Jurnal Teknologi

Full paper

Malaysian Transverse Rumble Strips: A Review and Recommendations for Practice

Mohd Hanifi Othman [a], Zaiton Haron[a*], Mohd Rosli Hainin[b], Khairulzan Yahya[a], Haryati Yaacob[b], Mohd Erwan Sanik[c]

[a]Department of Structure and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia
[b]Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia
[c]Department of Infrastructures and Geomatic Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

*Corresponding author: zaitonharon@utm.my

Article history

Received: 15 November 2014
Received in revised form:
2 January 2015
Accepted: 30 January 2015

Graphical abstract

Abstract

Transverse rumble strips (TRS) is a common choice to reduce vehicle speed and increase driver alertness on roadway. TRS is a series of marked (either flat or raised) transverse bars placed across the road in direction of traffic flow. It functions to assist driver to become aware through optical, vibration and audible effect thus encouraging drivers to reduce speed and increase their alertness in order to face any hazard that may exist ahead. Although often being used, in reality TRS usage in Malaysia still has some aspects that can be improved. The purpose of this paper is to critically review the definition of thermoplastic TRS, its effectiveness, standard guidelines in Malaysia, thermoplastic materials and colour and also to propose the recommendation in regard practice of TRS in order to increase its effectiveness. Besides the available literature source in the light of the latest published findings, personal interview have been done to several authorities which are headquarter and district public work department, local municipal and university regarding TRS application guidelines and practice in Malaysia. The authors synthesize the available findings on the TRS performance and standard guidelines to propose some recommendations for a better application practice of TRS in particular in Malaysia. The proposal of all the findings hopefully would be beneficial to authorities in improving the practices of TRS.

Keywords: Transverse rumble strips, thermoplastic materials, standard guidelines, recommendation for practice

1.0 INTRODUCTION

World Health Organization (WHO) claimed that motor vehicle accidents are the second most frequent death for entire world for people aged 5-29 years old. WHO summarized an around 1.2 million people are killed each year on road and 50 million are injured [1]. In Malaysia, a ten-year road traffic statistic showed that the total number of accidents had raised from 215,632 cases in 1997 to 363,314 cases in 2007. This is equivalent to 3.73 deaths for every 10 000 registered vehicles in the same year [2]. Speeding and carelessness are two main causes of accident, contributing 32.8 and 28.2 percent respectively to the total number of accidents [3].

Martindale and Ulrich [4] stated the easiest and cheapest measure in order to control road accidents caused by excessive speed and carelessness factors is by using road sign and markings. However, when it comes to situation where drivers confronting with too many sign to comprehend, drivers tend to ignore the excessive information thus limiting the warning effect. This situation is named as 'clutter effect' [5]. It has been suggested that one of the reasons for their limited effectiveness may be due to their overuse, particularly in situations of lesser risk [6, 7]. As example, Jorgensen and Wentzel-Larsen [6] stated that the effect of curve warning signs on drivers' perceptions of risk is quite low, only 6% overall safety impacts.

Therefore, an alternatives measure consist road layout and its associated features which able to subconsciously inform drivers regarding upcoming road condition were introduced. One of them is transverse rumble strips (TRS). TRS is intended to give audible, visual and tactile cue effect when operational decision point is approaching [8].

TRS is widely used in Malaysia and it can be said that all the road authorities in this country used it. TRS is classified as passive speed control measures, serve to alter drivers' perceptions of the correct speed for a particular road so drivers may assume a lower speed is more appropriate [9]. Based on road safety factors, TRS potential for reducing crashes, alerting drivers, improving sign effectiveness, and increasing the rate of deceleration of vehicles and may also reduce right-angle accidents, which are commonly associated with running through a stop sign or signal, by alerting drivers to an upcoming condition [10, 11]. As compared to other speed control devices, TRS generally is relatively inexpensive and easier to install and maintain [12]. In addition, their impacts on driving comfort are considered to be minor as compared to speed humps and speed bumps [13].

This paper is to critically review the definition of thermoplastic TRS, its effectiveness, standard guidelines in Malaysia, thermoplastic materials and colour and also to propose recommendation in regard practice of thermoplastic TRS in order to increase its effectiveness.

■2.0 DEFINITION OF TRS

Generally, there are three types of rumble strips that based on the location of its installation i.e. 1) shoulder rumble strips 2) centreline rumble strips and 3) transverse rumble strips [14]. Shoulder rumble strips are placed on roadway shoulders, outside of the travel lane as can be seen in Figure 1. The purpose of shoulder rumble strips is mitigating single vehicle run-of-road type crashes. Centreline rumble strips are installed on or near centreline of roadway as in Figure 2. The purpose is to mitigate head-on crashes and opposite-direction sideswipe crashes [14].

