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A COMPARATIVE TRAFFIC NOISE STUDY BETWEEN SIGNALIZED INTERSECTIONS AND ROUNDABOUTS

BY

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ABSTRACT

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Title: A Comparative Traffic Noise Study between Signalized Intersections and Roundabouts

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This study presents a comparative traffic noise study done between signals and roundabouts in Doha, Qatar. Traffic noise and volume data were collected at four signals (two 2-lane and two 3-lane) and four roundabouts (two 2-lane and two 3-lane) for daytime hours during weekday and weekend. In general, the mean daytime noise levels exceeded the local (55 dB(A)) and the WHO’s (65 dB(A)) allowable thresholds. Based on the before-and-after noise study conducted at one of the roundabouts being converted to a signal, the noise at the signal was 3.5 dB(A) more. Results of noise level comparisons between the eight intersections suggest that 3-lane signals are noisier than 2-lane signals, 2-lane roundabouts are noisier than 3-lane roundabouts, 3-lane signals are noisier than 3-lane roundabouts, and 2-lane roundabouts are noisier than 2-lane signals. Finally, traffic noise prediction models were developed based on the data collected.

DEDICATION

To my parents, Md. Abdur Rouf and Mosammat Suraiya Perveen;

my husband, Md. Hosne Mobarok Shamim;

my brothers, Zakaria Bin Abdur Rouf and Zahid Bin Abdur Rouf;

and all my sisters, friends, relatives, teachers, and well-wishers.

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CHAPTER 1: INTRODUCTION

1.1. Traffic Noise Pollution

Noise is defined as sound that is unwanted, annoying, or disturbing (EPA), the intensity of which is measured in decibels (dB) (United States Environmental Protection Agency, n.d.). Moreover, noise above certain allowable threshold is termed as environmental pollution, and cumulative exposure to it can cause adverse short-term or long-term effects. Sleep disturbance, reduced cognitive performance, loss of hearing, cardio-vascular diseases, increased stress levels, irritability, and anti-social behavior are some common physical, physiological, or psychological health issues that have been linked to noise pollution (Manish Raman and R C Chhipa, 2014; OUIS, 2001; WHO Regional Office for Europe, 2011). Hence, after air pollution, noise pollution originating from roads is the second most hazardous issue that directly or indirectly affects the health and well-being of a population (WHO Regional Office for Europe, 2011). For example, Western Europe alone bears a burden of about one million healthy life years lost annually due to it (WHO Regional Office for Europe, 2011). As a result, the World Health Organization (WHO) and many other environmental protection agencies recommend keeping road noise levels well below 65 dB(A) and 55 dB(A) during daytime and nighttime respectively (WHO Regional Office for Europe, 2011).

Additionally, since high noise intensities generated on roads, mainly due to automobiles, can make built environments, especially in urban areas, unhealthy and unsustainable, it is considered a nuisance by urban planners, acoustic designers, researchers, and policymakers alike (OUIS, 2001). About 40% of the people living in the European Union countries have been reported to be exposed to traffic noise levels above 55 dB(A) (WHO Regional Office for Europe, 2011). Similarly, many urban areas in other countries are also exposed to traffic noise levels that exceed the limitations set by their governments such as the U.S. (Lee, Jerrett, Ross, Coogan, & Seto, 2014; McAlexander, Gershon, & Neitzel, 2015; Seong et al., 2011), Canada (Apparicio, Carrier, Gelb, Séguin, & Kingham, 2016; Carrier, Apparicio, & Séguin, 2016; King, Roland-Mieszkowski, Jason, & Rainham, 2012), Colombia (Quiñones-Bolaños, Bustillo-Lecompte, & Mehrvar, 2016), Chile (Sommerhoff, Recuero, & Suárez, 2004), Brazil (Calixto, Diniz, & Zannin, 2003), Jordan (Abo-Qudais & Alhiary, 2007; Obaidat, 2011), India (D. Banerjee, Chakraborty, Bhattacharyya, & Gangopadhyay, 2008; Manish Raman and R C Chhipa, 2014; Vilas & Prashant, 2015), Pakistan (Mehdi, Kim, Seong, & Arsalan, 2011), Bangladesh (Arif & Ali, 2014), the U.A.E (Elmehdi, 2014; Hamad, Ali Khalil, & Shanableh, 2017), and so on.

1.2. Background

Newer studies on traffic noise levels remain essential as common factors contributing to it such as traffic volume and composition, vehicle make, engine technology, pavement quality, road network, neighborhood, etc. continue to change over time along with the sensitivity and capability of noise measurement instruments (Abo-Qudais & Alhiary, 2007; Carrier et al., 2016; Quiñones-Bolaños et al., 2016). One such noise level study namely the contribution of traffic intersection and control type in the generation of urban traffic noise levels has become important in recent times (Gardziejczyk & Motylewicz, 2016; Namikawa et al., 2010). In many cities around the world, there is a trend of switching from one intersection type or intersection control type to another in an attempt to solve problems related to increasingly crowded urban road networks (Elvik, 2003; H. N. Isebrands, 2009; Jensen, 2013; Shaaban, Abou-Senna, Elnashar, & Radwan, 2019; Várhelyi, 2002; Vlahos et al., 2009). Although governments are aiming to make more sustainable modes of travel such as mass transit, biking, or walking more common in cities, automobiles still remain the most common mode of transport (Guarnaccia, 2010). Consequently, studies on operational, safety, and environmental aspects of roadways and intersections remain necessary.

Accordingly, many researchers have compared or studied signalized intersections and roundabouts based on safety (Flannery, Elefteriadou, Koza, & McFadden, 1998; Gross et al., 2013; H. Isebrands, 2009; Polders, Daniels, Hermans, Brijs, & Wets, 2015; Retting, Persaud, Garder, & Lord, 2001; Saccomanno et al., 2008), intersection capacity (Brilon & Vandehey, 2008; FDOT, 1995; Manage, Nakamura, & Suzuki, 2003; Yang, Li, & Xue, 2004), average traffic delay (Ahn, Kronprasert, & Rakha, 2009; Hummer, Ii, Schroeder, & Salamati, 2014; Kakooza, Luboobi, & Mugisha, 2005; Tracz & Chodur, 2012), and total pollutant emissions (Coelho, Farias, & Rouphail, 2006; Hallmark, Wang, Mudgal, & Isebrands, 2011; Mandavilli et al., 2008; Pandian, Gokhale, & Ghoshal, 2009; Ranjitkar, Shahin, & Shirwali, 2014; Salamati, Rouphail, Frey, Liu, & Schroeder, 2015). However, a few have compared the operational efficiencies of signalized intersections and roundabouts based on noise pressure levels to study their contribution towards noise pollution in urban areas. Hence, a comparative analysis, particularly from the perspective of analyzing traffic noise contributions of signalized intersections and roundabouts – two of the most common intersection types found in urban cities – has become indispensable. Nonetheless, no study has yet compared traffic noise levels at the same traffic intersection before and after the intersection type was changed. Such a study in which most other site conditions except the intersection type remain constant could infer which of the two intersection types generates more traffic noise.

1.3. Significance

As Qatar's population and the total number of registered vehicles continue to grow exponentially, due to a recent boom in the field of construction, the urban environment in Doha, the capital of Qatar, will be becoming more crowded. Regular peak hour traffic congestions combined with closely spaced buildings and a lack of adequate urban green spaces in the capital is expected to increase air and noise pollution within the city and adversely affect the health and well-being of the population (Qatar General Secretariat for Development Planning, 2011). As a result, the Qatar government has been expanding roadways and introducing mass transit systems such as the public bus and Doha metro to reduce traffic congestion and encourage its residents to choose more sustainable and efficient means of transport (Qatar General Secretariat for Development Planning, 2011). Nevertheless, studies to measure if and to what extent the existing automobile system contributes to noise pollution in Doha has not been done yet. Thus, a noise level study done in Doha city would be informative to the government, the policy makers, and the urban planners in understanding the level the noise pollution in the city is at and in planning any required countermeasures. Additionally, such a study could also be used in the future as a benchmark of traffic noise levels in the city after the implementation of the new metro system.

Moreover, since traffic noise level data are not always available, traffic noise prediction models have been developed by governments and researchers to predict traffic noise levels at roadways, sections of highway, and traffic intersections to deal with traffic noise originating from roadways. These noise models are usually developed as a factor of expected or measured traffic volume and other vehicle and site characteristics. The FHWA STAMINA and FHWA TNM v1 highway traffic noise prediction models developed in the US, the CORTN noise prediction model developed in the UK, the RLS 90 noise prediction model developed in Germany, the 01 dB MITHRA model developed in France, the STL-86 developed in Switzerland, and the ASJ-1993 Method developed in Japan are some examples of noise prediction models that are used by environment and transport agencies around the world (Steele, 2001). Consequently, recent studies have focused on either statistically developing new generalized traffic noise prediction models (Ahmed et al., 2016; Calixto et al., 2003; Hamad et al., 2017) or customizing the established models such as the CORTN for different countries such as Australia (Samuels & Saunders, 1982; Saunders, Samuels, Leach, & Hall, 1983), Columbia (Quiñones-Bolaños et al., 2016), Iran (Givargis & Mahmoodi, 2008) and so on based on region-specific site and traffic characteristics. Nevertheless, intersection type-specific noise prediction models that can be used to predict varying traffic noise levels as expected at the two very geometrically and operationally different traffic intersection types – signals and roundabouts – separately have not yet been developed.

In addition, no traffic noise prediction model has been developed or customized for use in Qatar or other similar countries within the Middle Eastern region which have different weather, site, pavement, and vehicle type characteristics compared to other regions. Hence, developing a customized general traffic noise prediction model for Qatar or a set of intersection type-specific models, whichever provides a better prediction of traffic noise levels at signals and roundabouts in Qatar or in general, has become indispensable. Such a noise prediction model could be utilized in planning future land use or modifying current land use based on newly developed noise risk zones. In addition, the results of the prediction model could serve as a factor in determining speed limits on roadways and highways to limit or mitigate current and future traffic noise pollution levels based on intersection type. In short, it could be used to design a more sustainable network of urban transport system based on anticipated land use of the surrounding areas.

1.4. Objectives

The main objective of this study is to develop a general and intersection type (roundabout or signal) specific noise prediction models appropriate for the unique geographic, socio-economic, and traffic features of Qatar and other similar regions as a case study to investigate whether intersection type-specific models are better than calibrated generalized models to predict traffic noise levels at two very different intersection types - the signal and the roundabout. Besides, the calibrated models could be used to determine whether traffic noise levels at various traffic intersections in Doha, Qatar is within the WHO’s acceptable daytime noise level threshold of 65 dB(A). Moreover, the customized models are expected to be especially advantageous in terms of predicting and comparing traffic noise levels at different intersection types so that governments, policymakers, and urban planners can better understand the noise contribution of the two intersection types and adopt noise management and mitigation plans and strategies accordingly.

CHAPTER 2: LITERATURE REVIEW

Environmental noise is generated from a number of immobile and mobile sources such as manufacturing, construction, industries, transportation, entertainment, education, human gatherings etc. (Quiñones-Bolaños et al., 2016). Nonetheless, the noise generated through various means of transport, particularly automobiles, is studied widely around the world. As a result, the impacts of environmental traffic noise have been studied from various perspectives such as its effects on human health, vulnerable age groups, quality of active and leisure hours, property value of neighborhoods, quality of roadway intersections and surrounding areas, etc. (Carrier et al., 2016; Manish Raman and R C Chhipa, 2014; OUIS, 2001). In addition, researchers have focused on developing noise prediction models which are limited to distinctive features such as socio-economic circumstances and traffic characteristics of their region of study (Abo-Qudais & Alhiary, 2007; Quiñones-Bolaños et al., 2016). Others have focused on creating noise maps for important cities (Obaidat, 2011). Also, some studies identified noise risk zones based on increasing severity of noise intensity and proposed land use for the zones (D. Banerjee et al., 2008). Moreover, researchers have evaluated if the noise intensity in their area of study falls within a standard acceptable range (D. Banerjee et al., 2008; Manish Raman and R C Chhipa, 2014; Vilas & Prashant, 2015). Others have studied the various factors affecting noise intensity measured in the vicinity of several important intersections within a city (Arif & Ali, 2014; Quiñones-Bolaños et al., 2016). Some of the factors commonly studied in these studies are traffic volume, characteristics, and speed, number and width of lanes, road slope, pavement surface, weather conditions, temperature, humidity, horn using effect, and so on (Abo-Qudais & Alhiary, 2007). Nevertheless, newer and more in-depth traffic noise level studies done from a variety of other perspectives continue to remain important.

2.1. Traffic Noise Level Guidelines

As noise pollution originating from various sources continues to increase, more and more people have been reported to complain about it to environmental protection agencies (Dibyendu Banerjee, 2013; Berglund, Lindvall, Schwela, & World Health Organization Occupational and Environmental Health Team, 1999; Environment Protection Authority Victoria, 2018; Quiñones-Bolaños et al., 2016). In addition, long-term exposure to traffic noise has also been associated with adverse health effects. Although, in some cases the associations have been reported to be weak, addressing long-term cumulative exposure to noise pollution is important as it affects large populations in any given area. Besides the annoyance and adverse health effects experienced by the current population, the growing noise pollution, if kept unchecked, will affect the future generations' social, esthetic, and economic welfare.

Besides, $L_{Aeq,T,}$ the A-weighted equivalent continuous noise level over a certain duration T is the measure used to quantify the continuous noise generated from road traffic (Berglund et al., 1999; Gracey & Associates, n.d.-a). It is commonly used as the descriptor of environmental noise in various noise control guidelines. Accordingly, the WHO provides an environment-specific guideline for community noise based on the expected critical health effects caused by equivalent noise levels. Based on this guideline, a 16-hr equivalent noise level of 55 dB(A) at school, playground, and outdoor living areas may cause annoyance to serious annoyance due to an external noise source. On the other hand, in industrial, commercial, indoor, outdoor, and traffic areas, $L_{Aeq.24hr.}$ of 70 dB(A) can cause critical health effects such as hearing impairment. In other words, the guideline values are given for specific indoor or outdoor settings and periods.

Similarly, based on the expected community reaction to noise exposure and its consequent harmful health effects, noise rating scales (Pandya, 2001) and risk zone criteria (D. Banerjee et al., 2008) have been developed to measure and compare community noise levels (see Table 1). Rating scales or risk zone criteria helps assess area-specific noise exposure and also identify noise hotspots. Noise level above 76 dB(A) has been categorized as very severe noise exposure with moderate to extremely high risk of harmful health effects.

Table 1. Noise Level Scale for Categorizing Noise Exposure & Noise Risk Zones

Noise Rating Scale (Pandya, 2001)		**Noise Risk Zone Criteria** (D. Banerjee et al., 2008)	
L_{dn}, day night level in dB(A)	Noise Exposure	Noise Level in dB(A)	Risk Zone
≤ 55	Minimal	< 66	Safe
56-60	Moderate		
61-65	Significant		
66-70	Severe	66-71	Tolerable
71-76	Moderately Severe	71-76	Low Risk
≥ 76	Very Severe	76-81	Moderate Risk
		81-86	High Risk
		> 86	Extremely High Risk

Moreover, according to the WHO, noise pollution caused mainly due to traffic on densely crowded roads can be as high as 75-80 dB(A), particularly in the urban areas of developing nations. As a result, governments around the world have developed ambient noise standards to deal with the increasing problem of noise pollution in various sectors such as residential, commercial, industrial, and silent areas. For example, in 1989, the Central Pollution Control Board (CPCB) in India established ambient air quality standards for different areas (CPCB, 2001). Similarly, the Columbian Ministry of Environment, Housing, and Territorial Development in 2006 also set the maximum permissible noise levels for Columbia (MAVDT, 2006). Likewise, the Annex (3/5th) of the Qatar State Environment Protection Law (QSEPL) of 2002 states the area-specific maximum allowable ambient noise limits for Qatar

(SCENR, 2002).

Accordingly, Table 2 summarizes the specified limits set by the three governments respectively. In general, daytime is considered between 6 AM and 9 PM whereas nighttime is considered between 9 PM and 6 AM. Besides, in case of mixed areas, when at least 50% use of that area falls within one of the specified areas in Table 2, it is considered to belong to that category (SCENR, 2002). However, in some cases, the category of the mixed area is declared by an appropriate authority (D. Banerjee et al., 2008; Pandya, 2001). In Qatar, the silence zone is combined with the residential area, and the daytime noise limit is 55 dB(A). On the other hand, commercial and industrial areas are combined in Columbia with the daytime noise limit set at 75 dB(A). Columbia also has a higher daytime noise limit for the residential area (65 dB(A)) unlike India and Qatar – both of which have a lower daytime noise limit of 55 dB(A). Columbia also has a higher silence zone daytime noise limit of 55 dB(A) when compared to India (50 dB(A)).

Besides, according to the National Academy of Engineering (NAE), similar to most developed nations in the world, road, rail, and air traffic and occupational and industrial activities are the main sources of noise in the U.S. (Hammer, Swinburn, & Neitzel, 2014). Therefore, in residential areas, the United States Environmental Protection Agency (U.S. EPA) recommends a day-night 24-hr average noise level (L_{DN}) exposure limit of 55 dB(A) to keep the public safe from all adverse health effects (US Environmental Protection Agency, 1974). In this case, a 10 dB(A) penalty is applied to the nighttime noise levels recorded between 10:00 PM and 7:00 AM to account for disruption to sleep whereas no penalty is applied to the measured daytime noise levels. Likewise, 55 dB(A) is the European Union’s (EU’s) threshold for daily noise exposure (Berglund et al., 1999).

Moreover, based on population density and land use, the Italian legislation (1997) recommends a maximum noise level of 55 dB(A) and 60 dB(A) for residential and mixed land use respectively (King et al., 2012). Along new roads, the New South Wales Australian Environmental Protection Authority specifies a maximum $L_{Aeq.}$ a noise limit of 60 dB(A) for the daytime. On the other hand, in Thailand, noise pollution guidelines (1996) allow a maximum of 70 dB(A) $L_{Aeq.24h}$ in residential areas (Berglund et al., 1999; Prasanchuk, 1997).

Table 2. Land Use or Area Specific Noise Level Threshold Guidelines as per Columbia, India, and Qatar

Columbia (MAVDT, 2006)			**India** (CPCB, 2001)			**Qatar** (SCENR, 2002)		
Areas	Day	Night	Areas	Day	Night	Areas	Day	Night
Hospitals, libraries, and public health buildings etc.	55	50	Silence zone (areas 100 m around hospitals, educational institutions, and public service buildings)	50	40			
Residential, hotels, educational institutions, research facilities, parks etc.	65	55	Residential	55	45	Residential and public corporations (schools, hospitals, and mosques)	55	45
			Commercial	65	55	Commercial (department stores, business offices, garages, and places of work)	65	55
Commercial and industrial	75	75	Industrial	75	70	Industrial facilities	75	75

Nevertheless, irrespective of the land use, the WHO specifies an allowable noise level threshold of 65 dB(A) and 55 dB(A) for daytime and nighttime noise levels respectively to avoid the adverse health effects caused by environmental traffic noise (WHO Regional Office for Europe, 2011). In addition, the WHO recommends governments and environment protection authorities to shift from varying noise regulations to global noise policies to maximize the health benefits of the entire global population (Berglund et al., 1999).

2.2. Measuring Traffic Noise Levels

Several studies have measured noise levels at traffic intersections (signals, roundabouts, or both), in the areas between traffic intersections, or near traffic intersections to compare the noise level results with respect to the local or the WHO's allowable noise level thresholds (Ahmed et al., 2016; Obaidat, 2011; Quiñones-Bolaños et al., 2016). For instance, Pandya studied urban noise at four typical cities in India namely Delhi, Jamshedpur, Dehradun, and Nagpur (Pandya, 2001). They measured $L_{eq.}$ continuously during the daytime (6 AM to 9 PM) and nighttime (9 PM to 6 AM) using precision integrated sound level meter along with 94 dB(A) calibrator with an accuracy of ±0.3 dB(A). Also, they considered a nighttime penalty of 10 dB(A) in their study. Based on their results, they found that Delhi and Jamshedpur experienced very severe noise exposure (>76 dB(A)) compared to the other two cities.

In another similar study done at Nashik city, Maharashtra, India, traffic noise levels at four signalized intersections were measured for two hours during morning, afternoon, and evening peak hours (8:00 AM to 10:00 AM, 2:30 PM to 4:30 PM, and 5:00 PM to 7:00 PM) (Vilas & Prashant, 2015). Additionally, the traffic volumes were measured at 1-min intervals. Yet again, the measured equivalent noise levels at these intersections were found to range between 85.3 dB(A) and 91.0 dB(A) with a mean value of 79.1 dB(A), all exceeding the permissible noise levels specified by the Central Pollution Control Board of India (CPCB).

Similarly, in a noise study done at the capital Dhaka in Bangladesh, noise level and traffic flow data for a period of 1-month on both working and non-working days were collected at five major and busy signalized intersections (Arif & Ali, 2014). Similar to Pandya (2001), they calibrated the Sound Level Meter (set at A-weighting scale and fast response mode at 1-second intervals) with 94 dB Sound Level Calibrator before and after taking each noise level data. The resulting $L_{eq.}$ found at all the five intersections ranged between 77.0 dB(A) and 80.5 dB(A) – above the standard limit set by the Department of Environment, Bangladesh. The causes of high noise levels and their relative contribution to the overall noise level were derived in this study using a combination of video and sound level data. Based on the findings, factors such as pedestrians, motorcycle drivers, manual signaling, congestion, use of horn, on-street parking, etc. mainly contributed to the high traffic noise found at the intersections.

On the other hand, Banerjee et. al. attempted to create noise maps for a city in India to facilitate modification of land-use and policies and to check if the noise levels in an area were within the prescribed limits set by the government (D. Banerjee et al., 2008). They collected $L_{Aeq.}$ at residential, silence, commercial, and industrial zones on regular business days using Sound Level Meter Type-2 (set at A-weighting frequency and fast range) along with 94 dB(A) multi-function acoustic calibrator. Based on the findings, they developed noise contour maps for the city and classified the study area into different noise risk-zones ranging from safe (< 66 dB), tolerable, low risk to extremely high risk, with intensities greater than 86 dB (see Table 1). They also suggested modification of land-use based on the noise quality observed in the area.

Besides, about 40% of people living in the European Union countries have been reported to be exposed to traffic noise levels above 55 dB(A) (WHO Regional Office for Europe, 2011). Similarly, many urban areas in other countries are also exposed to traffic noise levels that exceed the limitations set by their governments such as the U.S. (Lee et al., 2014; McAlexander et al., 2015; Seong et al., 2011), Canada (Apparicio et al., 2016; Carrier et al., 2016; King et al., 2012), Colombia (Quiñones-Bolaños et al., 2016), Chile (Sommerhoff et al., 2004), Brazil (Calixto et al., 2003), Jordan (Abo-Qudais & Alhiary, 2007; Obaidat, 2011), India (D. Banerjee et al., 2008; Manish Raman and R C Chhipa, 2014; Vilas & Prashant, 2015), Pakistan (Mehdi et al., 2011), Bangladesh (Arif & Ali, 2014), the U.A.E (Elmehdi, 2014; Hamad et al., 2017), and so on.

However, the high noise levels observed in all these studies are not uncommon for roadways located near major urban intersections. According to the WHO, noise pollution caused by traffic on densely crowded roads can be as high as 75-80 dB(A), particularly in the urban areas of developing nations (Berglund et al., 1999). Nevertheless, such noise levels are perceivably higher than the allowable noise level thresholds and need to be addressed by the government, urban planners, and policymakers alike. Yet, no comprehensive traffic noise studies have been done in the Gulf region to investigate the presence and extent of noise pollution in the region and suggest any necessary countermeasures. Therefore, a local traffic noise study structured around the identified contributing factors combined with an evaluation of the resulting traffic noise levels against the prescribed noise level limits has become necessary in Qatar and other neighboring countries in the region.

2.3. Measuring Noise at Intersections

While some studies specified the intersection and the control type of the sites they studied, many did not differentiate between the intersection types and only discussed the overall noise levels observed at these sites (Manish Raman and R C Chhipa, 2014; Mehdi et al., 2011). For instance, noise data were collected at an interval of 10 seconds for 6 minutes during two days at 11 intersections within Jaipur city in Rajasthan state, India (Manish Raman and R C Chhipa, 2014). The intersections were located in commercial, residential, industrial, or silence zones within the city. The measured average daytime noise levels at these sites were 77.10 dB (A) (industrial), 71.40 dB (A) (commercial), 58.0 dB (A) (residential) and 56.13 dB (A) (silence zone), that is, 2.1 dB(A), 6.4 dB(A), 3.0 dB(A), and 6.13 dB(A) above the permissible noise level limits specified by the Central Pollution Control Board of India (CPCB) for each zone type respectively (Debnath & Singh, 2018) due to increase of vehicles and transportation facilities in the city.

Likewise, to assess road traffic noise pollution in Karachi, Pakistan, data was collected at 308 sites mostly located around severely congested traffic intersections for two weeks from 6:30 to 24:00 (Mehdi et al., 2011). The mean noise levels found at these sites were above the WHO’s allowable threshold of 65 dB(A) for daytime outdoor noise. Additionally, in this study, due to trip patterns of the commuters, high noise levels were observed, especially during morning and evening hours.

Besides, in a noise level study done in the capital city Amman in Jordan, noise data was collected during three traffic peak hours (7:30 AM to 9:00 AM, 1:30 PM to 3:00 PM, and 9:00 PM to 11:00 PM) at 27 traffic signals with three or four approaches located mainly at residential areas (Obaidat, 2011). At these intersections, the mean noise levels found during the morning, afternoon, and evening hours were 58.6, 59.2, and 55.6 dB(A) respectively. That is, the morning and afternoon mean values and the evening mean value were just below the Jordanian noise standards for daytime (60 dB(A)) and nighttime (50 dB(A)) noise levels respectively in residential areas in cities. Furthermore, in this study, traffic volume at the intersection was found to be the main factor affecting the equivalent noise levels besides the effects of road geometry, approach slope, traffic speed, percentage of heavy vehicles, road surface texture, and others.

Again, in Jordan, a total of 4745 1-min $L_{eq.}$ noise samples were collected at 40 signalized intersections (Abo-Qudais & Alhiary, 2007). 68 dB(A), 91.6 dB(A), and 76.1 dB(A) were the minimum, maximum, and mean 1-min equivalent traffic noise levels found respectively in this study, all of which exceeded the local and the WHO's recommended noise level threshold of 65 dB(A) for daytime exposure.

Furthermore, a noise study in Cartagena, Columbia analyzed traffic noise levels collected at seven busy signalized intersections and one roundabout during three peak hour periods (6:00-9:00, 11:00-2:00, 5:00-7:00) identified for the city for weekdays and weekends (Quiñones-Bolaños et al., 2016). The aim of this study was to correlate the measured traffic noise levels as a function of vehicle flow going through the intersections. Six out of the eight intersections did not comply with the local limit of 70 dB(A) specified for urban areas classified under intermediate and restricted noise (MAVDT, 2006). In addition, all eight intersections exceeded the WHO's allowable noise level threshold of 65 dB(A).

Also, in this study, the highest noise levels on a weekday (79.7 dB(A)) and weekend (77.7 dB(A)) were observed at two different signalized intersections respectively (Quiñones-Bolaños et al., 2016). On the other hand, the noise level at the only roundabout was comparatively lower on both days. However, the highest traffic volume was observed at the roundabout. Hence, the highest noise level was not observed at the intersection with the most traffic flow, although road traffic and noise level were expected to be related.

