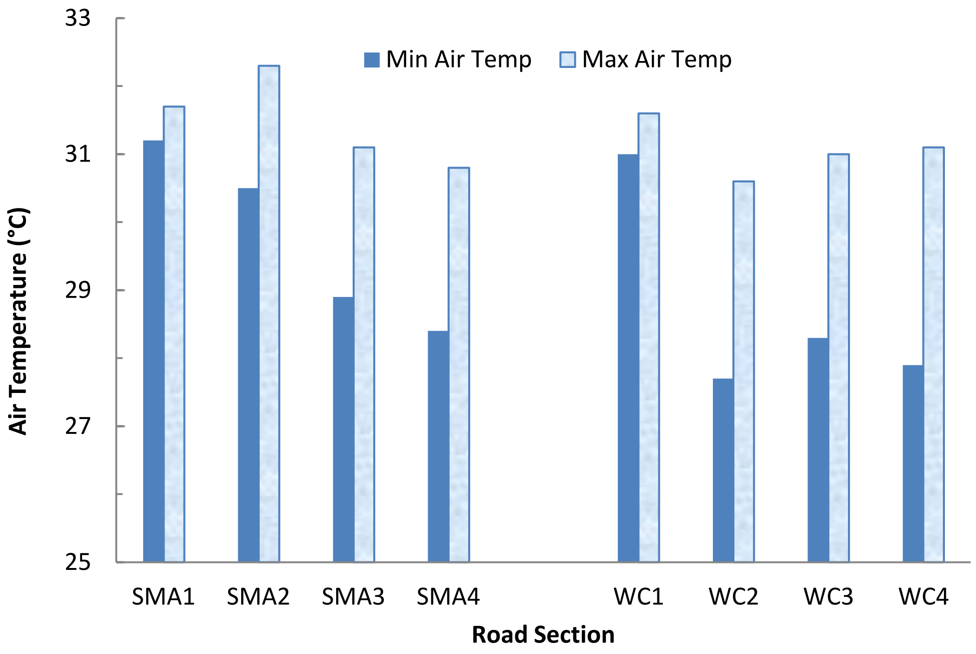


Figure 6.1 Variation in air temperature.

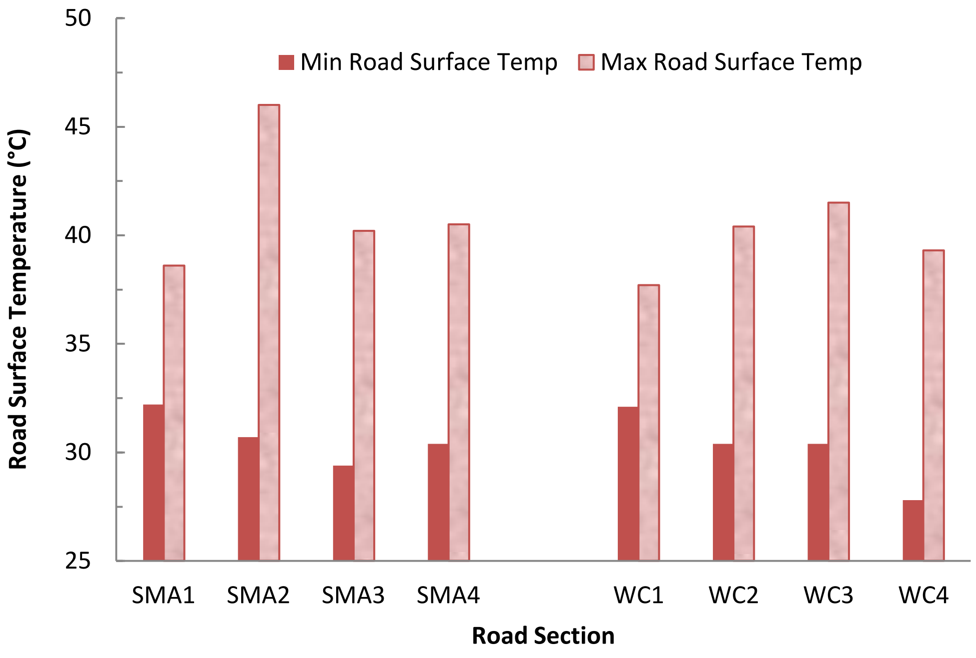
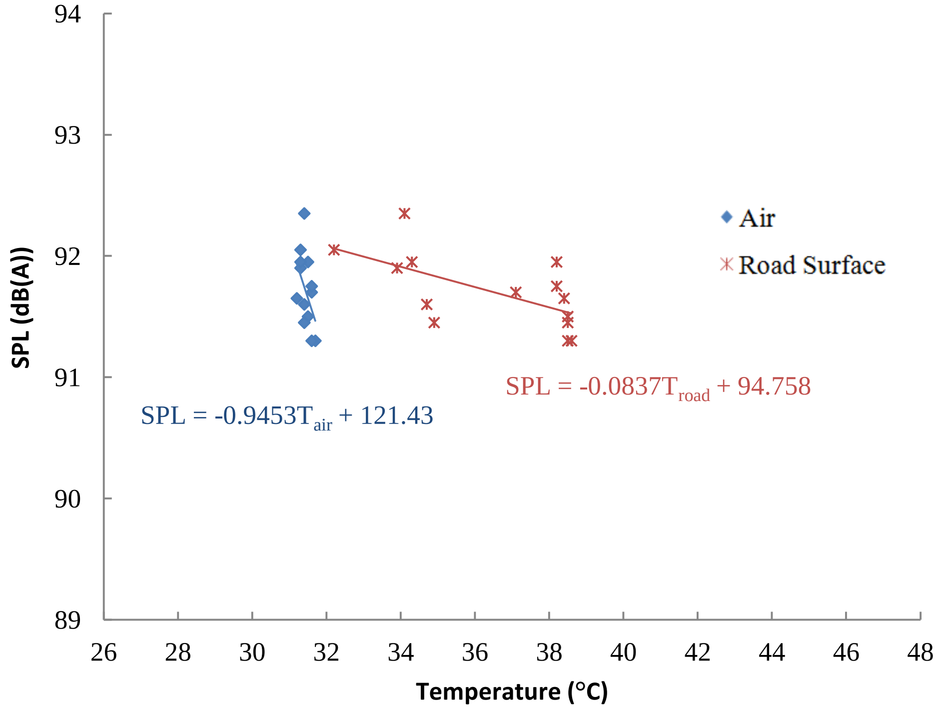
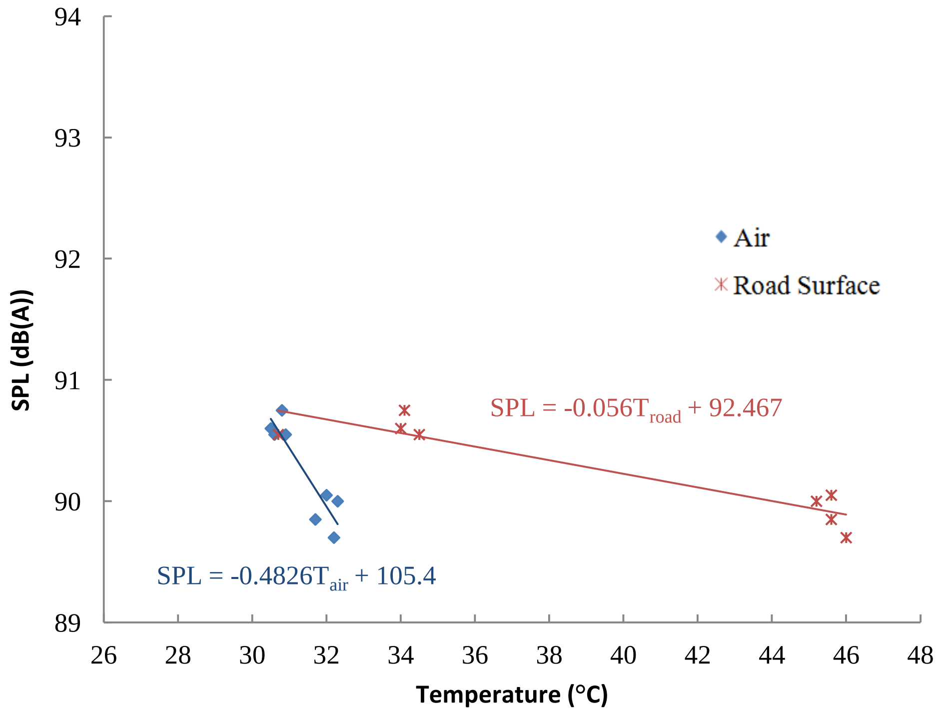


Figure 6.2 Variation in road surface temperature.

