

Exterior Noise Due to Interaction of Tyre-Thermoplastic Transverse Rumble Strips

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Transverse rumble strips (TRS) are a common choice to reduce vehicle speed and increase driver alertness on roadways. However, there is a potential trade-off using them on rural roadway due to the noise problem created when vehicles go over the strips. The present study investigated the noise level, spectral analysis, and the possible noise generation mechanism when the TRS is hit by a vehicle. Ten-raised-rumbler (RR) and three-layer-overlapped (TLO) TRS were selected in this study as they have received complaints from the public. Results showed that RR generated a relatively higher noise and impulse at a low speed, and increased sound level in each octave band. Based on these results, RR may irritate human ears even when the vehicle travels at a low speed. It was found that RR increased all noise generation mechanisms of tyre-pavement interaction whilst TLO increased structural resonance, sidewall and surface texture vibration.

Keywords: transverse rumble strips; vehicle speed; noise problem.

1. Introduction

Motor vehicle accidents are the second most frequent cause of death in the entire world. Around 1.2 million people are killed each year on the road and 50 million more are injured (SHINAR, 2007). Speeding and careless driving are the two main causes of accidents, contributing 32.8 and 28.2 percent respectively to the total number of accidents in Malaysia (NG, SELVA, 2003). Speeding also contributed to about 30 percent of fatal crashes in the United States (KATZ, 2007). Al-

ternative measures consisting of a road layout and its associated features including transverse rumble strips which are able to inform drivers of upcoming road conditions at the subconscious level were introduced. Transverse rumble strips (TRS) made of a groove or raised lateral pattern are introduced to reduce vehicle speed and increase drivers' alertness on the roadway. Generally, TRS around the world are diverse in terms of configuration, dimensions, colour, and profile. TRS are intended to give an audible, visual, and tactile cue of when an operational decision point is approaching

(THOMPSON *et al.*, 2006). TRS vertically deflect the wheels of a vehicle driving over them and produces both noise and vibration (BAHAR *et al.*, 2005).

In Malaysia, thermoplastic TRS are one of the most frequently used forms. They are classified as raised rumble strips with the thickness in the range of 3–7 mm (MOW, 2002). Thermoplastic TRS are commonly applied as they contribute several factors including the readiness for immediate use, high durability, good retro reflectivity, and relatively low cost. In order to increase the visibility through retro reflectivity elements, glass beads are also intermixed into the thermoplastic and partially embedded onto the surface of the marking binder material (LOPEZ, 2004). Studies of TRS made of thermoplastic have shown that it is able to reduce vehicle speed and road accidents (LIU *et al.*, 2011). According to BENDTSEN *et al.* (2004), thermoplastic TRS with narrow strips are able to increase the road noise level, LA_{eq} by around 2–4 dB(A). In addition, TRS noise is claimed to be in the pattern of impulse noise which is the most annoying to people (BENDTSEN *et al.*, 2004; YANO, KOBAYASHI, 1990).

Malaysia is a developing country, and is presently suffering from an increase in noise pollution arising from traffic noise. The problem is compounded with TRS which are widely used for reasons of safety due to the fact that many premises are built alongside the roads. Malaysia has not also yet developed a practical policy to cope with this situation.

The primary purpose of the present study, therefore, was to assess the characteristics of noise generated by roads with the installation of thermoplastic transverse rumble strips. Two typical TRS profiles widely used in Malaysia were selected and the anticipated noise mechanism generation levels for the typical TRS were obtained to facilitate the local authorities in the selection of the reliable installation of TRS. This specific characteristic should be given close attention since many premises are located close to the road.

1.1. Tyre-pavement noise generation

Sound generated by interaction between tyre and pavement plays a significant role when the vehicle's speed exceeds 30 km/h. According to previous research sound could be generated by the followings mechanisms: tyre tread block impact occurred at 600–900 Hz (KIM *et al.*, 2007), surface texture impact was dominant at 700–1300 Hz (SANDBERG, EJSMT, 2002), tyre belt/carcass vibration was the dominant mechanism for the frequency around 500 Hz (BOLTON, KWON, 1998), side wall vibration occurred at the frequency < 1000 Hz (KIM *et al.*, 2007; WAYSON, 1998), and the air pumping mechanism was dominant at the frequency range between 500 Hz – 3 kHz (KEULEN, DUŠKOV, 2005) or above 1 kHz (WAYSON, 1998).

