ACOUSTICAL CHARACTERISTIC CHANGES DUE TO TRANSVERSE RUMBLE STRIPS INSTALLATION ON ROADWAY

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DEDICATION

This thesis is dedicated to my big family. Firstly, to my hardworking father, ***Darus bin Dir*** who taught me the meaning of effort as a way to survive and success. It is also dedicated to my lovely mother, ***Haslina binti Zakaria*** who never stop to support and motivate me. A special dedication also goes to my younger sisters and brothers, *Nadia*, *Nadimi*, *Nabilah*, *Nabihah*, *Muhammad Nadhir Adha*, *Muhammad Naim*, *Najwa Dayana*, *Najla Dania*, *Muhammad Nasif* and *Najat Damia* for their hope and belief on me to complete my PhD journey.

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ABSTRACT

Transverse rumble strips (TRS) acts as a traffic calming device to alert inattentive drivers through the optical, sound and vibration effects. Currently, the existing TRS guidelines have been found to be very basic with no detailed explanation on the TRS profile. Inappropriate design of TRS profile may generate excessive external noise level that can affect the nearby residents. Besides, the real cause of TRS roadside noise annoyance is still unknown. Therefore, this study aims to evaluate the acoustical characteristic changes due to TRS installation at residential areas in contributing to the framework of optimum TRS design selection for future installation. The objectives of this study are to investigate current TRS designs and characteristics, determine road and traffic characteristics at selected roadways, evaluate noise annoyance due to TRS installation and develop empirical model of TRS roadside noise level for the proposal of framework of optimum TRS design selection. Visual investigation and on-site measurement were conducted to investigate the current TRS design and characteristic. Measurement of road and traffic measurements were also carried out to evaluate the skid number (SN), vehicle speed, traffic volume and composition that may affect sound level changes. This study measured the external noise generated by a range of gross vehicle weight (GVW) between 850 kg and 7700 kg which travel over three types of TRS, namely middle overlapped (MO), middle layer overlapped (MLO) and raised rumbler (RR) with speed range of between 30 km/h to 70 km/h. Controlled pass-by (CPB) method was conducted to determine the sound level changes. Actual traffic condition due to TRS installation was also measured. Meanwhile, assessment of sound level changes and impulse, low frequency noise (LFN) and tonal, noise limit and traffic noise index (TNI) were carried out to assess the noise annoyance from TRS. Statistical analyses were used to test all related variables of roadside noise level due to TRS. Significant variables were used for the development of empirical noise models by using multiple linear regression. Then, framework of optimum TRS selection design was proposed to assist local authorities for future TRS installation. TRS thickness was limited to 3 mm for all profile types. TRS roadside noise may affect nearby residents as the sound level increment was more than 6 dBA. The sound level changes for vehicles transit on MLO were higher than MO and RR of more and less than 3 dBA, respectively. Besides, MLO showed the most significant impulsivity regardless of the multiple vehicles transit. TRS roadside noise was also characterized by LFN at frequency region of 20 Hz to 125 Hz. Tonality was also found significant especially due to heavier vehicles with GVW of 5000 kg and above at speed of 50 km/h. Among the three types of TRS, MO showed the best performance due to its insignificant acoustical characteristics. SN, vehicle speed, traffic volume and GVW were found to be significant variable for the generation of TRS roadside noise level. Meanwhile, other variables, such as TRS width, length, spacing, profile and strip number, traffic volume and skid resistance were found insignificant. The established empirical models based on the real causes of TRS noise annoyance were used in the proposal for framework of optimum TRS design selection for future installation. This proposed framework could enable exploration of TRS impact on the traffic noise condition to facilitate the local authority on the best selection of TRS type during the surround area become critical for noise annoyance.