In addition, in a noise assessment study done in Curitiba, Brazil, the mean community noise level observed near roadways was reported to be 73.1 dB(A), 8.1 dB(A) above the WHO’s allowable noise threshold of 65 dB(A) (Calixto et al., 2003). Similar to other studies, this study also identified noise generated from road traffic to be the main source of community noise found within the city.

To sum up, according to the WHO, noise pollution caused by traffic on densely crowded roads can be as high as 75-80 dB(A), particularly in the urban areas of developing nations (Berglund et al., 1999). Hence, the high noise levels observed in all these studies are not uncommon for roadways located near major urban intersections. Nevertheless, such noise levels are perceivably higher than the allowable noise level thresholds and need to be addressed by the government, urban planners, and policymakers alike. Selecting or converting to traffic intersections types that would generate lower noise levels at these major urban intersections could be a viable solution.

2.4. Comparing Noise at Intersections

Before undertaking major construction or conversion initiatives, noise levels at different intersection and control types need to be compared. Accordingly, in a comparative noise level study, noise levels in the vicinity of one channelized signalized intersection (50-hr of $L_{Aeq.1hr.}$) and two roundabouts (61-hr of $L_{Aeq.1hr.}$) with comparable traffic characteristics were collected at similar distances from the geometric center (Gardziejczyk & Motylewicz, 2016). They found that traffic composition (especially the percentage of the heavy vehicles), traffic flow, and intersection type had a significant effect on the noise level observed in the vicinity of these intersections.

Ranges of traffic volume at these intersections were 600~4100 vph, 700~3750 vph, and 200~1500 vph with 1.5~14.4%, 2.9~8.6%, and 2.7~53.6% heavy vehicle percentage ranges respectively.

However, the first and the second roundabout yielded similar noise levels (about 61.0 dB(A) for different mean traffic volumes (3500 vph and 500 vph) (Gardziejczyk & Motylewicz, 2016). This was most like to due to 23.3% higher presence and movement of multiple axle heavy vehicles at the second roundabout combined with a greater concentration of sources of traffic noise at the second roundabout, the central island diameter of which was two times smaller than the first roundabout. Hence, both traffic volume and heavy vehicle composition had an influence on the noise levels generated at the roundabouts.

Also, due to significant differences in the traffic conditions at the second roundabout, it was excluded during analysis. Consequently, the mean $L_{Aeq.1hr.}$ at the channelized intersection and the first roundabout were 64.3 dB(A) and 61.0 dB(A) respectively in the vicinity of the entry points, 40 meters from the center of the intersections (Gardziejczyk & Motylewicz, 2016). Hence, the noise level at the first roundabout was approximately 3.3 dB(A) lower indicating that traffic condition and the intersection type had an influence on the noise level found in the vicinity of the intersections located in large urban areas.

Gardziejczyk & Motylewicz (2016) also found noise level assessment in the vicinity of intersection to be a widely complex issue since many connected and interdependent factors such as traffic volume, distribution, and composition (especially the % heavy vehicle), geometry of the intersection (number of lanes, traffic island diameter, distance between carriageway), and traffic management significantly affected the observed noise levels. Nevertheless, traffic composition, traffic flow, and intersection type had the most significant effects on the noise levels found at the channelized intersection and the roundabouts (Gardziejczyk & Motylewicz, 2016).

Other studies compared traffic intersections using various noise prediction models. For instance, CadnaA software was used to simulate the resulting noise effects of converting a three-legged road intersection into a three-legged roundabout in Fisciano, Italy with standard traffic flow conditions (continuous accelerated/decelerated traffic flow and average traffic speed). Based on the simulation results, keeping the same traffic flow conditions and replacing signalized intersection (71.5 dB(A)) with a roundabout (70.5 dB(A)) lowered the equivalent hourly noise level by 1 dB(A). On the other hand, the simulated noise level at the signal was 1.2 dB(A) higher than the field measurement (70.3 dB(A)) obtained at the signal. Therefore, although based on simulation the conversion of the signal to a roundabout reduced the noise level, simulation results obtained from the software were not without some minor prediction errors (Guarnaccia, 2010).

In another traffic noise simulation case study, Chevallier et al. studied the noise pressure levels at signalized intersection and roundabout using three types of noise prediction models– static, analytic, and micro-simulation (Chevallier, Can, Nadji, & Leclercq, 2009). The layout of the intersections (a major road crossing a minor road) in this case study were selected so that the location of the stop-lines of the signal matched the yield-lines of the roundabout entries. The resulting intersections were four-legged with one lane per approach that were 3 meters wide and 250 meters in length each since noise impacts were assumed insignificant farther than 250 meters. Moreover, the traffic demand inputs at the intersections were representative of the peak morning period. Based on the analysis, replacing a signalized intersection by a roundabout triggered a 2.5 dB(A) noise abatement when traffic condition was under-saturated (low and medium traffic), similar to the simulation findings of another study done with micro-simulation (De Coensel, Vanhove, Logghe, Wilmink, & Botteldooren, 2006).

However, when traffic condition was over-saturated in the simulation, the noise contributions of both the intersections were almost identical, but with higher noise levels compared to the under-saturated state. That is, the traffic calming effect of roundabouts became negligible in congested traffic scenario. Therefore, noise level increases at the intersections were mainly triggered by low velocities of undisturbed through traffic inside the junction combined with low stop-and-go periods during the saturated state (Chevallier, Can, et al., 2009). Likewise, in a dynamic micro-traffic simulation study done at a comparable roundabout and a signalized intersection in Guangzhou, China, traffic noise level at the intersections also reached an upper limit when traffic was saturated (Li, Lin, Cai, & Du, 2017). Moreover, the accuracy of the model developed and used for the prediction of the noise levels at these intersections were compared with actual field measurements done at the same intersections. The measured and the simulated results were found to be in good agreement with an absolute mean error 2 dB(A). Nevertheless, the prediction of traffic noise at road intersections is challenging due to the complex flow of traffic found near intersections (Li et al., 2017).

To sum up, studies have analyzed noise level contributions of similar intersections types (signalized intersection or roundabout) individually, different intersection types (signalized intersections and roundabouts) at different locations based on field measurements, or different intersection types at the same location-based on predictions models and noise simulation software. Nevertheless, before-and-after noise level study conducted at the same traffic intersection, before and after the intersection type was changed, so that most site characteristics and other contributing factors except the intersection type remained constant is one of the best means of comparing the traffic noise level at roundabout versus signal. Compared to other studies done at different locations or the same location, based on simulation or prediction models, the findings of such a study could be considered more conclusive in terms of indicating which intersection type generates more traffic noise. Since no such case study has been done yet, this study attempts to fill this particular knowledge gap by comparing traffic noise level and volume at a traffic intersection before and after it is converted to confirm further the noise abatement effects of converting a signal to a roundabout in an urban environment as found in the literature (Chevallier, Can, et al., 2009; Gardziejczyk & Motylewicz, 2016; Guarnaccia, 2010; Li et al., 2017).

2.5. Developing Traffic Noise Prediction Models

Steele reviewed seven principal traffic noise prediction models used by various governments namely FHWA STAMINA, FHWA TNM v1, 01 dB MITHRA, CORTN, RLS 90, STL-86, and ASJ-1993 (Steele, 2001). He suggested the necessity for the development of an ideal model that would be applicable and valid for most cases. Additionally, he found that most of the established models were not capable of predicting traffic volumes. Also, all the models were valid for constant speed only.

Moreover, input data such as traffic type, speed, environment etc. were required for most of the models. $L_{eq.}$ was the noise descriptor for all the models except the CORTN. All the existing models were limited to simple or single traffic streams. Options for vehicle type were also varied for the models such as light vehicles, heavy vehicles, medium trucks, heavy trucks, or trains. In short, Steele found that some models were somewhat obsolete, while others had limited prediction capabilities such as use for car parks, free-flowing traffic, or light rails only. None of the existing models had the capability to accurately calculate $L_{eq.}$, LN, $L_{max.}$, $L_{min.}$ while allowing local vehicle types as an input variable. Hence, a general or easily customizable noise prediction model needs to be established.

As a result, researchers have continued to construct noise prediction models theoretically or empirically. However, such models are always usually limited to particular traffic flow, traffic characteristics, environment etc. In 1999, Makarewicz, Fujimoto, and Kokowski developed a model of interrupted road traffic noise theoretically based on a number of assumptions (Makarewicz, Fujimoto, & Kokowski, 1999). One assumption was that all vehicles were of the light vehicle category since the number of heavy vehicles were negligible. Nevertheless, such assumptions are not valid for most city traffic nowadays.

Consequently, more recent research in this area is based on empirical noise data collection and statistical analysis. For example, Abo-Qudais and Alhiary collected 14,235 noise level measurements at 40 signalized intersections using an Integrated Sound Level Meter during 1-min intervals (Abo-Qudais & Alhiary, 2007). They recorded traffic characteristics and volume using video cameras. They also collected noise level data at various distances from the signal stop line such as 50, 100, 150, 200, 250, and 300 meters. Additionally, they used speed radar to find traffic speed. Finally, they developed statistical models to predict traffic noise levels in terms of a number of factors such as traffic volume, speed, pavement surface texture, number of heavy vehicles, number of lanes, lane width, approach width, green time interval, distance from signal stop line, and slope percentage. Next, they removed the variables that were strongly correlated by establishing a correlation matrix among all the variables before developing the prediction models through statistical regression analysis. Then, they created scatter plots among noise levels and various significant factors to predict models with the best fit.

In the end, Abo-Qudais and Alhiary developed prediction models for $L_{eq.}$, $L_{max.}$, and $L_{min.}$. The first was to predict $L_{eq.}$ as a function of traffic volume with $R^2 = 0.885$. Second, they developed a model for predicting $L_{max.}$ at zero distance from the signal which was a factor of the number of heavy vehicles and horn effect. The horn effect, in this case, was taken as a dummy variable. Consequently, if there was no horn, the horn effect was assumed to be zero. This model had a coefficient of multiple determination equal to 0.768. They also developed models to calculate $L_{max.}$ at various distances from the traffic stop line. The one 50 meters away was significantly affected by the number of heavy vehicles and traffic volume. The model for distances 200, 250, and 300 meters away from the signal stop line were similar to the model for 50 meters. At distances of 100 and 150 meters, the model was affected by the number of heavy vehicles, road slope, traffic volume, speed, and pavement surface texture. For predicting $L_{min.}$, lane width and pavement surface texture (British Pendulum Number) were most significant with $R^2 = 0.883$. To sum up, they concluded that their prediction models were a good fit for other measured traffic noise at selected intersections having a difference of -1.8 dB to 2.1 dB only.

More recently, in a similar study in 2016, Quinones-Bolanos, Bustillo-Lecompte, and Mehrvar developed modified versions of the Calculation of the Road Traffic Noise (CORTN) model, initially developed by the UK Department of Transport in 1988 (Department of Transport Welsh Office, 1988), for the road intersections of the city of Cartagena in Colombia (Quiñones-Bolaños et al., 2016). They found that since 30% of the traffic composition of the city of Cartagena is motorbike with distinctive overall traffic noise, using the original CORTN model that divides traffic into the light vehicle and heavy vehicle only would not give the most accurate noise prediction results for the city. Consequently, they aimed to develop a customized version of the CORTN model for Cartagena city.

For this purpose, Quinones-Bolanos et. al. (2016) collected sound pressure levels at eight busiest intersections within the city with a sound level meter type II (Extech Instrument, Model 407750). They recorded noise pressure levels at 3-hr intervals at three peak hours of eight business and non-business days (6 AM to 9 AM, 11 AM to 2 PM, and 5 PM to 7 PM). They collected the noise data at 1.2 meters above the ground within 7.5 meters from the edge of the road. In addition, they manually counted the traffic flow every 15-min during the same 3-hr intervals. They calculated average traffic speed by calculating from a reference point. Besides, they calculated meteorological data every 5-min using a portable meteorological station (LaCrosse Technology, Model WS-1612AL-IT).

The CORTN is an empirical model that is based on traffic flow through a particular road section in an hour and the sound pressure level. In addition, the researchers applied gradient, pavement type, distance, shielding, angle of view, and reflection adjustments to customize the model (Quiñones-Bolaños et al., 2016). The total equivalent traffic flow equation with three vehicle categories instead of two was then developed to use for traffic flow adjustment in the CORTN model. In the end, they developed a traffic noise model for the intersections of the city of Cartagena. In this model, the traffic flow of one heavy vehicle per hour was found equivalent to eight light vehicles in producing the same sound pressure level. On the other hand, traffic flow of one motorcycle per hour was found to produce the same sound pressure level generated by about five light vehicles.

Quinones-Bolanos et. al. (2016) thus concluded that the model could be used for other similar cities in Colombia provided that the approaching vehicle speeds were below 40 km/hr. Besides, they also found that 56% of the total road intersection of the city of Cartagena did not comply with their national noise emission standards. The highest mean sound pressure level on business days was found to be equal to 79.9 dB(A); on the other hand, on non-business days it was equal to 77.7 dB(A). Last but not least, they also developed two noise level maps for the city, one for daytime and the other for nighttime to aid designers and policymakers in city planning.

Therefore, this study aims to fill the gaps found in the literature by first collecting traffic noise level and volume data at some selected signalized intersections and roundabouts within Doha, Qatar. Using these data, the general 1988 CORTN traffic noise prediction model would be calibrated as per the local site and traffic conditions in Doha, resulting in a general modified CORTN model. This would result in a general traffic noise level prediction model much needed for Doha and other similar cities in the Middle Eastern region. Furthermore, the locally customized model would then be customized in order to predict traffic noise levels based on the two different intersection types namely signalized intersection and roundabout of two different sizes. Although the proposed models would be calibrated to represent the local site and traffic conditions in Qatar, the methodology used in developing the customized models is expected to be applicable to other regions as well.

CHAPTER 3: DATA COLLECTION

The main purpose of this study was to conduct a comparative case study between four (two 2-lane and two 3-lane) signalized traffic intersections and four (two 2-lane and two of the few remaining 3-lane) roundabouts in Doha city. For this, traffic noise levels, volumes, weather, and other relevant site data were collected at the eight sites for 16 consecutive daytime hours on weekdays and weekends to first check the level of noise pollution at the intersections. Then, the final conclusion for the comparative study was based on the equivalent hourly traffic noise levels generated by weekday and weekend traffic at the intersections during selected morning, afternoon, and evening peak traffic hours (9 hours). Using the same data, noise predictions models were also developed for the city.

3.1. Case Study

The study area of this research was the capital city of Qatar, Doha which is the largest city, the administrative center, and the economic hub of Qatar – located on its central east coast. It’s a small, low-lying, and a flat country situated in the GCC region with Saudi Arabia and the Arabian Gulf at its borders. Since Qatar is a fast developing Middle Eastern country, the government has been constructing new neighborhoods and roadways to keep up with the exponential population growth. Nonetheless, more than 80% of Qatar’s population live in the urban areas of Doha which comprises only 1.15% (132 km^2) of the country’s total area (11,437 km^2). Hence, Doha is the most densely populated city (10,984.8/km^2) in a country of only 176/km^2 density (K. Shaaban & Radwan, 2014).

In addition, residents in Qatar, in general, prefer driving private vehicles instead of walking or using public transport due to pedestrian safety (Khaled Shaaban, 2017; Khaled Shaaban, Muley, & Mohammed, 2018; Khaled Shaaban, Wood, & Gayah,

2017) and aggressive driving (K. Shaaban, Gaweesh, & Ahmed, 2018; Khaled Shaaban & Hassan, 2017; Khaled Shaaban & Pande, 2018) concerns combined with long, hot, and humid summers (Khaled Shaaban, Muley, & Elnashar, 2017; Khaled Shaaban & Pande, 2016). As a result, traffic congestion, air pollution, and noise pollution in Doha has become a common and serious problem during weekday and weekend peak hours. As a countermeasure, besides introducing the Doha Metro, the government has been converting major roundabouts in the city with signalized intersections to reduce serious peak hour traffic congestion in the capital (Khaled Shaaban et al., 2019).

3.2. Site Details

The eight intersections selected for this case study were located within Doha city as shown in Figure 1. Locations 1, 2, 3, and 4 (each representing a different intersection type) were situated closer to one another compared to the locations 5, 6, 7, and 8 (representing the second set of corresponding intersection types) which were scattered farther away. Locations were selected so that at least two of them belonged to the same intersection type. The intersection types of interest in this study were 2-lane signalized intersections (locations 3 and 7), 2-lane roundabouts (locations 4 and 8), 3-lane signalized intersections (locations 1 and 5), and 3-lane roundabouts (locations 2 and 6) so that the intersections could be compared to one another based on intersection type and number of lanes. Also, it is to be noted that intersection 1 and intersection 2 were situated at the same location since the 3-lane signal at location 1 was built by replacing the 3-lane roundabout at location 2. Although this was an exception in the intersection selection process, a comparison between these two intersections was expected to have a positive impact on the overall comparison since these two sites were most comparable in terms of site characteristics and traffic conditions.

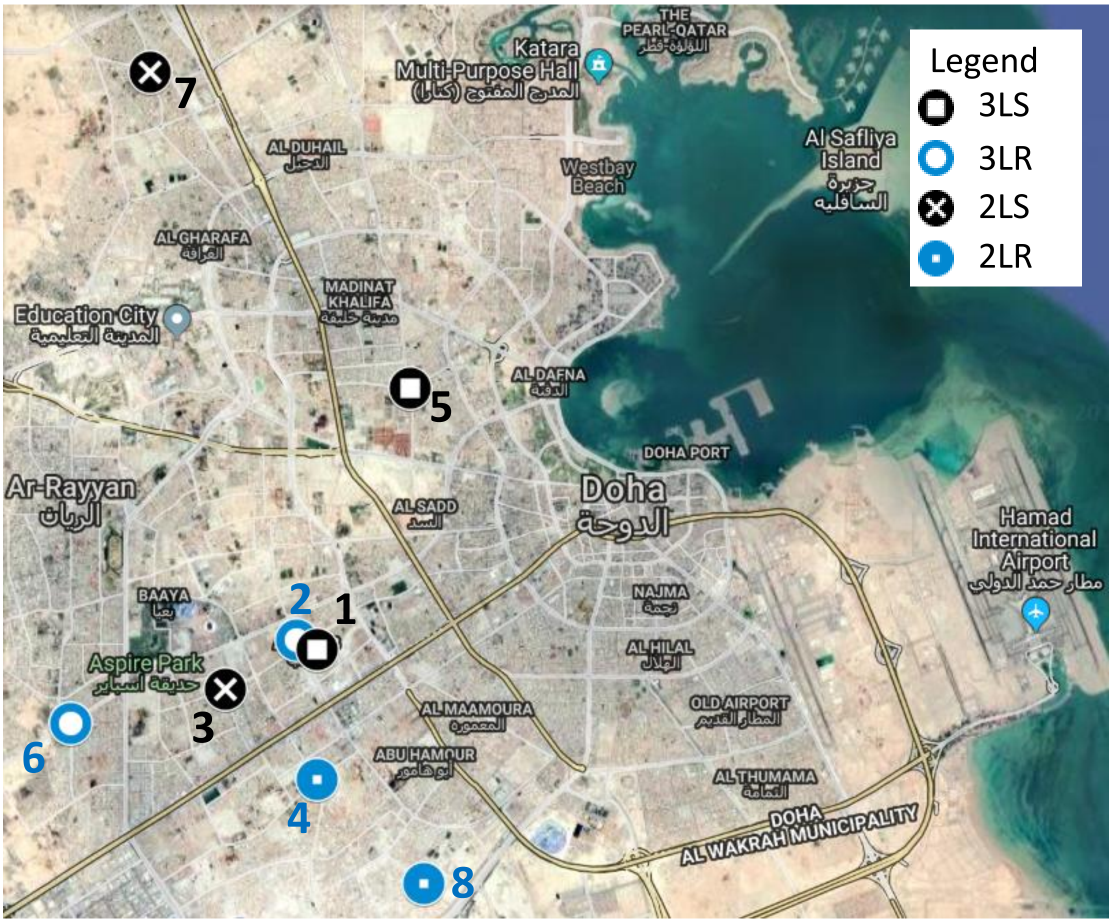


Figure 1. Site locations of the 8 traffic intersections in Doha, Qatar.

Moreover, Figure 2 illustrates the satellite images of all the eight intersections compared in this study. Instead of the total number of entry or exit lanes at the signalized intersections or the roundabouts, the total number of through lanes per approach was considered to be the defining factor in categorizing the two main intersection types into 2-lane or 3-lane intersections. The land-use in the areas surrounding the intersections were found to be mostly residential with rows of low-rise buildings and some open areas.

Besides, the 3-lane intersections were either connected to major highways or were considered to be critical/busy intersections within the main city. On the other hand, the 2-lane intersections were mainly connecting city blocks. The two 3-lane signalized intersections (S/I) were located near medical centers and residential buildings, the two 3-lane roundabouts (R/A) were surrounded by mostly residential buildings, and the remaining four intersections (two 2-lane S/I and two 2-lane R/A) were near schools, mosques, or residential buildings.

(a) Location # 1: 3LS-1
(25.259933, 51.466067)

(b) Location # 2: 3LR-1
(25.259933, 51.466067)

(c) Location # 3: 2LS-1
(25.252071, 51.450882)

(d) Location # 4: 2LR-1
(25.235948, 51.469355)

(e) Location # 5: 3LS-2
(25.306810, 51.488227)

(f) Location # 6 : 3LR-2
(25.245882, 51.420191)

(g) Location # 7: 2LS-2
(25.364280, 51.435920)

(h) Location # 8: 2LR-2
(25.216779, 51.490865)

Figure 2. General satellite view of the selected 8 traffic intersections in Doha, Qatar.

Additionally, Table 3 summarizes the general site characteristics, the average road slope, the pavement quality, and the distribution of through (T) lanes, left-turning (LT) lanes, and right turning (RT)/slip lanes at the intersections. Also, many site features between the comparable intersections were found to be similar. For instance, the speed limits indicated at the intersections were 50 km/h and 80 km/h at the 2-lane and the 3-lane intersections respectively. However, the most obvious difference between the roundabouts and the signals were in the lane details/layout. Also, the central island diameters of the 3LR-1, 3LR-2, 2LR-1, and 2LR-2 were 60 meters, 66 meters, 30 meters, and 40 meters respectively. Whereas, the inscribed circle diameters were 80 meters, 88 meters, 50 meters, and 60 meters respectively. On the other hand, the dimensions of the signalized intersections 3LS-1, 3LS-2, 2LS-1, and 2LS-2 were 40x45, 45x45, 20x30, and 25x30 square meters.

At the signals, the total number of lanes increased by double or more than double due to the inclusion of more left-turning, through, and right-turning lanes. The two 3-lane signals (locations 1 and 5) had a total of 28 lanes each, whereas the two 3-lane roundabouts had a total of 11 (location 2) and 10 lanes (location 6) respectively. Likewise, the two 2-lane signals (locations 3 and 7) had a total of 12 and 16 lanes respectively compared to the two 2-lane roundabouts (locations 4 and 8) which had only 8 lanes each. This disparity was not surprising since signalized intersections in Doha city generally have more dedicated turning lanes than roundabouts.

Furthermore, all intersections had almost flat terrains with less than 2% gradient. The first 3-lane signalized intersection (Site 1) and the first 2-lane R/A (Site 4) had the maximum negative and positive gradient of 1.6% and 1.1% respectively while the rest of the intersections had even lower negative or positive gradients (see Table 3). At all locations, the pavements were asphalt pavements; one-third of them had excellent pavement quality (smooth and even with clear road markings) and two-third of them had good pavement quality (even with some visible aggregates and lightly faded road markings). Nonetheless, all pavement surfaces appeared to have a smooth texture even if coarse aggregates were sometimes visible on the surface.

Table 3. Site Characteristics and Layout Details of the 8 Sites

Location	**Site ID**	**Approach**	**Street Name**	**Speed Limit, km/h**	**Lanes/ Direction**			**Lanes/ Approach**	**Total Lanes**	**Approach Slope, G%**	**Mean Slope, G%**	**Bitumen Pavement Quality**
					LT	T	RT					
1	3LS-1	NB	Al Sidr St.	80	3	3	1	7	28	1.9	-1.6	Excellent
		SB			3	3	1	7		-1.3		
		EB	Snay bu Hasa		3	3	1	7		-1.6		
		WB			3	3	1	7		-5.5		
2	3LR-1	NB	Al Sidr St.	80	1	1	1	3	11	1.9	-1.6	Good
		SB			1	1	1	3		-1.3		
		EB	Snay bu Hasa		1	1	0	2		-1.6		
		WB			1	1	1	3		-5.5		
3	2LS-1	NB	Al-Aziziya	50	1	1	1	3	12	0.6	0.7	Excellent
		SB			1	2	1	4		0.9		
		EB	Osama Bint Zaid St.		1	1	0	2		0.8		
		WB			1	1	1	3		0.5		
4	2LR-1	NB	Umm Al Seneem St.	80	1	1	0	2	8	1.2	1.1	Good
		SB			1	1	0	2		-0.7		
		EB	Khaled Bin Ahmed St.	50	1	1	0	2		2.1		
		WB			1	1	0	2		1.6		
5	3LS-2	NB	Jasim Bin Hamad St.	80	3	3	1	7	28	0.7	-0.3	Excellent
		SB			3	3	1	7		-1.3		
		EB	Al Jazira Al Arabiya St.		3	3	1	7		0.6		
		WB			3	3	1	7		-1.0		

Location	**Site ID**	**Approach**	**Street Name**	**Speed Limit, km/h**	**Lanes/ Direction**			**Lanes/ Approach**	**Total Lanes**	**Approach Slope, G%**	**Mean Slope, G%**	**Bitumen Pavement Quality**
					LT	T	RT					
6	3LR-2	NB	Al Sedaira St.	80	1	1	0	2	10	-1.1	-0.8	Good
		SB			1	1	0	2		-0.7		
		EB	Al Waab St.		1	1	1	3		-0.8		
		WB			1	1	1	3		-0.6		
7	2LS-1	NB	Al Zaghwa St.	80	1	2	1	4	16	-0.7	-0.9	Good
		SB		60	1	2	1	4		-0.5		
		EB	Zekreet St.		1	2	1	4		-0.6		
		WB			1	2	1	4		-1.8		
8	2LR-2	NB	Wadi Al Utooriya St.	50	1	1	0	2	8	0.6	-0.4	Good
		SB			1	1	0	2		-1.5		
		EB	Umm Al Seneem St.		1	1	0	2		-1.6		
		WB			1	1	0	2		1.1		

3.2. Variables

3.2.1. Traffic Noise Level

According to the WHO’s Guidelines for Community Noise, sound pressure levels of noises - which are essentially a measure of air vibrations causing a sound - are integrated over a time interval as they tend to fluctuate over time. The levels are measured on a logarithmic scale, with decibels (dB) as the unit, since the human ear can detect sound pressure levels as low as 10 Pascal and as high as 102 Pascal. As a result, all sound pressure measures are referenced to 1000 Hertz (Hz), the human hearing threshold, and imply how much the measured noises are above the hearing threshold (Berglund et al., 1999). Moreover, A-weighted noise measurements are known to cover the entire human audio range from 20 Hz to 20 kHz and as a result approximates the response of the human hearing system at lower sound levels (Berglund et al., 1999; Gracey & Associates, n.d.-b).