An adhesion mechanism is produced as the tyre rolls on the surface of the pavement. The release of the block produces tangential or radial vibration and yields a carcass response and side wall vibration. If the tyres hit the contact surface with a high angle of attack compared with the road surface, the tangential and radial vibration become higher. Air pumping occurs when the tread blocks enter the contact patch and trap air between the pavement and tyre which is then compressed and pumped out of the tread block. According to WAYSON (1998), the macrotexture and megatexture of the road surface play significant roles in noise generation. Increases in megatexture to 80 mm will increase the tyre noise in the low frequency of less than 1 kHz and when the macrotexture increases to 3 mm the tyre noise in the frequency greater than 1 kHz decreases due to air pumping. The megatexture is responsible for radial and tangential vibration of the tyre, which causes the mechanism in low and high frequency ranges.

The authors consider that the interaction of the tyre and TRS have similarities with the interaction of the tyre and road. Thus, an experimental method was conducted based on the controlled pass by method test procedure, derived from the Coast-By Method (SANDBERG, EJSMT, 2002; ISO, 2003) for the selected sites.

2. Materials and methods

Two sites installed with typical thermoplastic rumble strips were selected. Site 1 was installed with the saw blade pattern or ten-raised-rumbler (RR) profile, and Site 2 had the three-layer-overlapped profile (TLO) (Fig. 1).

The Coast-By Method was used as it can directly measure tyre-pavement noise from individual vehicles in free-flowing and essentially constant-speed traffic. To avoid the effect of the test vehicle type and the conditions of the test site (SANDBERG, EJSMT, 2002), the same test vehicle was used throughout the experiments at both sites. For each site, the test vehicle was ran on the roadway using four speed: 30 km/h, 50 km/h, 70 km/h, and 90 km/h. The specification of each profile can be seen in Fig. 1, and both roads are considered straight in order to meet the requirements of ISO 13325 (ISO, 2003), with the condition of the pavement and TRS surfaces being good and dry.

The test vehicle was a typical passenger car used on the road in Malaysia, which is a 2005 model Perodua Myvi with a weight capacity of 950 kg. This vehicle is classified as a light vehicle since the gross vehicle weight (GVW) is up to 4500 kg. The tyre size is 175/65 R14. The tyre pressure was fixed at 250 kPa for all measurements. A type-1 integrating-averaging Pulsar Model 33 sound level meter was used for the measurement. The sound level meter was calibrated using a Model 105 acoustic calibrator before and after