ABSTRAK

Jalur jidar rentas (*TRS*) bertindak sebagai peranti redaan trafik untuk memberi amaran kepada pemandu yang tidak fokus melalui kesan pandangan, bunyi dan getaran. Pada masa ini, garis panduan *TRS* yang sedia ada didapati sangat umum tanpa penjelasan terperinci mengenai profil *TRS*. Reka bentuk *TRS* yang tidak sesuai menghasilkan paras bunyi bising berlebihan yang boleh menjejaskan penduduk berdekatan. Selain itu, sebab sebenar gangguan bunyi bising *TRS* di tepi jalan masih tidak diketahui. Oleh itu, kajian ini bertujuan untuk menilai perubahan ciri-ciri akustik disebabkan pemasangan *TRS* di kawasan perumahan bagi menyumbang kepada rangka kerja pemilihan reka bentuk *TRS* yang optimum untuk pemasangan di masa hadapan. Objektif kajian ini adalah untuk menyiasat reka bentuk dan ciri-ciri semasa *TRS*, mengenal pasti ciri-ciri jalan dan lalu lintas di jalan-jalan yang terpilih, menilai gangguan bunyi bising disebabkan pemasangan *TRS* dan membangunkan model empirikal untuk bunyi bising *TRS* di tepi jalan bagi cadangan rangka kerja pemilihan reka bentuk *TRS* yang optimum. Penyiasatan visual dan pengukuran di tapak dijalankan untuk menyiasat reka bentuk dan ciri-ciri semasa *TRS*. Pengukuran ciri-ciri jalan dan lalu lintas juga dijalankan untuk menilai nombor gelinciran (*SN*), kelajuan kenderaan, jumlah dan komposisi lalu lintas yang boleh mempengaruhi perubahan tahap bunyi. Kajian ini mengukur bunyi bising luaran yang dihasilkan oleh pelbagai berat kasar kenderaan (*GVW*) antara 850 kg hingga 7700 kg yang bergerak melalui tiga jenis *TRS* iaitu *middle overlapped* (*MO*), *middle layer overlapped* (*MLO*) and *raised rumbler* (*RR*) dengan kelajuan antara 30 km/j hingga 70 km/j. Kaedah *Controlled Pass-By* (*CPB*) telah dijalankan untuk menentukan perubahan tahap bunyi. Keadaan sebenar lalu lintas disebabkan pemasangan *TRS* juga telah diukur. Sementara itu, penilaian perubahan tahap bunyi dan impuls, bunyi frekuensi rendah (*LFN*) dan nada, had bunyi dan indeks bunyi bising lalu lintas (*TNI)* telah dijalankan untuk menilai ganguan bunyi bising disebabkan *TRS*. Analisis statistik telah digunakan untuk menguji semua pemboleh ubah yang berkaitan dengan tahap bunyi bising di tepi jalan disebabkan *TRS*. Pemboleh ubah yang signifikan digunakan untuk pembangunan model bunyi bising empirikal dengan menggunakan kaedah *multiple linear regression*. Kemudian, rangka kerja pemilihan reka bentuk *TRS* yang optimum telah dicadangkan untuk membantu pihak berkuasa tempatan bagi pemasangan *TRS* di masa hadapan. Kebanyakannya, ketebalan *TRS* semasa adalah 3 mm untuk semua jenis profil. Bunyi bising *TRS* di tepi jalan boleh menjejaskan penduduk berdekatan apabila kenaikan tahap bunyi lebih dari 6 dBA. Perubahan tahap bunyi bising untuk transit kenderaan melalui *MLO* adalah lebih tinggi dari *MO* dan *RR*, masing-masing lebih dan kurang dari 3 dBA. Selain itu, *MLO* menunjukkan impuls dan nada yang paling signifikan tanpa mengira pelbagai transit kenderaan. Bunyi bising *TRS* di tepi jalan juga bercirikan *LFN* pada frekuensi 20 Hz hingga 125 Hz. Nada juga didapati signifikan terutamanya disebabkan kenderaan berat *GVW* 5000 kg dan ke atas pada kelajuan 50 km/j. Di antara ketiga-tiga jenis *TRS*, *MO* menunjukkan prestasi yang terbaik disebabkan oleh ciri-ciri akustik yang tidak signifikan. *SN*, kelajuan kenderaan, jumlah lalu lintas dan *GVW* didapati sebagai pemboleh ubah yang signifikan bagi penjanaan tahap bunyi bising *TRS* di tepi jalan. Sementara itu, pemboleh ubah lain seperti lebar, panjang, jarak, profil dan nombor jalur *TRS*, jumlah trafik dan rintangan gelinciran didapati tidak signifikan. Model empirikal yang dibangunkan berdasarkan sebab-sebab sebenar gangguan bunyi bising *TRS* telah digunakan dalam cadangan rangka kerja pemilihan reka bentuk *TRS* yang optimum untuk pemasangan di masa hadapan. Rangka kerja yang dicadangkan ini membolehkan penerokaan kesan *TRS* terhadap keadaan bunyi bising supaya dapat membantu pihak berkuasa tempatan mengenai pemilihan jenis *TRS* yang terbaik apabila gangguan bising di kawasan sekitar menjadi isu utama.

