Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Transverse rumble strips thickness design for road users' comfort

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ARTICLE INFO

Article history:
Received 27 December 2015
Received in revised form
19 January 2016
Accepted 19 January 2016

Keywords:
Transverse rumble strips (TRS)
Speed reduction
Traffic safety
In-cabin vibration

ABSTRACT

Transverse rumble strips (TRS) have been used as a common approach by road planners to enhance road traffic safety. It functions to reduce vehicle speed and increase the drivers' alertness by generating vibration and sound effects to the vehicles. However, while TRS vibration is necessary to alert drivers, it may also become an issue when it is inappropriately designed as it generates excessive vibration that could affect road users' comfort. This paper aimed to evaluate how TRS thickness and vehicle speed influence the vibration level and subsequently come up with an appropriate design of the thickness that could generate noticeable vibration to drivers but not too much in which can affect their comfort. In-cabin vibration measurement in the acceleration root-mean-square value, RMS (m/s^2) was recorded while a test car was moving on the TRS samples with various thickness measurements on an actual road. The findings from a previous study on estimating the drivers' vibration difference threshold by using Weber's Law were used to estimate the appropriate TRS vibration and then the TRS thickness. The results indicated that vehicle speed and TRS thickness are highly significant to determine the TRS vibration. The recommendation for TRS thickness design for different average speed was proposed at the end of this paper.

1. Introduction

Transverse rumble strips (TRS) (Fig. 1) are effective to reduce vehicle speed and accidents (Finley et al., 2005; Liu et al., 2011). It has been widely used in Malaysia and many other countries. Furthermore, thermoplastic material that TRS are always made from is relatively cost-effective and easy to install (Thomas and Schloz, 2001). TRS function is to reduce the vehicle speed and increase driver's alertness by generating vibration and sound to the vehicles. However, it is quite common that TRS vibration that aims to enhance driver's alertness also generate excessive vibration to the extent where it affects the drivers and passengers comfort. Moreover, frequent commute on the road with excessive TRS vibration would damage the vehicles (Bahar, 2007).

The TRS specifications in Malaysia are based on Malaysian Ministry of Work (MOW) guidelines as illustrated in Fig. 2 (MOW, 2002) and it is recommended by MOW (2002) that the thickness of TRS should range between 3 and 7mm. Some of TRS thickness on the road is measured more than 7 mm. This indicated that some road planners ignore the recommendation assigned by MOW (2002) and come up with their own design.

Meyer (2006) and Lank and Steinauer (2011) support the common knowledge of TRS where the TRS thickness and vehicle speed deeply influence the level of TRS vibration. In regard to speed, Meyer (2006) stated that increasing the speed does not necessarily generate higher vibration. In some cases, the vibration decreases as speed increases but the data obtained was not consistent enough for Meyer (2006) to provide conclusive results. Yet, this situation does raise questions about the effectiveness of TRS for the purpose of speed reduction. Nevertheless, both studies did not put forward any model that could explain the TRS thickness and vehicle speed as predictor variables in estimating TRS vibration. Moreover, there is still a gap in the knowledge of how much thickness could generate vibration to road users.

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Fig. 1: Typical TRS in Malaysia

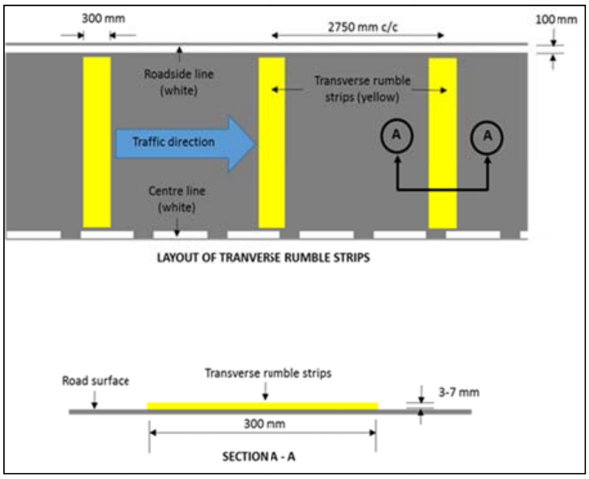

Fig. 2: TRS specifications

Following this questions, this paper aims to evaluate how much TRS thickness and vehicle speed influence the TRS vibration level and subsequently come up with a TRS thickness design that could generate a noticeable vibration to the drivers but not too much that would affect their comfort. Although it is suggested that the TRS vibration are also influenced by other parameters such as TRS width, surface profile, and configuration, the scope of this paper is only limited to the effect of TRS thickness and vehicle speed as those are the most significant parameters in previous studies (Meyer, 2006; Lank and Steinauer, 2011). The determination of noticeable TRS threshold is carried out using Weber's Law as discussed in the following section.