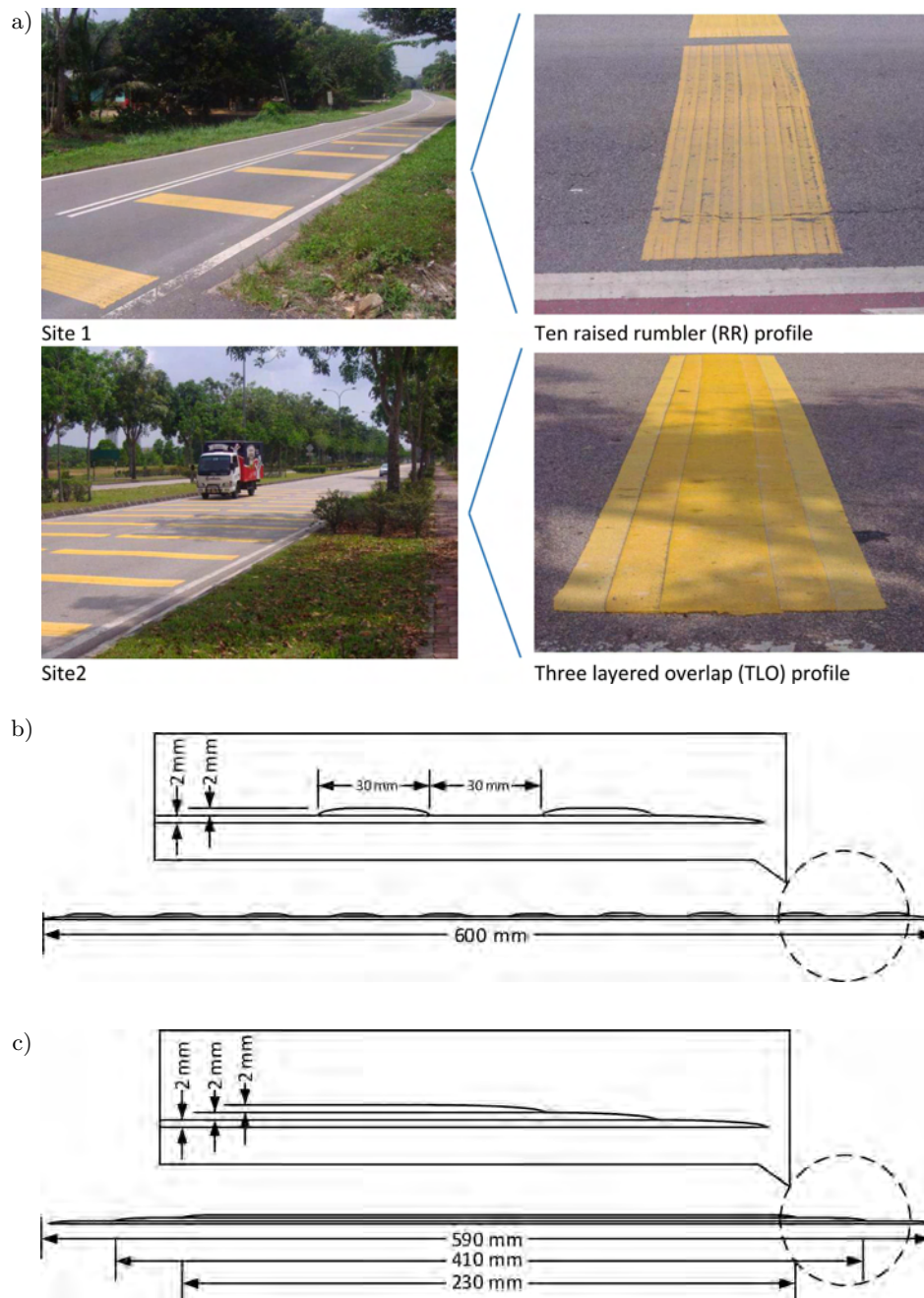


Fig. 1. Profile of thermoplastic TRS and their dimensions: a) types of thermoplastic profile and the experimental sites, b) RR profile, c) TLO profile.

the measurements. The microphone was equipped with a foam windscreen to reduce the effect of wind noise on the data. A multifunctional anemometer was used for measuring the wind speed and air temperature, and an IR thermometer was used to measure TRS and pavement temperature.

Each site has two points of measurement (Fig. 2). Point 1 is located in the middle of a set of TRS. At this location the readings were taken 4 times, i.e. once for each speed. At Point 2 the measurements were carried out at 300 m from Point 1 to avoid the effect of TRS.

This position is sufficient because it is larger than the value proposed by the Transportation Association of Canada which states that the noise due to the grooved surface of the TRS will be dissipated at 100 m (BAHAR *et al.*, 2005). At Point 2 the same experiments were repeated without TRS. The sound level meter was installed at 7.5 m from the middle of the test lane and the microphone was at a height of 1.5 m. The sound measurements were carried out using fast time weighting (fast) and A-frequency weighting, impulse time weighting (impulse) and A-frequency weighting, and spectral

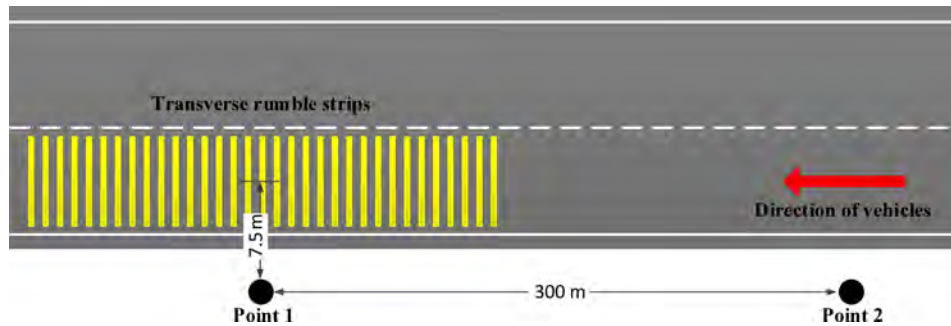


Fig. 2. Location of the sound level meter.

mode analysis of the one-third octave band were measured.

The parameters considered in the comparison between the sound level for the roadway with and without TRS were maximum measured LAF_{max} , and maximum measured LAI_{max} , LAF_{max} and LAI_{max} were the maximum reading when the test car was 7.5 m from the sound level meter. Readings for the wind speed and temperature of the air, TRS and pavement surface were taken before and after the measurements. Surface temperature correction was applied for every reading, as required by ISO 13325 (ISO, 2003). LAF_{max} and LAI_{max} were then corrected using Equation 1 to obtain LAF and LAI, and instead of pavement, in this study TRS temperature was taken as the surface temperature. To avoid external noise from other vehicles that can lead to data bias, the measurement process was carried out between 12:00 am and 3:00 am.

$$LAF = LAF_{max} + K(20 - t), \quad (1)$$

where LAF is the corrected measured LAF_{max} , K is the coefficient equal to -0.03 dB (A-weighted)/ $^{\circ}C$ when the measured test surface temperature is $> 20^{\circ}C$ and -0.06 dB (A-weighted)/ $^{\circ}C$ when the measured test surface temperature is less than $20^{\circ}C$, t is the surface temperature.