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TRS	-	Transverse Rumble Strips
SRS	-	Shoulder Rumble Strips
CRS/CLRS	-	Centreline Rumble Strips
ERS/ELRS	-	Edge Line Rumble Strips
TPM	-	Transverse Pavement Marking
OSB	-	Optical Speed Bar
SL	-	Single Layer
MO	-	Middle Overlapped
MLO	-	Middle Layer Overlapped
RR	-	Raised Rumbler
USA	-	United States of America
UK	-	United Kingdom
PWD	-	Public Works Department
DOE	-	Department of Environment
BSI	-	British Standard Institution
ISO	-	International Organization for Standardization
WHO	-	World Health Organization
FHWA	-	Federal Highway Administration
ASEAN	-	Association of Southeast Asian Nations
SLM	-	Sound Level Meter
RN	-	Registration Number
BCP	-	Barton Comb Profilometer
BPT	-	British Pendulum Tester
dBA	-	A-weighted Decibel
dBC	-	C-weighted Decibel
CPB	-	Controlled Pass-By
CBM	-	Coast-By Method
SPB	-	Statistical Pass-By
HMA	-	Hot Mixed Asphalt
SMA	-	Stone Mastic Asphalt

ABS	-	Acrylonitrile Butadiene Styrene
PVC	-	Poly Vinyl Chloride
LFN	-	Low Frequency Noise
TNI	-	Traffic Noise Index
TNM	-	Traffic Noise Model
CoRTN	-	Calculation of Road Traffic Noise
MPV	-	Multi-Purpose Vehicle
SUV	-	Sport Utility Vehicle
mv	-	Multiple Vehicles
sv	-	Single Vehicle
w	-	With TRS
wo	-	Without TRS
v	-	Vehicle Speed
V	-	Traffic Volume
GVW	-	Gross Vehicle Weight
SN	-	Skid Number
sn	-	Strip Number

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Transportation is one of the key contributors to Malaysia's economic growth in achieving the vision of becoming a developed nation by year 2020 (Economic Planning Unit, 2015; Ministry of Transport Malaysia, 2018). The increase of demand for transportation can be observed by the increment of the country's population and its projection in the future (Department of Statistics Malaysia, 2016). In the future, the transportation demand will be likely to increase with the rate of 0.8 % per annum as the estimated population growth from 28.6 million in 2010 to 41.5 million people in 2040. Over two decades since 1997 to 2017, the number of population and registered vehicles increased from 8,550,469 to 28,738,194 and 21,655,600 to 32,049,700, respectively (Road Safety Department of Malaysia, 2018). It can be observed that the number of population increased three times over two decades.

Based on the total number of registered vehicles in Malaysia in September 2018, almost half was represented by motorcar (passenger vehicles) for 47.36 %, followed by motorcycles for 45.80 % and the rest comprised of commercial vehicles (Road Safety Department of Malaysia, 2018). Meanwhile, the top three states with the highest number of registered vehicles in Malaysia were represented by the Federal Territory of Kuala Lumpur, Selangor and Johor. Based on this statistics, there will be an increase of traffic vehicular, road congestions, traffic accidents on roadways and noise pollution due to traffic flows. According to World Health Organization (2018) and Lum (2019), road traffic accidents become the leading cause of road traffic death where the number of cases has been increasing since more than a decade ago. These cases are intolerably high among young people aged between 15 to 29 years old.

The main cause of road traffic accidents is due to poor driving behaviour, especially speeding. Malaysian Institute of Road Safety Research (MIROS) in 2011 reported that 80.6 % of the accidents was caused by this factor, while road condition and vehicles factors only contributed for 13.2 % and 6.2 %, respectively (Road Safety Department of Malaysia, 2018). The same problem was also faced by many other Association of Southeast Asian Nations (ASEAN) countries, especially Thailand and Vietnam. Therefore, the enforcement and improvement of alternative measures to cater this problem is necessary. As suggested by World Health Organization (2018), the enforcement of national speed limits is most crucial for effective speed management. It is also required for legal and local authorities to manage the local speed according to the specific road situation in conjunction with necessary traffic calming measures.

Traffic calming is used to control drivers from any undesirable driving practices which may lead to road traffic accidents. Many research has been conducted where each country has come up with own traffic calming guidelines to cater the mentioned problems (Public Works Department, 1985, 2014a; Pharaoh and Russell, 1991; Institute of Transportation Engineers, 1999). One of the traffic calming measures is rumble strips, where a set of strips is installed on roadways to alert inattentive driver through optical, sound and vibration effects (Datta, Gates and Savolainen, 2012; Othman *et al.*, 2012; 2015a; Othman, 2016). It was first installed on road shoulders of concrete pavement roadway in New Jersey around 1955 and ever since known as singing shoulders (Hirasawa, Saito and Asano, 2005).