Likewise, to make all sound pressure measurements and their variations over time representative of the integration time of the human hearing system, the fast response time (corresponding to a time constant of 0.125 seconds) mode is used. The fast response also gives a good correlation between noise from passing vehicles and the integration of its loudness by the human ear (Berglund et al., 1999). Also, arithmetically adding or averaging sound pressure levels are not possible since they are measured on a logarithmic scale. Due to this, unlike arithmetic additions, the summation of two equal sound pressure levels does not double the total noise. Instead, in such a case, the total sound pressure level is only 3 dB greater than the individual sound pressure level (Berglund et al., 1999).

Thus, $L_{Aeq,T}$, the A-weighted equivalent continuous noise level over a certain duration T is the measure used to quantify the continuous noise generated from road traffic (Berglund et al., 1999; Gracey & Associates, n.d.-a). It is also commonly used as the descriptor of environmental noise in various noise control guidelines. Accordingly, the WHO provides an environment-specific guideline for community noise based on the expected critical health effects caused by equivalent noise levels. Guideline values are generally given for specific indoor or outdoor settings and periods. Likewise, the WHO recommends keeping road noise levels well below 65 dB(A) during daytime hours (6:00-22:00). Therefore, $L_{Aeq,16hr.}$ was the main variable used in this comparative study to analyze noise levels at the two intersection types.

In addition, when it comes to noise levels, only when the residual (positive or negative) is more than or equal to 5 dB(A), the noise level change is readily perceptible to an observer which otherwise would be barely perceptible to the human ear (U.S. Department of Transportation - Federal Highway Administration, 2017). Consequently, an increase or decrease of 10 dB(A) in noise level would be perceived as twice or half as loud respectively. For example, the noise level of 75 dB(A) to an observer would sound twice as loud as the sound at the allowable threshold of 65 dB(A). Hence, an increase of 20 dB(A) to an observer would be four times as loud (U.S. Department of Transportation - Federal Highway Administration, 2017).

Besides using $L_{Aeq.T}$ – the energy average descriptor for environmental noise, statistical average or the noise pollution indice – $L_{An,T}$ is also commonly used to analyze noise pollution due to road traffic. With $L_{An,T}$, the noise level which exceeds for n% of the time T is expressed in decibels, the value of n being anywhere between 0.01% and 99.99%. However, the most commonly used L_{AnT} to quantify road traffic noise levels and background noise levels are $L_{A10,T}$ and $L_{A90,T}$ respectively (Gracey & Associates, n.d.-a). By definition, $L_{A10,T}$ – the noise level exceeded for 10% of the time T – is used to measure the annoying peaks of the noise level in dB(A). It is a traffic noise descriptor that expresses the disturbance felt by people near busy traffic roads. On the other hand, $L_{A90,T}$ – the noise level exceeded for 90% of the time T – takes account of the noise levels in the background. Therefore, the variables $L_{A10,T}$ and $L_{A90,T}$ were used to further explain the $L_{Aeq,T}$ values.

3.2.2. Traffic Volume and Vehicle Type

Variables such as traffic volume and characteristics, approach speed, number of lanes, slope gradient, and pavement surface texture are some common factors used in noise level comparison or prediction studies done at traffic intersections (Abo-Qudais & Alhiary, 2007; Calixto et al., 2003; Obaidat, 2011) (Givargis & Mahmoodi, 2008; Quiñones-Bolaños et al., 2016). Consequently, these variables were collected during the 16-hr data collection periods along with the variable $L_{Aeq,T}$. Besides, since pairs of similar and most common traffic intersection types were selected for this case study, most of these variables were expected to remain similar between comparable sites. Nevertheless, traffic volume and characteristic were most likely to be the primary source of traffic noise variations observed at the intersections (Calixto et al., 2003; Obaidat, 2011; Quiñones-Bolaños et al., 2016) beside the intersection type. Since most city traffic nowadays are composed of a variety of different vehicle types, the traffic composition data extracted from the traffic volume data were mainly divided into sedan (S), SUV, single-unit truck (SUT), small bus (SB), large bus (LB), heavy truck (HT), and motorcycle (MC) – the seven most commonly found vehicle types in most major urban cities (Quiñones-Bolaños et al., 2016). For development of the prediction models, however, sedan, SUV, single-unit truck, small bus, and motorcycle were categorized as light vehicle type, whereas large bus and heavy truck were assumed to be heavy vehicle type.

3.3. Field Measurements

The equivalent sound pressure level, traffic volume, and weather data at the eight traffic intersections were recorded at 5-min intervals on eight weekdays and eight weekends from 6 AM until 10 PM (16 hours) to capture noise variations over morning (6:00-11:00), afternoon (11:00-16:00), and evening (16-22:00) hours including the green intervals. The overall data collection process is summarized in Figure 3.

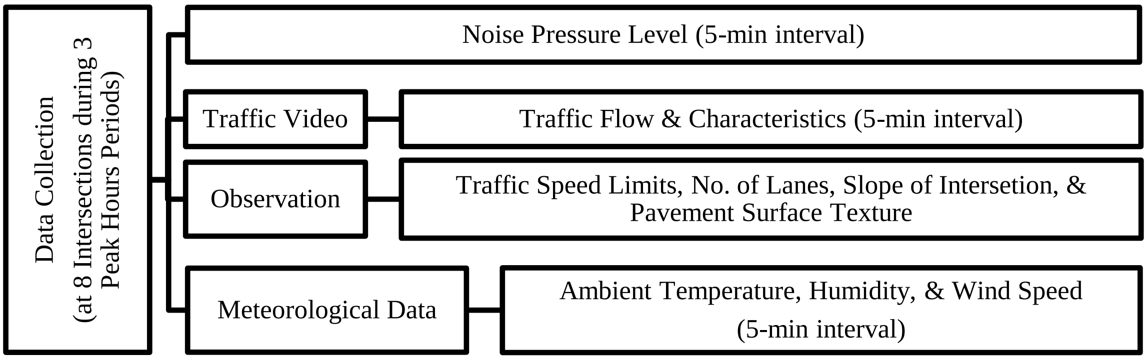


Figure 3. Flow chart for data collection.

Although the traffic noise level, volume, and weather data were recorded throughout the 16-hr periods, at first, only the mean 16-hr traffic noise level and weather data were analyzed to evaluate if the traffic noise levels were within the WHO's allowable threshold of 65 dB(A) for daytime (mean 16-hr) traffic noise levels. Next, while comparing the noise levels between the different traffic intersections, more importance was given to traffic noise levels generated by peak traffic hours. As a result, two different sets of morning (3 hours), afternoon (3 hours), and evening (3 hours) peak traffic periods for weekdays and weekends were selected based on 16-hr weekday and weekend peak traffic volume data extracted at the first site (3LS-1). Accordingly, for all other sites, corresponding to the recorded noise level measurements, the traffic volume data at all four approaches (northbound, southbound, eastbound, and westbound) of each intersection were extracted and divided into seven vehicle types at 5-min intervals from the captured video data during the selected three peak hours periods for weekdays and weekends respectively.

Besides, Type-II Cirrus Optimus Green CR1720 sound level meter (ranging 20 dB(A) to 140 dB(A)), Cirrus sound level calibrator CR514 (94.0 dB ± 0.4dB; 1kHz ± 1%), MioVision traffic video recording camera, and Kestrel weather meter 5500 were the main tools used for the purpose of data collection. Hence, the sound pressure levels were recorded at 5-min intervals including the green interval using the Sound Level Meter (SLM) set at 1.2 meters above the ground level and within 4 meters from the edge of the road at each of the eight intersections. The time history data rate of the SLM device was set at 1 second, that is, it measured noise level every 1 second within the 5-min intervals. In addition, the SLM was set to record equivalent (energy-average) measurements at A-weighting scale and Fast response mode. Furthermore, the 94 dB Sound Level Calibrator was used to calibrate the SLM before and after each measurement.

On the other hand, the corresponding 16-hr traffic flow data at the intersections, including the green intervals, were captured using the traffic video cameras recording the streams of traffic passing through every approach of the intersections. Traffic volumes during the data collection days were found to be regular, that is, data were not collected during vacation or public holiday periods. Also, in all cases, data were collected only on days with no rainfall to keep the data at all sites consistent and to avoid noise level recording errors related to wet roadways. Besides, other site factors such as traffic speed limits, slope, number of lanes, and pavement surface texture (good or excellent) for each approach at the intersections were also observed and discussed for comparison purposes.

Also, based on ISO Standards (1993, 1996), corrections for noise attenuation due to meteorological parameters such as ambient temperature, relative humidity, and wind speed would be required if the mean temperature and the relative humidity doesn’t fall between 20-40°C and 60-80% respectively, and if the wind speed is not less than 4 m/s at the time of noise level data collection period (ISO, 1993, 1996; Quiñones-Bolaños et al., 2016). Consequently, corresponding to the recorded noise level measurements, meteorological data such as the mean ambient temperature, humidity, and wind speed at all the sites were recorded using a professional weather meter during the same 16-hr periods. Since the mean temperature, relative humidity, and wind speed were found to be 29.2°C, 65.2%, and 0.8 m/s respectively (see Table 4), correction for noise attenuation due to the meteorological parameters were not required for this study.

Table 4. Mean Temperature, Relative Humidity, and Wind Speed at the 8 Sites

Site ID	**Weekday Site Avg. (n=16)**			**Weekend Site Avg. (n=16)**			**Site Avg. (n=32)**		
	Temp. (°C)	Rel. Hum. (%)	Wind (m/s)	Temp. (°C)	Rel. Hum. (%)	Wind (m/s)	Temp. (°C)	Rel. Hum. (%)	Wind (m/s)
3LS-1	32.2	70.2	0.7	32.0	69.7	0.8	32.1	70.0	0.7
3LR-1	39.9	62.3	0.5	37.2	60.5	0.4	38.6	61.4	0.4
2LS-1	27.6	61.8	1.7	30.6	73.1	0.5	29.1	67.5	1.1
2LR-1	31.1	60.6	0.7	28.3	66.6	1.3	29.7	63.6	1.0
3LS-2	30.9	60.7	1.1	31.5	61.8	0.6	31.2	61.3	0.9
3LR-2	32.9	64.6	0.7	30.8	67.4	0.8	31.9	66.0	0.8
2LS-2	24.5	62.8	1.3	27.4	71.5	0.4	25.9	67.1	0.9
2LR-2	25.6	61.3	0.5	26.8	60.7	0.5	26.2	61.0	0.5
Mean	30.6	63.0	0.9	30.6	66.4	0.7	30.6	64.7	0.8

CHAPTER 4: A BEFORE-AND-AFTER TRAFFIC NOISE ANALYSIS

4.1. Introduction

Comparing noise levels at the same traffic intersection before and after the intersection type is changed could help identify the intersection type that generates higher traffic noise since most other site conditions except the intersection type would remain constant in this case. On the other hand, Qatar government has been converting major roundabouts in Doha, the capital and the busiest city in Qatar, with signalized intersections or freeways at a fast pace to reduce serious traffic congestions observed in the city during peak hours of the day (Khaled Shaaban et al., 2019). As a result, this study took the rare opportunity of conducting a novel comparative case study at one of the few remaining major three-lane roundabouts in Doha that was being converted to a three-lane signal. Accordingly, the results of the before-and-after traffic noise level study done at the selected traffic intersection is presented in this chapter.

4.2. Methodology

This study took advantage of conducting a before-and-after noise level study at one of the few remaining roundabouts in Doha before and after it was converted to a signalized intersection. Besides being a rare and novel opportunity, analysis of the two data sets was expected to be insightful and advantageous in terms of comparing traffic noise levels at the two major intersection types.

4.2.1. Case Study

As a case study, the equivalent traffic noise level, weather, traffic, and other relevant site data at a three-lane roundabout in Doha, Qatar just before and six months after it was converted to a three-lane signalized intersection were collected for 16 hours (6:00-22:00) at 5-min intervals on both weekday and weekend. The selected traffic intersection was situated between Al Waab Street and Al Sidr Street in Doha, Qatar.

The three-lane intersection was a busy and critical intersection connecting major city blocks in the capital. The land-use in the surrounding area was found to be residential with rows of low-rise buildings and some open areas. Moreover, the data collection points at the signal (see Figure 4 (b)) were slightly different from the roundabout (see Figure 4 (a)) to accommodate the geometric changes caused by the removal of the circular central island of the roundabout and the addition of newer lanes and the signalized traffic junction.

(a) Satellite view of the roundabout (b) Satellite view of the signal

Figure 4. Aerial view of the site before and after.

4.2.2. Variables

The main comparison variable used in this study was $L_{Aeq.}$, an A-weighted equivalent continuous noise level. In addition, the noise pollution indices, $L_{A10,T}$ and $L_{A90,T}$ were also statistically calculated from $L_{Aeq.}$ to quantify annoyance and background noise level observed at the traffic intersection respectively. Corresponding to the collection time of $L_{Aeq.}$, the other main contributing variable, traffic volume (with the vehicle type) was also collected for analysis (see Chapter 3 for more details).

4.2.3. Field Measurements

The sound pressure levels, traffic flow, and weather data were recorded at the intersection (roundabout and signal) on 2 weekdays and 2 weekends from 6 AM until 10 PM (16 hours). The corresponding traffic flow volumes and characteristics at all approaches were then extracted from the captured 16 hourly video data. Other factors such as speed limit, total number of lanes, slope, and pavement surface texture (good or excellent) for each approach were also observed (see Chapter 3 for more details). Besides, the mean ambient temperature, relative humidity, and wind speed at the intersection was 35.3°C, 65.7%, and 0.6 m/s respectively (see Table 5). Hence, corrections to noise attenuation due to the meteorological parameters were not required for this case study (ISO, 1993, 1996; Quiñones-Bolaños et al., 2016). (ISO, 1993, 1996).

Table 5. Summary of Weather Parameters at the Roundabout and the Signal

Site/Day	**Roundabout**			**Signal**		
	Weekday (16-Hr)	Weekend (16-Hr)	Mean (32-Hr)	Weekday (16-Hr)	Weekend (16-Hr)	Mean (32-Hr)
Temperature (°C)	39.9	37.2	38.6	32.2	32.0	32.1
Relative Humidity (%)	62.3	60.5	61.4	70.2	69.7	70.0
Wind Speed (m/s)	0.5	0.4	0.4	0.7	0.8	0.7

4.3. Analysis

Through a series of statistical evaluations, comparative analyses were done between the four data sets of weekday and weekend traffic noise level and traffic volume data at the roundabout and the signal to find out which intersection type contributed to higher noise levels and why. Additionally, the most likely reasons for the noise level variations observed within and between the data sets were also discussed.

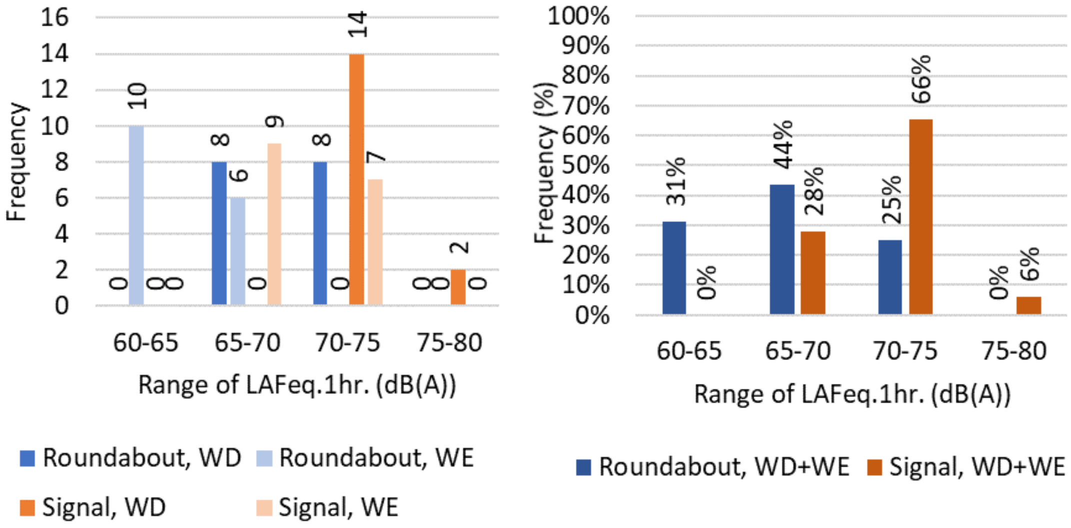
Since variables such as the pavement quality, speed limit, number of lanes, approach gradient, and other site characteristics at the roundabout and the signal were found to be mostly similar, traffic volume and composition were assumed to be the main contributing variables towards traffic noise generation at the intersections beside the intersection type itself. As a result, the four sets of 16 hourly equivalent noise pressure level and traffic volume data collected at the roundabout and the signal on the two weekdays and two weekends respectively were mainly analyzed in this case study to determine which intersection type generated more traffic noise.

First, the existence and the extent of the mean 5-hr morning, 5-hr afternoon, 6-hr evening, and 16-hr daytime traffic noise pollution levels at the roundabout and the signal were investigated based on the WHO's allowable daytime noise level threshold of 65 dB(A) through bar charts and histograms. Also, the background and the annoyance noise levels found at the intersections were analyzed based on noise pollution indices statistically calculated from the 16 hourly equivalent noise level data. Then, the four sets of 16 hourly traffic volume data were extracted from recorded traffic videos and split into seven vehicle categories. The hourly and the mean traffic composition variations over the four 16-hr periods were then discussed. That is, the weekday and the weekend noise level data and the traffic volume data found at the roundabout and the signal were evaluated separately until this point.

Second, the two main variables – noise level and traffic volume - were evaluated together, starting with a comparison of common descriptive statistics for hourly and mean data. Then, line charts of the 16 hourly and the 5-min noise levels versus the corresponding traffic volumes at the roundabout and the signal were studied to observe the relationship between the two variables. Any trend discrepancies observed between the two variables during hourly comparisons were checked and analyzed based on the rate of increase or decrease in the noise level due to the increase or decrease in corresponding traffic volume respectively from one hour to the next. Finally, a summary of the distribution of the 16-hr noise levels and traffic volumes was discussed. In addition, the four sets of mean 16-hr noise level versus traffic volume were compared with a bubble chart to show the combined differences between the four data sets.

4.3.1. Traffic Noise Level

The percent frequency of occurrence or the distribution of all $L_{AFeq.1hr.}$ values, that is, 16 hourly noise level data per day per intersection were illustrated with the help of histograms (see Figure 5). Depending on the range of $L_{AFeq.1hr.}$ values, four equally sized (5dB(A)) bins/buckets/intervals were created starting from 60 dB(A) to 80 dB(A). 68.8 dB(A) and 72.4 dB(A) were the combined weekday and weekend mean $L_{AFeq.1hr.}$ values at the roundabout and the signal respectively.

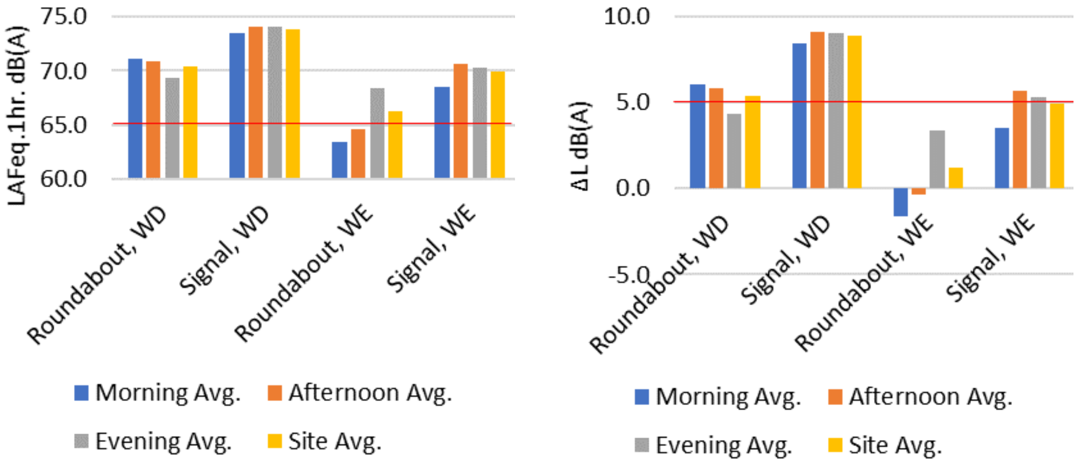


(a) Weekday and weekend histograms (b) Combined histograms

Figure 5. Histogram of hourly noise levels at the roundabout and the signal (n=16-hr/day/site).

Also, both weekday and the weekend values at the roundabout ranged between 60 and 75 dB(A) whereas for the signal the range was between 65 and 80 dB(A), that is, 5 dB(A) higher than the range of roundabout. Overall, weekdays had higher percent frequencies on the higher bin values for both the roundabout (65-70 and 70-75) and the signal (70-75 and 75-80). Whereas, the weekend percent frequencies were higher on the lower side of the bins for the roundabout (60-65 and 65-70) and the signal (65-70 and 70-75). Likewise, the combined % frequencies were also comparatively higher on the lower side of the bins.

Regardless, the majority (44% and 66%) of the combined weekday and weekend values for the roundabout and the signal were in the (65-70) dB(A) and (70-75) dB(A) bins respectively indicating that most of the hourly noise levels not only exceeded the allowable threshold of 65 dB(A) but did so with high values, especially on weekdays and at the signal. Moreover, the mean 16-hr weekday traffic noise levels at the roundabout and the signal exceeded the WHO’s acceptable daytime noise level threshold of 65 dB(A) by 5.4 dB(A) and 8.9 dB(A) respectively (see Figure 6 (a)). Likewise, on the weekend, the mean noise levels exceeded by 1.2 dB(A) and 5.0 dB(A) respectively. The noise levels at the signal were found to exceed the noise levels observed at the roundabout throughout the 16-hr period on both weekday and weekend. The weekday and weekend mean afternoon (11:00-16:00) and evening (16-22:00) noise levels observed at the signal were mostly similar, that is, around 74.1 dB(A) and 70.5 dB(A) respectively. Likewise, the weekday (73.4 dB(A)) and the weekend (68.6 dB(A)) morning (6:00-11:00) mean noise levels were lower in comparison. On the other hand, no such trends within the various mean values were observed at the roundabout. Nonetheless, the weekday and the weekend mean values throughout the day were around 70 dB(A) and 65 dB(A) respectively. Also, on the weekend, the mean morning and afternoon values at the roundabout were below 65 dB(A) with a comparatively higher evening mean noise level of 68.4 dB(A).

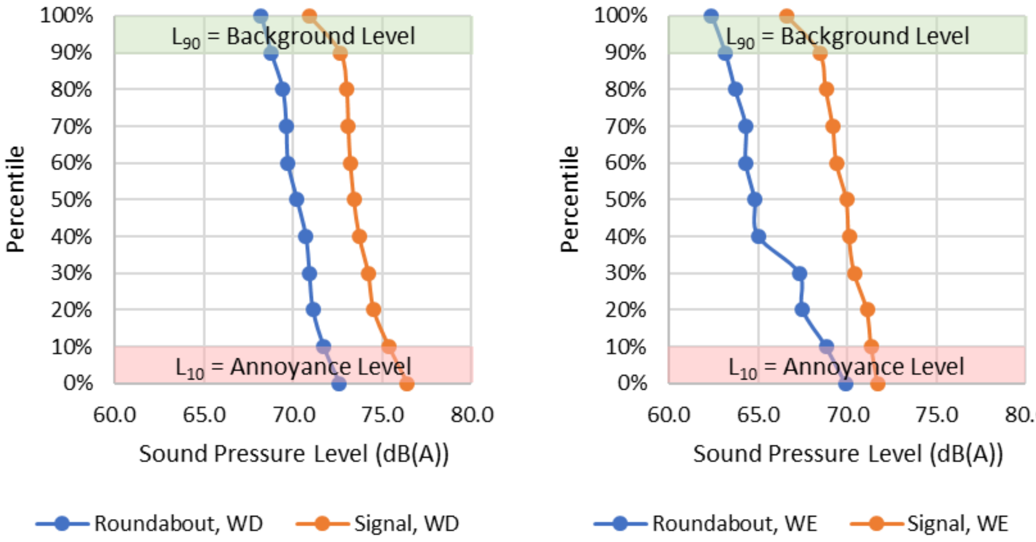


(a) Mean noise levels, $L_{AFeq.1hr.}$, dB(A) (b) Residuals, (65 - $L_{AFeq.1hr.}$) dB(A)

Figure 6. Mean noise levels and residual noise levels at the roundabout and the signal.

Besides, similar conclusions could be drawn from the weekday and weekend residual values as they were directly related to the noise levels. However, the residuals (see Figure 6 (b)) additionally provided a sense of how an observer at these intersections would perceive the varying noise level differences from the allowable threshold of 65 dB(A). Most of the weekday residual values at the roundabout and most of the weekend values at the signal were equal to or above 5 dB(A) indicating that the increase in the noise levels from the allowable threshold in these cases were readily perceptible to an observer. On the other hand, all the residual weekend values at the roundabout to an observer would be barely perceivable as they were less than 5 dB(A). Whereas, the weekday residual values at the signal were expected to be perceived as almost twice as loud since they were close to 10 dB(A)). To sum up, the weekend residuals were barely perceivable at the roundabout and just perceivable at the signal. Whereas, the weekday residual were just perceivable at the roundabout and almost doubly perceivable at the signal.

In addition, the data were used to find the weekday and the weekend annoyance noise levels and the background noise levels from the 16 hourly noise level measurements collected at the roundabout and the signal respectively. The resulting weekday and weekend noise pollution indice, $LA_{n,1hr.}$ found as percentiles were plotted against the corresponding noise levels as shown in Figure 7 (a) and (b) respectively. The statistical distribution of weekday noise levels showed that the background noise levels were between 68.2 dB(A) and 68.8 dB(A) at the roundabout, the quieter of the two intersections, based on $LA_{90,1hr}$ data. On the other hand, the annoyance noise levels at the signal was between 73.0 dB(A) and 78.2 dB(A) due to $LA_{10,1hr.}$ noise data.



(a) Weekday (b) Weekend

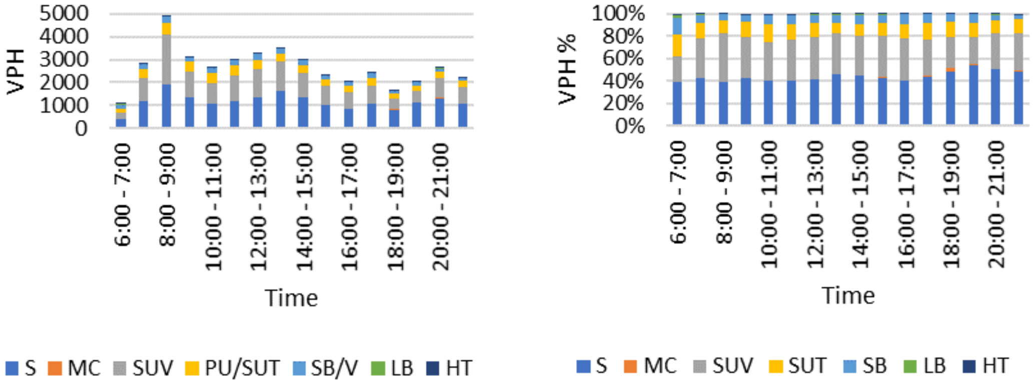
Figure 7. Distribution of noise levels at the roundabout and the signal (16-hr/site/day).