The spectrum analysis for when the TRS was hit by vehicles were analysed and compared with previous findings from tyre/road interaction frequency spectra analysis conducted by KIM *et al.* (2007), SANDBERG, EJSMONT (2002), KEULEN, DUŠKOV (2005), and WAYSON (1998).

3. Results and analysis

3.1. Relationship between the sound level and vehicle speed

Figure 3 presents the variation in maximum LAF generated when a vehicle hit RR and TLO, with and without TRS. Generally, for both RR and TLO profiles, it was clearly observed that higher vehicle speeds generate a higher noise. The sound pressure levels have

been corrected based on the TRS surface temperature using Eq. (1) as the pavement, and the TRS temperatures were $29.2^{\circ}C$ and $29.6^{\circ}C$, respectively, at Site 1 and $30.3^{\circ}C$ and $31.3^{\circ}C$, respectively, at Site 2. Both locations had the same background noise level, 45 dB(A). The readings were valid as air temperatures were within $5^{\circ}C$ to $40^{\circ}C$ and the measured wind speed at the microphone height was lower than 5 m/s, as recommended by ISO 13325 (ISO, 2003) to avoid sound refraction that will affect the readings (CROCKER, 2007).

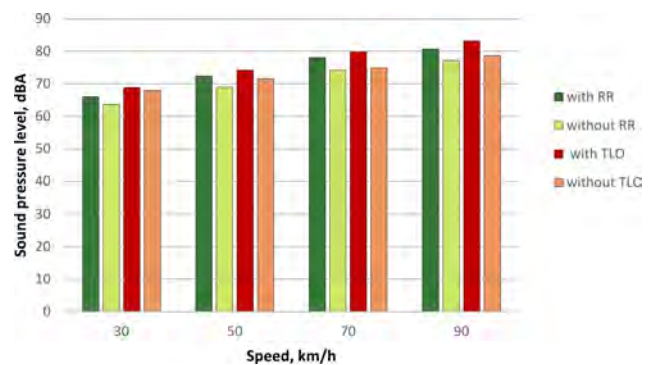


Fig. 3. LAF generated by roads installed with and without RR and a road installed with and without TLO.

Figure 4 shows in detail the increment in noise level with and without both of the TRS profiles and a com-

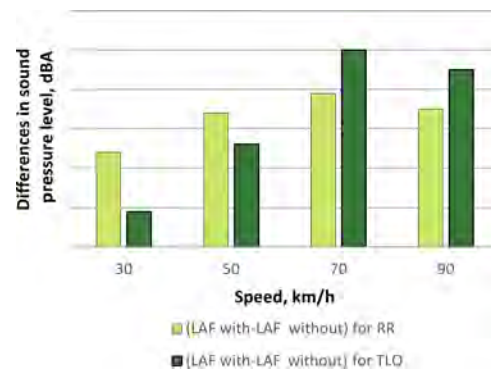


Fig. 4. Differences in LAF between roads installed with and without RR and a road installed with and without TLO.

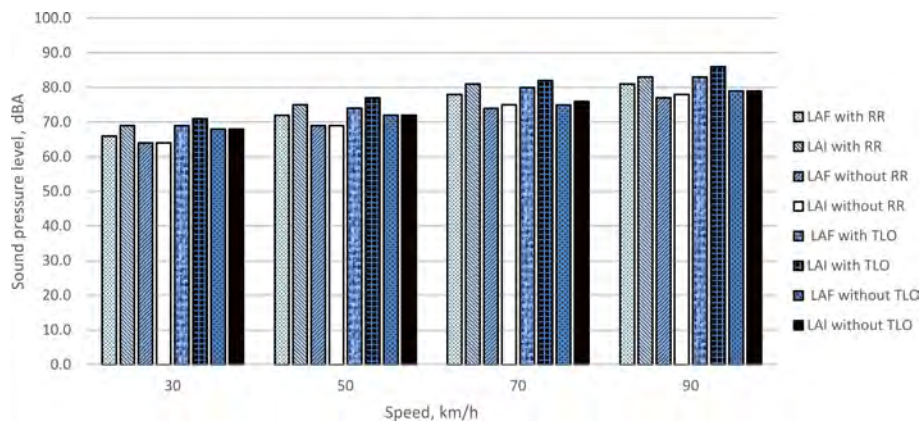


Fig. 5. LAF and LAI generated by roads installed with and without RR and a road installed with and without TLO.