Rumble strips can be categorised based on its installation location, such as shoulder, centreline, mid-lane and transverse. They are namely shoulder rumble strips (SRS), centreline rumble strips (CRS), mid-lane rumble strips (MRS) and transverse rumble strips (TRS) (Perrillo, 1998; Torbic *et al.*, 2009; Othman, 2016; Kalathas *et al.*, 2018). SRS is usually installed at a road shoulder outside the travel lane in order to prevent vehicles run-off as shown in Figure 1.1. Besides, SRS is also installed along the edge line of the travel lane which is called as edge line rumble strips (ERS) (Torbic *et al.*, 2009; Himes *et al.*, 2017). Basically, both SRS and ERS are the same rumble strips that are also effectively used in reducing crashes due to run-off-road cases (Savolainen *et al.*, 2017).

Figure 1.2 shows another type of rumble strips which is CRS, usually in the middle of two opposite travel lanes of the roadways, widely used in many countries to prevent cross over and head-on collision between the vehicles on opposite lanes (Hirasawa *et al.*, 2005; Datta *et al.*, 2012; Himes *et al.*, 2017). Based on previous studies, the installation of CRS on urban and rural two lanes road is very effective in reducing fatal and severe injury crashes (Noyce and Elango, 2004; Torbic *et al.*, 2009; Holmes, 2018). MRS among other rumble strips is the only a conceptual configuration being discussed to be used for narrow roads or no-shoulder roads as in Figure 1.3. Based on previous studies, it should be installed in the middle of each travel lane where its actual installation is yet to be found (Torbic *et al.*, 2009; Villwock-Witte and Veneziano, 2013; Yathiraju, 2015).

Meanwhile, in Malaysia, TRS is widely installed by the local authorities as traffic calming as shown in Figure 1.4 (Public Works Department, 1985, 2014a; Highway Planning Unit, 2002; Road Engineering Association of Malaysia, 2004). It has also been used in the United States of America (USA), China, Thailand, Korea, Singapore and Australia (Horowitz and Notbohm, 2002; Maryland State Highway Administration, 2005; Liu *et al.*, 2011; Thanasupsin *et al.*, 2011; Lee *et al.*, 2013; Sabato and Niezrecki, 2016; Yang *et al.*, 2016; Road and Traffic Engineering, 2017). TRS is also known as transverse bars, transverse strips, log strips, speed breakers, in-lane or travel way rumble strips due its installation's location which is perpendicular to the traffic flows or vehicle directions. According to national guidelines, it is also known as transverse yellow bars due to its common colour.

TRS among other traffic calming devices, such as speed hump and speed bump is a common approach used by the local authorities to enhance road traffic safety. This is due to its advantages including readiness for immediate use, high durability, good-retro reflectivity, relatively low cost and low driving impact (Liu *et al.*, 2011; Othman, Haron, Hainin, *et al.*, 2015; Othman, 2016). Its application varies in terms of configurations, profiles, dimensions and colours. Basically, TRS installation designs are uniform all over the country where it should be installed according to the national guidelines of TRS installation (Public Works Department, 1985, 2014a; Highway Planning Unit, 2002; Road Engineering Association of Malaysia, 2004).