On the other hand, based on the statistical distribution of weekend noise levels, the background noise levels at the roundabout, once again the quieter intersection, was between 63.5 dB(A) and 64.9 dB(A) due to $L_{A90,1hr.}$ data. The annoyance noise levels in this case was between 71.4 dB(A) and 71.7 dB(A) due to traffic at the noisier signalized intersection.

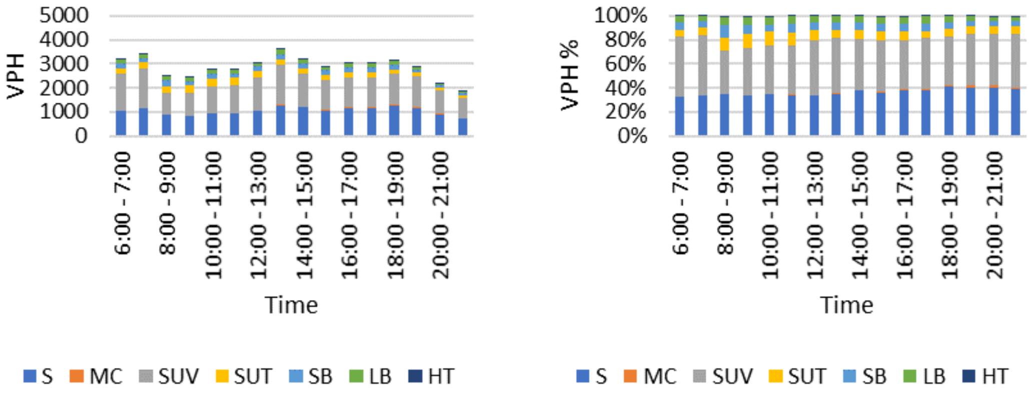
Afterward, to check if the mean group noise for the before case significantly different from the after case, a two-tailed paired t-test was conducted. The null hypothesis was that the mean noise for the before case did not differ significantly from the after case. The paired t-test returned a t-statistic of -15.110 and a p-value of 0.02, so the null hypothesis could not be rejected at a 0.05 probability of Type-I error (α). Therefore, the noise for the before case did differ significantly from that of the after case.

4.3.2. Traffic Volume and Vehicle Type

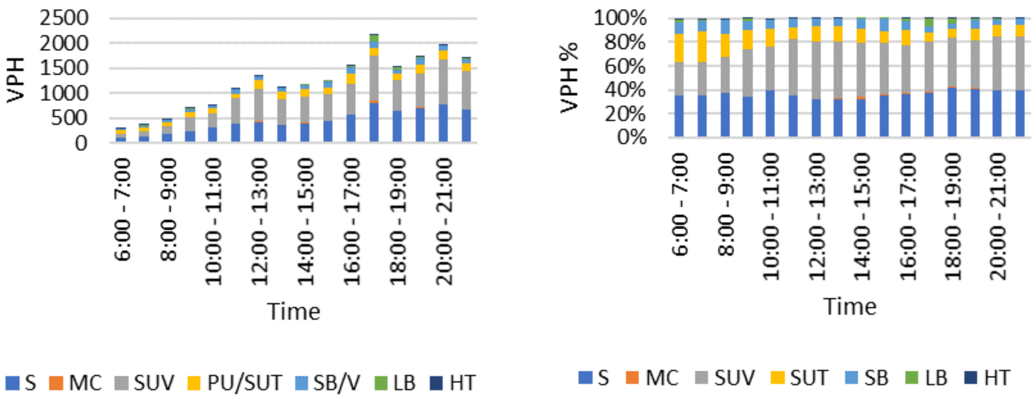
Besides the hourly traffic volumes, hourly traffic compositions were also expected to be a contributing factor to the overall noise levels found at the intersections. Consequently, the weekday and the weekend traffic volume composition and the percent traffic composition at the roundabout and the signal over a period of 16 hours were illustrated in Figure 8 with the help of bar charts. The hourly traffic volume distribution over the 16 hours at the roundabout and the signal appeared almost similar on weekdays and weekends respectively.



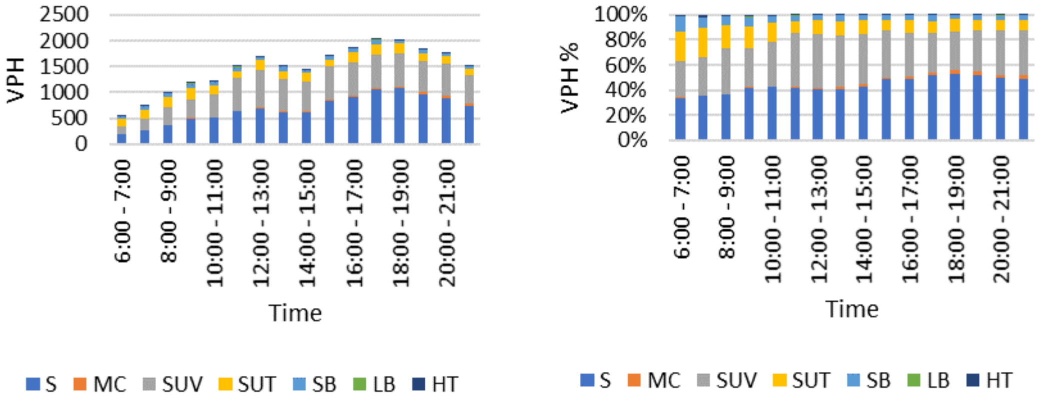
(a) Roundabout (weekday)



(b) Signal (weekday)



(c) Roundabout (weekend)



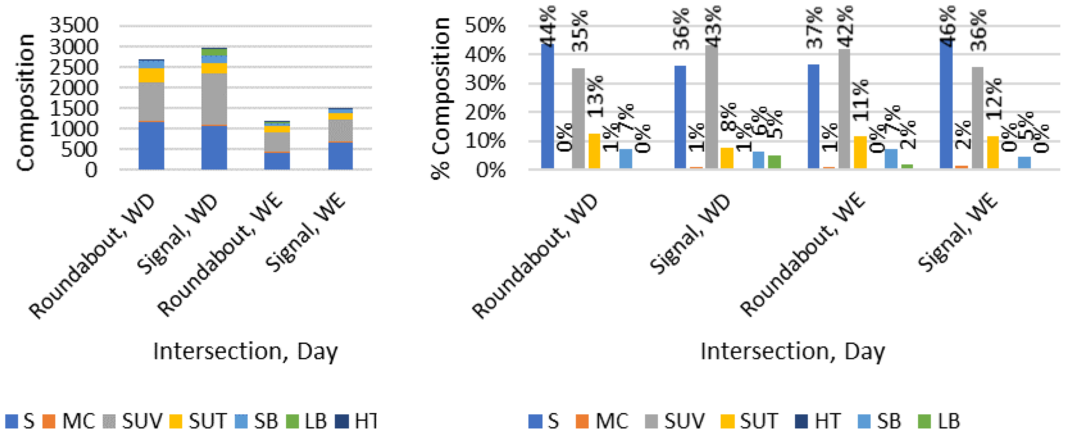
(d) Signal (weekend)

Figure 8. Hourly traffic composition and percent hourly traffic composition at the roundabout and the signal.

Also, in all cases, it was commonly observed that sedans (S) and SUV made up the majority of the composition followed by comparatively fewer numbers of single-unit trucks (SUT) and small buses (SB). The percentage of sedans were higher than SUV in some cases and vice versa. The same was true for single-unit trucks and small buses. The numbers of large buses (LB), heavy trucks (HT), and motorcycle (MC) were the least. Therefore, it was expected that sedan and SUV type vehicles contributed the most to the resulting noise at the roundabout and the signal. However, further analysis of the composition distribution of the vehicle types with corresponding noise levels is required to say if and how much the traffic composition contributed to the noise levels observed at the intersections.

Likewise, similar conclusions could be drawn from the mean hourly traffic composition and percent composition bar charts (see Figure 9). However, the similarities between the traffic volumes and compositions observed at the roundabout and the signal on weekday and weekend respectively were more clearly depicted by these mean charts. The weekday mean traffic volume at the roundabout (2669 vehicle/hr) and the signal (2875 vehicle/hr) were found to be quite similar. Moreover, the weekend mean volumes at the roundabout (1194 vehicle/hr) and the signal (1473 vehicle/hr) were again very similar and almost half the weekday volumes. Consequently, the traffic volume conditions in this case study remained mostly similar as initially expected. In terms of before-and-after comparison of traffic noise levels done at the same traffic intersection, such similarities in traffic composition and distribution were expected to be valuable.

Again, like the percent composition distributions in Figure 9, in all cases the mean percent composition distributions for sedans (S) and SUV were interchangeably the highest followed by single-unit trucks (SUT) and small buses (SB) and much lower percentages of large buses (LB), heavy trucks (HT), and motorcycle (MC).



(a) Composition count (b) Percent composition

Figure 9. 16-hr mean traffic composition count and percent composition at the roundabout and the signal.

4.3.3. Traffic Noise Level VS Traffic Volume

Table 6 tabulates the hourly, mean morning (5-hr), mean afternoon (5-hr), mean evening (6-hr) traffic noise level and volume values along with a summary of descriptive statistics found for the 4 sets of 16 hourly traffic noise and volume data collected at the roundabout and the signal on weekday and weekend respectively from 6 AM to 22 PM. Perceivable hourly noise level differences (above 5dB(A)) were observed between the roundabout and the signal ranging 0.9~6.8 dB(A) and 0.6~7.4 dB(A) on weekday and weekend respectively. On the other hand, the 16 hourly and mean 16-hr traffic volumes at the roundabout and signal were almost similar on weekday and weekend respectively. This indicated that traffic characteristics at the roundabout and the signal did not drastically change as expected.

In addition, some recurring patterns were observed from the overall analysis in Table 6. For instance, on the weekday, the afternoon and the evening mean values were mostly the highest and the lowest respectively at both the signal and the roundabout. Whereas the pattern changed on the weekend seemingly due to higher mean traffic volumes during evening and lower volumes during the morning period. Also, based on descriptive statistics of 16 hourly data/intersection/day, during early morning hours (6:00-7:00) or late evening hour (20:00-22:00), the noise level and the traffic volume were the minimum. Whereas, the values were maximum between late morning and early evening hours (8:00-18:00).

Besides, it was observed that the highest or the lowest hourly noise level did not always directly correspond to the highest or the lowest hourly traffic volume respectively. For instance, on the weekday, the maximum hourly volume (4915 vph) was observed at the roundabout, but the hourly noise level was found to be maximum (76.4 dB(A) at the signal. The same was true for the maximum hourly weekend values. Nevertheless, there was an overall positive relationship between the two variables. For example, on the weekend, both the hourly noise (1076 vph) and volume (68.2 dB(A)) were minimum at the roundabout and the same pattern was found during the weekend as well.

Additionally, although the range of volume was the highest (3839 vph) at the roundabout on the weekday, the range of noise level was the lowest (4.4 dB(A)). On the contrary, on the weekend, both the lowest range of volume (1474 vph) and noise level (5.1 dB(A)) were found at the signal and the highest ranges were found at the roundabout. Moreover, on the weekday, the mean 16-hr volume and noise level were higher at the signal (2875 vph and 73.9 dB(A)) than the roundabout (2699 vph and 70.4 dB(A)). Similarly, on the weekend, the mean traffic volume and noise level at the signal (1473 vph and 70.0 dB(A)) exceeded the mean values at the roundabout (1194 vph and 66.2 dB(A)).

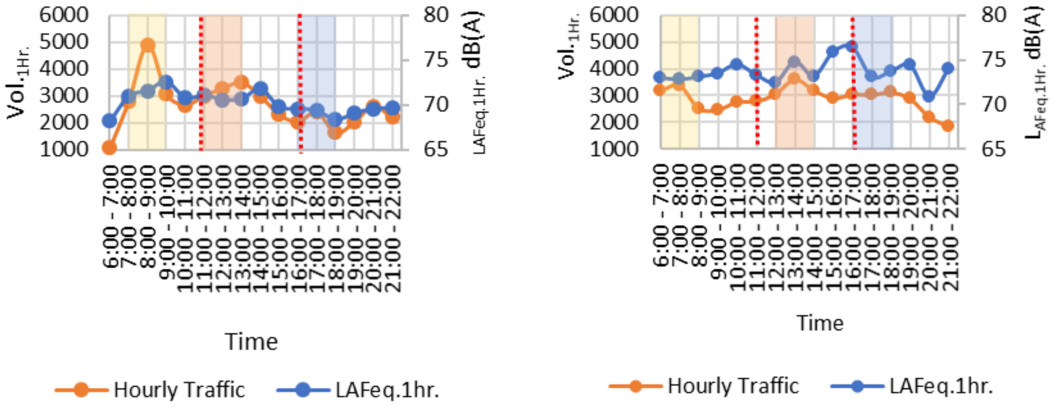
Table 6. Descriptive Statistics of 16 Hourly Traffic Noise Level and Volume at the Roundabout and the Signal

Intersection, Day		**Roundabout, WD**		**Signal, WD**		**Roundabout, WE**		**Signal, WE**	
Time		Vol.$_{1hr}$	$L_{AFeq.1hr}$	Vol.$_{1hr}$	$L_{AFeq.1hr}$	Vol.$_{1hr}$	$L_{AFeq.1hr}$	Vol.$_{1hr}$	$L_{AFeq.1hr}$
Morning	6:00-7:00	1076	68.2	3170	73	295	62.4	550	66.6
	7:00-8:00	2816	71	3387	72.8	351	63.1	749	68.4
	8:00-9:00	4915	71.6	2524	73.1	481	63.2	987	68.8
	9:00-10:00	3099	72.6	2470	73.5	685	64.3	1191	69.1
	10:00-11:00	2670	70.8	2766	74.5	759	63.7	1218	69.4
Afternoon	11:00-12:00	3013	71.1	2784	73.3	1073	64.9	1502	68.5
	12:00-13:00	3287	70.6	3061	72.5	1338	64.7	1691	70.1
	13:00-14:00	3505	70.7	3608	74.8	1095	65	1498	71.2
	14:00-15:00	3002	71.8	3195	73.2	1169	64.3	1440	71.1
	15:00-16:00	2315	69.8	2906	75.9	1240	64.3	1713	71.7
Evening	16:00-17:00	2057	69.6	3043	76.4	1549	67.4	1860	71.5
	17:00-18:00	2417	69.4	3026	73.1	2172	69.4	2024	70.4
	18:00-19:00	1638	68.4	3119	73.7	1524	67.5	2015	70.4
	19:00-20:00	2042	69.1	2884	74.4	1537	67.2	1838	69.9
	20:00-21:00	2630	69.6	2204	70.9	1762	68.2	1772	70
	21:00-22:00	2216	69.7	1857	74	1686	69.9	1522	69.3
Mean	Morning	2915	71.1	2863	73.4	514	63.4	939	68.6
	Afternoon	3024	70.8	3111	74.1	1183	64.6	1569	70.7
	Evening	2167	69.3	2689	74.1	1705	68.4	1839	70.3
Descriptive Statistics	Mean	2699	70.4	2875	73.9	1194	66.2	1473	70
	Max.	4915	72.6	3608	76.4	2172	69.9	2024	71.7
	Min.	1076	68.2	1857	70.9	295	62.4	550	66.6
	Range	3839	4.4	1751	5.5	1877	7.5	1474	5.1
	SD	869	1.2	442	1.3	541	2.3	435	1.3
	CV	32%	1.7%	15%	1.8%	45%	3.5%	30%	1.9%
	SE	217	0.3	110	0.3	135	0.6	109	0.3

However, the maximum weekday standard deviation (SD), coefficient of variance (CV), and standard error (SE) for volume and noise were found at the roundabout and the signal respectively. On the other hand, the maximum and the minimum weekend values were found at the roundabout and the signal respectively. Since the SD varied significantly from one set of data to another, the ratio of SD to the mean or the CV was used to compare relative variability between the data sets.

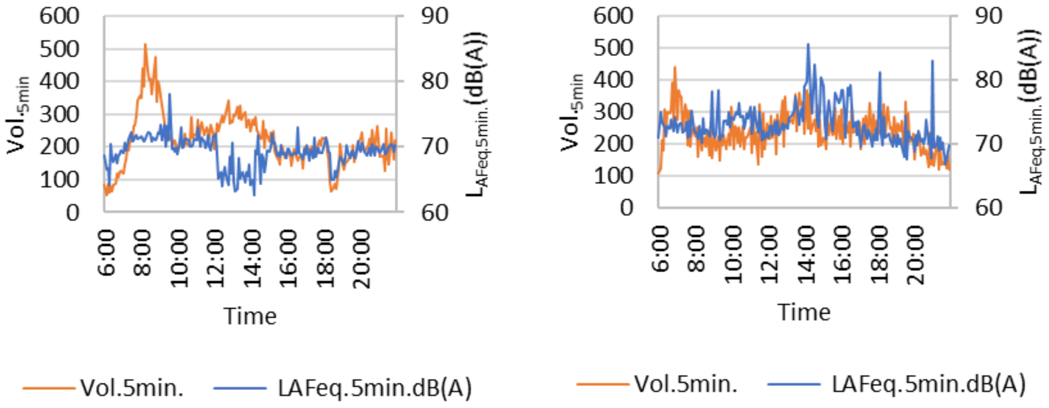
As such, variations in traffic volumes were higher at the roundabout (32~45%) than the signal (15~30%) on both weekday and weekend. Whereas, the noise variations observed at the roundabout and the signal were almost similar (1.7~1.8%) on the weekday and much higher at the roundabout (3.5%) than at the signal (1.9%) on the weekend. Lastly, the range of values of standard error for the traffic volume (109~217 vph) and noise level (0.3~0.6 dB(A)) at the intersections were still quite low.

Furthermore, the hourly and the 5-min traffic noise level data and traffic volume data were plotted as combined line graphs with similar axes ranges and intervals in order to compare and observe the overall relationship between the two variables over a period of 16 hours (see Figure 10). The hourly or 5-min traffic volumes were mostly within similar ranges at the roundabout and the signal on weekday and weekend respectively. This confirmed the assumption that in a before-and-after study conducted at the same intersection, similar traffic characteristics would be observed before and after the conversion. Likewise, the range of traffic noise levels was also more similar at the roundabout and the signal during weekdays and weekends respectively.

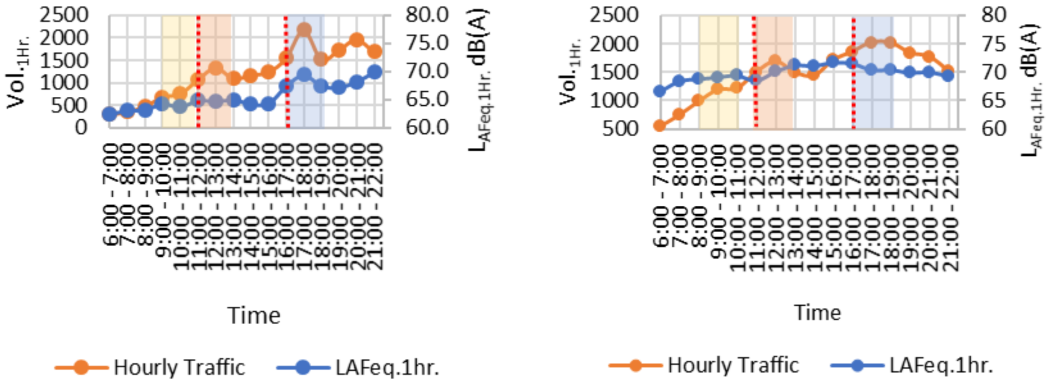


(a) Roundabout (Weekday) – 1hr.

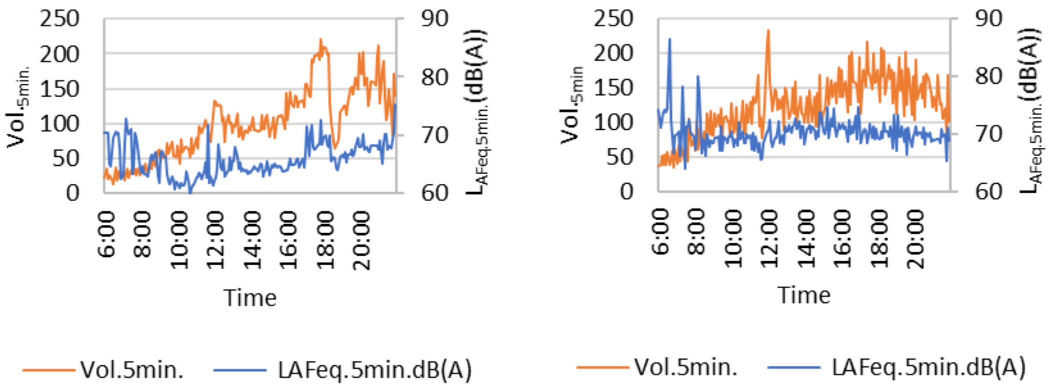
(b) Signal (Weekday) – 1hr.



(c) Roundabout (Weekday) – 5-min (d) Signal (Weekday) – 5-min



(e) Roundabout (Weekend) – 1-hr (f) Signal (Weekend) – 1-hr



(g) Roundabout (Weekend) – 5-min (h) Signal (Weekend) – 5-min

Figure 10. Hourly and 5-min noise level versus traffic count at the roundabout and the signal (n=16-hr/site/day).

Nonetheless, the weekday hourly noise levels were slightly higher at the signal (around 75 dB(A)) compared to the roundabout (around 70 dB(A)). Again, the weekend hourly noise levels were comparatively higher at the signal roundabout (around 70 dB(A)) than the roundabout (around 65 dB(A)). Likewise, the hourly weekday volumes at the signal (around 3000 vph) were also slightly higher than the roundabout (around 2500 vph). Similarly, the hourly weekend volumes at the signal (around 1500 vph) were also slightly more than that at the roundabout (around 1000 vph). Higher values at the signal could be attributed to the geometric layout of the intersection, traffic signal stop-and-go periods, and the presence of more turning lanes at the signalized intersection and not the roundabout.

Moreover, the 16 hours period was divided into three 5-6 hours intervals: 6 AM – 11 AM were defined as morning hours, 11 AM – 16 PM were the afternoon hours, and 18 PM – 22 PM were defined as evening period. On the hourly graphs, the peak three hours for morning, afternoon, and evening periods were indicated (with orange, yellow and blue box respectively) in each of the four cases based on maximum hourly traffic counts. It was observed that the morning peak three hours at the roundabout, and the signal differed only by an hour on weekday and weekend respectively. Whereas, the afternoon and evening peak three hours overlapped at both the intersections on weekday and weekend. In addition, the overall traffic counts and the noise levels were lower during the evening periods (16:00-22:00) of weekdays and the morning period (6:00-12:00) of the weekend.

To sum up, an overall observation of the hourly and 5-min graphs show that the noise levels and the traffic volumes were mostly positively related over the 16 hours period, that is, as one goes high the other also follows a similar trend and vice versa. Although the noise and traffic count curves mostly matched, some inconsistencies in the generally positive relationship between the two variables were observed, which could be seen more pronounced in the 5-min graphs. These were most likely to be a factor of hourly traffic compositions or other site characteristics. Nonetheless, both the hourly noise levels and volumes were lower at the roundabout than the signal regardless of the day.

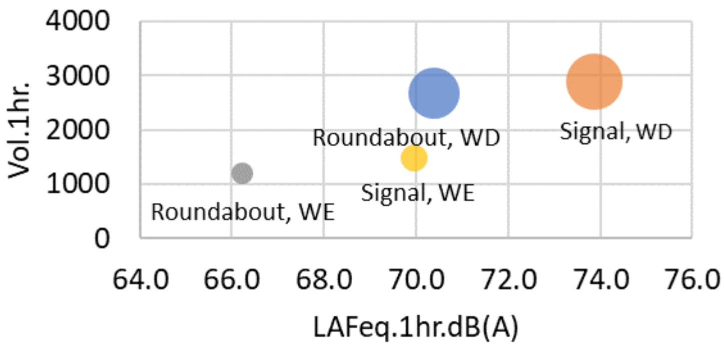
The trend discrepancies (indicated by bold text) observed between the two variables were checked and analyzed based on the increase or decrease in noise level (ΔNoise) due to an increase or decrease in corresponding traffic volume (ΔVol.) from one hour to the next (see Table 7). Results showed that in all cases the change in the noise levels from one hour to the next were barely perceivable as they were all below 5 dB(A) (WHO). Nonetheless, the relationship between the two variables, although mostly positive, were sometimes negative most likely due to some other contributing variable besides the traffic count. Hence, the reasons behind such discrepancies still need to be further analyzed.

Also, the 16-hr mean difference between the noise level and the volume at the roundabout were compared to the mean values found at the signal for weekday and weekend respectively. The mean 16-hr traffic noise level corresponding to the mean traffic volume at the signal was found to exceed the roundabout by 3.5 dB(A), the traffic volume at the signal being 8% more (207 vehicles). Similarly, on the weekend, the mean traffic noise level corresponding to the mean traffic volume at the signal exceeded the roundabout by 3.7 dB(A) due to 23% more (279 vehicles) traffic volume at the signal.

Table 7. Change of Hourly $L_{AFeq.1hr.}$ with Respect to Change of Hourly Vol.$_{1hr.}$ at the Roundabout and the Signal

Variable (1hr.)	**Vol.** vph	**$L_{AFeq.}$** dB(A)	**ΔVol.** vph	**ΔNoise** dB(A)	**Vol.** vph	**$L_{AFeq.}$** dB(A)	**ΔVol.** vph	**ΔNoise** dB(A)
Time	**Roundabout (Weekday)**				**Roundabout (Weekend)**			
6:00-7:00	1076	68.2			295	62.4		
7:00-8:00	2816	71.0	1740	2.8	351	63.1	56	0.7
8:00-9:00	4915	71.6	2099	0.6	481	63.2	130	0.1
9:00-10:00	3099	72.6	**-1816**	**1.0**	685	64.3	204	1.1
10:00-11:00	2670	70.8	-429	-1.8	759	63.7	**74**	**-0.6**
11:00-12:00	3013	71.1	343	0.3	1073	64.9	314	1.2
12:00-13:00	3287	70.6	**274**	**-0.5**	1338	64.7	**265**	**-0.2**
13:00-14:00	3505	70.7	218	0.1	1095	65.0	**-243**	**0.3**
14:00-15:00	3002	71.8	**-503**	**1.1**	1169	64.3	**74**	**-0.7**
15:00-16:00	2315	69.8	-687	-2.0	1240	64.3	71	0.0
16:00-17:00	2057	69.6	-258	-0.2	1549	67.4	309	3.1
17:00-18:00	2417	69.4	**360**	**-0.2**	2172	69.4	623	2.0
18:00-19:00	1638	68.4	-779	-1.0	1524	67.5	-648	-1.9
19:00-20:00	2042	69.1	404	0.7	1726	67.2	**202**	**-0.3**
20:00-21:00	2630	69.6	588	0.5	1962	68.2	236	1.0
21:00-22:00	2216	69.7	**-414**	**0.1**	1686	69.9	**-277**	**1.7**
Time	**Signal (Weekday)**				**Signal (Weekend)**			
6:00-7:00	3170	73.0			550	66.6		
7:00-8:00	3387	72.8	**217**	**-0.2**	749	68.4	199	1.8
8:00-9:00	2524	73.1	**-863**	**0.3**	987	68.8	238	0.4
9:00-10:00	2470	73.5	**-54**	**0.4**	1191	69.1	204	0.3
10:00-11:00	2766	74.5	296	1.0	1218	69.4	27	0.3
11:00-12:00	2784	73.3	**18**	**-1.2**	1502	68.5	**284**	**-0.9**
12:00-13:00	3061	72.5	**277**	**-0.8**	1691	70.1	189	1.6
13:00-14:00	3608	74.8	547	2.3	1498	71.2	**-193**	**1.1**
14:00-15:00	3195	73.2	**-413**	**-1.6**	1440	71.1	-58	-0.1
15:00-16:00	2906	75.9	**-289**	**2.7**	1713	71.7	273	0.6
16:00-17:00	3043	76.4	137	0.5	1860	71.5	**147**	**-0.2**
17:00-18:00	3026	73.1	-17	-3.3	2024	70.4	**164**	**-1.1**
18:00-19:00	3119	73.7	93	0.6	2015	70.4	**-9**	**0.0**
19:00-20:00	2884	74.4	**-235**	**0.7**	1838	69.9	-177	-0.5
20:00-21:00	2204	70.9	-680	-3.5	1772	70.0	**-66**	**0.1**
21:00-22:00	1857	74.0	**-347**	**3.1**	1522	69.3	-250	-0.7
Mean 16-Hr	**Roundabout VS Signal (Weekday)**				**Roundabout VS Signal (Weekend)**			
Roundabout	70.4	2669			66.2	1194		
Signal	73.9	2875	207	3.5	70.0	1473	279	3.7

Besides, the four sets of 16-hr mean values of the hourly traffic noise levels and volumes were plotted in a bubble chart (see Figure 11) to display the third dimension of the data, the product of the traffic noise and volume data, represented by bubbles of different sizes found as a factor of the product. As a result, the combined differences between the mean values of the four data sets were more visually comprehensible from this chart.