Figure 1 Shoulder rumble strips [15]

Figure 2 Centerline rumble strips [14]

Transverse Rumble strips are placed across the travel lanes of the roadway and perpendicular to flow of vehicles. TRS usually be applied on roadways approaches to intersections of expressways, rural highways, and parkways to reduce approach vehicle speeds and prevent intersection crashes [10]. TRS are placed in the lane and generally traverse more than two-thirds of the travel path perpendicular to the direction of travel [11]. That is why it is called in lane rumble strips in United Sates. In Malaysia, they were called by authorities by various names such as transverse bar, yellow bar and speed breaker.

TRS is basically intends to alert drivers only through the effect of tactile and audible. Therefore, it is assumed that by only through TRS vibration and noise sensation, drivers will become alert. This item is compatible with the definition of the Transportation Association of Canada (TAC) which describes TRS as a "lateral pattern of grooves or raised pavement material that vertically deflects wheels of a vehicle driving over them thereby producing both noise and vibration" [16]. Manual on Uniform Traffic Control Devices (MUTCD) Millennium edition used in the United States, however, states that TRS "consist of intermittent narrow, transverse areas of rough-textured or slightly raised or depressed road surface that alert drivers to unusual motor vehicle traffic conditions. Through noise and vibration they attract driver's attention towards hazardous features such as unexpected changes in alignment [17]. Then it can be seen in the use of asphalt, which is commonly TRS has no colour elements that would appeal to drivers as shown in Figure 3. However, TRS has innovated to get the optimum efficiency by combining the concept of transverse pavement markings (TPM) (Figure 4), which provides optical effects in giving warning to drivers

Figure 3 TRS in several states in USA – not rely on optical effect [18]

Figure 4 Transverse pavement marking in USA [19]

According to Martindale and Ulrich [4], TPM is "a series of marked (either flat or raised) transverse bars placed across the road in the direction of traffic flow. They are used to assist in raising driver awareness of risk through perceptual optical effects, thus encouraging drivers to reduce their speed in anticipation of an upcoming hazard". To produce the optical effect is the TPM is coloured with colour that appeals to drivers like white and yellow as shown in Figure 6 (a-c). TPM known as optical speed bars and not rely on vibration and sound effect. The bars were applied with paint, so the thickness was negligible [19]. By taking the concept of TPM, TRS is able to give the effect of vibration, auditory and optical in alerting drivers as can be explained in the Figure 5. This kind of TRS is widely used in Malaysia because of guidelines set by the Malaysian Traffic Calming Guidelines that demand coloured bar TRS is printed on road surface and can produce slight vibration to warn drivers to gradually slow down [20]. In China, the design of TRS also combining the warning effects of optical, vibration and sound. But it differ with Malaysian design since it consisting of several set of 3 strips as shown in Figure 6 (b). The strips thickness can be flexibly adjusted to actual situations within a certain range to accommodate both the purpose of speed control and ensure driving comfort [21]. The effect of vibration is likely to force drivers to slow down while the effects of optical and noise are more to reminding drivers of the dangers ahead [16]. Thus, by optimizing all of these effects of alertness, TRS effectiveness as a safety measures can be improved.

■3.0 EFFECTIVENESS OF TRS IN REDUCE SPEED AND ACCIDENT

Liu et al. [13] have conducted a study to evaluate the impacts of TRS in reducing crashes and vehicle speeds at pedestrian crosswalks on rural roads in China. TRS is a type of thermoplastic in white colour. Using crash data reported at 366 sites, the research team conducted an observational before-after study using a comparison group and the Empirical Bayesian (EB) method to evaluate the effectiveness of TRS in reducing crashes at pedestrian crosswalks. It was found that TRS may reduce expected crash frequency at pedestrian crosswalks by 25%. The research team collected more than 15,000 speed observations at 12 sites. The speed data analysis results show that TRS significantly reduce vehicle speeds in vicinity of pedestrian crosswalks on rural roads with posted speed limits of 60 km/h and 80 km/h. On average, the mean speed at pedestrian crosswalks declined 9.2 km/h on roads with a speed limit of 60 km/h; and 11.9 km/h on roads with a speed limit of 80 km/h. The 85th percentile speed declined 9.1 km/h on roads with a speed limit of 60 km/h; and 12.0 km/h on roads with a speed limit of 80 km/h. However, the speed reduction impacts were not found to be statistically significant for the pedestrian crosswalk on the road with a speed limit of 40 km/h [13].