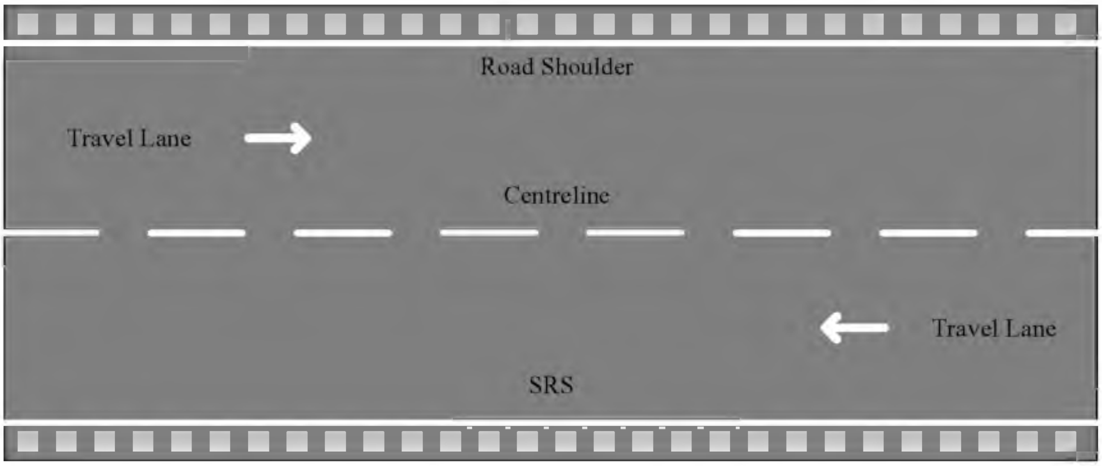

Figure 1.1 Shoulder rumble strips/edge line rumble strips

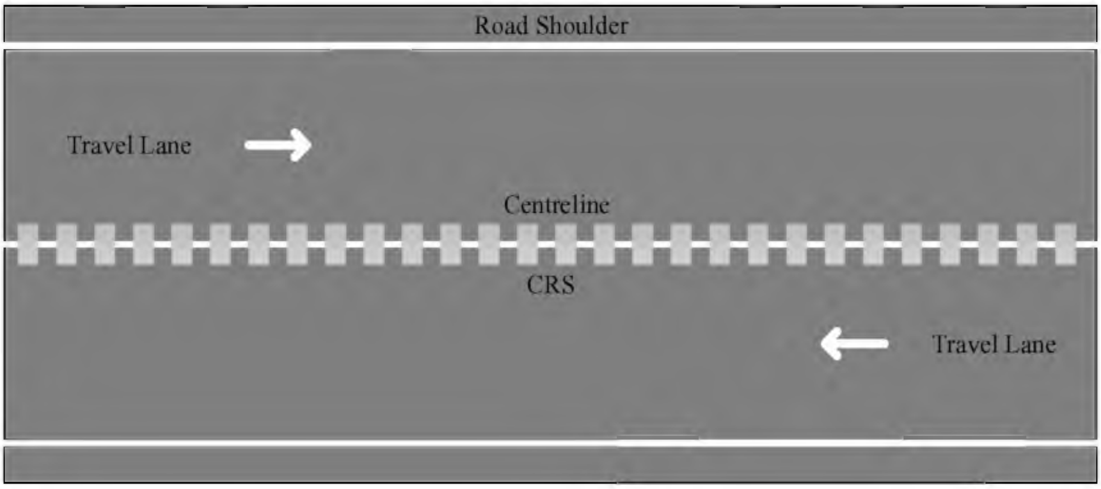

Figure 1.2 Centreline rumble strips

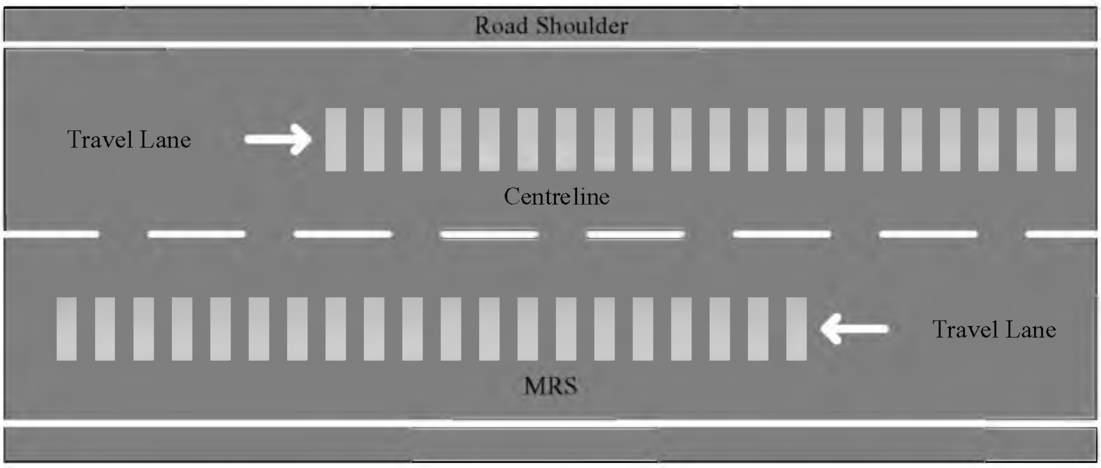

Figure 1.3 Mid-lane rumble strips

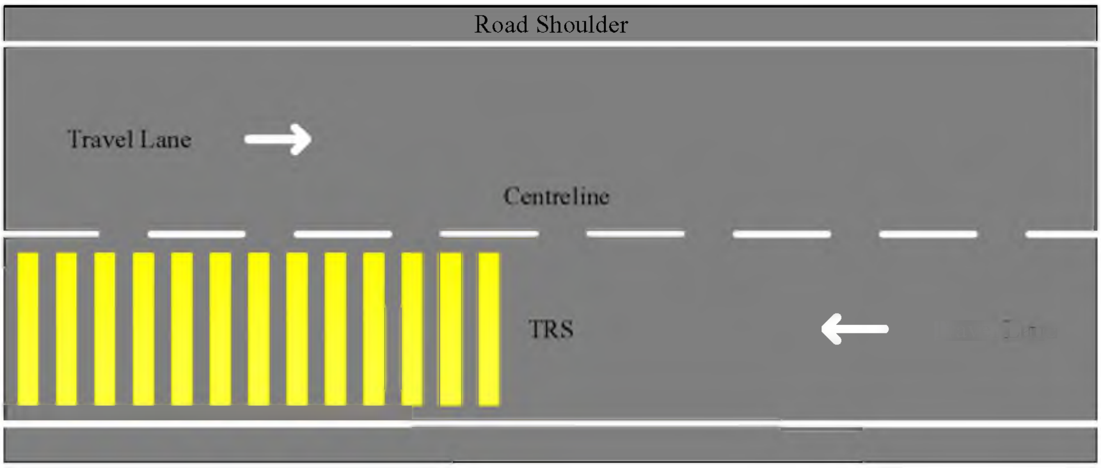

Figure 1.4 Transverse rumble strips

1.2 Problem Statement

The existing TRS guidelines have been found to be very basic with no detailed explanation on the TRS profile. In actual practice, the selection of TRS design and application on district road falls under the responsibility and judgement of Public Works Department (PWD) districts and municipal councils' road engineers. This means that different profiles and dimensions may generate different sounds and for some cases it may trigger noise annoyance among the nearby residents who live adjacent to the roadways (Boruff, 2019). The excessive noise generated due to TRS installation in residential vicinity poses a number of noise complaints lodged by the affected residents or public to the local authorities (Haron *et al.*, 2012; 2013).

TRS noise problem is not only a local issue but widely spread all over other countries (Clarkin, 2010; Terhaar and Braslau, 2015). It led researchers to study of sound level which triggers noise annoyance. Several studies have been conducted to determine the sound level (L_{Aeq}) changes due to TRS installation (Higgins and Barbel, 1984; Thompson, Burris and Carlson, 2006; Haron *et al.*, 2012; 2013; Othman *et al.*, 2012; Pimentel, Melo and Rolim, 2014; Othman, 2016). The first TRS study in Malaysia by Haron *et al.* (2012) reported that installation of TRS generate noticeable noise change of 14 dBA. Othman (2016) further investigated on single vehicle stated that tyre-TRS interaction mechanism may cause noise annoyance due to TRS.