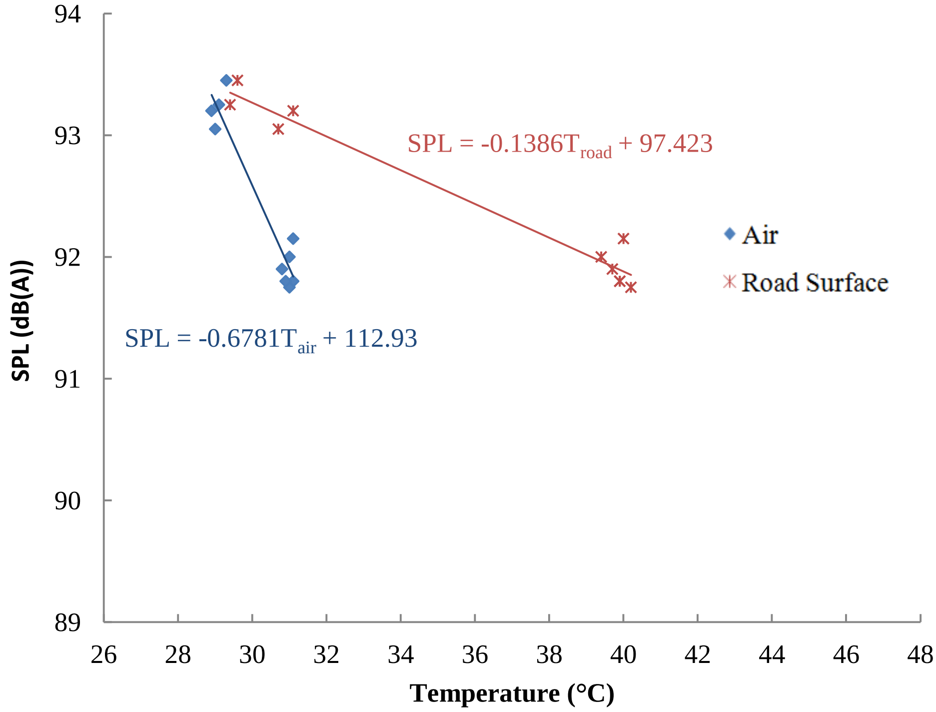
The noise levels are plotted against the air and road surface temperatures for the SMA and WC road sections in Figures 6.3 and 6.4 respectively. All the slopes are consistently negative which means tyre/road noise level decreases when air/road surface temperature increases. This findings comply with researchers elsewhere (Kuijpers, 2002; Anfosso-Lédée and Pichaud, 2007; Bueno et al., 2011; Bühlmann and Ziegler, 2011; Jabben, 2011). A decreasing trend of the noise level with air temperature is observable for most of the sections except SMA1 and WC1. These two exceptional cases are due to the relatively low variation of the air temperature registered which is less than 1 ℃. The drops in air temperature from daytime to nighttime for these two sections are relatively low (Figure 6.1). From the observation of the consistent decreasing trend for most of the temperature/road surface combinations, the devised approach of conducting two sets of measurements in daytime and nighttime during late summer in Hong Kong is found practical for revealing the temperature effect.


94
93
92
91
90
89
SPL (dB(A))
26
28
30
32
34
36
38
40
42
44
46
48
Temperature (°C)
Air
Road Surface
SPL = -0.0837T$_{road}$ + 94.758
SPL = -0.9453T$_{air}$ + 121.43

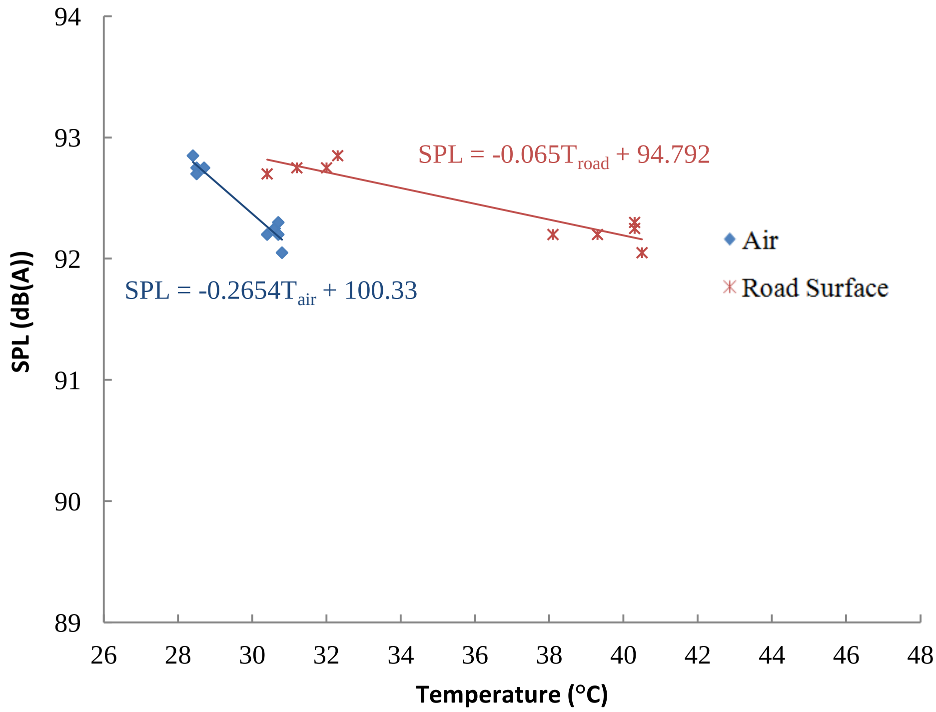
(a) SMA 1


94
93
92
91
90
89
SPL (dB(A))
26
28
30
32
34
36
38
40
42
44
46
48
Temperature (°C)
Air
Road Surface
SPL = -0.056T$_{road}$ + 92.467
SPL = -0.4826T$_{air}$ + 105.4