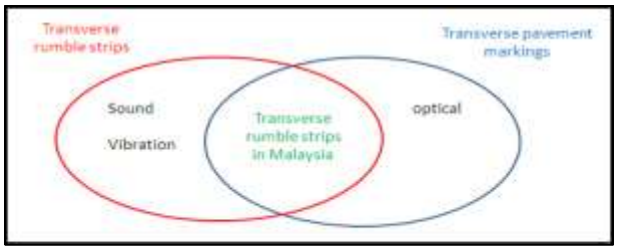


Figure 5 The characteristic of TRS in Malaysia combining the effect of noise, vibration and optical

a) Typical TRS in Malaysia

b) TRS in China [13]

c) TRS at Lyngby, Denmark [22]

Figure 6 TRS that combine optical effects, vibration and auditory

In USA, Thompson et al. [8] conducted a study to evaluate effectiveness in reducing speed of vehicles TRS and evaluate the effectiveness of TRS in different periods time which are daytime, night time and weekends. Vehicle speeds were measured at three locations along the approach to rural stop-controlled intersections both before and after the installation of the TRS. The researchers evaluated nine rural stop-controlled intersection approaches in Texas during both day and night conditions on both weekends and weekdays. In most site, the installation of TRS generally produced small speed reduction which is 1.6 km/h (1 mph) but statistically significant ($p \leq .05$) reductions in approach speeds. However, speed must achieved 6.4 km/h (4 mph) or greater to be practically significant or meaningful [23]. Thompson et al. [8](2006) did not find any conclusion in relation to the impact on speed reduction during day, night, weekend and weekday periods.

Yang et al. [21] conducted a study to investigate the effectiveness of TRS in the shape of chevron pattern in China. The TRS is yellow chevron shaped which is formed by six groups with a total length of 95 meters. They conducted a random survey of vehicle speed on two highways. Several findings are obtained from their study which are: (1) the effectiveness of TRS on cars is better than on trucks. The 85th percentile average speed of trucks and cars decreased by 16.2 percent and 21.0 percent respectively after passed the TRS. In addition, almost all cars speed indexes decreases more than trucks. The speed distribution of car is more concentrated. The bump amplitude closely related to vehicle's weight and speed. (2) It is improve traffic safety to a certain extent. However, there is occur rapid acceleration of vehicles downstream which can create serious safety problems. (3) Data collected indicated that the effect of TRS and speed limit signs used in combination is obviously better than using TRS alone. But it is also depends on the physical dimension of highway, form of colour of TRS and so on. (4) There are some relationships between the effectiveness of TRS and their density according to its principle, but what the optimum density is still needs further study. (5) In the case of using TRS alone, the effectiveness of yellow TRS is better than white TRS [21].

■4.0 STANDARD GUIIDELINES AND SPECIFICATIONS IN MALAYSIA

As mentioned by Yang et al. [21] specifications of TRS play certain role in determining its effectiveness. Bahar et al. [16] stated that the critical design elements include: 1) Number of set (series of TRS grouped together form a set, 2) Length of set, 3) Distance between two sets, 4) Number of strips per set, 5) Distance between strips, 6) Depth or height of strip, 7) Length of strip, 8) Full lane or partial/wheel-width and, 9) Duration of audible and tactile stimuli based on vehicle speed and length of set. [16].

Basically, the TRS design and specification are uniform for the entire country in Malaysia is according to specifications set in REAM -GL8/2004 (Guidelines on Traffic Control Devices and Management), Part-4, pavement marking and Delineation [24]. Current design of TRS in Malaysia generally consists of yellow thermoplastic lines (3mm to 7mm thick) lay across the carriageway. Typical design of TRS in Malaysia is shown in Table 1 and Figure 7.

However, it was found that these guidelines were very basic. Thus installation in of TRS in district roadway relies on judgment of district engineer. It was also found that local authorities have their own design of TRS profile. Profiles of TRS is the key important factor in determining the impact of sound and vibration generated when the TRS crossings by vehicles. Table 2 shows the profiles used by the authorities in Malaysia.

■5.0 THERMOPLASTIC MATERIAL AND COLOURS

There are various types of materials for TRS such as thermoplastic, epoxy, water-based paint, and preformed tape [26, 27]. Each material contains three primary components: binder (glue), surface glass beads (reflectors), and pigment (colour). It is also important to realize that some materials are more appropriate for a given set of circumstances than other materials [27]. Materials should be selected that will meet or exceed the performance requirements at the lowest cost. To maximize cost-effectiveness, material selection should be based on roadway surface type, traffic volumes, and expected remaining service life of the pavement [27]. Paint is the easiest and cheapest marking material, but it is also the least durable [28].

Table 1 Typical Specification of TRS in Malaysia [20]

Material use	Dimension	Signage/ Road Marking
Skid Resistance Material	Width: 300mm Thickness: 3-7mm Spaced: 2750mm (centre to centre)	No specific signage