1.1. Weber's law

Weber's Law is under the subject of psychophysics, a sub-discipline of psychology which deals with the relationship between physical stimuli and their perception. This field of study is concerned to determine experimentally how perception changes as a function of the changes of physical intensity. In Weber's Law, the ability to notice a change in stimulus intensity is a function of the intensity level of the original stimulus: where I is the initial stimulus intensity, ΔI is the change in intensity or 'difference threshold', and k is the Weber fraction or Weber constant as shown in equation (1).

$$\Delta I / I = K \qquad (1)$$

By using this law, the noticeable automobile seat vibration has been studied by Mansfield and Griffin (2000). By setting up a laboratory test with 20 male and female subjects, they found that the participants generally began to notice the difference in their increment of vibration level at approximately 13% of the original vibration level.

2. Methods

2.1. Test procedure

On-road experimental procedure was carried out by applying the controlled pass-by (CPB) test procedure, a test where a car is driven over test tracks with TRS samples and baseline tracks presented on the site with constant speed as illustrated in Fig. 3 (Sandberg and Ejsmont, 2002); the baseline track which is a smooth road without TRS on the site. It functions as a control track. In terms of pavement condition, the road gradient and measurement time, TRS, and baseline tracks were assured to be as identical as possible to minimize any bias.

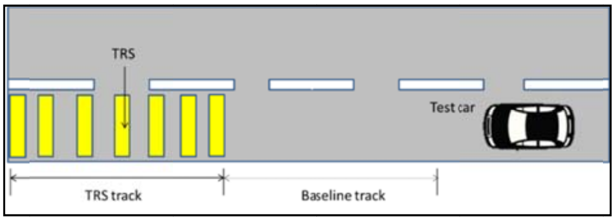

Fig. 3: Illustration of a test track on site (Sandberg and Ejsmont, 2002)

In-cabin vibration level of the test car as it was driven over the TRS and baseline tracks were recorded using Bruel and Kjaer 4507 B2 DeltaTron accelerometer which was connected to Type 3160-A-022 Analyzer as the data station as shown in Fig. 4 The procedure was repeated with four different speed which were 30, 50, 70, and 90km/h and each speed were run thrice. The accelerometer was mounted on the seat as shown in Fig. 5 and then it was connected to the analyser. All measurements were carried out with the windows rolled up, the air-conditioner was at its minimum, and the stereo was turned off. The analyser was connected to a personal computer and the reading was recorded.

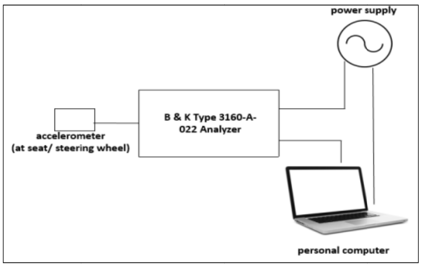

Fig. 4: The instruments layout

Fig. 5: Accelerometer on the seat

The vibration level was recorded in root-mean-square, RMS acceleration value (m/s^2). RMS_w stands for TRS track vibration while RMS_{wo} stands for baseline track vibration. For further analysis, the relative difference between RMS_w and RMS_{wo} ($RMS_w - RMS_{wo}$) was calculated and the value was represented as RMS_Δ.

2.2. Measurement sites and TRS samples

To carry out the on-road experimental procedure, 16 roadway stretches were selected for the case study locations. All these sites are situated in Johor Bahru and Pontian district in Johor, the southern state of Malaysia. All the sites were selected because of its TRS and pavements are in good condition, and the road surfaces are flat and even.

The TRS samples were measured in a variety of thickness i.e. from 2 to 10 mm. The samples measured were slightly different in width and configuration. Since the study used actual TRS on the road as the samples, they were assured to be in good condition as well as the test tracks.

2.3. TRS thickness measurement

Barton comb profile meter (BCP) (**Error! Reference source not found.** 2.4) was used to measure the TRS thickness. BCP was placed on the TRS sample and pavement, and then the acquired pattern at the BCP teeth was drawn on graph papers, hence the TRS thickness were obtained (Fig. 6).