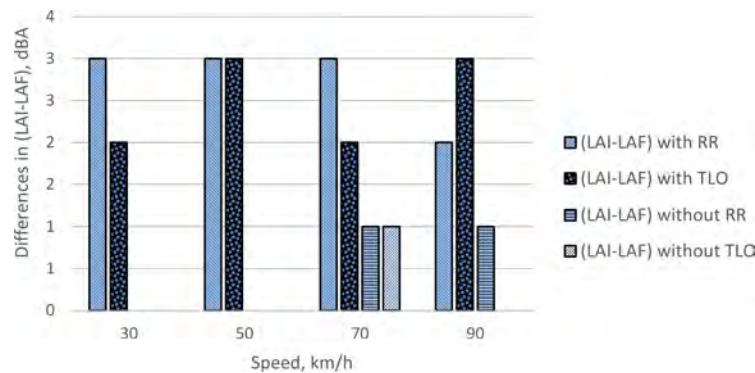


Fig. 6. Determination of the impulsive character.

parison between these profiles. It is seen that RR increased in noise level by 2.4 dB(A) (3.8%), while TLO only increased by 0.9 dB(A) (3.2%) for the single vehicle speed of 30 km/h. At a vehicle speed of 50 km/h the RR profiles exhibited a similar trend with a higher increase in noise level. However, at 70 km/h the TLO exhibits a higher increase than RR of 4.5 dB(A) (5.7%), and at a vehicle speed of 90 km/h, both profiles generated a similar increase. This finding shows that the RR is able to produce a just noticeable difference at 70 km/h and 90 km/h. Thus the installation of RR or TLO is able to exhibit noise changes that can be detected by the local residents near the roadway.

Figure 5 presents a comparison between the LAF and LAI generated from the road installed with either profile. It can be clearly seen that LAI for each speed and each profile exhibits a higher sound pressure level. The increase in Fig. 6 shows the (LAI-LAF) values for RR of 3 dB(A) for a speed of 70 km/h and below which are reduced afterwards. However, the trend for the TLO fluctuates. This result indicates that the noise has an impulsive character. In comparison with the road without RR and TLO, the (LAI-LAF) has differences of up to 1 dB(A). This finding shows that the thermoplastic RR and TLO are similar to pavement groove types of TRS and roads with metal cleats (KARKLE *et al.*, 2011; PERISSE, 2002).

3.2. Frequency spectrum analysis and anticipated tyre-TRS mechanism of noise generation

The frequency spectrum of noise at the moment the tyre hits the RR and TLO can be seen in Fig. 7 and Fig. 8, respectively. This reading was the maximum reading when the test car was 7.5 m from the sound level meter. The RR profile tends to have a more uniform increase in all of the frequencies. The anticipated mechanism was air pumping, side wall vibration, and surface and tyre impact. Air pumping as a result of the findings of KEULEN, DUŠKOV (2005) was dominant for the frequency range between 1–3 kHz. Air pumping occurs when the tyre is rolling and a volume of air is enclosed in the contact patch within the grooved line between the raised lines and pores constituted by the tread pattern grooves and the surface texture. Air is compressed and pressed away at the front of the contact patch and expanded and sucked into the cavities at the rear. The variations in the surface texture and tread pattern grooves, the latter of which will be rapidly squeezed, produce variations in the air flow over time. This generates vibrations in the surrounding air and therefore constitutes a source of sound.

Alternatively, sidewall vibration, surface and texture tread block, according to KIM *et al.* (2007) and