(b) SMA 2

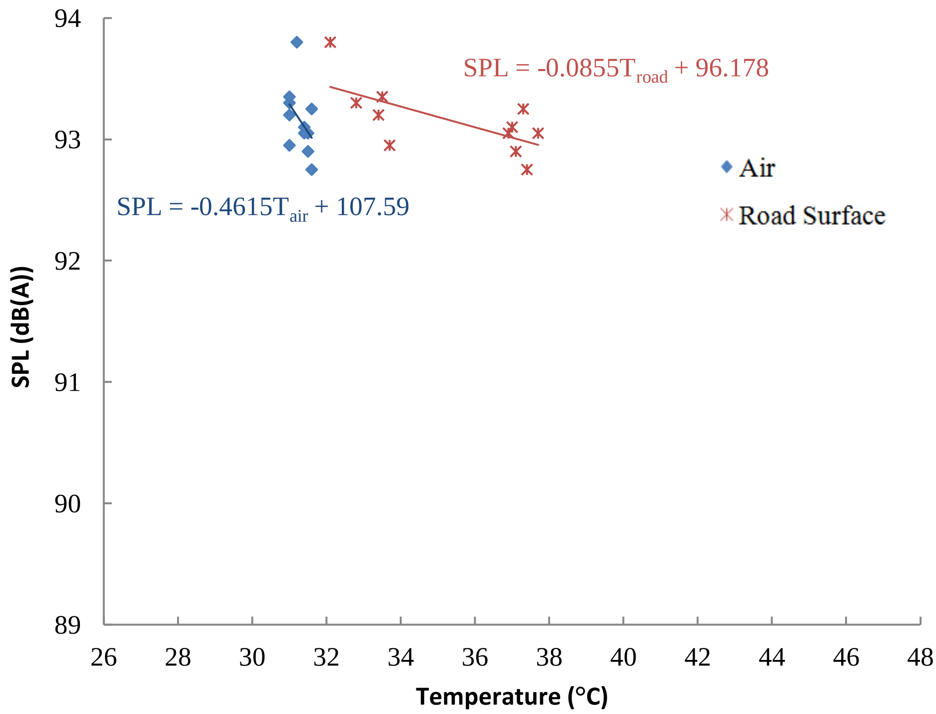


(c) SMA 3



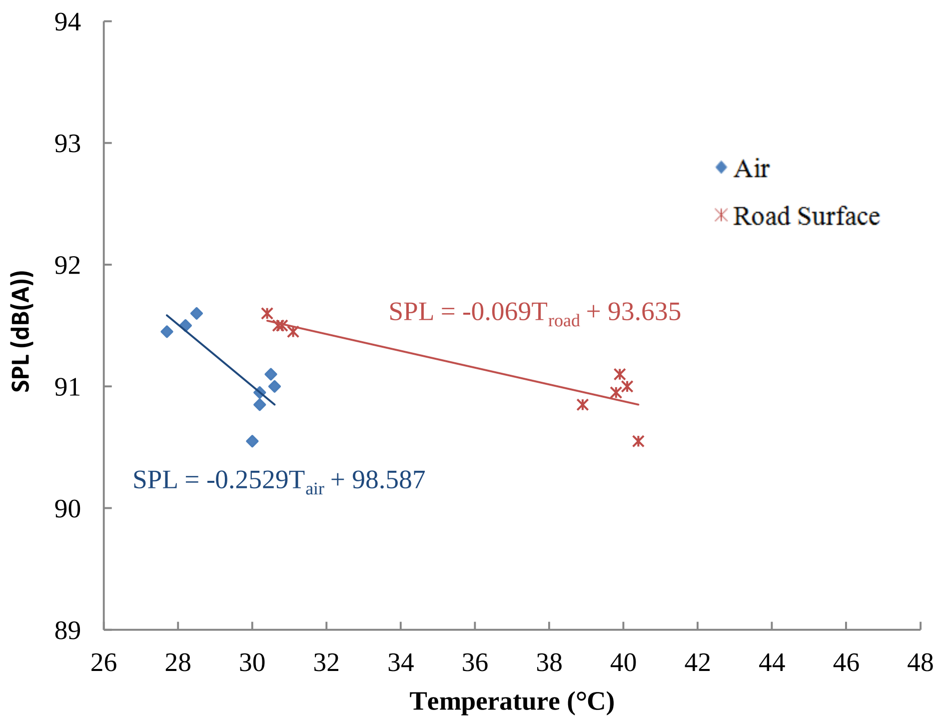
(d) SMA 4

Figure 6.3 Tyre/road noise level and air/road surface temperature on SMA surfaces.



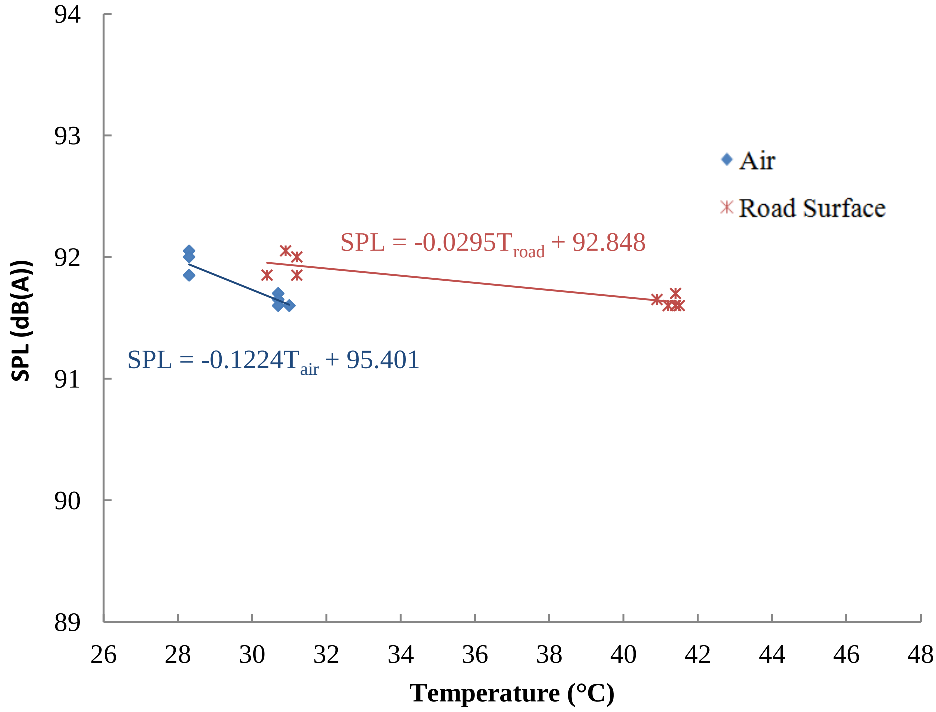
SPL (dB(A))
94
93
92
91
90
89
26
28
30
32
34
36
38
40
42
44
46
48
Temperature (°C)
SPL = -0.0855T road + 96.178
SPL = -0.4615T air + 107.59
Air
Road Surface