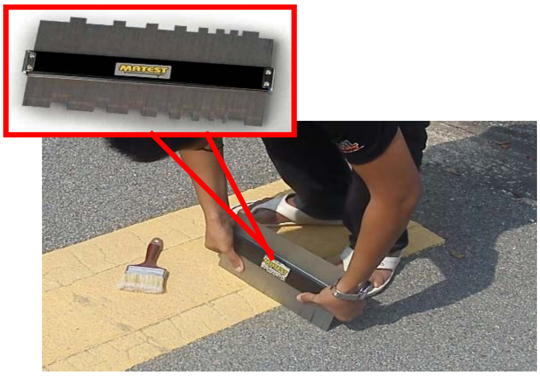

Fig. 6: Barton comb profile meter to measure the TRS thickness

2.4. Test vehicle

A typical car used in Malaysia was selected as the test car for this experiment. The year 2005 model Perodua Myvi (**Error! Reference source not found.** 7) with a weight capacity of 950 kg was used for this experiment. With the gross vehicle weight (GVW) was less than 4500 kg, the vehicle is classified as a light vehicle. The tire size is 175/65 R14. The tire pressure was fixed at 250 kPa for all measurements.

Fig. 7: Test vehicle - 2005 Perodua Myvi

2.5. Statistical analysis

The readings were then analyzed using SPSS package 16 statistical analysis software. Wilcoxon Signed-Rank test was used to test the statistical difference between RMS_w and RMS_{wo}. The difference was denoted as RMS_Δ. Descriptive statistics was presented as mean ±, standard deviation values, z-score and significant, and p-value. Linear regression model for in-cabin vibration was performed to calculate the beta value for each significant predictor variable. Unstandardized beta values were used to develop the in-cabin vibration regression model.

3. Results

3.1. Descriptive statistics

The results of in-cabin vibration measurement showed that the TRS vibration and RMS_w generally possess linear increment with increasing of TRS thickness as shown in Fig. 8 and Table 1. Wilcoxon Signed-Rank test was used to compare the RMS_w and RMS_{wo} measurements. With p-value <0.05, there were significant differences between both measurements for all TRS thickness. The highest RMS_w value was recorded at a TRS thickness of 10 mm ($RMS_w = 3.24 \pm 1.00$ m/s^2, $z = -2.20$, $p = 0.028$) while the lowest was recorded at TRS thickness of 2 mm ($RMS_w = 2.24 \pm 0.82$ m/s^2, $z = -5.84$, $p < 0.001$).

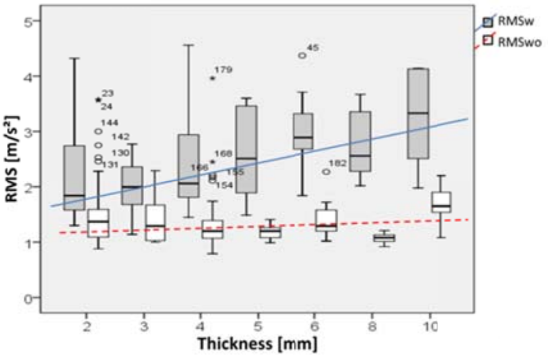

Fig. 8: RMS vs. TRS thickness

Fig. 9 and Table 2 illustrate the pattern of in-cabin vibration against vehicle speed. TRS vibration and RMS_w apparently possess linear increment with increasing of speed. However, baseline vibration and RMS_{wo} possess a logarithmic relationship with increasing of speed.

When tested with Wilcoxon signed-rank test, with p-value <0.05, there were significant differences between both measurements at all speeds. A vibration of 30 km/h (RMS_{wo} = 1.28±0.31 m/s^2) recorded higher reading than 50 km/h vibration (RMS_{wo} = 1.18±0.23 m/s^2). This was because lower gear transmission at 30 km/h speed generated higher vibration than 50 km/h speed. The relative vibration, RMS_Δ showed inconsistent pattern as it rose from 30 km/h (RMS_Δ = 0.56 m/s^2), peak at 70 km/h speed (RMS_Δ = 1.41 m/s^2), and then diminished at 90 km/h speed (RMS_Δ = 0.73 m/s^2).