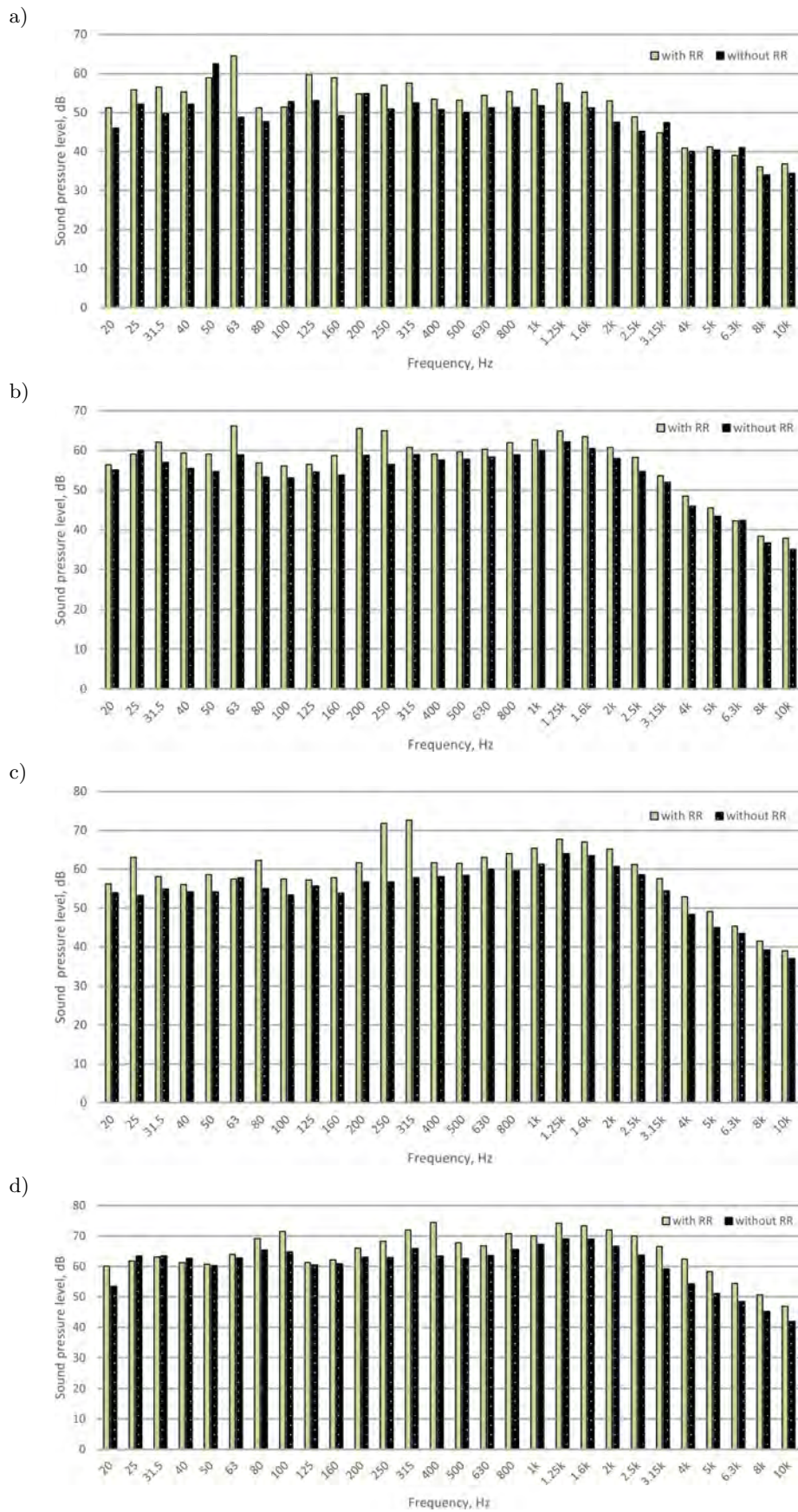


Fig. 7. Spectral frequency analysis of each vehicle’s speed for roads with and without RR: a) 30 km/h, b) 50 km/h, c) 70 km/h, d) 90 km/h.