(a) WC 1

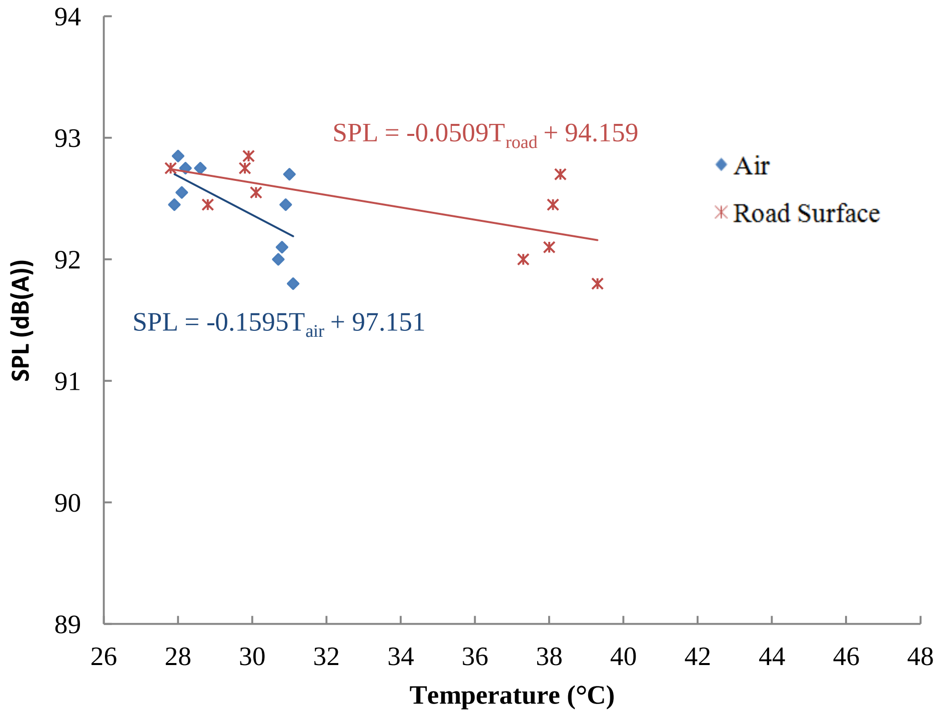


SPL (dB(A))
94
93
92
91
90
89
26
28
30
32
34
36
38
40
42
44
46
48
Temperature (°C)
Air
Road Surface
SPL = -0.069T road + 93.635
SPL = -0.2529T air + 98.587

(b) WC 2



(c) WC 3



(d) WC 4

Figure 6.4 Tyre/road noise level and air/road surface temperature on WC surfaces.

6.2.2 (ii) Better temperature descriptor for correction: air or road surface

Kuijpers (2002) has attempted to find the interrelationships between tyre/road noise level, air, road surface and tyre temperatures. It is found that the correlations of the noise level with all the three temperatures are equally strong. Results also indicate that air and road surface temperatures are closely related while tyre and road surface temperatures are less correlated. He reaches the conclusion to adopt air temperature since it is independent of any other measurement parameters. Bühlmann and Ziegler (2011) have also conducted a study to identify the best temperature descriptors out of air, road surface and tyre temperatures. It is found that the measured tyre/road noise levels are strongly correlated with all the descriptors. Similar to Kuijpers (2002), they suggest adopting air temperature since it is independent of other factors in the field such as solar radiation and color of the road surface material. Although the researchers above suggest that various types of the temperature descriptors demonstrate high correlation with one another, implying that any of them can be used for temperature correction, the author is of the view that the fundamental rationale on the choice of temperature descriptor should be its level of correlation with the noise level. This is because the temperature correction process has its basis on the effect estimation from the interrelationship between the noise level and the temperature. Thus, the temperature descriptor more correlated to the noise level gives a more reliable correction. The correlation coefficients between the measured noise level and air/road surface temperature are shown in Figure 6.5. The correlations for road surface temperature are higher than those of air temperature for most of the road sections. Besides, for SMA1 and WC1, where the variation of air temperature is relatively low (Figure 6.1), the correlations for road surface temperature become much stronger over the air temperature. These findings indicate that road surface temperature is more reliable than air temperature for the temperature correction in ISO/CD 11819-2 (2010).

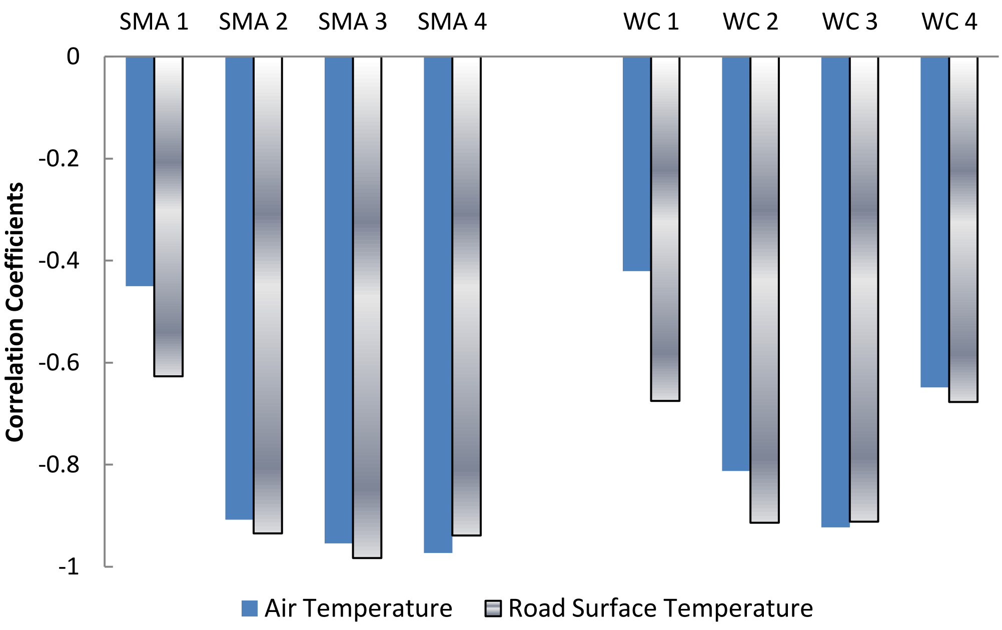


Figure 6.5 Correlation between tyre/road noise level and temperatures.

6.2.2 (iii) Air and road surface temperature constants

The air and road surface temperature constants (Equation 6.2) for temperature correction are developed in this section. The correction is to compensate the temperature effect to the reference temperature using the slope of linear regression of tyre/road noise level against the temperature. The yielded air and road surface temperature constants in this study are therefore equivalent to the slopes in the plots of the noise level against the temperatures (i.e. Figures 6.3 and 6.4). They are summarized in Table 6.2. In computation of the average air temperature constant, the results from sections SMA 1 and WC 1 are not adopted due to the their relatively much weaker correlations with the noise level (Figure 6.1). The yielded average air temperature constants for SMA and WC are −0.48 dB(A)/℃ and −0.18 dB(A)/ ℃ respectively. The yielded average road surface temperature constant for SMA and WC are −0.09 dB(A)/℃ and −0.06 dB(A)/℃ respectively. Moreover, these temperature constants indicate that SMA is more sensitive to temperature effect than WC does. A plausible explanation is that SMA is darker in color which is more easily subjected to heat absorption.

Road Sections	a_{air} **(dB(A)/℃)**	a_{road} **(dB(A)/℃)**
SMA1	~~−0.95~~	−0.08
SMA2	−0.48	−0.06
SMA3	−0.68	−0.14
SMA4	−0.27	−0.07
Average	***−0.48***	***−0.09***
WC1	~~−0.46~~	−0.09
WC2	−0.25	−0.07
WC3	−0.12	−0.03
WC4	−0.16	−0.05
Average	***−0.18***	***−0.06***

Table 6.2 Temperature constants and goodness of tyre/road noise level-temperature linear regression fit.

As temperature correction is still an optional step in data computation of ISO/CD 11819-2 (2010), literature on the temperature constants for the exact same combinations of tyre model and road surface types, obtained from the same measurement method is limited. The best available information including the setup and the yielded results by researches elsewhere is summarized in Table 6.3 to compare with this study. The air temperature constants obtained from the researches elsewhere and this study range from –0.13 to –0.03 dB(A)/℃

and –0.68 to –0.12 dB(A)/℃. For road surface temperature constants, the results by others and this study range from –0.13 to –0.02 dB(A)/℃ and –0.14 to –0.03 dB(A)/℃ respectively. The range of road surface temperature constant is almost the same as that by researches elsewhere; the range of air temperature constant from this study appears on the high side to results elsewhere but the ranges are in connection. These findings may have again justified that road surface temperature is a more reliable temperature descriptor over air temperature for the correction process.