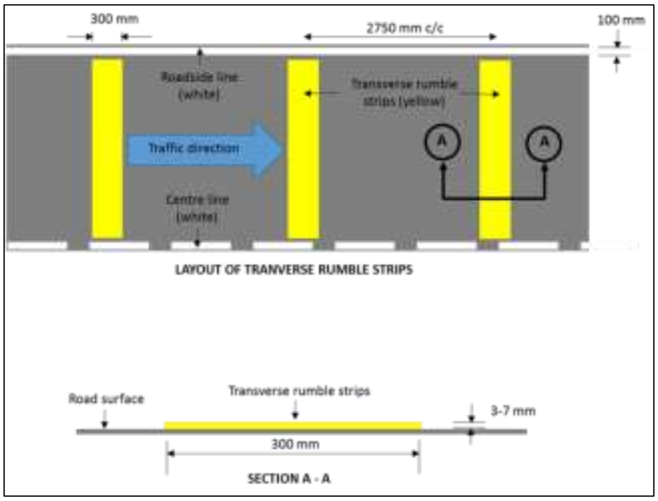


Figure 7 Design of typical TRS in Malaysia [25]

Materials that commonly used in Malaysia is thermoplastic material. MOW [20] guidelines demand thermoplastic as material for TRS. The popularity of thermoplastic markings can be attributed to several factors including: readiness for immediate use, high durability, good retro reflectivity and relatively low cost [27, 29]. In Malaysia, the price is around MYR 25/m^2 (USD 7.8/m^2). Thermoplastics have been used as a pavement marking material in the United States since the late 1950s. Thermoplastic gain its name from the mixture of plasticizer and resins that serves to hold all of the other ingredients together exist as a solid at room temperature, but becomes liquid when heated. When properly formulated for a given roadway surface and correctly applied, thermoplastic pavement markings have been known to last from 5 to 8 years depending on traffic volumes, but research and experience has shown that usual service lives range from 2 to 3 years depending on traffic volumes [27].

Thermoplastic materials consist of four general components: binder, pigment, glass beads, and filler material (usually calcium carbonate, sand, or both). Thermoplastic materials are classified into two main basic categories based on the type of binder: hydrocarbon and alkyd [27]. There are other types of preformed (hot-tape), and some polymeric blends [30]. Hydrocarbon thermoplastic is made from petroleum-derived resins, while alkyd thermoplastics are made from wood-derived resins. A comparison of the two types of thermoplastic materials is shown in Table 3 [27].

Table 2 Examples TRS profiles available in Malaysia

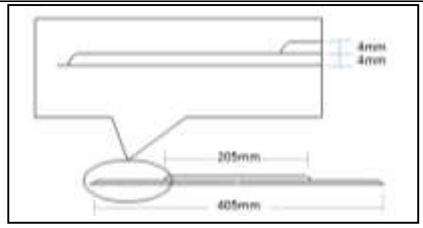
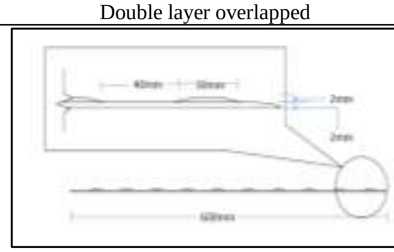
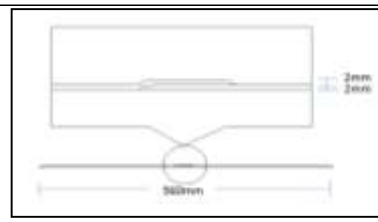
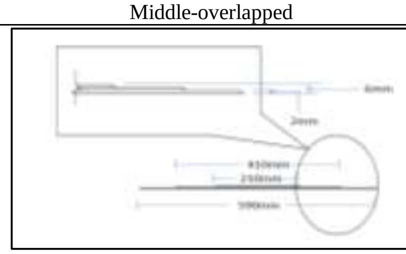
Profiles and Specification
  Double layer overlapped
  Ten raised rumbler
  Middle-overlapped
  Triple layer overlapped

Table 3 Comparison of the two types of thermoplastic materials [27]

Characteristic	Type of thermoplastic	
	hydrocarbon	Alkyd
Binder source	Petroleum	Wood
Application Temperature	Approximately 420º	Approximately 420º
Oil soluble	Yes	No
Heat Stability	More	Less
Sensitivity to changes in application properties	Better suited	Not as well suited
Durability	Less	More
Expected life under normal conditions	Up to 5 years	Up to 5 years

The ability for thermoplastic materials to bond to the roadway surface is based on the thermal properties of the thermoplastic binder and the roadway surface along with the porosity of the surface. Thermoplastic is well suited for use on asphalt surfaces because the thermoplastic develops a thermal bond with the asphalt via heat fusion [27]. For cement concrete surface, bond formation occurs by the liquid thermoplastic seeping into the pores of the concrete and forming a mechanical lock to the concrete surface. Primers are recommended prior to thermoplastic application on all hydraulic cement concrete surfaces and asphalt surfaces that are more than two years old, heavily oxidized, or have exposed aggregates [27].