Higher level of noise annoyance is caused by impulse noise pattern generated by the vehicles' transit over TRS compared to continuous noise pattern (Bendtsen *et al.*, 2004; Sabato, Sabato and Reda, 2013; Sabato *et al.*, 2016; Sexton, 2014). Most of previous studies have focused on sound level changes where the study on impulsive characteristics of noise due to TRS installation is limited to examine the extent of noise annoyance among the neighbourhood. According to Murphy and King (2014), the typical evaluation of noise annoyance based on A-weighted continuous equivalent sound pressure level (L_{Aeq}) is insufficient which may lead to inaccurate decision by the regulatory authorities. This is because L_{Aeq} is the average sound level over time which fluctuates and has impulse and tonal characteristics.

On top of that, noise annoyance is caused by low-frequency noise (LFN) region of 20 Hz up to 125 Hz which cannot be evaluated solely using L_{Aeq} assessment (Persson and Björkman, 1988; DeGagne and Lapka, 2008; Broner, 2010; Shehap, Shawky and El-Basheer, 2016). C-weighted equivalent continuous sound pressure level (L_{Ceq}) must be considered in this case to properly evaluate the extent of noise annoyance. As to date, the real causes of TRS noise annoyance, such as impulsivity, tonality and LFN have not yet addressed and still unknown. There is no proper evaluation method to evaluate the TRS noise problem. In addition, previous TRS roadside noise study by Othman (2016) has only evaluated limited acoustical characteristic of TRS roadside noise.