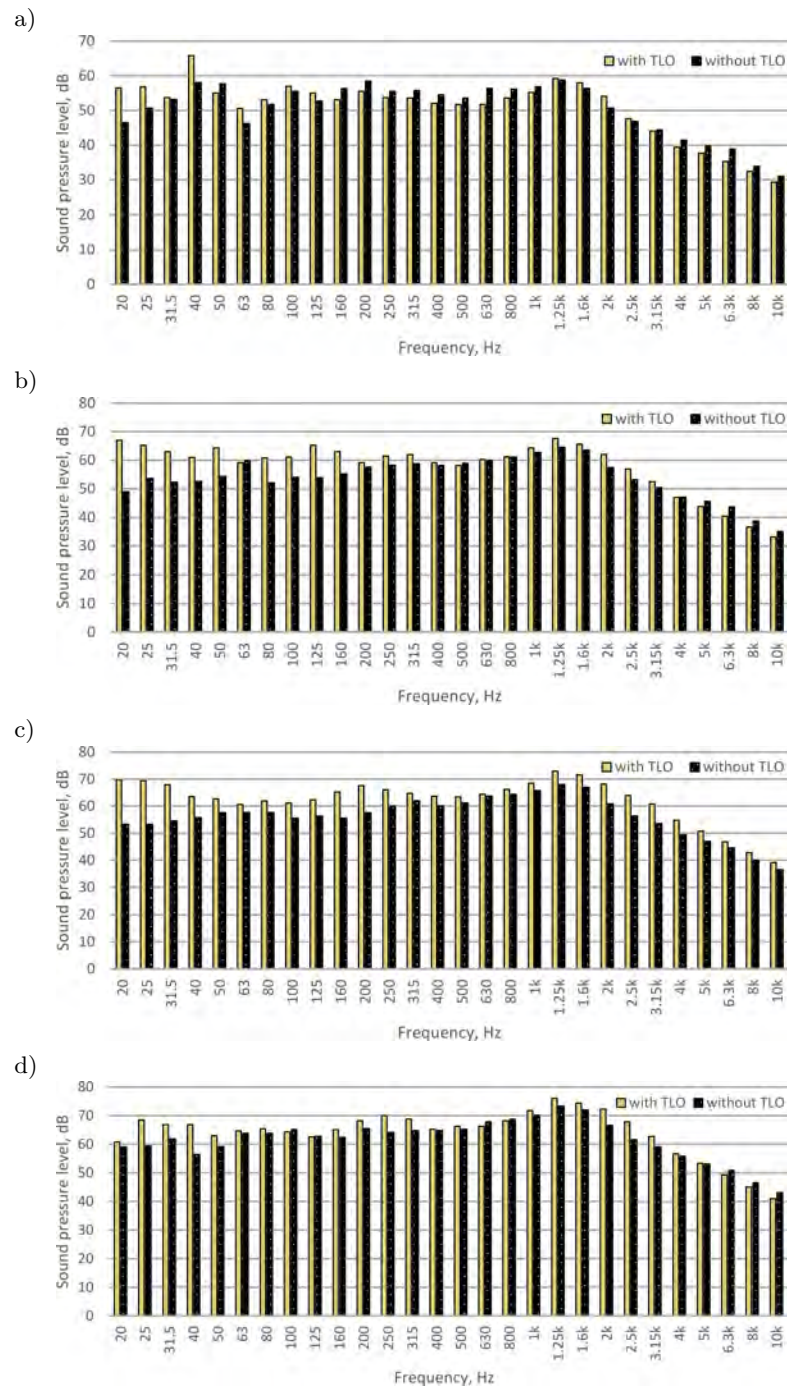


Fig. 8. Spectral frequency analysis of each vehicle's speed for roads with and without TLO:
a) 30 km/h, b) 50 km/h, c) 70 km/h, d) 90 km/h.

SANDBERG, EJSMONT (2002) were found for frequencies less than 1000 Hz, 700–1300 Hz, and 600–900 Hz, respectively. Side wall vibration is caused by a collision between the tread blocks and TRS. As the tyre interacts with the macro-texture of the RR (2 mm), the tread vibrations are transported to the side wall which acts as a 'sounding board' and radiates sound. Surface texture impact is generated when the tyre tread enters the contact zone at certain angles relative to the road, the tyre tread displacement itself contains

a radial and tangential component. TRS with a macro-texture of 2 mm gives a higher attack angle and generates more gradual displacement. Tyre tread impact is represented by the radial vibration which is the sudden displacement of the tread element, in relation to its original position in the rotating tyre, when it impacts the TRS surface. This may explain why the ten-raised-rumbler profile produced a more uniform increment in the sound level for each frequency since it was dominated by these three mechanisms. In addition, the

RR profile has a relatively high height of unevenness (2 mm), width (30 mm), and spacing (40 mm). The asperity height unevenness and the asperity spacing are defined as important parameters that govern tyre vibration noise.