Study	**Setup**	**T_{air} range (℃)**	**a_{air} range (dB(A)/℃)**	**T_{road} range (℃)**	**a_{road} range (dB(A)/℃)**
This study	▪ Single day ▪ CPX ▪ SRTT tyres ▪ 8 asphalts	27, 32	–0.12, –0.68	30, 46	–0.03, –0.14
Anfosso-Lédée and Pichaud (2007)	▪ 1 year ▪ Controlled pass-by ▪ 2 Michelin tyre models ▪ 3 asphalts ▪ 2 surface dressings ▪ 2 concretes	0, 30	–0.06, –0.1	0, 50	–0.04, –0.06

Bühlmann and Ziegler (2011)	▪ Single day ▪ CPX ▪ SRTT ▪ 21 asphalts ▪ 16 concretes ▪ 2 others	10, 30	–0.1*	8, 50	n/a
Jabben (2011)	▪ 1 year ▪ Roadside pass-by ▪ 8750 random passenger cars and trucks	3, 18	–0.03*	n/a	n/a
Kuijper (2002)	▪ 10 months ▪ Controlled pass-by ▪ 20 tyre models ▪ 3 asphalts	0, 35	–0.04, –0.13	3, 50	–0.02, –0.13

* Only average value is available

Table 6.3 Comparison of temperature constants.

6.3 Conclusions

Literature survey on the relationship between the tyre/road noise level and the temperatures is conducted. Approaches by researchers elsewhere to test for temperature effect on the noise level are discussed. A single-day test is devised with considerations on the local situations in terms of the anticipated higher rate of road surface aging and wearing, the climate as well as the constraints on the resources. Results indicate that road surface temperature is more reliable than air temperature for the correction by showing stronger correlation with the noise level. This reliability becomes even higher for road surface temperature over air temperature when temperature change is small. The air and road surface temperature constants of two common types of asphalt road surfaces, stone mastic asphalt (SMA) and wearing course (WC) are yielded. The air temperature constants for SMA and WC are –0.48 dB(A)/℃ and –0.18 dB(A)/℃ respectively while the road surface temperature constants for SMA and WC are –0.09 dB(A)/℃ and –0.06 dB(A)/℃ respectively. It is found that SMA is more sensitive to temperature effect than WC does. The range of road surface temperature constants obtained in this study is almost the same as the researches elsewhere conducted with different combinations of measurement method, tyre models and asphalt surface properties. The air temperature constants however appear on the high side to the others. This may again justify that road surface temperature is more reliable over air temperature for the temperature correction in tyre/road noise measurement with CPX Method.

CHAPTER 7

ROAD CURVATURE EFFECT ON TYRE/ROAD NOISE

Tyre/road noise measurement with CPX Method is often conducted on long straight roads to assess the noise performance of different road surfaces (Lam et al., 2012; Ho et al., 2013) However, in an urbanized city like Hong Kong, the choices of road sections practically feasible for measurement are relatively limited compared to other foreign countries. Quite often it is necessary to conduct measurement on curved road sections. Knowing the fact that the centripetal force for cornering of vehicle is applied at the tread blocks by its friction with the road surface, the tyre/road noise generation mechanism maybe interfered. To prevent possible unfair comparison between surfaces paved on different roads, this study investigates the level of road curvature effect on the measured noise level. The mechanism interfered by the effect is explored. Two minimum radii of road curvature coupled with speeds for conduction of CPX measurement are found.

7.1 Road curvature effect on tyre/road interaction

When an object is travelling along a circular trajectory, its velocity is in fact changing due to the continuous variation of the velocity vector. By Newton's Second Law, when there is change in velocity and thus momentum, there exists an external force acting on the object. The strength of centripetal force required is related to the radius of curvature of the trajectory, the speed and the mass of the object as expressed in Equation 7.1 (Ayra, 1998).

$$F_c = \frac{mv^2}{r} \qquad \text{Equation 7.1}$$

where F_c is the centripetal force in N, m is the object mass in kg, v is the object speed in m/s and r is the radius of curvature in m.

For the case of a vehicle going round a corner, the centripetal force is provided by the friction between the tyre tread blocks and the road surface. Tönük and Ünlüsoy (2001) has shown with experiment and finite element modeling that such force on the tread blocks can reach as much as 3500 N depending on the inflation pressure and angle of wheel turning. This force can deform the elastic rubber tread blocks so the structure-borne noise generation mechanisms (e.g. tread impact, stick-slip and stick-snap) as shown in Chapter 2 may be interfered. A commonly observed example of such effect is the emission of loud squeal when a vehicle goes round a corner at high speed with the tyres scratching the road surface strongly. If the measured noise level is significantly influenced by this effect, the comparison of noise performance of one road surface paved on a straight road and another paved on a curved road will be unfair. This may result in misleading conclusions to the acoustic performance of the two surface materials. In order to avoid this, ISO/CD 11819-2 (2010) just suggests the minimum radii of curvature of the road under CPX measurement should be 250 m and 500 m for two reference speeds of 50 and 80 km/h respectively. No further information is given such as the possible level of influence to the measured noise level. It is necessary to explore the level of effect and review the minimum of radius of curvature.

7.2 Test for road curvature effect on tyre/road noise

7.2.1 Methodology

To assess the road curvature effect on the tyre/road noise level, a parametric study with varied radius of curvature was conducted on 8 curved road sections and 1 straight section as control case. All of the sections are located at Tolo Highway (Table 7.1). Two common local posted speed limits of 50 and 70 km/h are selected. There is an advantage from the adoption of road sections on the same highway. Since the content and variation of traffic flow is more or less the same, the variation of surface conditions along the entire road should be relatively uniform. Besides, the highway appears a safer place for cornering of the whole CPX trailer especially at high speeds.

Road Index	Location (Chainage)	Radius (m)	Road Surface Type	Ref. Speed (km/h)
C1	9.4 – 9.6	479	Friction Course# (FC)	50 & 70
C2	10.7 – 11.4	601		
C3	12.5 – 13.0	583		
C4	14.5 – 14.8	588		
C5	14.8 – 14.5	587		
C6	13.0 – 12.3	601		
C7	11.4 – 10.7	664		
C8	16.0 – 16.1	555		
S1	15.1 – 14.9	/		

The only available surface type for local highways.

Table 7.1 Details of measurement to test for road curvature effect.

Before a CPX measurement, the test tyres were well warmed up by rolling them over a distance of travel of more than 20 km. Whole sets of the measurements were finished within half day to minimize any other possible environmental discrepancies such as ambient air temperature. For each road section, at least 5 runs were conducted for each speed. The route of travel was tracked with the GPS receiver (Table 3.1 of Chapter 3) from which the radius of road curvature was estimated.

7.2.2 Results and findings

The measured tyre/road noise levels are plotted against the road curvature radii in Figure 7.1 to search for any specific trend between them. The reference noise levels of the straight section are indicated with the two horizontal dotted lines. It is a general fact that a curved road can be regarded straight for a certainly large radius of curvature. The road curvature effect is anticipated to converge to zero above this radius. Second order polynomial fitting is therefore applied to the plots. They fit well by showing high coefficients of determination of 0.95 and 0.82 for reference speeds of 50 and 70 km/h respectively. It is observed that the noise level is higher for smaller radius. The deviation between the curved and straight road sections can reach over 2 dB(A). Results indicate that road curvature has significant influence on the measured tyre/road noise level with CPX Method and its effect is traceable from the radius.

