PERFORMANCE AND MODELLING OF TRANSVERSE RUMBLE STRIPS ON NOISE AND VIBRATION STIMULI

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Specially dedicated to *my grandfather*

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ABSTRACT

Transverse rumble strips (TRS) are commonly used in reducing vehicle speed and increasing drivers' alertness on roadway through optical, sound and vibration effects. However, when inappropriately designed, TRS sound and vibration may become too excessive, thus compromise road users' comfort and annoy local residents who live adjacent to the roadway. This study aims to contribute to the knowledge that will be used to improve the optimisation of TRS cross-section design for road user's comfort and sustainable living of the neighbourhood. The objectives of this study were to: classify TRS profiles and assess the noise annoyance response towards TRS noise; measure and model TRS roadside noise level and analyse the possible tyre-TRS interaction mechanisms that involved in the TRS roadside noise generation; evaluate and estimate vehicle in-cabin TRS sound and vibration; develop the optimum TRS cross section design for road users' comfort. Site investigation and social survey study had been carried out to classify the type of TRS profile used on the roadway and to assess the noise annoyance response towards TRS noise experienced by neighbourhood. Traffic noise assessment and controlled pass-by method were carried out to evaluate and estimate roadside noise level due to TRS and to analyse the possible tyre-TRS vibration mechanisms that were involved in the generation of TRS noise. In-cabin sound and vibration measurements were conducted to evaluate in-cabin vibration and sound due to TRS. Weber's Law was used to determine appropriate vibration to road user comfort, hence optimum TRS cross section design was proposed. The results indicated that three main types of TRS profile existed on the road namely; raised rumbler, middle overlap and multi-layer overlap. Generally, respondents were annoyed with TRS noise. TRS noise depended on the factor of traffic volume, speed, TRS profile and thickness. TRS vibration depended on the factor of vehicle speed and TRS thickness. Raised rumbler's profile generated the highest noise as a result from air pumping tyre-pavement mechanism. TRS optimum cross section design was proposed to enhance TRS performance in providing appropriate vibration to road user.

ABSTRAK

Jalur jedar (TRS) sering digunakan untuk mengurangkan kelajuan kenderaan dan meningkatkan kewaspadaan pemandu di jalan raya melalui kesan pandangan, bunyi dan gegaran. Walau bagaimanapun, apabila tidak direka bentuk sebaiknya, bunyi dan gegaran TRS mungkin akan menjadi terlalu besar, menyebabkan keselesaan pengguna jalan raya dikompromi dan mengganggu penduduk yang tinggal berdekatannya. Kajian ini bertujuan untuk menyumbang kepada pengetahuan yang akan digunakan untuk membaiki reka bentuk keratan rentas TRS yang akan meningkatkan keselesaan pengguna jalan raya dan kelestarian kehidupan di kawasan tempat tinggal. Objektif tesis ini adalah: mengelaskan profil TRS yang digunakan di jalan raya dan menilai respon gangguan bunyi terhadap bunyi TRS yang dialami oleh kejiranan;mengukur dan memodelkan tahap bunyi tepi jalan yang dihasilkan oleh TRS dan menganalisa mekanisma getaran tayar-jalan raya yang terlibat dalam penghasilan bunyi TRS; menilai dan menganggarkan bunyi dan gegaran dalam-kabin kenderaan yang terhasil daripada TRS; Menilai reka bentuk keratan rentas optimum TRS untuk tujuan keselesaan pengguna jalan raya. Kerja penyiasatan tapak dan soal selidik telah dijalankan untuk mengelaskan jenis profil TRS yang digunakan di jalan raya dan menilai respon gangguan bunyi TRS yang dialami oleh kejiranan. Penilaian bunyi trafik dan ‘controlled pass-by method’ dijalankan untuk menilai dan menganggarkan tahap bunyi tepi jalan yang dihasilkan oleh TRS dan menganalisa mekanisma getaran tayar-jalan raya yang mungkin terlibat dalam penghasilan bunyi TRS. Pengukuran bunyi dan gegaran dalam-kabin kenderaan juga dijalankan untuk menilai dan menganggarkan bunyi dalam-kabin dan gegaran bagi kenderaan yang terhasil daripada TRS. Hukum Weber digunakan untuk menentukan gegaran yang sesuai untuk keselesaan pengguna jalan raya dan reka bentuk keratan rentas optimum TRS dicadangkan. Keputusan menunjukkan bahawa terdapat tiga jenis profil TRS wujud di jalan raya iaitu: ‘raised rumbler’, ‘middle overlapped’ dan ‘multi-layer overlapped’. Secara umumnya responden adalah terganggu dengan bunyi bising daripada TRS. Bunyi TRS bergantung kepada faktor isipadu trafik, kelajuan, ketebalan dan profil TRS. Gegaran TRS pula bergantung kepada kelajuan kenderaan dan Profil ‘raised rumbler’ menghasilkan bunyi yang terhasil daripada mekanisma tayar-jalan raya pengepaman udara. Reka bentuk keratan rentas optimum dicadangkan untuk meningkatkan keupayaan TRS dalam memberikan gegaran sesuai kepada pengguna jalan raya.