In order to increase the visibility through retro reflectivity elements, glass beads are intermixed into the thermoplastic and partially embedded on the surface of the marking binder material as shown in Figure 8 [27]. Glass beads play the most important role in pavement-marking retro reflectivity. The mechanism of retro electivity can be seen in Figure 9. Markings without beads are virtually useless at night [27]. Bead properties that are controlled during the manufacturing process include those that are chemical and physical in nature. The chemical and physical properties of beads have a major influence on how well the beads reflect light. These properties include: 1) bead size, 2) refractive index, 3) clarity and 4) roundness. These properties are controlled by manufacturing factors, such as: type, quality, and clarity of the glass; furnace type and temperature; and sieve size. [27]. However, the glass beads are often become exposed as the binder material is worn down by traffic and causing the worn TRS not as visible as it supposed to be.

To optimize the effect of optical to driver, the element of colour is important to TRS. Thermoplastic pavement markings are available in numerous colour such as white, yellow, blue, red, green, black, orange, purple, grey, and yellow-green [30]. The line colours used for transverse road marking are usually either white (e.g. in United States and China) or yellow (all applications in Malaysia and the United Kingdom). The Netherlands is the only country known to use different line colours to distinguish between speed zones (e.g. a 100km/h speed zone can be indicated by a green line between two white lines in the centre of the road). This Dutch system would allow speed changes to be easily recognisable [4]. Two component liquids: In this category, epoxy, polyurea, and methyl methacrylate (MMA) based product lines are offered. These markings are exclusively yellow and white, as no other colours are available. For yellow, normally manufacturers use organic pigments including PY65, PY75, and PY83 [30].

Pavement marking colour perceived by drivers is primarily influenced by the incident light spectrum and intensity, pavement marking spectral and spatial reflectivity, and driver's light and chromaticity adaptation conditions. This means that it is not only the colour of the pavement markings, but also the colour of the headlights that determine colour classification [30]. Typically, performance will decrease in wet conditions. The degradation is a result of flooding of the marking optics and a change in the optical media, thereby reducing retro reflectivity and the visibility distance [31]. Pavement markings may appear yellow during daytime but may not appear yellow at night under automobile headlamp illumination. Pavement marking colour perceived by drivers is primarily influenced by the incident light spectrum and intensity, pavement marking spectral and spatial reflectivity, and driver's light and chromaticity adaptation conditions. This means that it is not only the colour of the pavement markings, but also the colour of the headlights that determine colour classification [30].

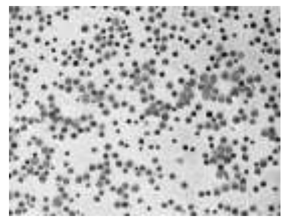


Figure 8 Good glass-bead dispersion of beads in thermoplastic [27]

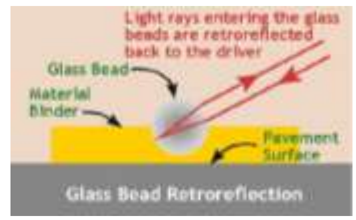


Figure 9 Retro reflectivity using glass beads [27]

Gates and Hawkins [32] claimed that wider pavement marking able to be more visible to driver. Brighter pavement markings produce longer detection distances but the relationship is non-linear. As the markings become brighter, more luminance is needed to increase detection distance. Wider markings (in this case, 6-inch wide) do not provide longer detection distances than 4-inch wide markings [11].

■6.0 RECOMMENDATION IN INSTALLATION

Because of TRS practice guidelines in Malaysia were very basic, the installation of TRS in district roadway relies on judgment of district engineer. This resulted several important aspects of the TRS installation may be overlooked by some of them. This section is specifically to suggest the recommendation in optimizing the application of TRS. The authors critically select in their opinions the best practice of TRS guidelines from several countries.

6.1 Best Suit Traffic Safety Approach to Cope With Certain Situation

The first thing to be seen is whether TRS is the best traffic safety measures in those locations. Failure to evaluate these things can cause problems such as noise problems in residential areas, as mention by Bendtsen et al. [22] and Bahar et al. [16]. In order to prevent the effect of noise from TRS, Bendtsen et al. [22] and Bahar et al. [16] suggest the TRS location should be more than 200m from residential areas. In addition, the TRS may not be effective if it is not to be in the right place. For example, Bahar et al. [16] indicates that the excessive usage of the TRS will cause familiar effect to road users and its existence will be ignored. This view is consistent with the opinion of Corkle et al. [12] where TRS should be used sparingly to retain its element of surprise. It is suggested that two TRS is only used in locations where there is a documented collision overrepresentation and where conventional warning methods, such as signs and signals, are inadequate [12].

In the installation of TRS, Carlson and Miles [11] suggest consideration should be given to the possible necessity of developing ways and means for preventing the local motorist, familiar with the installation, from deliberately driving around it. This is dangerous to the motorist and may encourage other non-local motorists to follow the local driver in this behaviour. The effect of TRS diminishes with decreasing average operating speed, thus TRS has a greater effect in areas with higher speed/posted speed limits [16]. This view is consistent with the finding from Liu et al. [13]. Therefore, TRS should only be used in areas with higher speed/posted speed limits.