On the other hand, the generation of noise from TLO is governed by structural resonance, surface texture vibration, and side wall vibration. In Fig. 8, TLO tends to have a significant increase in the sound level at low frequencies below 315 Hz. Based on the finding by BOLTON, KWON (1998), structural resonance (Fig. 9) is the dominant mechanism at low frequencies. Structural resonance is represented by tyre belt/carcass vibration (SANDBERG, EJSMONT, 2002). The overall thickness of the TLO is relatively high at 6 mm, which may be a key factor to this type of mechanism. However, according to PERISSE (2002), the increment in the sound level occurs at a higher frequency as the speed is increased. This can be seen in Fig. 8c and 8d for the vehicle speeds of 70 km/h and 90 km/h. TLO also induced more dominant surface texture vibrations, which is combination of radial (Fig. 10) and tangential vibration (Fig. 11; SANDBERG, EJSMONT, 2002). Frequency is quite dominant in the 250 Hz to 2 kHz range at speeds of 70 km/h and 90 km/h, which may be due to this mechanism since SANDBERG, EJSMONT (2002) state that this mechanism is dominant at 700–1300 Hz. Sidewall vibration involve dominant frequency < 1000 kHz (KIM *et al.*, 2007). Sidewall vibration (Fig. 12) induces collision between the tread blocks and the road (KEULEN, DUŠKOV, 2005), and in this case the tread block and TRS. As the TLO is rela-

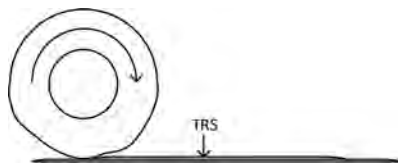


Fig. 9. Structural resonance – tyre belt/carcass vibration.

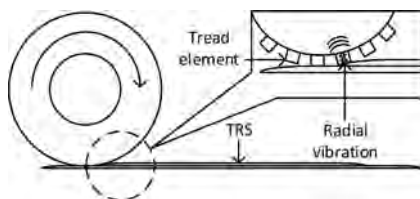


Fig. 10. Radial vibration.

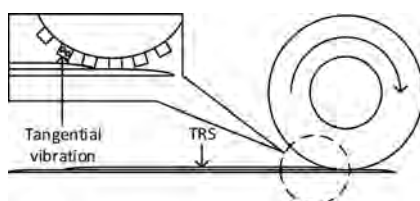


Fig. 11. Tangential vibration.

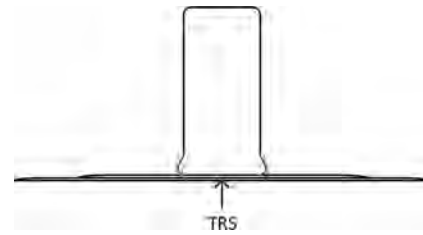


Fig. 12. Sidewall vibration.

tively thick, the collision becomes stronger and results in higher sound pressure levels for frequencies of less than 1000 Hz.

3.3. Effect of TRS on noise exposure

From the above findings, it is notable that TRS increase the noise level by up to 5 dB(A), and both profiles have impulsive characteristics. Furthermore, although TRS increases the noise level by a relatively small amount, their psychological impact may be greater because of the impulsive impact. In the work of BENDTSEN *et al.* (2004), TRS generated impulsive noise impact and suggested a 5 dB penalty for impulsive noise in order to predict the community response. The saw blade pattern or RR increases the sound pressure level at high frequencies (1 to 4 KHz), which affects the ear most sensitive human ears, while the TLO mainly increases the sound pressure level in the low frequency which cannot be heard by the human ear. Thus, based on the impulsive nature and frequency spectral analysis, it is recommended that the saw blade pattern or RR can only be installed on roads that are located away from sensitive premises.

4. Conclusion

This study revealed the characteristics of the noise of tyre-TRS interaction for two types of typical TRS profile that are widely used in Malaysia. The results showed that the ten-raised-rumbler profile and three-layer-overlapped profile increased the noise level and have impulsive characteristics. The ten-raised-rumbler is capable of generating a relatively high noise at low speeds, compared to the three-layer-overlapped system. Frequency spectral analysis showed that the ten-raised-rumbler profile produces a uniform increase in the sound level for each octave band, and that the three-layer-overlapped profile has a dominant noise at the low level frequency, which is at about < 315 Hz. Thus, the ten-raised-rumbler tends to irritate human ears. Based on this result and on the previous findings in the literature, the dominant generating mechanisms for the ten-raised-rumbler profile noise are tyre tread vibration, surface texture vibration, 'air pumping', and slight structural resonance and sidewall vibration. Meanwhile, for the three-layer-overlapped pro-

file it is structural resonance, sidewall vibration, and surface texture vibration. However, the mechanism is just an anticipated speculation based on a comparison of spectral frequency with the previous literature. It should be noted that the frequency spectra for each mechanism are also influenced by tyre design, tyre pressure, and road design. These findings will hopefully provide a contribution to the development of a new approach in the manipulation of TRS profiles that can provide an optimal auditory impact to road users without compromising their comfort and generating excessive noise that may disturb surrounding localities.

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