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LIST OF ABBREVIATIONS

v	-	Vehicle speed
V	-	Traffic volume
h	-	TRS thickness
w	-	TRS width
sp	-	TRS spacing
ROR		Run- of-road

LIST OF SYMBOLS

Exterior Noise from traffic

$LAeq_{ACTw}$	-	Absolute roadside sound level from actual traffic passing through 'with TRS' track
$LAeq_{ACTwo}$	-	Absolute roadside sound level from actual traffic passing through baseline or 'without TRS' track
$LAeq_{ACT\Delta}$	-	Relative roadside sound level ('with TRS' –'without TRS') from a single vehicle test car

Exterior Impulse Noise from traffic

$LAIeq_{ACTw}$	-	Absolute roadside impulse sound level from actual traffic passing through 'with TRS' track
$LAIeq_{ACTwo}$	-	Absolute roadside impulse sound level from actual traffic passing through baseline or 'without TRS' track.
$LAIeq_{ACT\Delta}$	-	Relative roadside impulse sound level ('with TRS' –'without TRS') from single vehicle test car

Exterior Noise from single vehicle test

$LAeq_{CPBw}$	-	Absolute roadside sound level from single vehicle test car passing through 'with TRS' track
$LAeq_{CPBwo}$	-	Absolute roadside sound level from single vehicle test car passing through baseline or 'without TRS' track
$LAeq_{CPB\Delta}$	-	Relative roadside sound level ('with TRS' –'without TRS') from a single vehicle test car

In-cabin vibration

RMS_w	-	Absolute in-cabin vibration level in test car when passing through 'with TRS' track
RMS_{wo}	-	Absolute in-cabin vibration level in test car when passing through 'without TRS' track
RMS_Δ	-	Relative in-cabin vibration ('with TRS' –'without TRS') in test car.

In-cabin noise

$LAeq_{IVw}$	-	Absolute in-cabin sound level in test car when passing through 'with TRS' track.
$LAeq_{IVwo}$	-	Absolute in-cabin equivalent sound level in test car when passing through baseline or 'without TRS' track
$LAeq_{IV\Delta}$	-	Relative in-cabin sound level ('with TRS' –'without TRS') in test car.

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CHAPTER 1

INTRODUCTION

1.1 Background

The World Health Organization (WHO) has claimed that accidents caused by motor vehicle accidents are the second most frequent death for the entire world involving people aged 5-29 years old. WHO summarised that around 1.2 million people are killed each year on roads and 50 million are injured (Shinar, 2007). In Malaysia, a 10-year road traffic statistics had shown that the total number of accidents had risen 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 (Kee et al., 2010). Based on the evidence, speeding and carelessness are two main causes of accidents, contributing 32.8 and 28.2 percent respectively to the total number of accidents (Ng and Selva, 2003).

Martindale and Ulrich (2010) state that the easiest and cheapest measure in order to control road accidents caused by excessive speed and carelessness is by using road signs and markings. However, when situations, where drivers confront with too many signs take place, drivers tend to ignore the excessive information thus limit the warning effect. This situation is named as ‘clutter effect’ (Edquist, 2008). It has been suggested that one of the reasons of their limited effectiveness may be due to their overuse, particularly in situations of having less risk (Charlton, 2007; Jørgensen and Wentzel-Larsen, 1999). For example, Jorgensen and Wentzel-Larsen (1999) state that the effect of curve warning signs on drivers' perceptions of risk is quite low, with only 6% overall safety impacts.

Therefore, an alternative measure consisting of road layout and its associated features, which is able to subconsciously inform drivers regarding upcoming road condition is introduced. One of them is transverse rumble strips (TRS). TRS is intended to give audible, visual and vibration cue effects when an operational decision point is approaching (Thompson et al., 2006). Moreover, TRS is widely used in Malaysia and all the road authorities in this country are believed to be using it. TRS is classified as passive speed control measure, which serves to alter drivers' perceptions of the correct speed for a particular road so that drivers may assume that a lower speed is more appropriate (Rothenberg et al., 2004). Based on road safety factors, the TRS has the potential for reducing crashes, alerting drivers, improving signs effectiveness, and increasing the rate of deceleration of vehicles along side having to reduce right-angle accidents, which are commonly associated with running through a stop sign or signal, by alerting drivers to an upcoming condition (Carlson and Miles, 2003; Freeman *et al.*, 2008). As compared to other speed control devices, TRS has generally been relatively inexpensive and easy to install and maintain (Corkle et al., 2001). In addition, the impacts on driving comfort are considered minor as compared to speed humps and speed bumps (Liu et al., 2011).