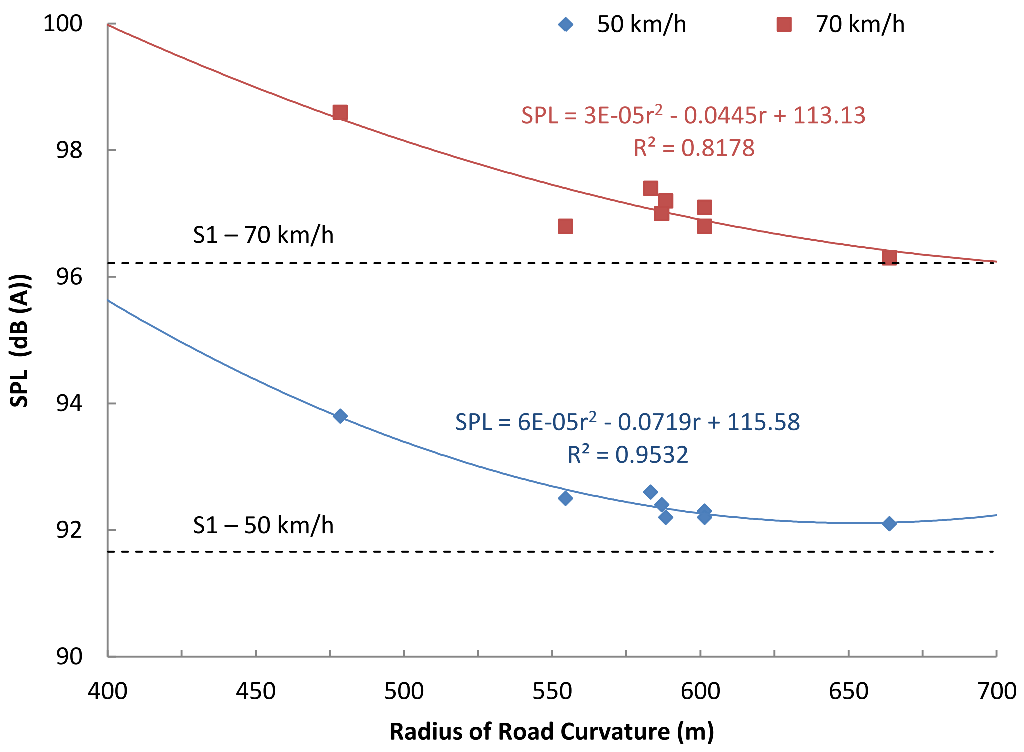


Figure 7.1 Tyre/road noise level and radius of road curvature.

7.2.2 (i) Critical radius

The critical radius above which a curved road section can just be considered straight for CPX measurement is of particular importance for fair comparison of the noise performance of surfaces materials paved on different roads. It is equivalent to the radius at the lowest turning point of the plot with the noise level against the radius (i.e. Figure 7.1). The turning point is at the radius at which the differentiated fitting equation (Figure 7.1) is equal to zero (i.e. zero slope). The calculation steps involved are illustrated below. The critical radii are found to be 599 m and 742 m for reference speed 50 and 70 km/h respectively. The finding of high critical radius for higher speed justifies the hypothesis on road curvature effect by the centripetal force on the tyre tread blocks where the force is higher for higher vehicle speed.

<u>Critical radius for 50 km/h</u>

$$\frac{d}{dr}(6 \times 10^{-5} \times r^2 - 0.0719r + 115.58) = 0$$

$$1.2 \times 10^{-4}r - 0.0719 = 0$$

$$r = 599\ m$$

<u>Critical radius for 70 km/h</u>

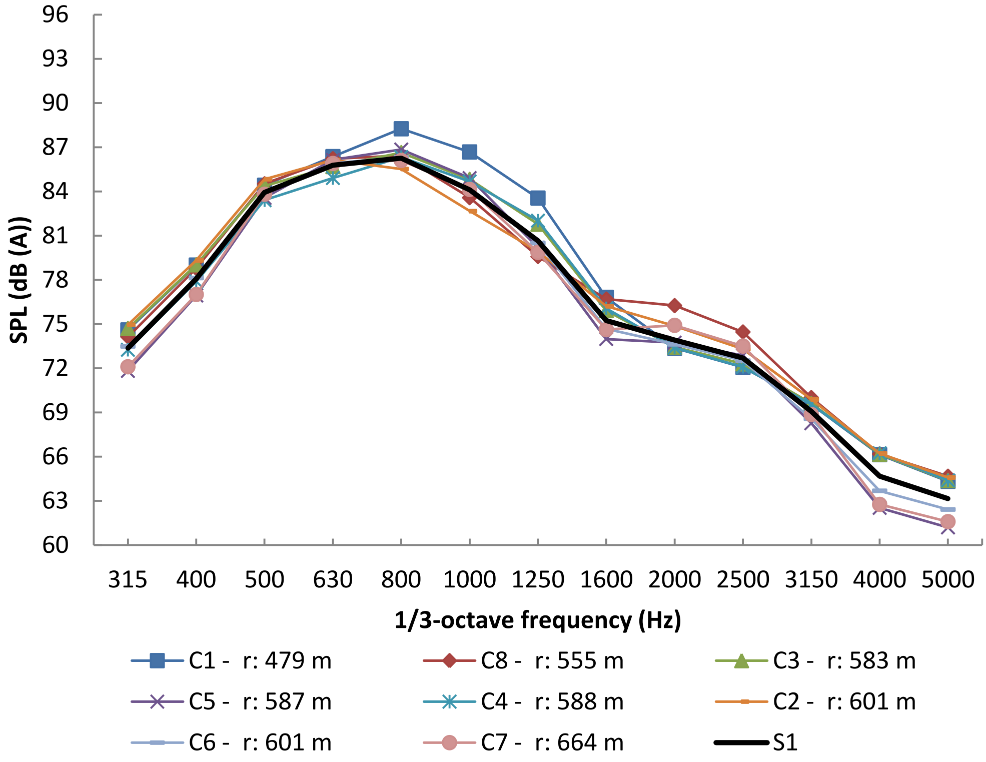
$$\frac{d}{dr}(3 \times 10^{-5} \times r^2 - 0.0445r + 113.13) = 0$$