*Size of the Bubbles = A factor of Noise x Vol.

Figure 11. $L_{AFeq.1hr.}$ versus $Vol._{1hr.}$ (16-hr mean).

To summarize, both the 16-hr mean traffic noise level and volume on weekday and weekend at the signal exceeded the 16-hr mean values found at the roundabout respectively. Hence, the conversion of the roundabout to the signal increased the mean traffic noise level observed at the selected busy traffic intersection in Doha city.

CHAPTER 5: A COMPARATIVE NOISE LEVEL STUDY BETWEEN SIGNALIZED INTERSECTIONS AND ROUNDABOUTS

5.1. Introduction

The main objective of the analysis in this chapter is to compare traffic noise levels and traffic volumes at signalized intersections and roundabouts of two different sizes to determine which intersection type generates lower noise levels and is more sustainable in terms of operational efficiency. Thus, the results of this study are expected to be insightful and advantageous in terms of comparing the traffic noise levels between different intersection types. Additionally, the findings of this case study could aid governments, policymakers, and urban planners to better understand the noise contribution of the two intersection types so that noise management and mitigation plans and strategies could be adopted accordingly. Besides, another objective of this study is to determine whether traffic noise levels measured at the 8 traffic intersections in Doha, Qatar is within the WHO’s acceptable daytime noise level threshold; if not, suggest solutions to mitigate the urban noise pollution at the intersections.

5.2. Methodology

The main aim of this study was to identify which of the two most common intersection types found in urban areas – the roundabout or the signal – generated higher traffic noise levels and why. One of the best means of doing this is to conduct a real-life comparative study done between sets of comparable roundabouts and signals of different sizes. Compared to previous noise level studies done at few different traffic intersections or at the same intersection based on simulation alone, findings of such a comparative study done between pairs of 4 different but common urban traffic intersections types (2-lane signal, 2-lane roundabout, 3-lane signal, and 3-lane roundabout) respectively was expected to better indicate the individual and the combined traffic noise contribution of each of the intersection types (Chevallier, Can, et al., 2009; Gardziejczyk & Motylewicz, 2016; Guarnaccia, 2010; Li et al., 2017).

5.2.1. Variables

Alongside the main comparison variable $L_{Aeq.}$ (A-weighted equivalent continuous noise level), ambient temperature, relative humidity, and temperature were collected to check if the noise levels needed modifications for any attenuations caused by the weather variables. Next, the two noise pollution indices, $LA_{10,T}$ and $LA_{90,T}$ were statistically calculated from $L_{Aeq.}$ to quantify annoyance and background noise level observed at the traffic intersections respectively. Corresponding to the collection time of $L_{Aeq.}$, the other main contributing variable, traffic volume (with the vehicle type) was also collected for analysis (see Chapter 3 for more details).

5.2.2. Field Measurements

The sound pressure levels, traffic flow, and weather data were recorded at all the eight intersections at 5-min intervals on 8 weekdays and 8 weekends from 6 AM until 10 PM (16 hours) to capture variations over morning (6:00-11:00), afternoon (11:00-16:00), and evening (16-22:00) hours. In addition, other factors such as speed limit, total number of lanes, slope, and pavement surface texture (good or excellent) for each approach were also observed at the intersections (see Chapter 3 for more details).

5.3. Analysis

The mean 16-hr traffic noise levels at the eight intersections were evaluated to determine whether the traffic noise levels were below or above the WHO’s acceptable noise level threshold of 65 dB(A) for daytime traffic. Since variables such as the pavement quality, speed limit, number of lanes, approach gradient, and other site characteristics between the comparable roundabouts and the signals were found to be mostly similar, traffic volume and composition were assumed to be the main contributing variables towards traffic noise generation at the intersections beside the intersection type itself. Accordingly, based on the intersection types, number of lanes, and traffic volumes, noise level comparisons between the four roundabouts and the four signals were done through a series of statistical evaluations and comparative analysis to find out which of the intersection types contributed to higher noise levels and why. Additionally, the most likely reasons for the noise level variations observed within and between the data sets were also discussed.

First, the measured 16 hourly traffic noise levels at the eight intersections were analyzed (see Table 8) with respect to the WHO’s allowable noise level threshold of 65 dB(A) for daytime followed by a discussion of the residuals (see Table 9). In addition, the frequency and percent frequency of occurrence or the distribution of all $L_{AFeq.1hr.}$ values at all sites were depicted using histogram charts (see Figure 12). Next, the background and the annoyance noise levels found at the intersections were analyzed based on noise pollution indices statistically calculated from the 16 hourly equivalent noise level data (see Figure 13). The overall noise levels recorded at the eight intersections during the morning, afternoon, evening, and daytime hours were then summarized (Table 10) and compared using line charts (see Figure 14). Finally, the mean noise levels were illustrated on maps of Doha city as noise heat maps to analyze the findings from a visual and geographical perspective (see Figure 15).

Second, for comparing noise levels between the different traffic intersections, more importance was given to traffic noise levels generated during peak traffic hours instead of the entire 16-hr daytime period. As a result, two different sets of morning (3 hours), afternoon (3 hours), and evening (3 hours) peak traffic periods for weekdays and weekends were selected based on 16-hr weekday and weekend peak traffic volume data extracted at the first site (3LS-1) as illustrated in Figure 16. Accordingly, for all other sites, corresponding to the recorded noise level measurements, the traffic volume data at all four approaches (northbound, southbound, eastbound, and westbound) of each intersection were extracted and divided into 7 vehicle types at 5-min intervals from the captured video data during the selected three peak hours periods for weekdays and weekends respectively.

Third, the weekday (see Figure 17), the weekend (see Figure 18), and mean (see Figure 19) traffic volume composition and the percent traffic composition at the roundabouts and the signals over the selected 9 hours peak periods were discussed with bar charts. Until this point, the weekday and the weekend 16-hr noise level data and the peak 9-hr traffic volume data found at the roundabouts and the signals were evaluated separately.

Fourth, the two main variables – noise level and traffic volume – at the eight intersections during the 9 peak hours were evaluated together using line charts (see Figure 20 and Figure 21) with hourly and 5-min time intervals to observe the overall relationship between the two variables. Following a discussion of the common descriptive statistics for the hourly and mean data (see Table 11), any trend discrepancies observed between the two variables during hourly comparisons were checked and analyzed based on the rate of increase or decrease in the noise level due to increase or decrease in corresponding traffic volume respectively from one hour to the next (see Table 12).

Finally, the 9 peak hours traffic noise levels corresponding to traffic volumes at all the eight sites for weekday and weekend were plotted again on line charts respectively (see Figure 22) to discuss the similarities and differences among the pairs of similar intersections types. Next, the data in each of the four pairs were combined to represent the four different intersection types (2LS, 3LS, 2LR, and 3LR) respectively and illustrated again using two separate line charts for weekday and weekend respectively (see Figure 23). This was done to observe any similarities or differences in the mean noise levels trends due to mean traffic volumes between similar intersections types and different sizes (2LS vs 3LS and 2LR vs 3LR) and vice versa (2LS vs 2LR and 3LS vs 3LR). Moreover, to compare which sets of intersections generated more traffic noise compared to the other sets, weekday, weekend, and overall 9-hr mean noise level vs 9-hr mean volume charts (see Figure 24) were prepared for all sites. In addition, to analyze noise differences corresponding to volume differences among the different sets of comparisons, change of 9-hr mean noise levels corresponding to the (%) traffic volume changes within each comparison sets were tabulated in Table 13.

5.3.1. Traffic Noise Level

The equivalent hourly noise level data collected at the eight intersections from 6 AM to 10 PM (16 hours) on 8 weekdays and 8 weekends are tabulated in Table 8. The primary land use in the surrounding areas of all the intersections was found to be residential, and the WHO guideline stipulated a maximum of 65 dB(A) noise level for residential areas during daytime (Berglund et al., 1999). Accordingly, 100% of the measured noise levels on weekdays at all eight sites exceeded the allowable noise level threshold of 65 dB(A), while only 11 (8.6%) out of the 128 hourly weekend noise level data ($L_{AFeq.1hr.}$) fell within the allowable threshold.

In other words, out of the total 256 hours, only 4.3% of the equivalent hourly noise levels were below the allowable threshold, and these occurred during early the morning hours of the weekend at Location 3 (2LS-1) and morning and afternoon hours at Location 2 (3LR-1) (see Table 8). The reason for comparatively lower levels of traffic noise during the morning hours of weekends at all sites was attributed to the usually low traffic volume expected during the early morning hours of weekends and not particularly the intersection type.

For further analysis, the noise levels in these tables were color-coded (blue → white → green → yellow → red) based on the range of their values. This helped in the process of identification of interesting and recurring patterns within the data sets. Accordingly, the blue and the white colors indicated that values were found to be within the WHO's allowable limit of 65 dB(A); lighter shades of blue indicated values closer to 65 dB(A). On the other hand, various shades of green, yellow, and red colors indicated values above 65 dB(A). Lighter shades of green indicated that values were above yet closer to 65 dB(A), yellow colors indicated moderately higher values around 70 dB(A), and deep orange followed by red colors indicated that values were close to 80 dB(A).

Consequently, the traffic noise level was found to be maximum (80.6 dB(A)) at 3LS-2 (location 5) and minimum (65.7 dB(A)) at 2LS-1 (location 3). Noise levels were mostly above 75 dB(A) at 2LR-1 (location 4), 3LS-2 (location 5), and 3LR-2 (location 6). Likewise, noise levels during weekends at the same sites were also much higher compared to other locations. The noise levels at 3LR-1 (location 2) and 2LS-1 (location 3) on both weekdays and weekends were particularly around 65 dB(A). Whereas, weekday and weekend noise levels at 3LS-1 (location 1), 2LS-2 (location 7), and 2LR-2 (location 8) were around 70 dB(A). The overall noise levels were higher on weekdays; however, the opposite was also true in some other cases indicating that factors other than the expected lower volume of traffic on weekends could be impacting the noise levels observed.

Table 8. Weekday and Weekend Noise Levels, $L_{AFeq.1hr.}$, dB(A)

Location		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Site ID		3LS-1	3LR-1	2LS-1	2LR-1	3LS-2	3LR-2	2LS-2	2LR-2
Weekday		Thu	Mon	Tue	Thu	Sun	Thu	Sun	Thu
Time/Date (DD.MM)		01.11	28.05	30.10	15.11	04.11	08.11	02.12	29.11
Morning	6:00-7:00	73.0	68.2	67.4	77.9	75.5	76.8	72.0	73.3
	7:00-8:00	72.8	71.0	66.4	76.1	75.2	76.1	71.1	73.7
	8:00-9:00	73.1	71.6	65.7	77.3	75.8	76.1	71.9	72.8
	9:00-10:00	73.5	72.6	69.4	77.2	75.7	75.9	71.1	72.4
	10:00-11:00	74.5	70.8	68.7	77.6	76.2	75.4	71.4	73.0
Afternoon	11:00-12:00	73.3	71.1	68.6	78.3	76.4	76.2	71.9	73.8
	12:00-13:00	72.5	70.6	67.9	77.4	76.3	76.4	70.3	72.4
	13:00-14:00	74.8	70.7	67.6	77.5	80.3	75.8	71.1	74.0
	14:00-15:00	73.2	71.8	66.8	76.9	76.9	76.2	72.0	74.9
	15:00-16:00	75.9	69.8	66.6	76.9	75.9	76.3	71.6	72.1
Evening	16:00-17:00	76.4	69.6	66.6	78.7	75.6	76.9	72.4	71.7
	17:00-18:00	73.1	69.4	67.5	78.2	75.1	76.3	71.5	71.2
	18:00-19:00	73.7	68.4	69.1	77.5	74.8	76.2	71.0	71.8
	19:00-20:00	74.4	69.1	66.4	77.1	80.6	76.2	71.5	71.5
	20:00-21:00	70.9	69.6	68.7	77.2	74.8	76.7	69.1	70.2
	21:00-22:00	74.0	69.7	66.5	76.9	75.9	75.7	69.6	69.1
Color Scales (dB(A))		-	-	≥ 65 dB(A), max. allowed			65.7	73.3	80.6
Weekend		Fri	Fri	Sat	Sat	Sat	Fri	Sat	Fri
Time/Date (DD.MM)		02.11	01.06	27.10	24.11	03.11	09.11	01.12	30.11
Morning	6:00-7:00	66.6	62.4	63.5	74.7	71.2	71.6	70.4	65.8
	7:00-8:00	68.4	63.1	64.3	75.0	72.6	71.7	70.3	66.7
	8:00-9:00	68.8	63.2	65.4	76.7	75.6	72.7	70.1	67.6
	9:00-10:00	69.1	64.3	67.2	77.0	74.7	72.6	71.2	68.1
	10:00-11:00	69.4	63.7	66.7	77.9	74.4	72.7	70.5	68.6
Afternoon	11:00-12:00	68.5	64.9	66.2	78.3	74.9	72.6	71.4	70.0
	12:00-13:00	70.1	64.7	69.1	78.5	74.2	74.4	69.5	70.1
	13:00-14:00	71.2	65.0	67.8	77.0	77.0	75.1	70.1	70.2
	14:00-15:00	71.1	64.3	76.6	76.7	74.2	75.8	70.7	71.6
	15:00-16:00	71.7	64.3	69.4	77.7	74.8	76.1	71.9	71.3
Evening	16:00-17:00	71.5	67.4	68.3	76.6	75.7	76.1	73.3	69.2
	17:00-18:00	70.4	69.4	66.8	77.6	74.7	76.4	71.0	68.3
	18:00-19:00	70.4	67.5	67.7	76.1	74.4	75.5	71.5	69.5
	19:00-20:00	69.9	67.2	66.7	76.0	74.9	75.9	70.3	69.1
	20:00-21:00	70.0	68.2	66.1	76.1	74.1	75.6	71.0	68.2
	21:00-22:00	69.3	69.9	65.7	75.9	73.7	76.3	69.9	72.7
Color Scales (dB(A))		62.4	64.9	≥ 65 dB(A), max. allowed			65.0	72.4	78.5

Likewise, based on the analysis of the weekday and the weekend residual data (see Table 9), the values of the residuals were mostly lower on weekends compared to the values on weekdays. Although these residual values were directly related to the noise level values tabulated in Table 8, the residuals provided a sense of how an observer at these sites would perceive the varying noise level differences from the allowable threshold of 65 dB(A). In Table 9, the shades of blue color indicated that the measured noise levels in those hours differed from the allowable 65 dB(A) threshold by less than 5 dB(A).

When it comes to noise levels, only when the residual (positive or negative) is more than or equal to 5 dB(A), the noise level change is readily perceptible to an observer which otherwise would be barely perceptible to the human ear. Accordingly, an increase or decrease of 10 dB(A) in noise level is perceived to be twice or half as loud respectively. For example, during the weekend 7-8 AM period, the noise level of 75 dB(A) at 2LR-1 (location 4) to an observer would sound twice as loud as the sound at the allowable threshold of 65 dB(A). Similarly, an increase of 20 dB(A) to an observer would be 4 times as loud (U.S. Department of Transportation - Federal Highway Administration, 2017). Therefore, the lighter the blue color, the lesser the noise level change would be perceived by an observer.

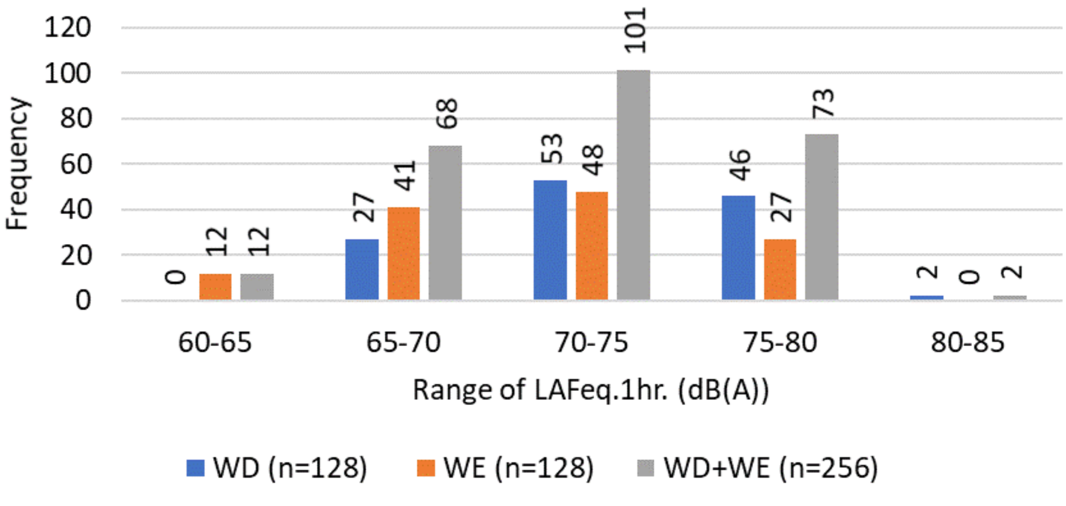
Additionally, in Table 9, all the residual values greater than 5 dB(A) were positive indicating that the increase in the noise levels from the allowable threshold at these sites were readily perceptible to an observer. Therefore, the residual values shaded in green colors indicated that they were above 5 dB(A) and readily perceptible. Next, the values shaded in yellow or light orange colors (around 10 dB(A)) were expected to be perceived as almost twice as loud. For instance, the maximum noise level residual value of 15.6 dB(A) at 3LS-2 (location 5) would be the most perceptible and sound about 2.9 times louder.

Table 9. Weekday and Weekend Residual (ΔL) Noise Level: 65 dB(A)-Hourly $L_{AFeq.1hr.}$

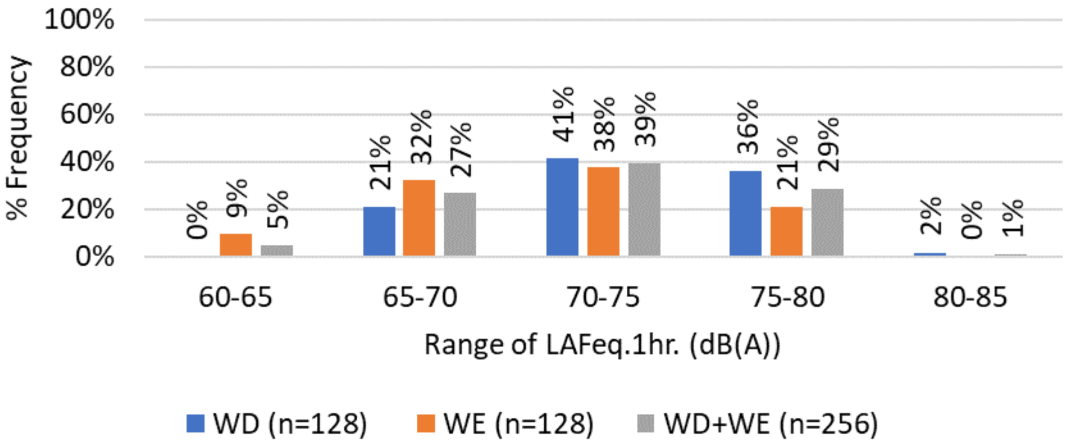
Location		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Time/Site ID		3LS-1	3LR-1	2LS-1	2LR-1	3LS-2	3LR-2	2LS-2	2LR-2
Weekday									
Morning	6:00-7:00	8.0	3.2	2.4	12.9	10.5	11.8	7.0	8.3
	7:00-8:00	7.8	6.0	1.4	11.1	10.2	11.1	6.1	8.7
	8:00-9:00	8.1	6.6	0.7	12.3	10.8	11.1	6.9	7.8
	9:00-10:00	8.5	7.6	4.4	12.2	10.7	10.9	6.1	7.4
	10:00-11:00	9.5	5.8	3.7	12.6	11.2	10.4	6.4	8.0
Afternoon	11:00-12:00	8.3	6.1	3.6	13.3	11.4	11.2	6.9	8.8
	12:00-13:00	7.5	5.6	2.9	12.4	11.3	11.4	5.3	7.4
	13:00-14:00	9.8	5.7	2.6	12.5	15.3	10.8	6.1	9.0
	14:00-15:00	8.2	6.8	1.8	11.9	11.9	11.2	7.0	9.9
	15:00-16:00	10.9	4.8	1.6	11.9	10.9	11.3	6.6	7.1
Evening	16:00-17:00	11.4	4.6	1.6	13.7	10.6	11.9	7.4	6.7
	17:00-18:00	8.1	4.4	2.5	13.2	10.1	11.3	6.5	6.2
	18:00-19:00	8.7	3.4	4.1	12.5	9.8	11.2	6.0	6.8
	19:00-20:00	9.4	4.1	1.4	12.1	15.6	11.2	6.5	6.5
	20:00-21:00	5.9	4.6	3.7	12.2	9.8	11.7	4.1	5.2
	21:00-22:00	9.0	4.7	1.5	11.9	10.9	10.7	4.6	4.1
Color Scales (dB(A))		0.7	4.8	≥ 5 dB(A), readily perceptible			5.3	9.2	15.6
Weekend									
Morning	6:00-7:00	1.6	-2.6	-1.5	9.7	6.2	6.6	5.4	0.8
	7:00-8:00	3.4	-1.9	-0.7	10.0	7.6	6.7	5.3	1.7
	8:00-9:00	3.8	-1.8	0.4	11.7	10.6	7.7	5.1	2.6
	9:00-10:00	4.1	-0.7	2.2	12.0	9.7	7.6	6.2	3.1
	10:00-11:00	4.4	-1.3	1.7	12.9	9.4	7.7	5.5	3.6
Afternoon	11:00-12:00	3.5	-0.1	1.2	13.3	9.9	7.6	6.4	5.0
	12:00-13:00	5.1	-0.3	4.1	13.5	9.2	9.4	4.5	5.1
	13:00-14:00	6.2	0.0	2.8	12.0	12.0	10.1	5.1	5.2
	14:00-15:00	6.1	-0.7	11.6	11.7	9.2	10.8	5.7	6.6
	15:00-16:00	6.7	-0.7	4.4	12.7	9.8	11.1	6.9	6.3
Evening	16:00-17:00	6.5	2.4	3.3	11.6	10.7	11.1	8.3	4.2
	17:00-18:00	5.4	4.4	1.8	12.6	9.7	11.4	6.0	3.3
	18:00-19:00	5.4	2.5	2.7	11.1	9.4	10.5	6.5	4.5
	19:00-20:00	4.9	2.2	1.7	11.0	9.9	10.9	5.3	4.1
	20:00-21:00	5.0	3.2	1.1	11.1	9.1	10.6	6.0	3.2
	21:00-22:00	4.3	4.9	0.7	10.9	8.7	11.3	4.9	7.7
Color Scales (dB(A))		-2.6	4.9	≥ 5 dB(A), readily perceptible			5.0	8.8	13.5

Moreover, the histogram in Figure 12 depicts the frequency (a) and percent frequency (b) of occurrence or distribution of all $L_{AFeq.1hr.}$ values, that is, 16 hourly noise level data per day per site. Depending on the range of $L_{AFeq.1hr.}$ values, 5 equally sized (5dB(A)) bins/buckets/intervals were created starting from 60 dB(A) to 85 dB(A). The mean values of the WD, WE, and the combined data were 74.4, 72.9, and 73.7 dB(A) respectively. Also, the graph appeared to be mostly symmetrical about the mean values and had a bell-shape. Consequently, the three data sets seemed to be almost normally distributed as the majority of the data were concentrated around the middle bin (70-75 dB(A)).

Nonetheless, the weekday values ranged between 65 to 85 dB(A) while the weekend values ranged between 60 and 80 dB(A). Overall, weekdays had higher frequencies (%) on the higher bin values (70-75, 75-80, and 80-85) whereas the weekend frequencies (%) were higher on the lower side of the bins (60-65 and 65-70). Combined frequencies (%) were also comparatively higher on the higher side of the bins. Regardless, 39% of all the values were in the middle bin (70-75 dB(A)), 29% were in a higher bin (75-80 dB(A)), and 27% were in the lower bin (65-70 dB(A)) indicating that majority of the noise level values found in the city not only exceeded the allowable threshold of 65 dB(A) but did so with high values.



(a) Frequency distribution



(b) Percent frequency distribution

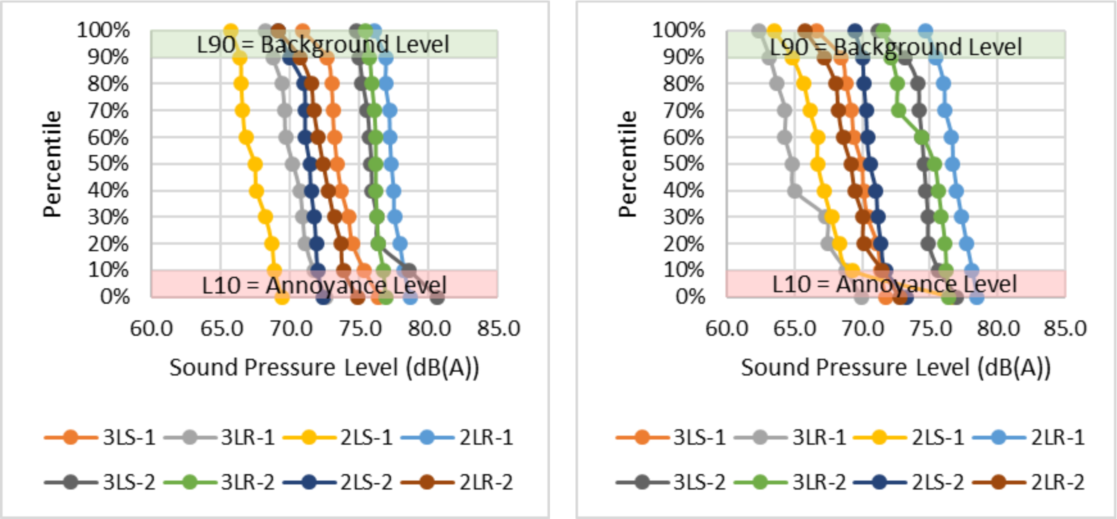
Figure 12. Frequency and percent frequency distribution graph of all $L_{AFeq.1hr.}$ values.