Generally, there are three types of rumble strips that are based on the location of its installation i.e. 1) TRS 2) centreline rumble strips and (CRS) and 3) shoulder rumble strips (SRS) (Torbic et al., 2009). For instance, TRS are placed across the travel lanes of the roadway and perpendicular to the flow of vehicles as shown in Figure 1.1. Other than that, a TRS is placed in the lane and generally traverse more than two-thirds of the travel path perpendicular to the direction of travel (Carlson and Miles, 2003). This is why it is called an in-lane rumble strip in the United States. In Malaysia, TRS is called by various names such as transverse bar, yellow bar and speed breaker. A SRS is usually placed on roadway shoulders, outside of the travel lane as can be seen in Figure 1.2. The purpose of having shoulder rumbles strips is to mitigate single vehicle run-off-road type crashes. A CRS is installed on or near the centreline of the roadway as in Figure 1.3, as the purpose is to mitigate head-on crashes and opposite-direction sideswipe crashes (Torbic*, et al.*, 2009).

Figure 1.1 Typical TRS in Malaysia

Figure 1.2 Shoulder rumble strips (Morena, 2002)

Figure 1.3 Centerline rumble strips (Torbic*, et al.*, 2009)

1.2 Problem Statement

Generally, TRS around the world are diverse in terms of configurations, dimensions, colours, and profiles. In Malaysia whereas the national guidelines are too basic, resulting in district application. Moreover, TRS design heavily relies on the judgment of district engineers and each TRS differs in terms of thickness, spacing, width, and profiles. All of these characteristics may play an important role in determining the level of TRS sound and vibration stimuli. Besides that, the agents of stimuli, which are visual, sound, and vibration are methodologically different in their functions (Bahar, *et al.*, 2005). The 'eye-catching' colour and sound are only able to increase drivers' alertness but the vibration can also force drivers to slow down (Bahar, *et al.*, 2005). In some areas where vehicles need to slow down, TRS design has been suggested to have the potential to maximise the vibration level so it can force drivers to slow down to the levels of comfortable driving. In other cases, a speed decrease may not be much necessary such as on high-speed highway, but road designer intends to increase driver's alertness, TRS may be used with a design of minimum vibration but is relatively higher in sound.

The lack of proper guidelines has made local engineers come up with their own design of TRS that intends to suit the TRS application in-situ. The design mostly comes from supplier proposal and it occasionally comes up with a poorly design of TRS. The main problem in the development of effective designs, apart from the consideration of the psychological parameters such as perception, is the complex physical processes when the tyres-road interaction is transferred to the driver (Lank and Steinauer, 2011). With poorly designed TRS, it may generate excessive vibration. Moreover, excessive vibration caused by TRS had increased the number of complaints in Dengkil, Selangor (Appendix A). Just as similar in road roughness cases, TRS dimension causes vehicle's tyres to move in a vertical variation on the pavement from an ideal plane. Therefore, it could be a bad choice of using TRS dimension as it can bring negative impact on “ride quality”. Excessive vibration also makes road users become fatigue easier, as it may also increase the dynamic loads applied to the pavement by the vehicle wheels, thus accelerate fatigue damage of the road structure (Cantisani and Loprencipe, 2010). Other than that, having short-term exposure to vibration causes small physiological effects such as an increase in heart rate and muscle tension while long-term exposure to vibration causes effects such as disk spine pain, digestive system, peripheral veins and the female reproductive organ problems (Katu et al., 2003). In exposure to TRS vibration, most drivers may not be subjected to long-term exposure but some drivers who are frequent users of the particular TRS road may be exposed to considerable health risk.

The inappropriate design creates another problem, which is the noise annoyance to adjacent residents. The sound produced by the TRS, which aims to alert the driver, may also be annoying to the local residences. Complaints were made by the local residences to the authority in Batu 30, Jalan Johor Bahru-Pontian, Pengkalan Raja, Pekan Nanas, Johor (Appendix B) and Taman Bukit Indah, Tampoi (Appendix C) regarding the issue of noise annoyance generated by TRS. For instance, this is not just a local issue but also it occurs in other countries as reported in Clarkin (2010, August 8). The TRS involving approaching of a roundabout had to be removed from following complaints as they were all on its noise from adjacent residents. TRS noise is classified as impulse noise that can cause more annoyance to the receiver (Bahar*, et al.*, 2005; Bendtsen *et al.*, 2004).