$$6\times 10^{-5}r - 0.0445 = 0$$

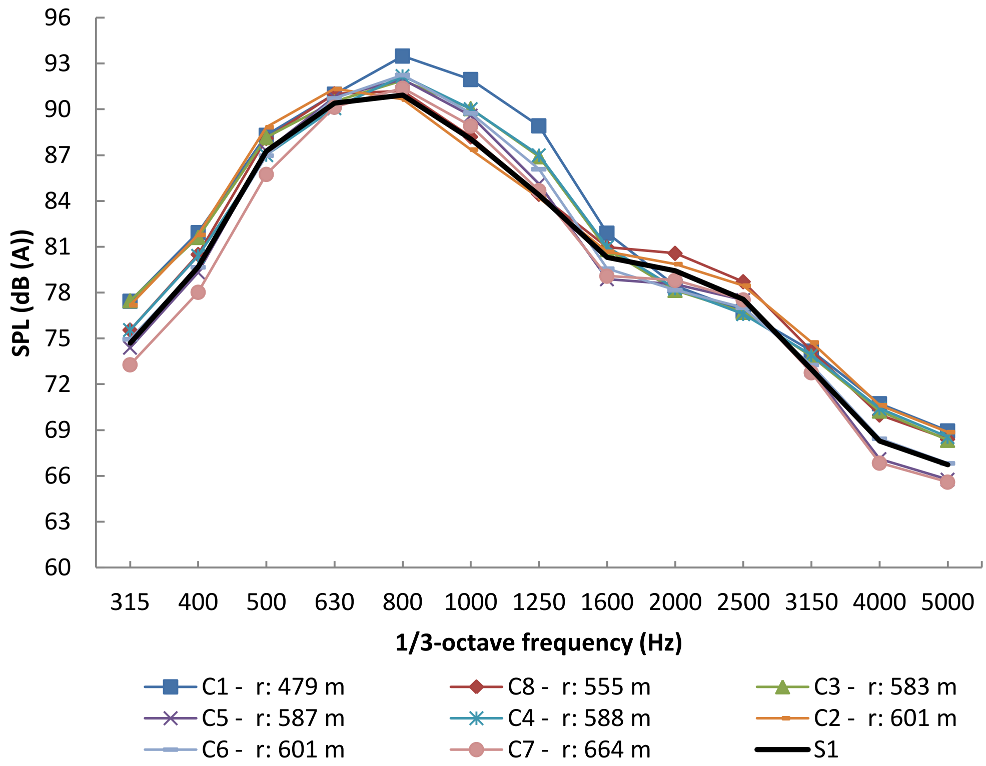
$$r = 742\ m$$

7.2.2 (ii) Influence on the tyre/road noise radiation

In search of the noise generation mechanism influenced by the road curvature effect, investigation is conducted on the tyre/road noise spectrum (Figure 7.2). From the plots, the spectra of all the curved and straight sections follow the same pattern by peaking at 800 Hz and dipping at 1600 Hz. This spectral signature among all the road sections adds confidence to the minimized difference in road surface properties. Most of the spectra of the curved sections appear on the top of the straight section. In order to ascertain the frequency range highly susceptible to road curvature effect, the correlation coefficients between the 1/3-octave band levels and the radius are plotted in Figure 7.3. For most of the bands, the coefficients are negative which conforms to the finding that smaller radius results in higher noise. The correlation magnitudes of most bands are larger for higher vehicle speed which indicates when the curvature effect is stronger. Only two frequency bands, centered at 2000 and 2500 Hz, are found to be insensitive to road curvature effect by showing negligible correlations. The negative correlations in band ranges 315 – 1600 Hz and 3150 – 5000 Hz, which correspond to structure-borne tyre/road noise generation mechanisms of tread impact and stick-snap respectively (Section 2.1.5), further justify the hypothesis that the road curvature influences the noise through altering the vibration of the tread blocks by the applied centripetal force from friction between the treads and the road surface.



(a) At 50km/h.



(b) At 70km/h.

Figure 7.2 Tyre/road noise spectra of the curved and straight sections.

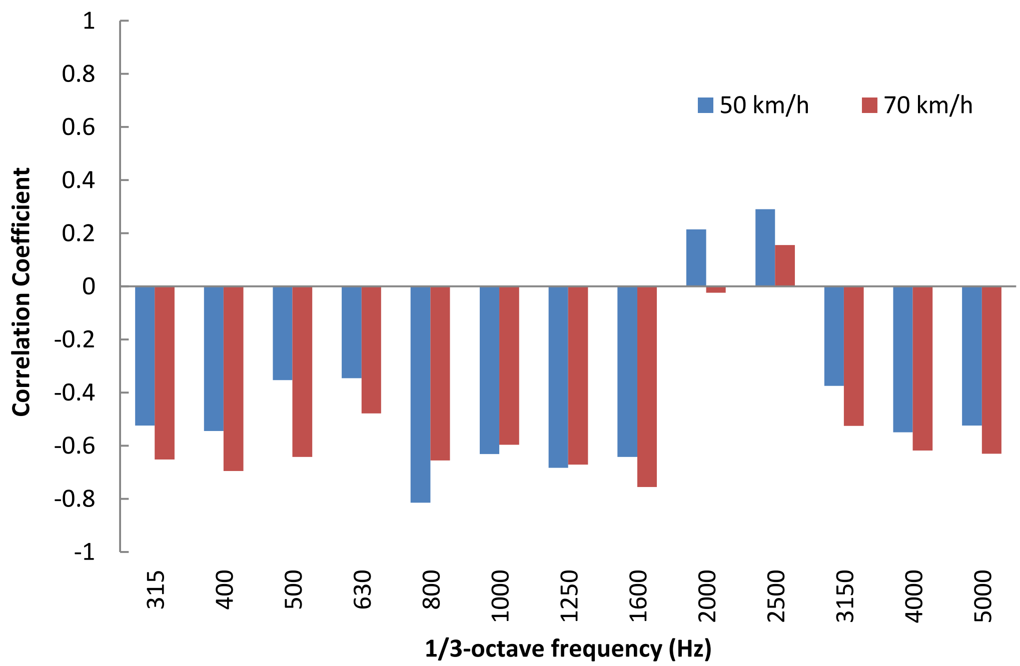


Figure 7.3 Correlation between tyre/road noise band level and radius of road curvature.

7.3 Conclusions

The road curvature effect on tyre/road noise is studied with a parametric test with varied radius of curvature on 8 curved road sections and 1 straight section as control case. Results indicate that the deviation of the noise level of a curved section from a straight section can reach as much as +2 dB(A). For friction course (FC), the critical radii at which can be regarded straight for speeds 50 and 70 km/h are 599 and 742 m respectively. The finding of high critical radius for higher speed justifies the hypothesis on road curvature effect by the centripetal force on the tyre tread blocks where the force is higher for higher vehicle speed. In the tyre/road noise spectrum, negative correlation coefficients with the radius for the two band ranges of 315 – 1600 Hz and 3150 – 5000 Hz are yielded. These two frequency ranges correspond to the structure-borne noise generation mechanisms of tread impact and stick-snap respectively. The magnitude of the correlations is higher for higher speed. The hypothesis is again justified.

CHAPTER 8

CONCLUSIONS

Traffic noise has been one of the major noise nuisance affecting the quality of life of citizens in highly urbanized city like Hong Kong. Since the contribution of tyre/road noise is getting more and more significant in traffic noise, a reliable and accurate method for assessing tyre/road noise in highly urbanized city is necessary. The Close-Proximity Method (CPX Method) (ISO/CD 11819-2, 2010) offers a convenient solution in this regard. However, the suitability of its application in highly urbanized city is in question due to the serve disturbances to the measurement in real practice, namely the high background traffic noise, the road bumpiness, the substantial variation of temperature and the variation due to road curvature. This study aims to develop a CPX Method suitable for tyre/road noise measurement in highly urbanized city with minimal influence from these disturbances.

A comprehensive literature survey is conducted to review the basic structure of modern vehicle tyres, their structure-borne and airborne noise generation and various amplification mechanisms involved in tyre/road interaction. Understanding of these basic knowledge is instrumental in the development of the new PolyU Mark II Twin-wheeled CPX Trailer for the tyre/road noise measurement in Hong Kong.

The basic principles, data collection and manipulation, the features and limitations of general CPX Method are introduced and reviewed. A literature review is given on the existing CPX trailer configurations worldwide with evaluation of their pros and cons in order to design a trailer suitable for the tough measurement environment in this highly urbanized city. The design features incorporated the Mark II CPX Trailer for tackling various measurement disturbances are presented. The fabricated Mark II CPX Trailer are evaluated against the certification criteria stipulated in ISO/CD 11819-2 (2010). Results indicate that the Mark II CPX Trailer pass all the three certification tests and can be used for tyre/road noise measurement with capability comparable to existing CPX designs.

The sensing mechanism and the hypothesis on vibration-induced error of CPX microphones are discussed. The laboratory and the trailer on-deck test are devised to evaluate the relationship between the erroneous noise level and the microphone vibration level. Results indicate that there exists traceable linear relationship between the two levels. It is found that the vibration effect can result in an overestimation of the noise level by as much as 3 dB (A). A method for correcting the vibration-induced error in the measured tyre/road noise level is proposed and illustrated with an evaluation study. Recommendations on adopting the original and corrected noise levels for different measurement scenarios are presented.