For these reasons, this study attempts to further investigate acoustical characteristic changes due to TRS installation at residential areas covering all noise characteristics such as impulsivity, tonality and LFN due to both single and multiple vehicles. Based on the cause of TRS roadside noise annoyance, the empirical models were established and proposed in the framework of optimum TRS design selection for future installation. The findings of this study may assist related parties, especially regulatory bodies and local authorities in selecting the suitable TRS for future installation at residential areas. The proposed framework can be used along with the guideline because noise and other effects have not yet considered in the local TRS design selection. Therefore, the effects of TRS installation on nearby residents can be considered during the process of decision making for TRS profile design.

1.3 Aim and Objective of the Study

This study aims to evaluate the acoustical characteristic changes due to TRS installation at residential areas in contributing to the framework of optimum TRS design selection for future installation. Apart from this, it may also enhance a better living environment in the neighbourhood areas. In order to achieve the aim of this study, several objectives are listed as follows:

i. To investigate current TRS designs and characteristics.
ii. To determine road and traffic characteristics at selected roadways.
iii. To evaluate noise annoyance due to TRS installation.
iv. To develop empirical model of TRS roadside noise level for the proposal of framework of optimum TRS design selection.

1.4 Scope of the Study

The scope of this study was established to achieve the aim and objectives of the study. The data for this study were obtained mainly through field work and on-site measurements conducted throughout the study. The following explains the scopes of this study accordingly based on research stages shown in Chapter 3:

i. Stage 1: Investigation of Current TRS Design and Characteristic

   The investigation was conducted around the Johor state where the first noise complaint regarding TRS was lodged by a resident to the local authority. This preliminary TRS investigation was carried out around Johor Bahru City and several districts including Pontian, Batu Pahat, Kulai, Kluang, Pasir Gudang and Iskandar Puteri Region in order to select suitable sampling site.

ii. Stage 2: Determination of Road and Traffic Characteristics

   In this study, only skid resistance of TRS and road surfaces were measured for road characteristic as required in the guideline by (Public Works Department, 2014a). Asphalt pavement surface was selected since it is commonly constructed instead of concrete pavement surface. It is also less noisy in terms of noise generation when vehicles transit over the roadways.

Other than that, straight road topography was considered in this study to avoid bad topography which may affect the measurement reading of roadside noise level. Similarly, flat road surface was also considered in this study to ensure that the gradient of the road surface is in good condition. Other road characteristics were not explored in this study.

Meanwhile, traffic characteristics, such as traffic composition, vehicle speed and traffic volume were determined to evaluate the traffic condition at each selected sampling site. Consistent traffic flow at each site is necessary to avoid any bias on traffic measurement readings. Therefore, the location of each selected sampling site is at least 70 m away from the nearest traffic light and junction.

iii. Stage 3: Measurement of Roadside Noise Level due to TRS Installation

In this study, seven types of vehicles were selected for the measurement of each vehicle transiting over roadways with and without TRS, to represent typical vehicles used in Malaysia. These vehicles were divided into two main categories based on gross vehicle weight (GVW) including passenger and commercial vehicles namely Perodua Axia, Proton Saga, Perodua Alza, Toyota Hilux, Toyota HiAce, Isuzu ELF lorry and Higer 40 seaters bus.

Meanwhile, for the measurement of multiple vehicles with and without TRS, 15-hour roadside noise measurements were conducted continuously during day time only from 7 a.m. until 10 p.m (Department of Environment, 2007). Besides, the frequency measurement was conducted during peak and non-peak hours in order to evaluate the frequency difference between these selected hours.

Other than that, doubling distances measurement due to multiple vehicles was also carried out to obtain the average sound pressure level (L_p) at each measurement point. Type 1 and Type 2 sound level meters (SLM) were used for this measurement due to the limitation in using the same SLM types at three measurement points.