In Malaysia, TRS has been used excessively in some areas thus eliminating the element of surprise. Beside, TRS also commonly found in locations which are not higher speed areas such as housing areas as shown in Figure 10.

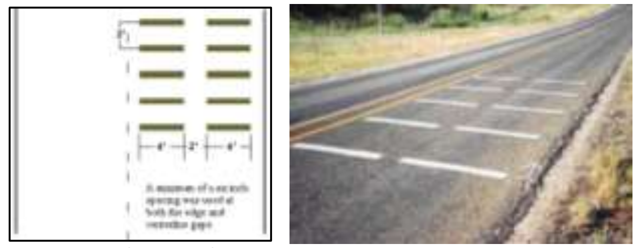
Figure 10 TRS in one housing area at Jalan Kolam Air, Johor Bahru

6.2 Distance From Decision Point, Numbers And Patterns

Every consideration should be given to establish the proper distance between the warning device and the critical area. If the distance is too far, acceleration, rather than deceleration, can be effected by the determined aggressive motorist; if too short, the alert motorist, who however, is exceeding the speed limit, is in trouble [11].

It has been suggested that the effectiveness of TRS is dependent upon the quality of the strips and their configuration pattern [34]. Presumably, to increase the effectiveness of TRS, the levels of stimuli produced by the strips must be increased, which can be done by varying the configuration and strip cross-section. Studies concluded that TRS with a depth less than 6 mm were largely ineffective [16]. Carlson and Miles [11] suggest these things to consider: Consideration should be given to whether a series of strip patterns, rather than only one, would better suit the purpose. Apart from that, when the decision to use TRS is reached, consideration should be given to whether they should be installed on one or more of the roads that form the dangerous intersection. Certain countries prefer to use TRS with several set/intermittent as shown in Figure 12. Commonly, on the Chinese freeway, TRS patterns are single strip, double strips or multiple strips and they are placed for one group or multiple groups respectively [35]. A study shows that intermittent (as opposed to continuous) and full lane (as opposed to 'partial' or 'wheel width') TRS are more effective and less likely to produce undesirable driver behaviour such as lane deviation and inconsistent and/or hard braking manoeuvres [16]. It is also suggested that TRS is installed with greater set of TRS but with less number of strips as in Figure 6.2. However, no more than four TRS sets should be installed as more pads have little addition effect [16].

Normal practice in Texas, USA that TRS was installed with a 'gap' in the middle to allow motorcycle passing through it without hitting the TRS (Figure 11) [11]. However, this gap may only be necessary if the thickness of the TRS is significantly thick and not suitable for small vehicles such as motorcycle. Converging patterns are not recommended because they have not been proven to more effective than equally spaced TRS sets. Instead of recommending a TRS layout pattern, TRS layout is recommended relative to the position of warning and approach conditions [16].



(a) The specification of TRS with middle 'gap' [36]

b) TRS in Texas, USA [37]

Figure 11 TRS in Texas, USA- it has a gap in the middle to allow motorcycle passing through it without hitting the TRS [11]

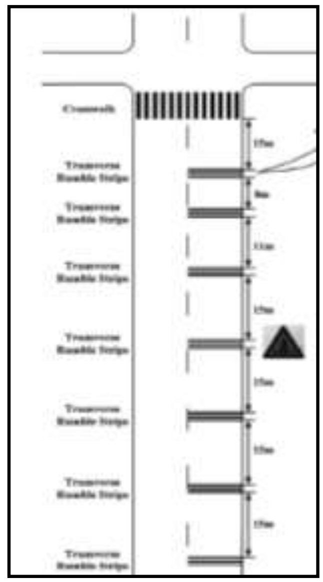


Figure 12 Rural TRS in approach to cross-walk in China [13]

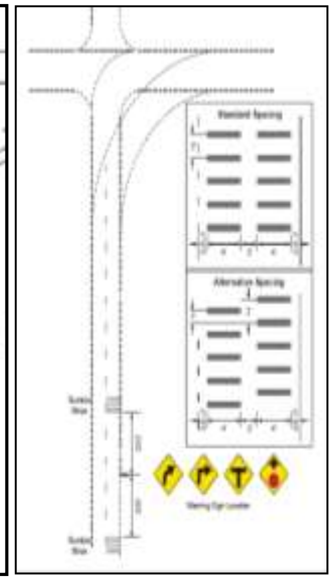


Figure 13 TRS used in conjunction with warning signs [11]

6.3 The Combination of Other Traffic Safety Measures with TRS

TRS are most effective when used in conjunction with other traffic control devices (e.g. lane shift signs, reduced speed limit signs, lanes divide sign, etc.) [12, 16]. TRS should be located in the vicinity of a warning sign, such that the sign and the TRS work together to provide additional emphasis of the upcoming intersection [12]. One of the benefits of this design is that the location of the TRS is based on the warning sign location and not on the intersection of the horizontal curve location. This situation is primarily because the intent or the TRS is to get inattentive drivers to become aware of the approaching conditions. The warning signs at these locations are already positioned in accordance with the vehicle speeds. Therefore, the use of the warning sign as a base measuring point for locating the TRS will provide drivers ample time to become aware of their conditions and react in time to be safe [11]. Carlson and Miles [11] suggested that the warning sign is placed between the group set of TRS as shown in Figure 13.