The variation of air temperature during measurement is anticipated to cause error in the measured tyre/road noise level as many researches showed that the noise level decreases as the temperature increases. Such effect is expected to be more prominent in Hong Kong as the heat within its highly urbanized environment is more difficult to spread away. A single-day test is developed from which the air and road surface temperature constants for temperature correction for two common asphalt road surfaces, stone mastic asphalt (SMA) and wearing course (WC), are yielded. The air temperature constants for SMA and WC are –0.48 dB (A)/℃ and –0.18 dB (A)/ ℃ respectively while the road surface temperature constants for SMA and WC are –0.09 dB (A)/℃ and –0.06 dB (A)/℃ respectively. It is found that SMA is more sensitive to temperature effect than WC. The air temperature constants however appear higher than those reported by other researchers. Moreover, results indicate that a correction based on road surface temperature is more reliable than that on air temperature.

A parametric study with varied radius of road curvature is conducted to find out the relationship between the noise level and the radius in order to determine minimum critical radius of a road section suitable for CPX measurement. For friction course (FC), the critical radii above which the road section can be regarded straight for speeds 50 and 70 km/h are 599 and 742 m respectively. It is found that the deviation of the noise level of a curved road from a straight one can reach up to +2 dB(A). Two frequency band ranges of 315 – 1600 Hz and 3150 – 5000 Hz are found to be sensitive to road curvature effect. They are closely linked to the structure-borne noise generation mechanisms of tread impact and stick-snap respectively.

In summary, various influencing disturbances to the tyre/road noise measurement in highly urbanized city with CPX Method have been duly addressed with reviewing the literature, devising special experiments, analysis and discussions on the results as well as proposal of corrective measures and their verification on the new PolyU Mark II CPX Trailer. With all these measures in force, it is believed that the CPX method developed in the present study should provide unbiased and accurate tyre/road noise measurement in any highly urbanized city like Hong Kong.

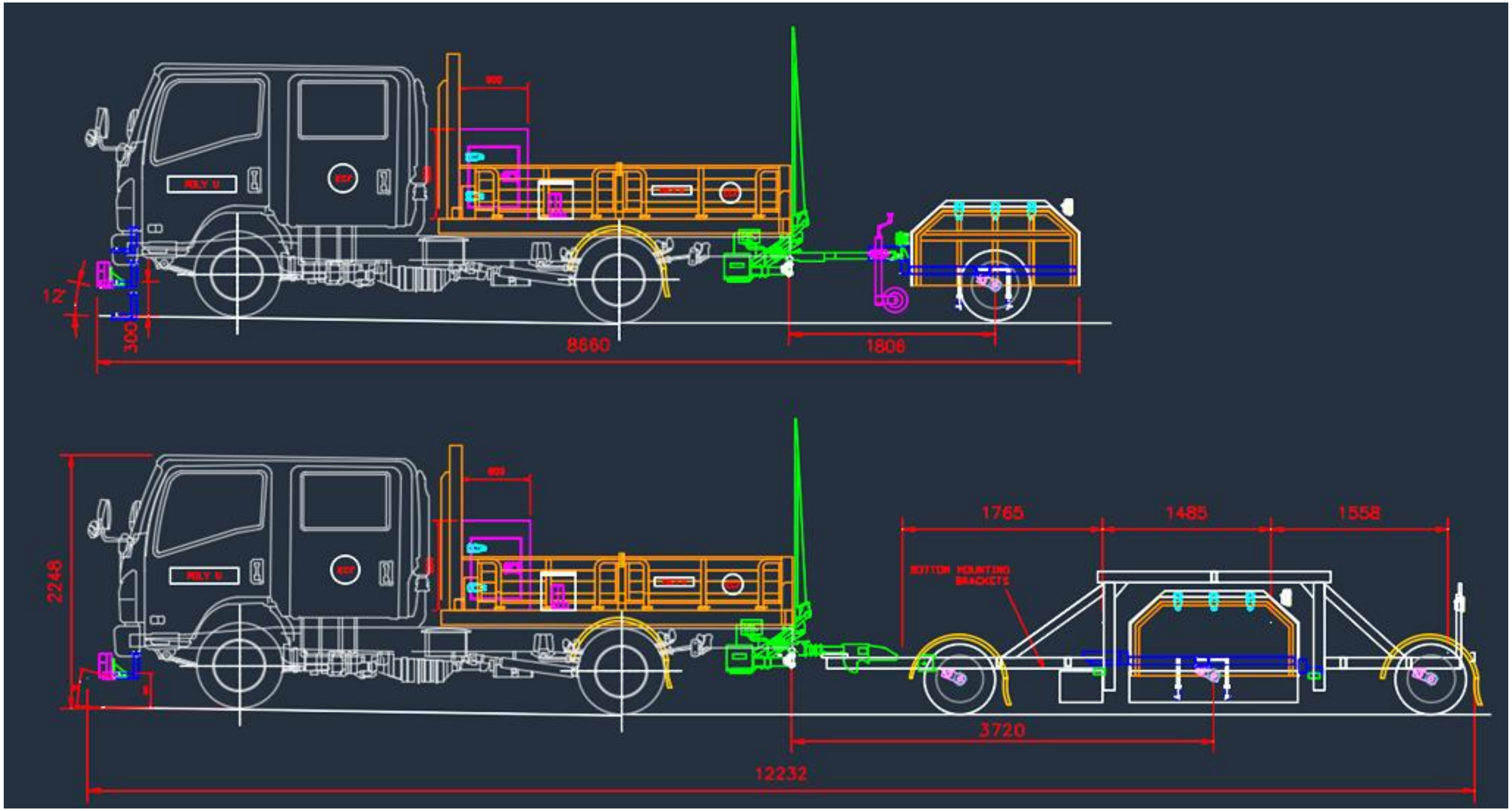
8.1 Future study

The present study has attempted to evaluate and alleviate various factors of disturbance to tyre/road noise measurement with CPX Method. The author would like to suggest conduction of further studies for the following aspects in the future.

For certification of the CPX trailer, acoustic treatments such as sound absorption material and sound isolation panel have been implemented. Although results demonstrates that it meets the criteria specified by ISO/CD 11819-2, the author would like to suggest exploration for some other new innovative measures for instance installation of micro-perforated panel on the internal walls of the enclosure to further alleviate the internal noise reflection. For the vibrational-induced error in CPX measurement, it is suggested to carry out large scale CPX survey with monitoring on the microphone vibration. Such approach would give a general idea on the portion of public roads that require correction to the vibration-induced error. The yielded result may stimulate researchers elsewhere or even the working group of ISO/CD 11819-2 to duly address the issue. For temperature correction, it is suggested to explore the temperature constants for more road surface types since a complete set of the constants will help reduce the temperature influence and increase the overall accuracy of ranking the noise performance of different road surface materials. For road curvature, there is in fact limited literature related to its effect on tyre/road noise. It is suggested to explore for some other parameters coupled with the hypothesis based of centripetal force action on the tread blocks, for instance tread depth and rubber hardness.

Last but not least, in hope of contributing to the reliability of CPX Method in highly urbanized city, it is proposed to report to the working group of ISO/CD 11819-2 on the factors of influences in CPX measurement as well as the corrective measures developed in this study.

Appendix 1


12°
300
8660
1808
2248
1765
1485
1558
BOTTOM MOUNTING
BRACKETS
3720
12232

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