The focus of this study is to evaluate the acoustical characteristics of noise produced mainly due to TRS installation at residential areas that may cause noise annoyance to the nearby residents. Therefore, the details of other noise propagation aspects, such as wind speed, air temperature, ground characteristics, natural barrier and other were not explored in this study.

iv. Stage 4: Evaluation of Roadside Noise Annoyance due to TRS Installation

Roadside noise annoyance due to TRS installation was evaluated objectively in this study. Several methods were applied including noise limit comparison, Traffic Noise Index (TNI), sound level changes, impulsivity and low frequency noise (LFN). These methods are necessary to evaluate the extent of noise annoyance among the affected neighbourhood.

v. Stage 5: Development of Empirical Model of Roadside Noise Level due to TRS Installation

All related variables were evaluated to establish multiple linear regression model that produces equation for proposed framework for optimum TRS design selection. In order to do so, all statistical methods as explained later in Chapter 3 were used to analyse all dependent (noise level) and independent variables (TRS, road and traffic characteristics).

vi. Stage 6: Proposal of Framework for Optimum TRS Design Selection

This study attempted to propose the framework for optimum TRS design selection by incorporating both previous data by (Othman, 2016) and main findings of this study. The previous findings on interior noise and in-vehicle vibration were combined with exterior noise of this study which evaluated different types of TRS profiles and single vehicle.

1.5 Significance of the Study

The findings of this study may aspire other researchers to focus more on acoustical characteristic changes due to TRS or other types of rumble strips installation in residential areas. This study also highlights the important criteria for noise annoyance evaluation due to TRS, which may help in enhancing sustainable living at the neighbourhood for better living environment. Apart from that, the output of this study which is the framework for optimum TRS design selection for future installation may assist the related parties, especially local authorities to properly consider the pros and cons for each TRS profile types. This is necessarily required in their decision making process regarding TRS installation. The findings of this study are potentially incorporated into the national guidelines for TRS installation in residential areas.

1.6 Thesis Outline

This thesis comprises seven (7) main chapters including Chapter 1 (Introduction), Chapter 2 (Literature Review), Chapter 3 (Research Methodology), Chapter 4 (Effect of TRS on Acoustical Characteristic Changes due to Single Vehicle), Chapter 5 (Effect of TRS on Acoustical Characteristic Changes due to Multiple Vehicles), Chapter 6 (Discussion) and Chapter 7 (Conclusion and Recommendation). Firstly, Chapter 1 (Introduction) consists of seven (7) essential components of this study, such as background of the study, problem statement, aim and objective of the study, scope of the study, significance of the study, thesis outline and chapter summary. In this chapter, the most essential element is problem statement as it explains the research gap of the study.

Chapter 2 (Literature Review) extensively explains the background of rumble strips installation as traffic calming devices, worldwide rumble strips installation, TRS installation in Malaysia, overview of traffic noise, acoustical noise annoyance assessment and rumble strips roadside noise. Meanwhile, Chapter 3 (Research Methodology) discusses the research flows in terms of sample and instrumentation used in this study and measurement procedures used to collect the required data. The detailed explanations were divided based on six different research stages according to the objectives of this study to ensure better understanding of the research flows throughout the study.

Chapter 4 (Effect of TRS on Acoustical Characteristic Changes due to Single Vehicle) presents the results and findings of the study in table and figure forms. All results are presented accordingly based on stages of research flow. In this chapter, all the related variables of single vehicle were statistically analysed to establish TRS roadside noise model. Then, the thesis continues with Chapter 5 (Effect of TRS on Acoustical Characteristic Changes due to Multiple Vehicles) which is mainly focused on all results and findings related to multiple vehicles. Similar with Chapter 4 (Effect of TRS on Acoustical Characteristic Changes due to Single Vehicle), all related variables were statistically analysed in this chapter in order to establish the TRS roadside noise model due to multiple vehicles variables.

Chapter 6 (Discussion) discusses the main results and findings obtained in Chapter 4 (Effect of TRS on Acoustical Characteristic Changes due to Single Vehicle) and Chapter 5 (Effect of TRS on Acoustical Characteristic Changes due to Multiple Vehicles). This chapter is divided into subchapters that represent each objective of the study as arranged in Chapter 3 (Research Methodology) to ensure better understanding of each element discussed. Finally, Chapter 7 (Conclusion and Recommendation) concludes the whole thesis by highlighting the foremost findings of this study. Contribution and implication of this study to the related parties are also explained accordingly. Then, the final subchapter of this chapter explains the recommendation of future research for further studies.

1.7 Chapter Summary

This chapter begins with the discussion on background of the TRS study. Basically, TRS among other configuration, such as CRS, SRS and MRS is installed in many countries including Malaysia. It is a common choice due to its advantages over other traffic calming devices, such as speed hump and speed bump. The next subchapter highlights the problems associated with the TRS installation at residential areas, especially the noise annoyance problem among the nearby residents. It is very important to present the research gap between this study with previous studies. The aim and objective of this study were specified according to the requirement of the stated problems. This chapter continues with explaining the scope, significance, thesis outline and summary. The details of each subchapter were presented and explained accordingly as required.

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