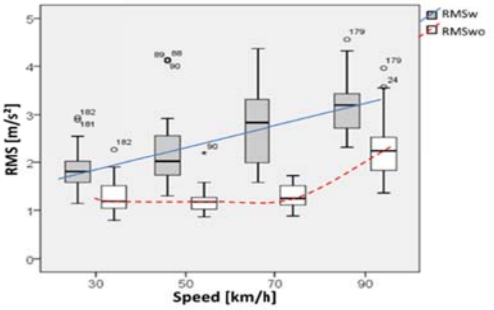

Fig. 9: RMS vs speed

Table 1: RMS vs. TRS thickness

Thickness [mm]	RMS_w [m/s^2]			RMS_{wo} [m/s^2]			RMS_Δ[m/s^2]	Δ [%]	z	p
	M	SD	N	M	SD	N				
2	2.24	0.82	46	1.60	0.71	47	0.64	40.00	-5.84	<0.001
3	2.02	0.48	24	1.40	0.39	24	0.62	44.29	-4.29	<0.001
4	2.40	0.77	44	1.42	0.71	42	0.98	69.01	-5.58	<0.001
5	2.60	0.82	9	1.18	0.13	9	1.42	120.34	-2.67	0.008
6	2.91	0.64	17	1.40	0.31	18	1.51	107.86	-3.62	<0.001
8	2.76	0.64	8	1.07	0.31	8	1.69	157.94	-2.52	<0.001
10	3.24	1.00	6	1.97	0.69	11	1.27	64.47	-2.20	0.028

*Tested with Wilcoxon Signed-Rank test

Table 2: RMS vs. speed

Speed [km/h]	RMS_w [m/s^2]			RMS_{wo} [m/s^2]			RMS_Δ[m/s^2]	Δ[%]	z	p
	M	SD	N	M	SD	N				
30	1.84	0.40	43	1.28	0.31	43	0.56	43.75	-5.64	<0.001
50	2.19	0.64	44	1.18	0.23	45	1.01	85.59	-5.78	<0.001
70	2.76	0.72	42	1.35	0.35	45	1.41	104.44	-5.65	<0.001
90	3.24	0.59	25	2.51	0.76	26	0.73	29.08	-4.11	<0.001

*Tested with Wilcoxon Signed-Rank testRegression model

A linear regression model was performed to obtain the relationship between TRS vibration, RMS_w, and its significant predictor variables. Table 3 shows the result of this analysis. The analysis showed that the TRS thickness and vehicle speed were statistically significant to estimate the level of RMS_w (thickness, Beta=0.464, t=7.083, p<0.01; Speed, Beta=0.731, t=14.557, p<0.01). Speed was the dominant predictor variable since it has higher standardized beta value, 0.731 compared to the thickness with beta value of 0.464. This model is strongly reliable since it possessed high adjusted R^2 value, 0.630.

Table 3: Coefficient of RMS_w model

Parameters	Unstandardized Coefficients		Standardized Coefficients	t	Sig. p
	B	Std. error	Beta		
Constant	-0.630	0.647		-0.974	0.013
Thickness	0.181	0.025	0.464	7.083	<0.001
speed	0.027	0.002	0.731	14.557	<0.001

*adjusted R^2 = 0.630

By using the non-standardized beta value, the equation model of RMS_w can be written as follows:-

$$RMS_w = -0.63 + 0.181h + 0.027v \tag{2}$$

3.2. Recommendation of TRS thickness

In order to design the TRS thickness, the appropriate vibration level to the driver needs to be defined. The appropriate vibration is supposed to be sufficiently noticeable to the driver but not to the extent that could affect drivers' and passengers' comfort. In this context, the in-cabin vibration level should be raised above the ambient level to the driver's noticeable threshold level.

In this process, the original vibration was denoted as RMS_{wo}. It is the value of vibration level when the test car passes through the baseline track i.e. ambient level vibration. Vibration above the ambient level would sufficiently achieve the drivers' vibration threshold and it was represented by RMS_N and was determined by Weber's Law.

By using the principle of Weber's Law, Mansfield (2000) suggested that a person who sits in a car will experience the noticeable vibration differences when the initial vibration is added 13% of its value.

$$\mathrm{RMS_N} = 1.13 \times \mathrm{RMS_{wo}} \tag{3}$$

By using equation (2) to design the TRS thickness, road planners are required to insert the average traffic speed, v which can be obtained by measuring the average speed at the location.

Substitute $\mathrm{RMS_w}$ with $\mathrm{RMS_N}$ into equation 2:-

$$\mathrm{RMS_N} = -0.63 + 0.181\mathrm{h} + 0.027\mathrm{v}$$
$$\mathrm{RMS_N} + 0.63 - 0.027\mathrm{v} = 0.181\mathrm{h}$$
$$\mathrm{h} = {\mathrm{RMS_N} + 0.63 - 0.027\mathrm{v}}/{0.181} \tag{4}$$
$$\mathrm{h} = 5.525\mathrm{RMS_N} - 0.149\mathrm{v} + 3.481$$

Where

h = recommended TRS thickness

$\mathrm{RMS_N}$ = noticeable difference threshold vibration; obtained from Weber's Law

v = average traffic speed

Work Example:-

To design the appropriate TRS thickness at locations that has average vehicle speed of 50 km/h.

The appropriate thickness would be able to generate a noticeable vibration to road users in a typical car but not too much to the extent that it can annoy them.