■7.0 CONCLUSION

This paper presents the definition of TRS, standard guidelines, material and colour, and also some other recommendations that can be used in oder to improve the TRS usage in Malaysia. Standard guideline for TRS in Malaysia is too basic and local engineer needs to plays an important role in determining the TRS installation. TRS application in Malaysia combine the optical, vibration and noise effects to alert drivers. Optical effects is maximized from the use of yellow colour. Thermoplastic material is the most suitable material for TRS because of its readiness for immediate use, high durability, good retro reflectivity and its relatively low cost of installation and maintenance. It is also found that TRS is able to significantly reduce speed and accidents, but the effectiveness of TRS will decrease at low speed road. To improved TRS application in Malaysia, it is recommended that the authorities should not use TRS excessively in order to maximize the surprise effect. It is also suggested that TRS shouldn't be applied at a low speed road and appropriate distance between TRS and decisssion point need to be assesed properly. Apart from that , the use of 'intermittent' pattern is recommended rather than continuous. For motorcyles routes, it is better to provide a gap for high thickness TRS strip and incorporate warning sign in conjunction with the use of TRS.

Acknowledgement

Deep appreciation goes to Universiti Teknologi Malaysia and UTM Research Management Centre for funding this project under Research University Grant (no. vot, Q.J130000.2522.00H62). The authors also would like to thank Engr. Mukhzani Abd Latif, Ms. Hafisza Abd. Hamid and Mr. Ng Chee Keong from Roads and Geotechnical Branch, Public Works Department headquarters, Mdm Sri Rahayu Nik Saad from Pontian District Public Works Department, Ms Aklima from Majlis Perbandaran Johor Bahru Tengah, and Mr. Mohd Hafeez Idris from UTM Office of Asset and Development for all technical information provided. Also special thanks to Mr. Syed Mohd Najmi Syed Talib and Mr. Nik Mohd Khairuddin Nik Ismail for technical support..

References

[1] Shinar, D. 2007. *Traffic Safety and Human Behaviour*, Amsterdam, Elsevier.

[2] Kee, S. S., Tamrin, S. B. M. & Goh, Y. M. 2010. Driving Fatigue and Performance among Occupational Drivers in Simulated Prolonged Driving. *Global Journal of Health Science*. 2(1): 167–177.

[3] Ng, W. K. & Selva, P. 2003. OSH Profile in the Transport Sector in Particular Commuting Hazard [Online]. Available: Http://Www.Mtuc.Org.My/Osh_Profile_Transport.Htm. [Accessed 5 February 2011].

[4] Martindale, A. & Urlich, C. 2010. Effectiveness of Transverse Road Markings on Reducing Vehicle Speeds. Wellington: NZ Transport Agency

[5] Edquist, J. 2008. *The Effects of Visual Clutter on Driving Performance*. Doctor of Philosophy, Monash University.

[6] Jørgensen, F. & Wentzel-Larsen, T. 1999. Optimal Use of Warning Signs in Traffic. *Accident Analysis and Prevention.* 31(6): 729–738.

[7] Charlton, S. G. 2007. The Role of Attention in Horizontal Curves: A Comparison of Advance Warning, Delineation, and Road Marking Treatments. *Accident Analysis and Prevention*. 39(5): 873–885.

[8] Thompson, T. D., Burris, M. W. & Carlson, P. J. 2006. Speed Changes Due To Transverse Rumble Strips On Approaches To High-Speed Stop-Controlled Intersections. Transportation Research Record: *Journal of the Transportation Research Board*: 1–9.

[9] Rothenberg, H., Benavente, M. & Swift, J. 2004. *Report on Passive Speed Control Devices*. Amherst: Massachusetts Traffic Safety Research Program.

[10] Freeman, J. R., Bansen, J. A., Wemple, B. & Spinks, R. 2008. *Innovative Operational Safety Improvements at Un-Signalized Intersections*. Tallahassee, Florida: Florida Department of Transportation.

[11] Carlson, P. J. & Miles, J. D. 2003. *Effectiveness Rumble Strips On Texas Highways: First Year Report*. Texas Transportation Institute.

[12] Corkle, J., Joni, L., Giese, M., Marti, M. 2001. *Investigating the Effectiveness of Traffic Calming Strategies on Driver Behaviour, Traffic Flow and Speed*. St. Paul, Minnesota: Minnesota Local Road Research Board.