5.3.1.1. Noise Pollution Indices

To find the annoyance noise levels and the background noise levels from the hourly noise level measurements collected at each site for 16 hours, statistical analysis was used. The resulting weekday and weekend $L_{An,1hr.}$ found as percentiles were plotted against the corresponding noise levels as shown in Figure 13 (a) and (b) respectively. The weekday statistical distribution of the noise levels shows that the background noise levels at 2LS-1 (location 3) - the quietest site - was between 65.7 dB(A) and 66.4 dB(A) based on $LA_{90,1hr}$ data. On the other hand, the annoyance noise levels due to traffic at the noisiest site, 3LS-2 (location 5) was between 78.6 dB(A) and 80.6 dB(A) due to $LA_{10,1hr.}$ noise data.

Likewise, from the weekend statistical distribution of the noise levels illustrated in Figure 13 (b), it was observed that the background noise levels at the quietest site, 3LR-1 (location 2) was between 62.4 dB(A) and 63.2 dB(A) due to $LA_{90,1hr}$. data. On the contrary, based on the $LA_{10,1hr.}$ data, the annoyance noise levels due to traffic noise at the noisiest site, 2LR-1 (location 4) was between 78.1 dB(A) and 78.5 dB(A).

Hence, due to weekday traffic, the quietest and the noisiest intersections were one of the two 2-lane and 3-lane signals respectively. On the contrary, on weekends, the quietest and the noisiest intersections were one of the two 3-lane and 2-lane roundabouts respectively. This indicates that background and annoyance noise levels vary with traffic volume, number of lanes, and the control type. Nevertheless, the 2LS-1 or the 3LR-1 seemed to be the quietest and the least annoying on weekday and weekend respectively. Whereas, the 2LR-1 was found to be both the loudest and the most annoying on both days.



(a) Weekday (b) Weekend

Figure 13. The statistical distribution of noise levels at all 8 sites (16 hours per site).

5.3.1.2. Mean Noise Levels

Finally, the morning (5-hr), afternoon (5-hr), evening (6-hr), daytime (16-hr), and daytime residual mean values of the hourly weekday and weekend noise level data discussed and analyzed so far were summarized in Table 10. This table was color-coded the same way the values in Table 8 and Table 9 were color-coded.

Accordingly, blue color was for values below the threshold or with no perceivable noise level change, green was for values at or above the threshold or with perceivable noise level change, and yellow followed by red was for the highest noise level and residual values.

An overall inspection of Table 10 shows that the least mean values for noise levels and residuals on weekdays occurred at 2LS-1 (location 3) followed by 3LR-1-WD (location 2). 2LR-1 (location 4) had the highest mean values followed by 3LS-2 (location 5) and 3LR-2 (location 6). On the other hand, on weekends, the least overall mean values were at 3LR-1 (location 2) followed by 2LS-1 (location 3) and 2LR-2 (location 8). However, similar to weekdays, 2LR-1 (location 4) again had the highest mean values of noise levels followed by 3LS-2 (location 5) and 3LR-2 (location 6).

Moreover, the mean 16-hr daytime weekday traffic noise levels at each of the 8 traffic intersections were found to exceed the WHO’s acceptable daytime noise level threshold of 65 dB(A) by 2.6 dB(A) and 12.5 dB(A) at 2LS-1 (location 3) and 2LR-1 (location 4) respectively. On weekends, the minimum and the maximum mean noise levels exceeded by 1.2 dB(A) and 11.9 dB(A) at 3LR-1 (location 2) and 2LR-1 (location 4) respectively. In other words, 2LS-1-WD and 3LR-1-WE generated the least traffic noise and 2LR-1 generated the most traffic noise on both days compared to the other 6 traffic intersections.

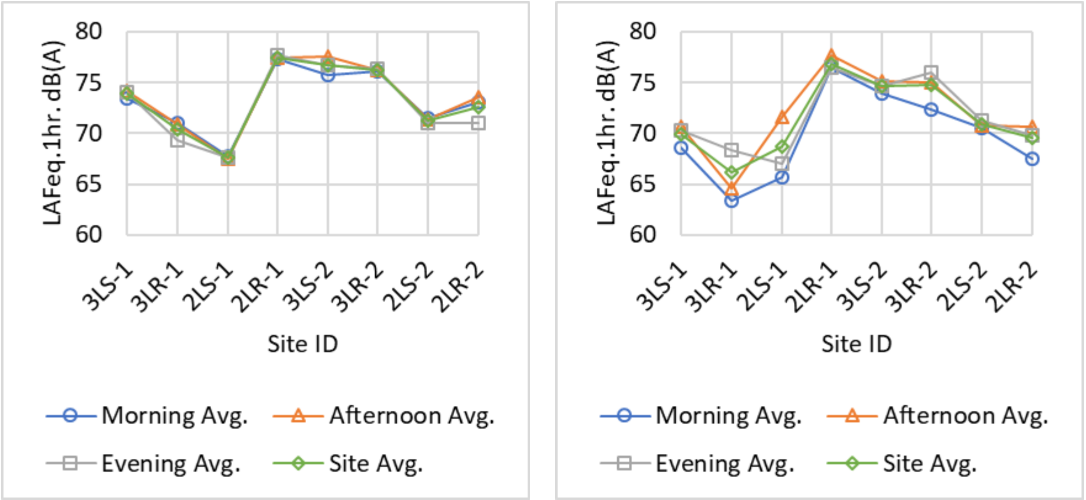
Table 10. Noise Level Measurements Summary of all 8 Sites

Site ID	$L_{AFeq.Morning}$, dB(A)	$L_{AFeq.Afternoon}$, dB(A)	$L_{AFeq.Evening}$, dB(A)	$L_{AFeq.Daytime}$, dB(A)	$\Delta L = L_{AFeq.Daytime}$ – 65 dB(A)
Weekday					
3LS-1-WD	73.4	74.1	74.1	73.9	8.9
3LR-1-WD	71.1	70.8	69.3	70.4	5.4
2LS-1-WD	67.7	67.6	67.6	67.6	2.6
2LR-1-WD	77.3	77.4	77.6	77.5	12.5
3LS-2-WD	75.7	77.5	76.7	76.7	11.7
3LR-2-WD	76.1	76.2	76.4	76.2	11.2
2LS-2-WD	71.5	71.4	71.0	71.3	6.3
2LR-2-WD	73.1	73.5	71.0	72.6	7.6
Weekend					
3LS-1-WE	68.6	70.7	70.3	70.0	5.0
3LR-1-WE	63.4	64.6	68.4	66.2	1.2
2LS-1-WE	65.6	71.6	67.0	68.8	3.8
2LR-1-WE	76.4	77.7	76.4	76.9	11.9
3LS-2-WE	74.0	75.2	74.6	74.6	9.6
3LR-2-WE	72.3	75.0	76.0	74.8	9.8
2LS-2-WE	70.5	70.8	71.3	70.9	5.9
2LR-2-WE	67.5	70.7	69.8	69.5	4.5

Besides, in order to further evaluate how the mean morning, afternoon, evening, and daytime noise levels at all the sites relate to one another, line charts (see Figure 14) were prepared by plotting the mean morning, afternoon, evening, and daytime $L_{AFeq.1hr.}$ for all the eight sites on weekday (a) and weekend (b) respectively. On weekdays, it was observed that the mean afternoon noise levels mostly exceeded the mean evening noise levels followed by the mean morning noise levels. Nonetheless, all their mean values were very close to one another and ranged between 65dB(A) and 80 dB(A). The maximum and the minimum noise level noticed were the mean evening noise level (77.6 dB(A)) and the mean evening noise level (67.6 dB(A)) at 2LR-1 (location 4) and 2LS-1 (location 3) respectively.

On the other hand, on weekends, the mean evening noise levels mostly exceeded the mean afternoon and the mean morning noise levels with more similar mean evening and mean afternoon values. In this case, the noise levels ranged between 60 dB(A) and 80 dB(A). Similar to the weekend, the maximum mean noise level (77.7 dB(A)) was again observed at 2LR-1 (location 4) but for mean afternoon noise level. Whereas, the minimum mean noise level (63.4 dB(A)) was observed for the mean morning noise level at 3LR-1 (location 2).

Additionally, the overall weekday and weekend 16-hr mean noise levels at all the sites were also shown on the same line charts in Figure 14. In this case, the mean 16-hr weekday noise levels at most of the sites were higher than those on the weekends except at 2LS-1 where the weekend noise level exceeded the weekday noise level by 1.2 dB(A)). The maximum (77.5 dB(A)) and the minimum (66.2 dB(A)) mean noise levels were observed at 2LR-1 (location 4) on weekday and at 3LR-1 (location 2) on weekend respectively.



(a) Weekday (b) Weekend

Figure 14. Mean morning, afternoon, evening, and daytime noise levels at all 8 sites.

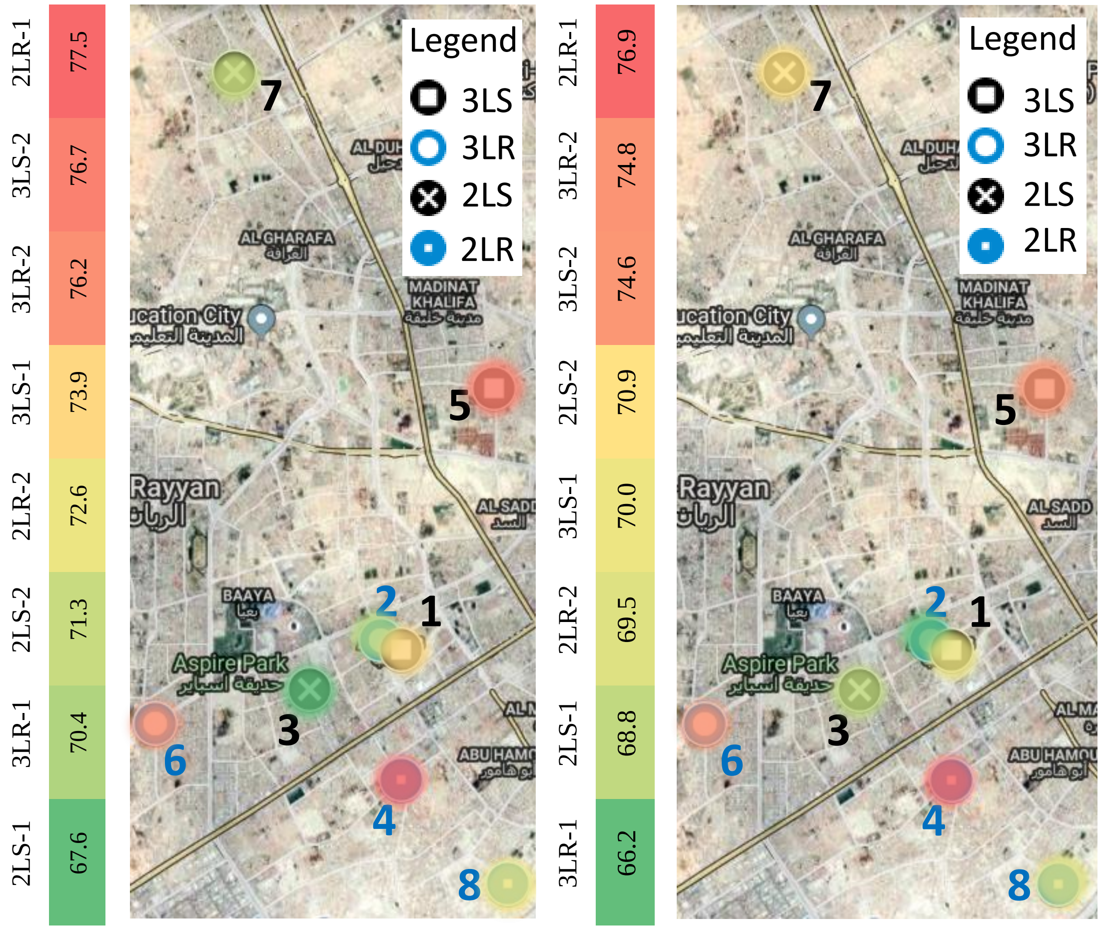
To sum up, on both weekdays and weekends, the overall noise levels at the 3-lane roundabouts were mostly lower than those at the 3-lane signals. On the contrary, the overall noise levels at the 2-lane roundabouts were mostly much higher than the 2-lane signals. Also, as expected, the noise levels at the 3-lane signals were mostly higher than the 2-lane signals. In contrast, the 2-lane roundabouts did not always generate lower traffic noise than the 3-lane roundabouts. Thus, the variations observed between the different intersection types were an indication that besides the control type and number of lanes, factors such as traffic volume and vehicle composition could be contributing towards the overall noise level differences.

5.3.1.3. Noise Heat Maps

Heat maps for 16-hr mean daytime weekday and weekend noise levels at the 8 sites were prepared as shown in Figure 15. Each site was color-coded in ascending order from the bottom (green) to top (red) (shown on the left of the noise maps). Using these color codes, the values of the mean daytime noise levels were illustrated on the heat maps. Along with indicating the changing mean values from one site to another and from one day to another, the heat maps also showed the spatial distribution of the mean noise levels compared to the mean noise level line charts shown earlier in Figure 14.

Based on the heat maps, the mean noise levels at 2LS-1-WD and 3LR-1-WE were the least, whereas 2LR-1 generated the most traffic noise on both weekday and weekend - regardless of their geographical position on the heat maps. Hence, the varied distribution of 16-hr mean $L_{AFeq.1hr.}$ across the heat maps indicated that the observed noise levels were most likely dependent on the intersection type and other site characteristics and not on their proximity to each other.

Nevertheless, with the aid of heat maps, the changing mean noise levels observed over the weekdays and the weekends become more visually noticeable. In addition, the heat maps can help policymakers and urban planners to locate high noise risk zones on the city's map, determine or modify land use accordingly, or mitigate high noise levels in the identified areas so that they conform to the allowable noise limits designated in those areas.



(a) Weekday (b) Weekend

Figure 15. $L_{AFeq.1hr.}$ dB(A) heat map of daytime noise levels at all 8 sites.

Therefore, although at most sites the noise level increments from the allowable threshold were found to be readily perceptible, no conclusive relationship was established between higher or lower noise levels found at the 8 intersections based on analysis of noise level, intersection type, and number of lanes alone. Nonetheless, the 2-lane signal followed by 3-lane roundabout and 3-lane signal seemed to perform the better in generating lower traffic noise compared to 2-lane roundabout. Moreover, since the noise levels sometimes varied even within the same intersection types, the traffic volumes and the vehicle types contributing to those noise levels need to be analyzed as well. Lastly, the overall noise level measurements were found to be higher on weekdays compared to weekends similar to the findings of Quiñones-Bolaños et al. (2016)

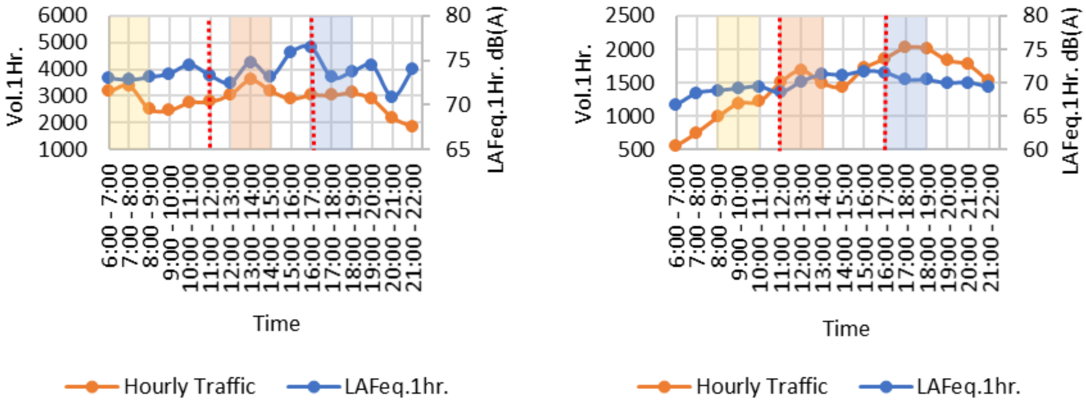
indicating a close relationship with traffic volumes which are generally higher on weekdays.

5.3.2. Peak Hours Selection

Comparative traffic noise level analysis between the eight traffic intersections (discussed in the following sections) was done based on measured traffic noise levels and extracted traffic volume data during 9 peak traffic hours instead of the entire 16 hours period. Consequently, the three periods of three peak hours for this study were selected based on the peak traffic counts observed during the morning, afternoon, and evening hours respectively at the first location (3LS-1), a busy 3-lane signalized intersection at the heart of Doha city. Also, as data at the other sites were collected around the same time as location 1, weekday and weekend 3 hours peak periods were selected based on the peak traffic counts at this site as shown in Figure 16 (a) and (b) respectively.

Moreover, the peak traffic count intervals at this site were assumed to be a reflection of the peak hours at the other sites, since it was also situated at the center of all other sites. Also, 9 hours of peak traffic count data in total per site per day was also expected to be more critical in comparing the traffic noise levels at the intersections, similar to other noise level studies which also investigated noise levels observed during morning, afternoon, and evening peaks hours in their respective cities (Obaidat, 2011; Quiñones-Bolaños et al., 2016). Therefore, 6:00-9:00, 12:00-15:00, and 16:00-19:00 were selected as the weekday morning, afternoon, and evening three hours peak periods respectively based on the peak hourly traffic counts observed during the measured 16 hours period at Site 1 on weekday. Likewise, 8:00-11:00, 11:00-14:00, and 16:00-19:00 were selected as the weekend morning, afternoon, and evening three hours peak periods respectively.

Besides, in Figure 16, the 16 hours period was divided into three 5-6 hours intervals: 6 AM – 11 AM were defined as morning hours, 11 AM – 16 PM were the afternoon hours, and 18 PM – 22 PM were defined as evening period. On the hourly graphs, the peak three hours for morning, afternoon, and evening periods were indicated (with orange, yellow and blue box respectively) in each of the four cases based on maximum hourly traffic counts. It was observed that the morning peak 3 hours at the signal on weekday and weekend differed only by two hours. Whereas, the afternoon and evening peak 3 hours differed by only an hour. In addition, the overall traffic counts and the noise levels were lower during the evening periods (16:00-22:00) of weekdays and the morning period (6:00-12:00) of the weekend.



(a) Signal (weekday) – 1-hr (b) Signal (weekend) – 1-hr

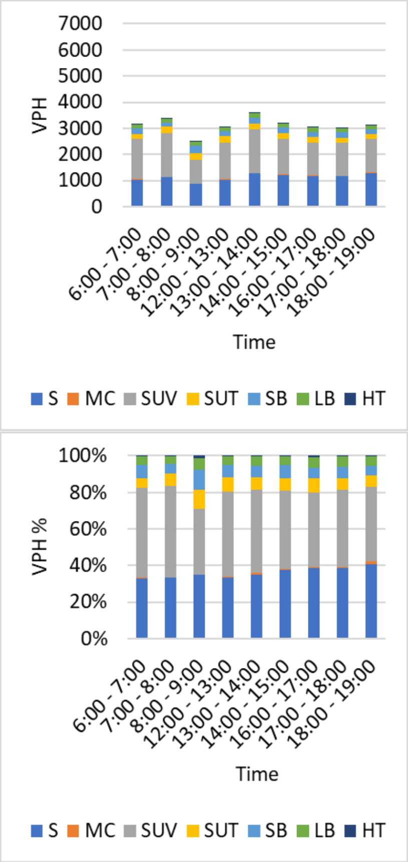
Figure 16. Hourly and 5-min noise levels vs traffic count at 3LR-1 (n=16-hr/site/day).

5.3.3. Peak Hours Traffic Volume and Composition

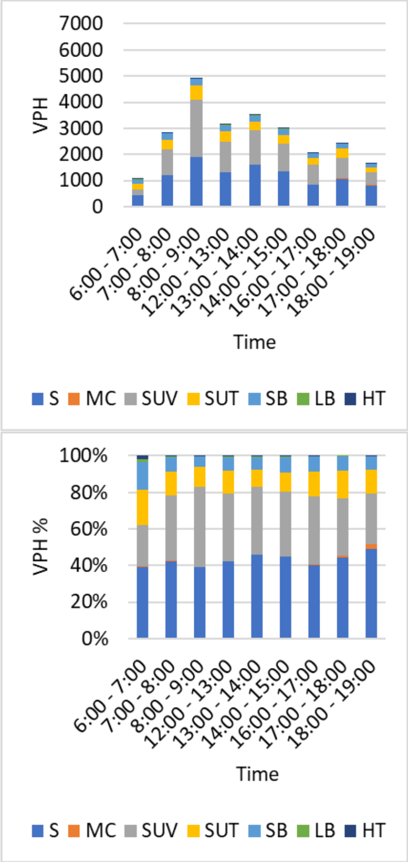
Besides the hourly traffic volumes, hourly traffic compositions were also expected to be a contributing factor to the overall noise levels found at the intersections. Consequently, the weekday (see Figure 17), the weekend (see Figure 18), and mean (see Figure 19) traffic volume composition and the percent traffic composition at the roundabouts and the signals over the selected 9 hours peak periods were discussed in this section with the help of separate bar charts for each intersection.

Accordingly, the weekday and the weekend traffic volume composition and the percent traffic composition at the roundabouts and the signals were illustrated separately (see Figure 17 and Figure 18) over two different sets of 9 peak hours periods selected for weekdays and weekends. In both cases, it was commonly observed that sedans (S) and SUV made up the majority of the traffic composition at any intersection followed by comparatively fewer numbers of single-unit trucks (SUT) and small buses (SB). The percentage of sedans were higher than SUV in some cases and vice versa. The same was true for single-unit trucks and small buses. The numbers of large buses (LB), heavy trucks (HT), and motorcycle (MC) were the least.

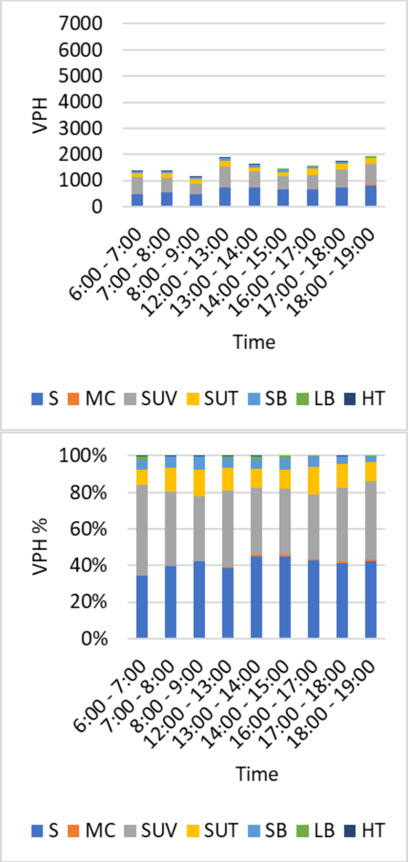
Besides, the 3-lane intersections had comparatively higher traffic volumes than the 2-lane intersections regardless of the control type. Also, the hourly traffic volume distribution over the peak hours appeared almost similar on weekdays and weekends respectively but with comparatively lower values on weekends. However, compared to the other 2-lane intersections, the range of hourly traffic volumes at 2LR-1 (location 4) was much higher on both weekday and weekend.



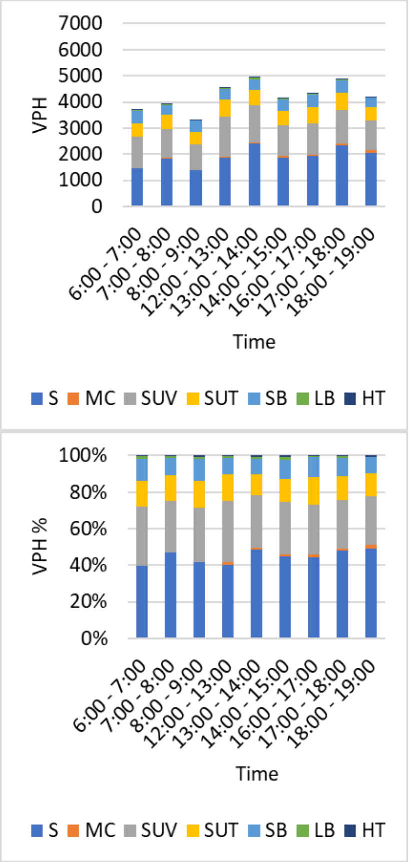
(a) 3LS-1-WD (Location 1)



(b) 3LR-1-WD (Location 2)



(c) 2LS-1-WD (Location 3)



(d) 2LR-1-WD (Location 4)

(e) 3LS-2-WD (Location 5) (f) 3LR-2-WD (Location 6) (g) 2LS-2-WD (Location 7) (h) 2LR-2-WD (Location 8)

Figure 17. Weekday hourly traffic volume versus noise during 9 peak hours at all 8 sites.

(a) 3LS-1-WE (Location 1) (b) 3LR-1-WE (Location 2) (c) 2LS-1-WE (Location 3) (d) 2LR-1-WE (Location 4)

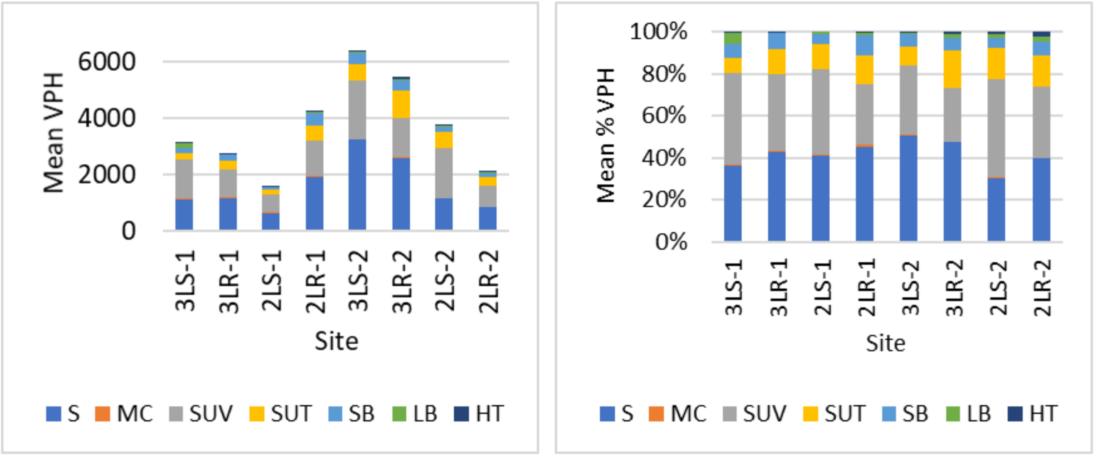
(e) 3LS-2-WE (Location 5) (f) 3LR-2-WE (Location 6) (g) 2LS-2-WE (Location 7) (h) 2LR-2-WE (Location 8)

Figure 18. Weekend hourly traffic volume versus noise during 9 peak hours at all 8 sites.