From Table 2, the value of $\mathrm{RMS_{wo}}$ when v=50 km/h is 1.18 m/s^2. To get the appropriate/noticeable vibration value, $\mathrm{RMS_N}$; $\mathrm{RMS_{wo}}$ should be added 13%. By using equation (3):-

$$\begin{aligned}\mathrm{RMS_N} &= 1.13 \times \mathrm{RMS_{wo}} \\ &= 1.18 \times 1.13 \\ &= 1.33\ \mathrm{m/s^2}\end{aligned} \tag{5}$$

With v=50 km/h and RMSN=1.33 m/s^2, to get the recommended TRS thickness, h; equation (4) should be applied.

$$\begin{aligned}\mathrm{h} &= 5.525\mathrm{RMS_N} - 0.149\mathrm{v} + 3.481 \\ \mathrm{h} &= 5.525(1.33) - 0.149(50) + 3.481 \\ &= 3.3 \approx 3\ \mathrm{mm}\end{aligned} \tag{6}$$

Therefore, the recommended TRS thickness for the location is 3 mm.

Table 4 shows the $\mathrm{RMS_N}$ by adding 13% to $\mathrm{RMS_{wo}}$. Then, the value of thickness, h was obtained by inserting the $\mathrm{RMS_N}$ and v value. It can be seen that the highest thickness recommended was 7 mm for 30km/h and the lowest was 2 mm at 70km/h.

Table 4: $\mathrm{RMS_{wo}}$ added with 13% of its value and recommended TRS thickness for respected speed

Speed, v (km/h)	$\mathrm{RMS_{wo}}$ (m/s^2)	*$\mathrm{RMS_N}$ (m/s^2)	**h from calculation (mm)	#Recommended h (mm)
30	1.28	1.45	7.0	7
50	1.18	1.33	3.3	3
70	1.35	1.57	1.7	2
90	2.51	2.84	5.8	6

Note: *$\mathrm{RMS_N}$ = $\mathrm{RMS_{wo}}$+13% = noticeable difference threshold vibration
**h= thickness
#recommended h are the rounded h from calculation value

4. Discussions

The TRS design guidelines in Malaysia are generally too basic and road planners usually come up with their own design. This has led to a various dimension of TRS thickness that eventually brings the issue of excessive vibration to road users. TRS vibration is essentially necessary to alert the drivers but it need to be controlled so it would not generate excessive vibration.

From the analysis, TRS vibration possessed a linear positive relationship with the TRS thickness which was consistent with the findings by Meyer (2006) and Lank and Steinauer (2011). Increasing the TRS thickness will increase the in-cabin vibration when the vehicle crosses over the TRS. However, to control the TRS vibration by just manipulating the TRS thickness is not possible since the vibration also heavily relies on the vehicle speed.

Meyer (2006) stated that increasing speed does not necessarily generate higher vibration. In some cases, the vibration decreases as the speed increases but the data obtained was not consistent enough for Meyer (2006) to provide conclusive results. In contrast, this study found that TRS vibration was linearly proportional to speed. Yet, the relative vibration possessed inconsistent pattern as it peaked at 70 km/h speed and then diminished at 90 km/h speed because the baseline vibration from 70 km/h speed to 90 km/h steeply rose. This might give the impression to the driver that vibration is less at 90 km/h, hence it may become counterproductive to lower the vehicle speed.

This paper also presented the in-cabin vibration model when a typical car passes through the TRS samples. The model estimated the vibration by taking into account the TRS thickness and vehicle speed. Therefore, by having these two parameters, the vibration level that will be experienced by road users can be estimated. The model was then used to estimate TRS thickness. Hence, road planners can decide which thickness is suitable for particular location.

5. Conclusion

Road planners have used a variety of TRS thickness based on their judgement in TRS installation since the TRS guidelines provide them freedom to select TRS thickness in within the range 3-7mm. Poor selection of TRS thickness will cause inappropriate vibration level to the vehicles.

From the analysis, it is concluded that TRS vibration is deeply influenced by TRS thickness and vehicle speed. Both parameters possessed a linear relationship with the TRS vibration. Relative vibration was peaked at medium speed and diminished at higher speed. This paper has presented a model to estimate TRS vibration level based on the information of TRS thickness and vehicle speed. Then, this paper used Weber's Law to determine the appropriate TRS vibration. The in-cabin vibration model and the information of appropriate TRS vibration together with the vehicle speed were then used to design TRS thickness. These findings hopefully would assist road planners in designing better TRS in future.

Acknowledgement

This work is supported by Research University Grant of UTM (Q.K130000.2540.06H51) financed by the Ministry of Education, Malaysia.

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