Better designs of TRS are required to keep drivers alert and reduce vehicle speed and at the same time minimise noise annoyance and vibration that can affect drivers and passengers' comfort and vehicle conditions. Based on a personal interview with several road authorities (Public Work Departments and municipal council), it is common among them that thicker TRS discourages over speed drivers and force them to slow down by generating relatively higher vibration. Although previous study found otherwise, it was unable to draw a strong conclusion (Meyer, 2006). Besides that, in some cases from observations, driving at 50km/h may cause someone to experience excessive vibration that affects his comfort level. This pattern does raise questions about the effectiveness of TRS used for the purpose of speed reduction. Therefore, this study takes a bigger role to justify and may support the previous finding.

1.3 Aims and Objectives of Studies

This study aims to contribute to the knowledge in improving the optimisation of TRS cross-section design for road user's comfort and sustainable living of the neighbourhood.

To achieve the aim of the study, the following objectives have been identified:

i. To classify TRS profiles and assess the noise annoyance response towards TRS noise.

ii. To measure and model TRS roadside noise level and analyse the possible tyre-TRS interaction mechanisms that involved in the TRS roadside noise generation.

iii. To evaluate and estimate vehicle in-cabin sound and vibration due to TRS.

iv. To develop the optimum TRS cross-section design for road users' comfort.

1.4 Scopes of Study

The scopes of study were as follow:

i. The CPB tests were carried out by using a passenger car (2005 Perodua Myvi 1.3) as a test car, which is among the most common types of passenger cars in Malaysia. The result may not be consistent and accurate if other types and classes of vehicles are used in the test as previous studies indicated that each type and class of vehicle has its own unique sound and vibration stimuli

(Gardner*, et al.*, 2007; Hirasawa *et al.*, 2005; Karkle*, et al.*, 2011; Lank and Steinauer, 2011; Meyer, 2006).

ii. The social survey study was carried out in three case study locations namely Kampung Parit Kudus at Pontian, Kampung Seri Kenangan at Pekan Nanas and Taman Bukit Indah at Tampoi Johor.

iii. Traffic noise assessment studies at the case study locations were measured at three-daytime hours at the location with TRS and without TRS. The longer period of assessment may be required in the future to represent noise characteristic at every hour in a day.

iv. The focus of this thesis is to determine the TRS noise characteristics that may trigger annoyance to the community. Therefore, the noise propagation aspects like the wind and temperature effect, ground characteristics, natural barrier and others were not discussed.

v. This study intends to propose the appropriate design that would able to alert drivers but would not compromise their comfort. It used the typical car on Malaysia road,such as Perodua Myvi. Therefore, the in-cabin vibration and sound performance of that model largely influenced the end result of the proposed design.

1.5 Contribution of Study

There were complaints from the community that the TRS could be annoying to residents who live adjacent to the roads. Although they had lodged complaints to the authorities, the latter took a long time to remove the TRS and this signals that they did not take this problem seriously. Therefore, this study had been able to assess and highlight this problem.

The study also has identified the key parameters to be the cause of the TRS noise increment, hence this helps road planners to design a quieter TRS for the residential areas. At the same time, TRS can be designed 'noisy' to maximise its warning effect on the road that is far from residential areas. This study is also expected to assists road planners and engineers in determining the thickness that provides appropriate vibration that they would like to apply to the typical car on the road.

1.6 Structure of Thesis

This thesis is divided into six chapters. Chapter 1 explains the introduction of study. This includes the background of the study, problem statement, objectives and scope of the study. Chapter 2 reports the literature review. Background of TRS application, its effectiveness, physical properties, background knowledge on traffic noise, sound and vibration stimuli and previous studies on factors affecting TRS sound and vibration are discussed. Next, Chapter 3 focuses on methodology of study, where it discusses the method behind each objective. The chapter ends with a discussion of data analysis method. Chapter 4 further reports the results of the study and Chapter 5 presents the discussion. This thesis ends with Chapter 6 that highlights the conclusion and recommendations for future study.

1.7 Chapter Summary

This chapter begins with a discussion of the background knowledge of TRS. TRS is widely used because it has generally been relatively inexpensive, easy to install and maintain and its impacts on driving comfort are considered to be minor as compared to speed humps and speed bumps. Poorly designed TRS may generate excessive vibration, which can bring negative impact on "ride quality". The inappropriate design also creates another problem, which is noise annoyance to adjacent residents. Four objectives have been organised in relation to problems that were stated above. However, this study is still bound to the scopes that have been described above.

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