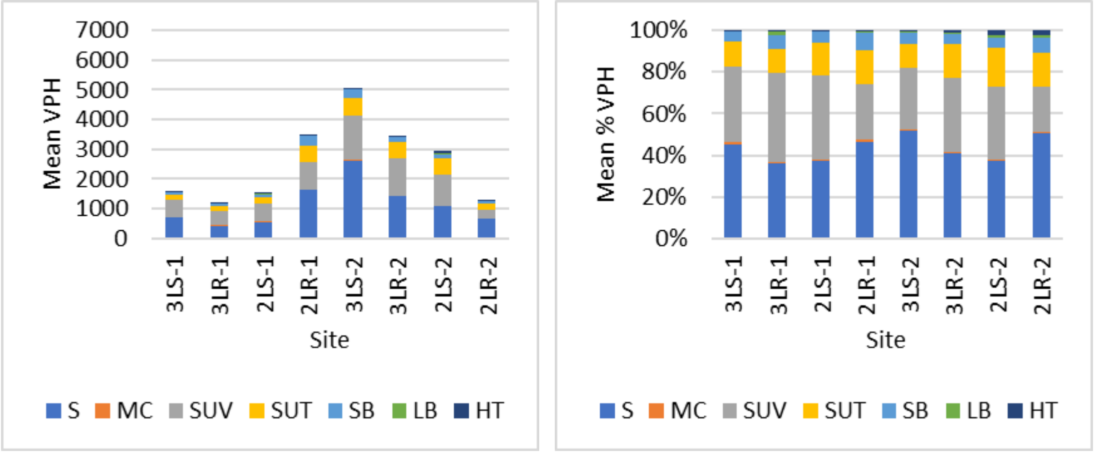
5.3.3.1. Mean Traffic Volume and Composition

Conclusions similar to the overall findings of Figure 17 and Figure 18 could be drawn from the 9-hr mean weekday, weekend, and overall traffic composition and percent composition bar charts in Figure 19. The mean volumes at 3-lane traffic intersections were higher than those at 2-lane traffic intersections. Also, the signals had higher traffic volumes compared to the roundabouts with the exception of 2LR-1, a 2-lane roundabout with much higher mean traffic volumes. Although the 9-hr mean volumes were comparatively lower on weekends, the relative distribution of the volumes across the sites remained almost similar. In terms of noise level comparison study, the similarities observed in traffic composition and distribution between similar and comparable traffic intersections were expected to be valuable.

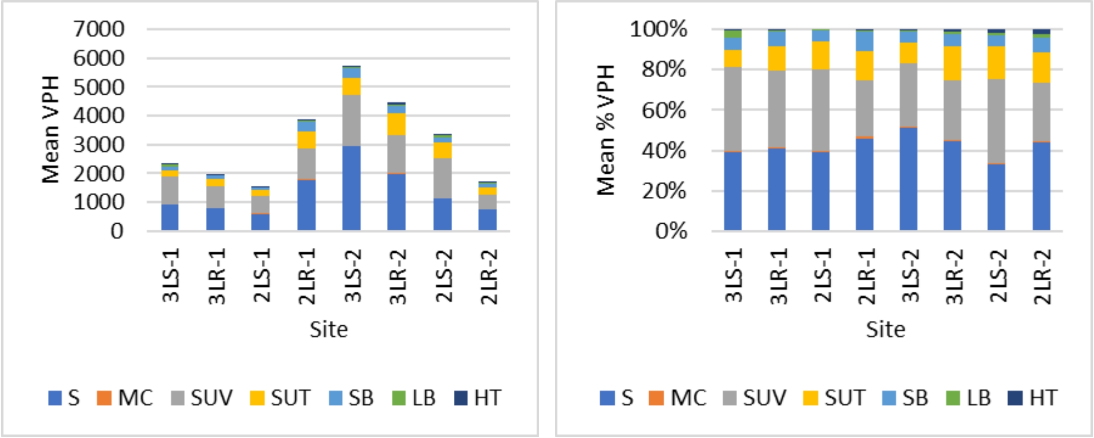
Again, in all cases, the mean percent composition distributions for sedans (S) and SUV were interchangeably the highest followed by single-unit trucks (SUT) and small buses (SB) and much lower percentages of large buses (LB), heavy trucks (HT), and motorcycle (MC). Therefore, due to the much higher percent composition of the sedan and SUV vehicle types compared to the other vehicle types across all sites and all days, it was expected that sedan and SUV type vehicles contributed the most to the resulting noise at the roundabouts and the signals. Besides, some high noise contributions from the lesser occurring but noisier or heavier vehicle types were also expected (Quiñones-Bolaños et al., 2016). Nonetheless, further analysis of the composition distribution of the vehicle types with corresponding noise levels is required to say if and how much the traffic composition contributed to the noise levels observed at the intersections.



(a) Weekday



(b) Weekend



(c) Overall

Figure 19. Mean hourly traffic count at all 8 sites (weekday, weekend, & overall).

5.3.4. Peak Hours Traffic Noise Levels and Traffic Volume

In this section, the weekday and weekend hourly and the 5-min traffic noise level data and traffic volume data observed over the 9 peak hours were plotted as combined line graphs as illustrated in Figure 20 and Figure 21 respectively. All the charts were prepared with the same intervals and ranges of axes in order to compare and observe the overall relationship between the two main variables – traffic volume and the corresponding traffic noise level - across the 8 intersections. In general, traffic noise levels are expected to increase with increasing traffic volumes. Likewise, an overall observation of the hourly and 5-min graphs show that the noise levels and the traffic volumes were mostly positively related over the 9 hours period, that is, as one goes high the other also follows a similar trend and vice versa.

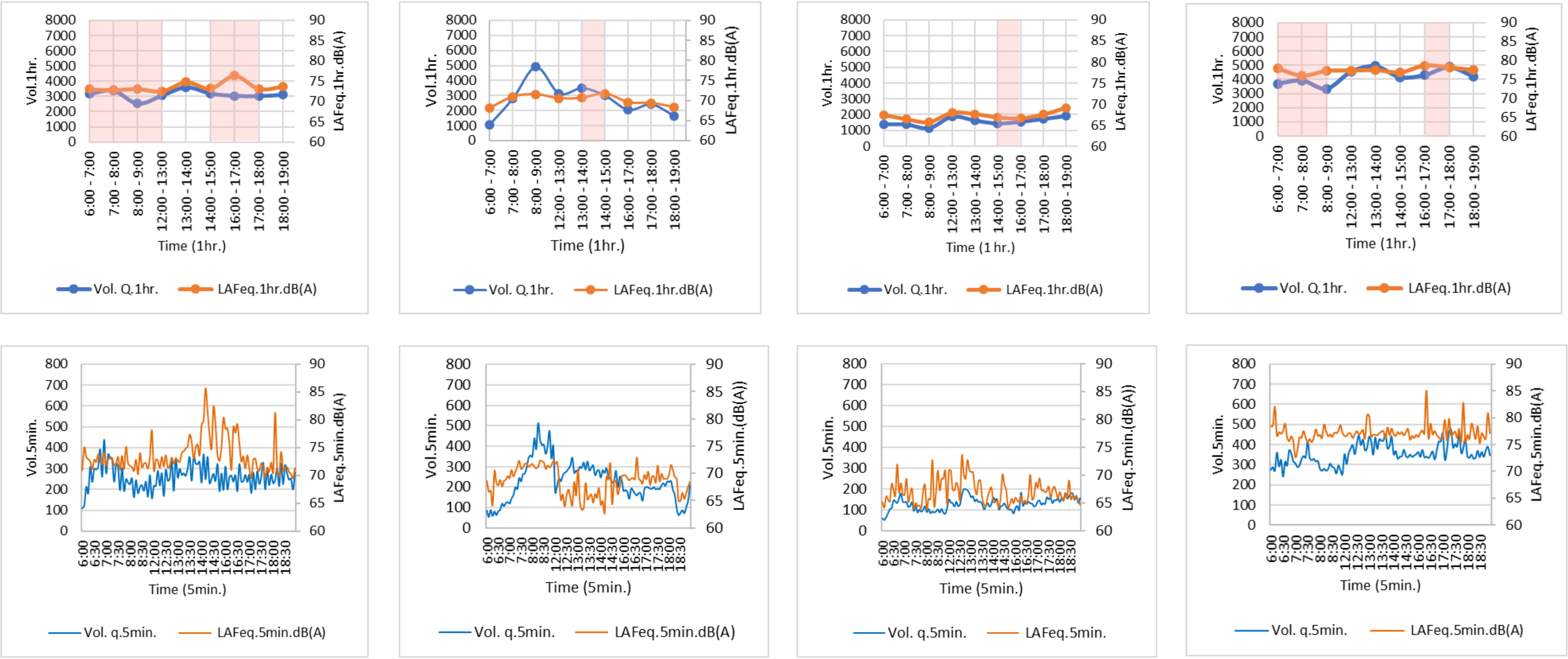
Although the noise and traffic count curves mostly matched, some inconsistencies in the generally positive relationship between the two variables were observed which could be seen more pronounced in the 5-min graphs. These were most likely due to the difference in hourly traffic compositions or other site characteristics. Nonetheless, within the hourly charts, the time periods in which discrepancies in the expected positive relationship were observed were marked with light red boxes placed across those time intervals. Although at some intersections the discrepancies occurred more than the other intersections, the differences in terms of noise levels were barely perceivable, that is, within 5 dB(A).

Moreover, regardless of the day, the noise levels at the 3-lane roundabouts were observed to be slightly lower than those at the 3-lane signals although the hourly and 5-min volumes at the two intersection types were almost similar. Overall, the noise levels corresponding to the traffic volumes were found to be the least at 2-lane signals followed by 3-lane roundabouts and 3-lane signals. However, both traffic volume and noise level at 2LR-1 appeared to be higher than those at the 2-lane signals and the 3-lane roundabouts. Traffic volume and noise level values found at 2LR-1 were fairly close to the 3-lane signal, 3LS-1 although it had a much fewer number of lanes.

Besides, the higher values at the 3-lane signals compared to the 2-lane signals and the 3-lane roundabouts could be attributed to the geometric layout, traffic signal stop-and-go periods, and the presence of more dedicated turning and through lanes. Although the 3-lane signals had a much smoother pavement surface texture compared to the 2-lanes signals and the 3-lane roundabouts, noise levels were still higher at the 3-lane signals due to comparatively higher traffic volumes.

On the other hand, the comparatively higher noise level observed at the 2-lane roundabout, 2LR-1 could be due to stop-and-go conditions, smaller diameter of the inner circle, and higher concentration of vehicles within a smaller area. Additionally, the surface texture at the 2-lane roundabout had a comparatively rougher surface texture compared to the other intersections which could also be a reason for the observed higher noise level.

In short, besides the intersection type and the traffic volume, factors such as vehicle type, pavement surface texture, site geometry, and layout of lanes could also contribute to the noise level differences observed between the sites. Also, the hourly and the 5 min traffic volumes observed at comparable traffic intersections were mostly within similar ranges during the weekdays and weekends respectively- making the findings of the comparative analysis more meaningful. Besides, which of the two intersection types, roundabout or signal, generated more traffic noise varied based on whether they were 2-lane or 3-lane. Nonetheless, further analysis of the distribution of the different vehicle types within the hourly traffic volumes observed at the eight intersections could provide more conclusive answers for some of the noise-volume relationship discrepancies observed at the sites.

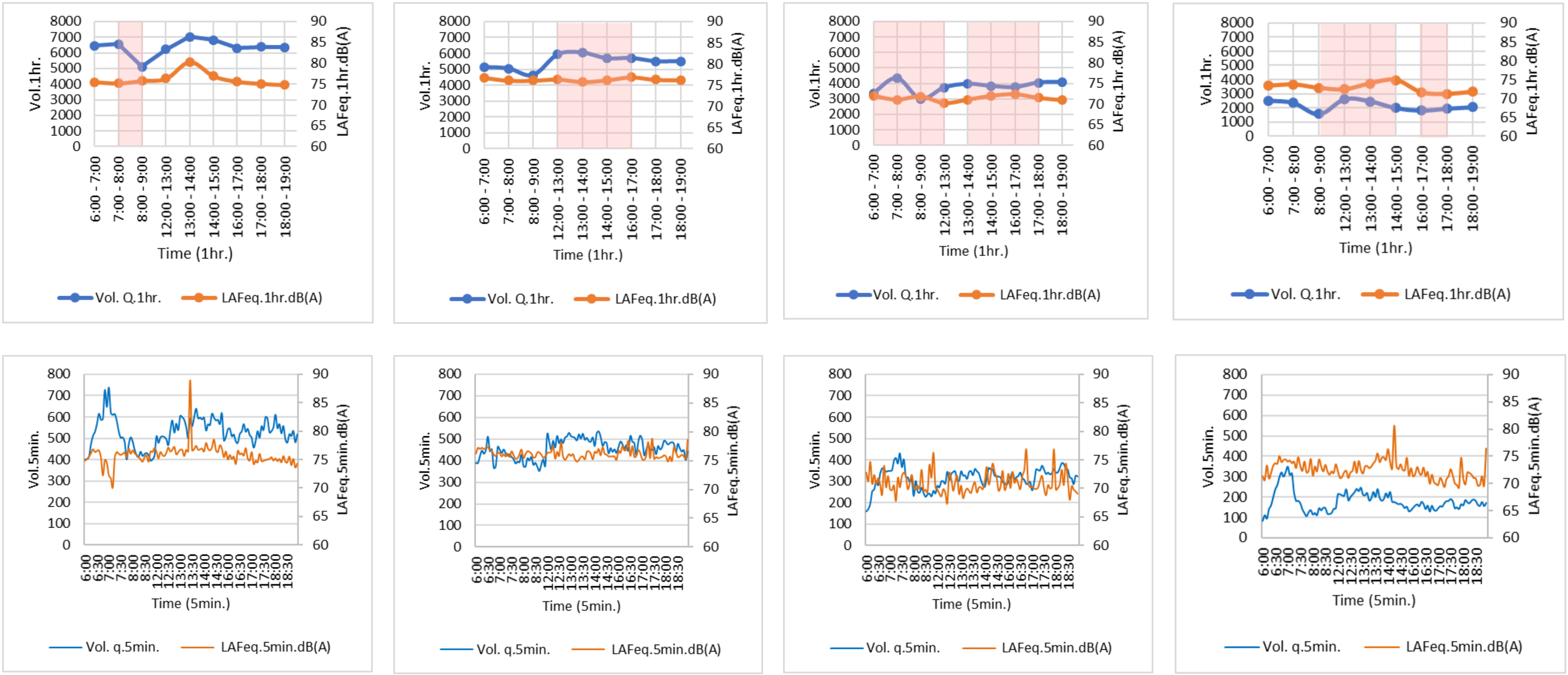


(a) 3LS-1-WD (Location 1)

(b) 3LR-1-WD (Location 2)

(c) 2LS-1-WD (Location 3)

(d) 2LR-1-WD (Location 4)



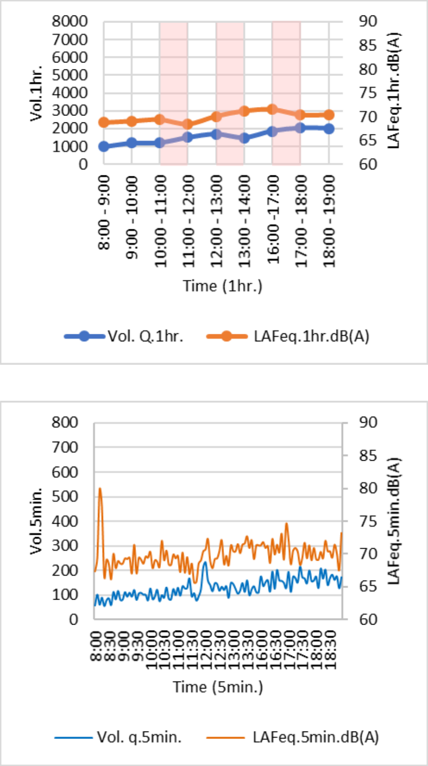
(e) 3LS-2-WD (Location 5)

(f) 3LR-2-WD (Location 6)

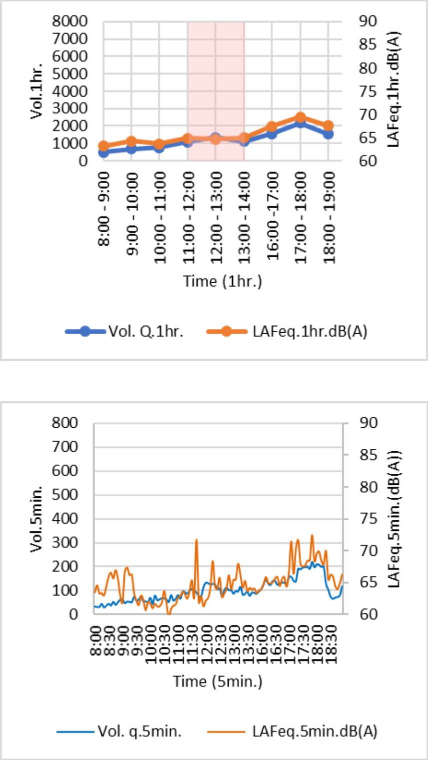
(g) 2LS-2-WD (Location 7)

(h) 2LR-2-WD (Location 8)

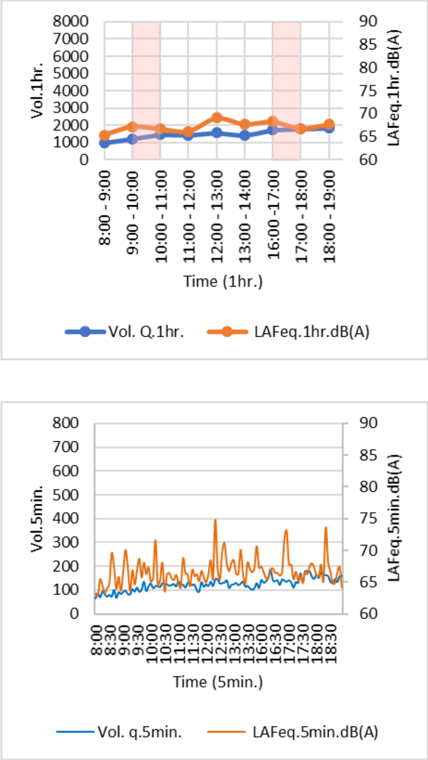
Figure 20. Hourly and 5-min traffic volume versus noise at all 8 sites during weekday peak hours.



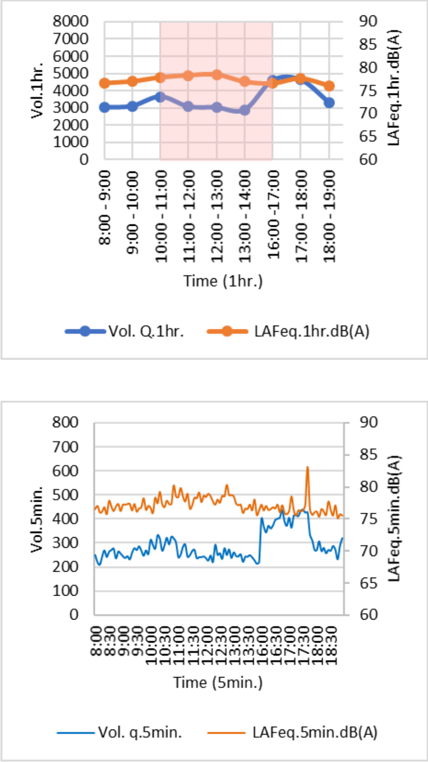
(a) 3LS-1-WE (Location 1)



(b) 3LR-1-WE (Location 2)



(c) 2LS-1-WE (Location 3)



(d) 2LR-1-WE (Location 4)

(e) 3LS-2-WE (Location 5) (f) 3LR-2-WE (Location 6) (g) 2LS-2-WE (Location 7) (h) 2LR-2-WE (Location 8)

Figure 21. Hourly and 5-min traffic volume versus noise at all sites during weekend peak hours.

5.3.4.1. Descriptive Statistics of Hourly Data

Table 11 tabulates the hourly, mean morning (3-hr), mean afternoon (3-hr), and mean evening (3-hr) traffic noise levels and volumes along with a summary of descriptive statistics for the 16 sets of 9 hourly traffic noise and volume data. Some recurring patterns were observed from the overall analysis of weekday and weekend values in Table 11. The maximum and the minimum traffic volume or noise level values per column (in the hourly and the 3-hr mean values section) were highlighted in red and green shades respectively. However, the maximum and the minimum values traffic volume and noise level values were highlighted per row in the descriptive statistics sections.

For instance, on both working and non-working days, the mean afternoon noise level values were comparatively higher than the mean evening and morning values seemingly due to higher mean traffic volumes during afternoon and evening periods and comparatively lower traffic volumes during the morning period. Moreover, based on descriptive statistics of the 9 hourly data/intersection/day, the noise level and the traffic volume were the minimum during early morning hour on both weekday (6:00-7:00) and weekend (8:00-9:00). On both weekdays (13:00-14:00) and weekends (12:00-13:00) the noise level values were maximum during the afternoon.

Besides, it was observed that the highest or the lowest hourly noise level did not always correspond to the highest or the lowest hourly traffic volume respectively. For example, both the maximum weekday hourly noise level (803 dB(A)) and volume (7014 vph) occurred at 3LS-2. Likewise, the maximum weekend volume (5800 vph) occurred at the same intersection. However, the maximum weekend noise level (78.5 dB(A)) occurred at 2LR-1 corresponding to the second-largest weekend traffic volume.

Likewise, the same was true for the minimum hourly weekday and weekend values and the 9-hr mean values. The minimum weekday noise level (65.7 dB(A)) was observed at 2LS-1 corresponding to the second least traffic volume (1128 vph). Again, the least weekday traffic volume was at 3LR-1 with the second least noise level (68.2 dB(A)). Whereas, both the minimum weekend noise level (63.2 dB(A)) and volume (481 vph) were found at 3LR-1.

Additionally, the weekday and weekend minimum 9-hr mean noise levels and traffic volumes were observed at 2LS-1 (67.3 dB(A) and 1555 vph) and 3LR-1 (66 dB(A)) and 1186 vph) respectively. However, both the weekday (77.5 dB(A) and 4228 vph) and weekend (77.4 dB(A) and 3480 vph) maximum noise levels coincided with the second-largest mean volumes observed at 2LR-1 respectively. The largest volumes were at 3LS-2 on both weekday (6363 vph and 76.5 dB(A)) and weekend (5063 vph and 75.3 dB(A)). Nevertheless, there was an overall positive relationship between the two main variables.

Furthermore, the weekday hourly noise level values ranged (the difference between the maximum and the minimum hourly values) from 260 vph to 531 vph. Whereas, the noise levels ranged between 1.1 dB(A) to 5.5 dB(A). On the other hand, the weekend traffic volume and noise level values ranged from 277 vph to 1290 vph and 0.8 dB(A) to 2.1 dB(A) respectively.

The weekday and weekend standard deviation (SD), coefficient of variance (CV), and standard error of the mean (SE) for the 9 hourly volume and noise level data were also tabulated. The range of weekday SD values (260~531 vph and 0.3~1.7 dB(A)) were lower than those on weekends (277~1280 vph and 0.8~2.1 dB(A)). Also, as the SD varied significantly from one set of data to another, the ratio of SD to the mean or the CV was used to compare relative variability between the data sets.

Whereas, the SE values represented the standard deviation of the mean value itself within each data set.

Both the maximum weekday and weekend CV and SE for volume and noise level were observed at 3LR-1. On the other hand, the minimum weekday and weekend CV and SE for volume and noise level were found at 3LR-2 and 3LS-2 respectively. In other words, both weekday (about 17% CV) and weekend (44% CV) traffic volumes varied the most at the first 3-lane roundabout corresponding to noise level CV of 2% and 3% respectively. Whereas, the least weekday volume CV corresponding to the least traffic volume CV was observed at 3LR-2. On the weekend, 14% and 1% were the least traffic volume and noise level CV found at 3LS-2.

Hence, similar to SD, the CV values for volumes and noise levels were higher on weekends compared to weekdays, meaning that weekend data had more variability. Also, the noise level data corresponding to the traffic volume data showed comparatively lower variability. Lastly, on both weekdays and weekends, the range of standard error of mean for traffic volumes (0.03~0.05) and noise levels (0~0.01 dB(A)) at the intersections were also quite low, indicating that the traffic volume and noise level data sets used in this study were accurate and representative enough for comparative purposes.

Table 11. Statistical Characteristics of Weekday and Weekend Peak Hours and Mean Noise Levels and Traffic Counts at all 8 Sites.