[13] Liu, P., Huang, J., Wang, W. & Xu, C. 2011. Effects of Transverse Rumble Strips on Safety of Pedestrian Crosswalks on Rural Roads in China. *Accident Analysis and Prevention*. 43(6): 1947–1954.

[14] Torbic, D. J., Hutton, J. M., Bokenkroger, C. D., Bauer, K. M., Harwood, D. W., Gilmore, D. K., Dunn, J. M. & Rochento, J. J. 2009. Guidance for the Design and Application of Shoulder and Centreline Rumble Strips. *NCHRP Report 641*. Washington D.C: Transportation Research Board.

[15] Morena, D. A. 2002. *The Nature And Severity Of Drift-Off Road Crashes On Michigan Freeways, And The Effectiveness Of Various Shoulder Rumble Strip Designs*. Lansing: Federal Highway Administration – Michigan Division.

[16] Bahar, G., Erwin, T., Mackay, M., Smiley, A. & Tighe, S. 2005. *Best Practice Guidelines for the Design and Application of Transverse Rumble Strips*. Ottawa, Canada: Transportation Association Of Canada

[17] Meyer, E. 2006. *Guidelines for the Application of Removable Rumble Strips*. Lawrence, Kansas: Meyer Intelligent Transportation Systems.

[18] Gorrill, D. 2007. Transverse Rumble Strips. *Transportation Research Synthesis*. Saint Paul, Minnesota: Minnesota Department of Transportation.

[19] Meyer, E. 2001. A New Look At Optical Speed Bars. *ITE Journal*. 44–48.

[20] MOW. 2002. *Traffic Calming Guidelines*. Kuala Lumpur: Highway Planning Unit, Ministry Of Work.

[21] Yang, Y., Sun, X. & He, Y. 2010. Effectiveness of Rumble Strips on Freeways. ICCTP 2010: Integrated Transportation Systems.

[22] Bendtsen, H., Haberl, J., Sandberg, U. & Watts, G. 2004. Traffic Management and Noise Reducing Pavements. Recommendations on Additional Noise Reducing Measures. SILVIA Deliverable 12. European Commission DG Tren- Growth.

[23] Dudek, C. L., Huchingson, R. D., Creasey, F. T. & Pendleton, O. J. 1988. Field Studies Of Temporary Pavement Markings At Overlay Project Work Zones On Two-Lane, Two-Way Rural Highways. *Transportation Research Record 1160*. Washington D.C.: National Research Council.

[24] REAM. 2004. *Guidelines on Traffic Control and Management Devices*. Kuala Lumpur, Road Engineering Association of Malaysia.

[25] Othman, M. H., Haron, Z., Yahya, K. & Yaacob, H. 2010. Transverse Rumble Strips Application in Malaysia. In: *Geotropika 2010*. Kota Kinabalu, Sabah.

[26] Thomas, G. B. & Schloz, C. 2001. *Durable, Cost-Effective Pavement Markings Phase I: Synthesis of Current Research*. Ames, Iowa: Centre for Transportation Research and Education, Iowa State University.

[27] Lopez, C. A. 2004. *Pavement Marking Handbook*. Austin: Texas Department of Transportation.

[28] Bachner, A. & Swain, K. 2008. *Traffic Signs and Pavement Markings*. Cornell Local Roads Program.

[29] Migletz, J., Fish, J. K. & Graham, J. L. 1994. *Roadway Delineation Practices Handbook*. Washington DC: Federal Highway Administration.

[30] Niessner, C. W. 2008. *Colour Effectiveness of Yellow Pavement Marking Materials*. Washington DC: Transportation Research Board.

[31] Gibbons, R. B. 2006. *Pavement Marking Visibility Requirements during Wet Night Conditions*. Charlottesville, Virginia: Virginia Transportation Research Council

[32] Gates, T. J. And Hawkins, H. G. 2002. The Use Of Wider Longitudinal Pavement Markings in the United States. *Paper Vis2002-31*. Texas Transportation Institute, College Station.

[33] Carlson, P. J., Pike, A. M., Miles, J. D. & Park, E. S. 2007. Pavement Marking Visibility: Brighter Versus Wider. *18th Biennial Transportation Research Board (TRB) Visibility Symposium College Station*. Texas: Transportation Research Board.

[34] Benekohal, R. F., Kastel, L. M. & Suhale, M. 1992. Evaluation and Summary of Studies in Speed Control Methods in Work Zones. *Report FHWA-Il-Ui-237*. Illinois Department of Transportation.

[35] Hou, S., Sun, X., He, Y. & Wang, J. 2010. Vehicle's Shock Absorbing Capacity and Roadway Rumble Strips. *ICCTP 2010: Integrated Transportation Systems*. 585–590.

[36] Thompson, T. D. 2004. *Evaluation of Rumble Strips at Rural Stop-Controlled Intersection in Texas*. Texas A&M University.