Site ID-Day		**3LS-1-WD**		**3LR-1-WD**		**2LS-1-WD**		**2LR-1-WD**		**3LS-2-WD**		**3LR-2-WD**		**2LS-2-WD**		**2LR-2-WD**	
Time		Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.
Morning	6:00-7:00	3170	73	1076	68.2	1371	67.4	3703	77.9	6468	75.5	5130	76.8	3372	72	2508	73.3
	7:00-8:00	3387	72.8	2816	71	1366	66.4	3928	76.1	6564	75.2	5043	76.1	4340	71.1	2345	73.7
	8:00-9:00	2524	73.1	4915	71.6	1128	65.7	3334	77.3	5122	75.8	4623	76.1	2991	71.9	1552	72.8
Afternoon	12:00-13:00	3061	72.5	3148	70.6	1876	67.9	4563	77.4	6230	76.3	5931	76.4	3725	70.3	2603	72.4
	13:00-14:00	3608	74.8	3505	70.7	1628	67.6	4949	77.5	7014	80.3	6051	75.8	3965	71.1	2455	74
	14:00-15:00	3195	73.2	3002	71.8	1437	66.8	4169	76.9	6826	76.9	5689	76.2	3829	72.0	1990	74.9
Evening	16:00-17:00	3043	76.4	2057	69.6	1540	66.6	4321	78.7	6293	75.6	5702	76.9	3754	72.4	1809	71.7
	17:00-18:00	3026	73.1	2417	69.4	1732	67.5	4879	78.2	6387	75.1	5498	76.3	4048	71.5	1943	71.2
	18:00-19:00	3119	73.7	1638	68.4	1921	69.1	4208	77.5	6350	74.8	5509	76.2	4096	71.0	2049	71.8
Mean	Morning	3027	73.0	2936	70.5	1288	66.6	3655	77.2	6051	75.5	4932	76.3	3568	71.7	2135	73.3
	Afternoon	3288	73.6	3218	71.1	1647	67.5	4560	77.3	6690	78.2	5890	76.1	3840	71.2	2349	73.9
	Evening	3063	74.6	2037	69.2	1731	67.9	4469	78.1	6343	75.2	5570	76.5	3966	71.7	1934	71.6
Descriptive Statistics	Mean	3126	73.8	2730	70.3	1555	67.3	4228	77.5	6362	76.5	5464	76.3	3791	71.5	2139	73
	Max.	3608	76.4	4915	71.8	1921	69.1	4949	78.7	7014	80.3	6051	76.9	4340	72.4	2603	74.9
	Min.	2524	72.5	1076	68.2	1128	65.7	3334	76.1	5122	74.8	4623	75.8	2991	70.3	1552	71.2
	Range	1084	3.9	3839	3.6	793	3.4	1615	2.6	1892	5.5	1428	1.1	1349	2.1	1051	3.6
	SD	294	1.2	472	1.3	260	1	528	0.7	531	1.7	457	0.3	405	0.7	356	1.2
	CV	9%	2%	17%	2%	17%	1%	12%	1%	8%	2%	8%	0%	11%	1%	17%	2%
	SE	0.03	0.01	0.06	0.01	0.06	0.00	0.04	0.00	0.03	0.01	0.03	0.00	0.04	0.00	0.06	0.01

Site ID-Day		3LS-1-WE		3LR-1-WE		2LS-1-WE		2LR-1-WE		3LS-2-WE		3LR-2-WE		2LS-2-WE		2LR-2-WE	
Time		Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.	Vol. 1hr.	$L_{AFeq.}$ 1hr.
Morning	08:00-09:00	987	68.8	481	63.2	984	65.4	3011	76.7	3730	75.6	1834	72.7	2014	70.1	663	67.6
	09:00-10:00	1191	69.1	685	64.3	1221	67.2	3103	77	4298	74.7	2045	72.6	2450	71.2	1064	68.1
	10:00-11:00	1218	69.4	759	63.7	1452	66.7	3656	77.9	4774	74.4	2430	72.7	2578	70.5	1144	68.6
Afternoon	11:00-12:00	1502	68.5	1073	64.9	1446	66.2	3072	78.3	5185	74.9	2439	72.6	2737	71.4	1180	70
	12:00-13:00	1691	70.1	1338	64.7	1556	69.1	3018	78.5	5570	74.2	3739	74.4	2876	69.5	1508	70.1
	13:00-14:00	1498	71.2	1095	65	1437	67.8	2876	77	5145	77.0	4042	75.1	2782	70.1	1283	70.2
Evening	16:00-17:00	1860	71.5	1549	67.4	1720	68.3	4612	76.6	5800	75.7	5070	76.1	3510	73.3	1574	69.2
	17:00-18:00	2024	70.4	2172	69.4	1799	66.8	4644	77.6	5692	74.7	4741	76.4	3971	71	1621	68.3
	18:00-19:00	2015	70.4	1524	67.5	1849	67.7	3326	76.1	5371	74.4	4770	75.5	3592	71.5	1719	69.5
Mean	Morning	1132	69.1	642	63.8	1219	66.5	3257	77.2	4267	74.9	2103	72.7	2347	70.6	957	68.1
	Afternoon	1564	70.1	1169	64.9	1480	67.8	2989	78.0	5300	75.5	3407	74.2	2798	70.4	1324	70.1
	Evening	1966	70.8	1748	68.2	1789	67.6	4194	76.8	5621	75.0	4860	76	3691	72	1638	69
Descriptive Statistics	Mean	1554	70	1186	66.0	1496	67.4	3480	77.4	5063	75.2	3457	74.5	2946	71.1	1306	69.2
	Max.	2024	71.5	2172	69.4	1849	69.1	4644	78.5	5800	77.0	5070	76.4	3971	73.3	1719	70.2
	Min.	987	68.5	481	63.2	984	65.4	2876	76.1	3730	74.2	1834	72.6	2014	69.5	663	67.6
	Range	1037	3.0	1691	6.2	865	3.7	1768	2.4	2070	2.8	3236	3.8	1957	3.8	1056	2.6
	SD	374	1.1	524	2.1	277	1.1	689	0.8	685	0.9	1280	1.6	624	1.1	335	1.0
	CV	24%	2%	44%	3%	19%	2%	20%	1%	14%	1%	37%	2%	21%	2%	26%	1%
	SE	0.08	0.01	0.15	0.01	0.06	0.01	0.07	0.00	0.05	0.00	0.12	0.01	0.07	0.01	0.09	0.00

**Max. *Min.

5.3.4.2. Change of Hourly Volume and Noise

The trend discrepancies observed earlier between the two variables during hourly and 5-min comparisons (highlighted with light red boxes in Figure 20 and Figure 21) were further checked and analyzed based on the increase or decrease in noise level (ΔNoise) due to increase or decrease in corresponding traffic volume (ΔVol.) from one hour to the next (see Table 12). Results showed that in all cases the change in the noise levels from one hour to the next were barely perceivable as they were all below 5 dB(A) (WHO). Likewise, the traffic volumes also did not drastically change from one hour to another.

Additionally, discrepancies in the expected positive relationship between traffic volume and noise were observed during a number of morning, afternoon and evening peak hours (indicated with bold text). In all other cases, the percent change of hourly traffic volume and noise levels showed a positive relationship. The sometimes negative relationship observed between the two main variables were most likely due to some other noise contributing variables besides the traffic volumes such as the distribution of vehicle types within each hour.

Table 12. Percent Change of Weekday and Weekend Peak Hours Hourly Traffic Volume and $L_{AFeq.1hr.}$ at all 8 Sites

Site ID	**3LS-1**		**3LR-1**		**2LS-1**		**2LR-1**		**3LS-2**		**3LR-2**		**2LS-2**		**2LR-2**	
Peak Hours	ΔV%	ΔL	ΔV%	ΔL	ΔV%	ΔL	ΔV%	ΔL	ΔV%	ΔL	ΔV%	ΔL	ΔV%	ΔL	ΔV%	ΔL
Weekday																
06:00 - 07:00	**7%**	**-0.2**	162%	2.8	**0%**	**-1**	**6%**	**-1.9**	**1%**	**-0.3**	**-2%**	**-0.7**	**29%**	**-0.9**	**-6%**	**0.4**
07:00 - 08:00	**-25%**	**0.3**	75%	0.6	-17%	-0.7	**-15%**	**1.2**	**-22%**	**0.6**	**-8%**	**0**	**-31%**	**0.8**	-34%	-0.9
08:00 - 09:00	**21%**	**-0.6**	-36%	-1	66%	2.2	37%	0.1	22%	0.5	28%	0.3	**25%**	**-1.6**	**68%**	**-0.4**
12:00 - 13:00	18%	2.3	11%	0.1	**-13%**	**-0.3**	8%	0.2	13%	4	2%	-0.6	6%	0.8	**-6%**	**1.5**
13:00 - 14:00	-11%	-1.6	**-14%**	**1.1**	-12%	-0.8	-16%	-0.6	**-3%**	**-3.4**	**-6%**	**0.4**	**-3%**	**0.9**	**-19%**	**0.9**
14:00 - 15:00	**-5%**	**3.2**	-31%	-2.2	**7%**	**-0.2**	4%	1.8	-8%	-1.3	0%	0.7	**-2%**	**0.4**	-9%	-3.2
16:00 - 17:00	-1%	-3.3	**18%**	**-0.2**	12%	0.9	**13%**	**-0.5**	**1%**	**-0.5**	**-4%**	**-0.6**	**8%**	**-0.8**	**7%**	**-0.4**
17:00 - 18:00	3%	0.6	-32%	-1	11%	1.6	-14%	-0.7	**-1%**	**-0.3**	**0%**	**-0.1**	**1%**	**-0.5**	5%	0.6
Weekend																
08:00 - 09:00	21%	0.3	42%	1.1	24%	1.8	3%	0.4	**15%**	**-0.9**	**12%**	**-0.1**	22%	1.1	60%	0.5
09:00 - 10:00	2%	0.3	**11%**	**-0.6**	**19%**	**-0.5**	18%	0.9	**11%**	**-0.3**	19%	0.1	**5%**	**-0.8**	8%	0.5
10:00 - 11:00	**23%**	**-0.9**	41%	1.2	-0.4%	-0.5	**-16%**	**0.4**	9%	0.5	**0%**	**-0.1**	6%	0.9	3%	1.4
11:00 - 12:00	13%	1.6	**25%**	**-0.2**	8%	2.9	**-2%**	**0.2**	**7%**	**-0.7**	53%	1.8	**5%**	**-1.9**	28%	0.2
12:00 - 13:00	**-11%**	**1.1**	**-18%**	**0.3**	-8%	-1.3	-5%	-1.5	**-8%**	**2.8**	8%	0.7	**-3%**	**0.7**	**-15%**	**0.0**
13:00 - 14:00	24%	0.3	41%	2.4	20%	0.5	**60%**	**-0.4**	**13%**	**-1.3**	25%	1	26%	3.1	**23%**	**-1.0**
16:00 - 17:00	**9%**	**-1.1**	40%	2	**5%**	**-1.5**	1%	1.0	**-2%**	**-1**	**-6%**	**0.3**	**13%**	**-2.2**	**3%**	**-0.9**
17:00 - 18:00	**-0.4%**	**0.0**	-30%	-1.9	3%	0.9	-28%	-1.5	-6%	-0.3	**1%**	**-0.9**	**-10%**	**0.5**	6%	1.1

5.3.5. Peak Hours Comparisons based on Different Parameters

Traffic noise levels corresponding to traffic volumes at all the 8 sites over the selected two sets of 9 peak hours for weekday and weekend were illustrated on two separate line charts respectively (see Figure 22) in order to discuss the similarities and differences among the pairs of similar intersections types (2-lane signals, 3-lane signals, 2-lane roundabouts, and 3-lane roundabouts).

5.3.5.1. Similar Intersection Types and Similar Sizes

Comparison of weekday and weekend peak hours traffic volumes and noise levels were done among similar intersection types and number of lanes based on the 9 hourly weekday and weekend charts in Figure 22 and 9-hr mean weekday, weekend, and overall noise level vs volume charts in Figure 24.

5.3.5.1.1. 2-lane signal-1 vs 2-lane signal-2

On both weekday and weekend, the traffic noise levels and traffic volumes throughout the 9 peak hours were mostly higher at 2LS-2 (see Figure 22 and Figure 24). The trend between the two variables were also mostly positive with some discrepancies observed especially at 2LS-2.

5.3.5.1.2. 3-lane signal-1 vs 3-lane signal-2

Both the traffic noise levels and traffic volumes at 3LS-2 were mostly higher than those at 3LS-1. Again, besides some small discrepancies, the trend between the variables appeared to be mostly positive. Overall, the volumes and noise levels at the 3-lane signals were higher than the 2-lane signals (see Figure 22 and Figure 24).

Also, with lower traffic volumes at 3LS-1 compared to 2LS-2 on both weekday and weekend, the noise level at the 3-lane signal were slightly higher than the 2-lane signal on weekday and almost similar on the weekend. Likewise, with almost similar traffic volumes on weekend at 3LS-1 and 2LS-1, noise at 3LS-1 were slightly higher.

Whereas, both the variables were higher at 3LS-1 compared to 2LS-1 on weekday. At 3LS-2, where the traffic volumes on both weekday and weekend were much higher compared to the other signals, the noise levels were also higher. That is, noise levels with respect to traffic volumes were higher at the 3-lane signals compared to the 2-lane signals.

5.3.5.1.3. 2-lane roundabout-1 vs 2-lane roundabout-2

On the other hand, when comparing the two 2-lane roundabouts, both the variables at the first roundabout (2LR-1) were mostly higher than that at the other 2-lane roundabout, 2LR-2 (see Figure 22 and Figure 24). The relationship between the variables were again mostly positive.

Besides, with almost similar traffic volumes between 2LS-1 and 2LR-2 on both weekday and weekend, the noise levels at the 2-lane roundabout were higher. The same was also true between 2LS-2 and 2LR-1. Hence, the two 2-lane roundabouts generated more traffic noise levels compared to the two 2-lane signals.

5.3.5.1.4. 3-lane roundabout-1 vs 3-lane roundabout-2

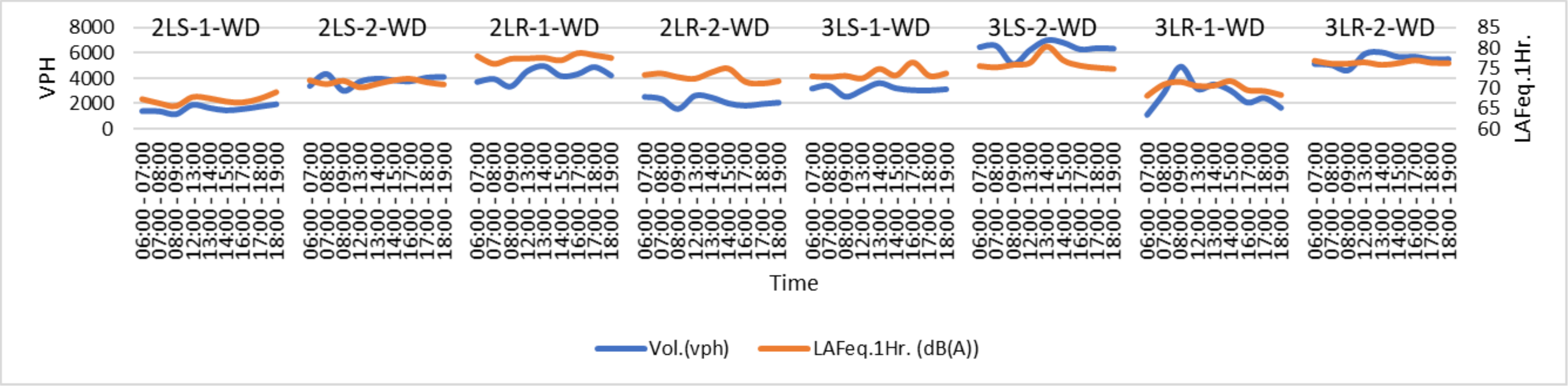
Finally, when comparing the two 3-lane roundabouts, the weekday and weekend traffic noise levels and volumes at 3LR-2 were found to be mostly higher than 3LR-1 (see Figure 22 and Figure 24). The rise and decline of the noise levels were also mostly following the rise and decline of the corresponding traffic volumes.

With almost similar traffic volumes between the first 3-lane signal and roundabout and the second 3-lane signal and roundabout, the roundabouts generated comparatively slightly lower traffic noise levels.

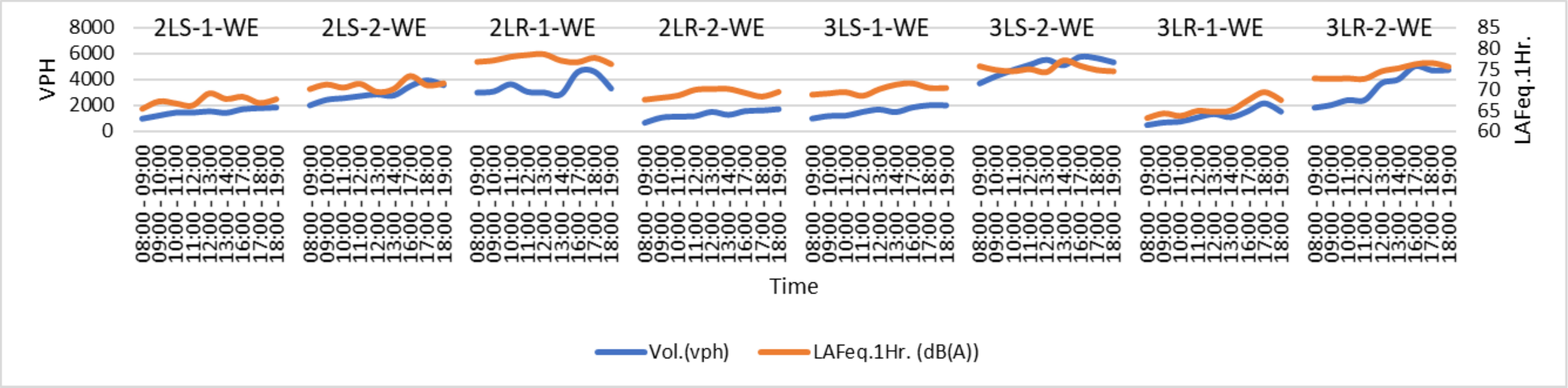
Again, on weekdays, the noise levels at 3LR-2 were lower than those at 2LR-1 although the traffic volumes were higher at the 3-lane roundabout. Likewise, although the traffic volumes were lower at 2LR-2, the noise levels were higher at the 2-lane roundabout compared to the 3-lane roundabout on weekday.

On weekends, however, with almost similar traffic volumes at 3LR-1 and 2LR-2, the noise levels at 2LR-2 were still higher. The same was also true for the noise level and traffic volume values observed between 3LR-2 and 2LR-1. Although the traffic volumes were mostly similar and only slightly higher at the 3-lane roundabout (3LR-2), the noise levels at the 2-lane roundabout (2LR-1) were still comparatively higher. In other words, compared to 2-lane roundabouts, 3-lane roundabouts generated lower traffic noise levels for almost similar or even slightly higher traffic volumes.

To sum up, the overall observation of the line charts in Figure 22 confirm that the noise levels and traffic volumes follow similar trends of rise and decline, with a few exceptions. That is, noise levels have a direct positive relationship with traffic count at any intersection regardless of the intersection type. Nevertheless, the noise levels between similar intersection types and comparable intersection types showed some common trends and variations.



(a) Weekday



(b) Weekend

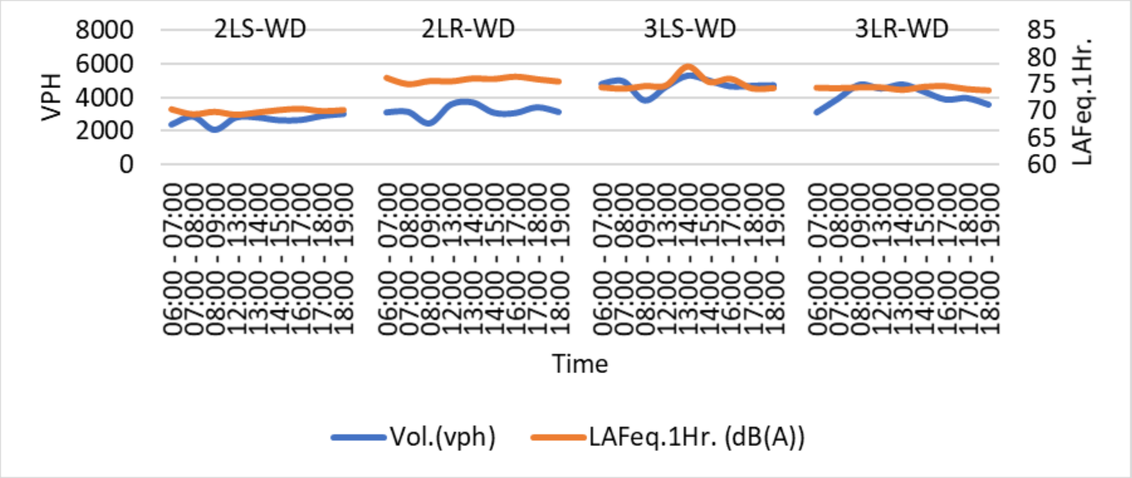
Figure 22. Weekday and weekend peak hourly traffic volume vs noise level at all 8 sites.

5.3.6. Mean Comparisons based on Different Parameters

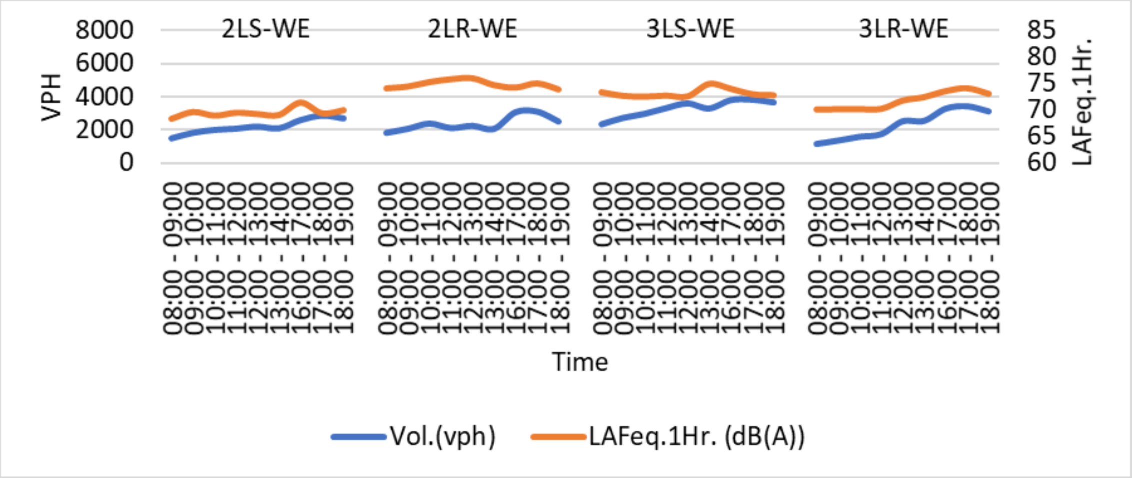
Comparisons were made between the four different intersection types (2LS, 2LR, 3LS, and 3LR) based on different parameters such as intersection type and size. For this, the traffic noise level and volume data observed during the selected (9-hr) weekday and weekend peak hours in each of the four pairs representing the four different intersection types (2LS, 3LS, 2LR, and 3LR) were first combined. Then, the weekday and weekend hourly means of the four types were plotted on two separate line charts for weekday and weekend respectively as shown Figure 23.

Based on these charts, any similarities or differences in the mean hourly noise levels trends due to mean hourly traffic volumes between similar intersections types and different sizes (2LS vs 3LS and 2LR vs 3LR) and vice versa (2LS vs 2LR and 3LS vs 3LR) were summarized in the following two sub-sections.

In addition, weekday, weekend, and overall 9-hr mean noise level (y-axis) vs 9-hr mean volume (x-axis) charts (see Figure 24) were prepared for all the eight sites and the four intersection types respectively to compare which set of intersection generated more traffic noise compared to the other sets. In these charts, the combined differences between the mean values of the 4 sets (each set containing two similar intersections) of four different types of traffic intersections were more visually comprehensible. The comparative analysis based on these charts were also done in the following two subsections.

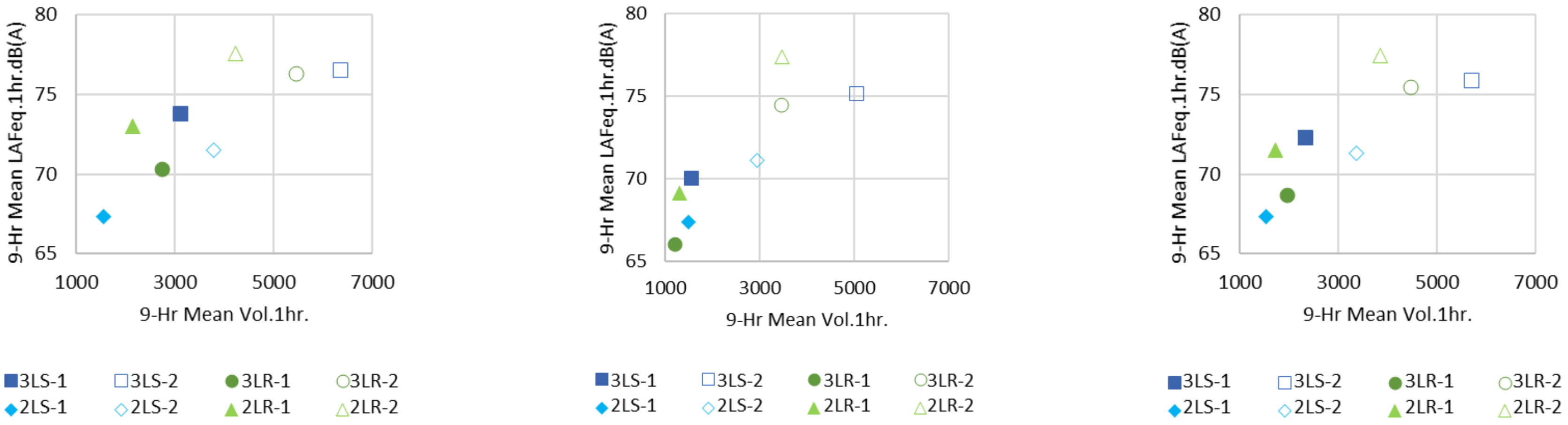


(a) Weekday (2LS vs 2LR and 3LS vs 3LR)

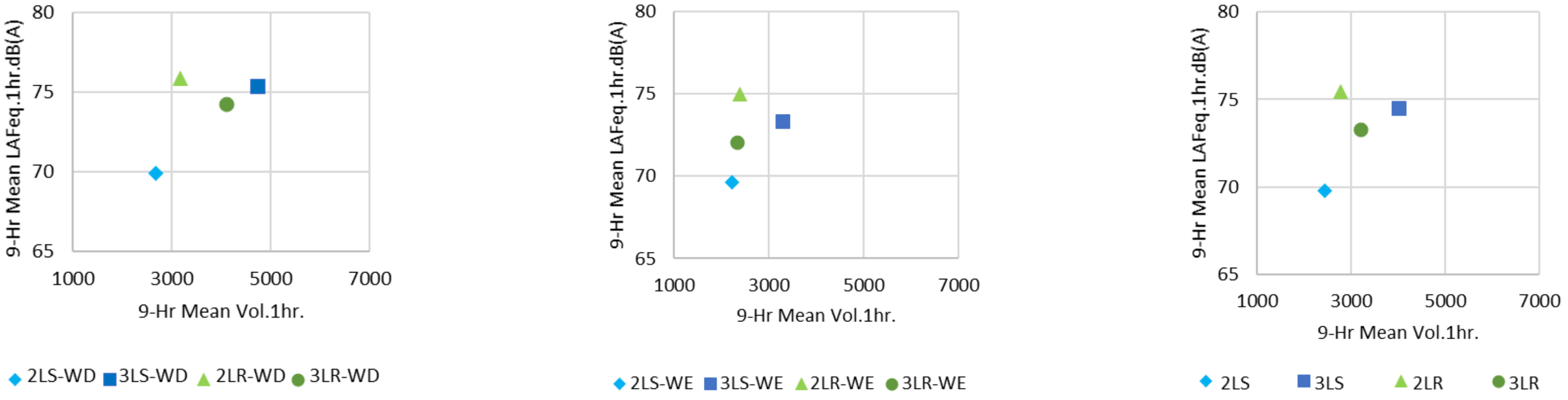


(b) Weekend (2LS vs 2LR and 3LS vs 3LR)

Figure 23. Mean weekday and weekend peak hourly traffic volumes vs noise levels at the four different intersection types.



(a) Weekday (All 8 Sites) (b) Weekend (All 8 Sites) (c) Overall (All 8 Sites)



(d) Weekday (2LS, 2LR, 3LS, and 3LR) (e) Weekend (2LS, 2LR, 3LS, and 3LR) (f) Overall (2LS, 2LR, 3LS, and 3LR)

Figure 24. 9-hr mean noise level vs traffic volume charts representing all 8 sites and the four different intersection types.

Furthermore, using the same mean data used in Figure 24, change of 9-hr mean noise levels corresponding to the 9-hr mean (%) traffic volume changes within each comparison sets were tabulated in Table 13. Accordingly, a discussion based on analysis of the noise level differences corresponding to the (%) volume differences among the different sets of comparisons were also done in the next two sub-sections.

Table 13. Change of 9-hr Mean Noise Level Corresponding to (%) Traffic Volume Change based on Different Parameters

9-Hr Mean	**Weekday (Peak Hours Mean)**					**Weekend (Peak Hours Mean)**					**Peak Hours Mean**				
Intersection Type	$L_{AFeq.1hr.}$	Vol.$_{1hr.}$	ΔL	ΔV	ΔV%	$L_{AFeq.1hr.}$	Vol.$_{1hr.}$	ΔL	ΔV	ΔV%	$L_{AFeq.1hr.}$	Vol.$_{1hr.}$	ΔL	ΔV	ΔV%
2-lane Signal VS 3-lane Signal															
2LS	69.9	2673	5.47	2070	77%	69.6	2221	3.69	1088	49%	69.8	2447	4.70	1579	65%
3LS	75.4	4744				73.3	3308				74.5	4026			
2-lane Roundabout VS 3-lane Roundabout															
2LR	75.8	3184	-1.56	913	29%	75.0	2393	-2.90	-72	-3%	75.4	2788	-2.11	421	15%
3LR	74.3	4097				72.1	2321				73.3	3209			
2-lane Signal VS 2-lane Roundabout															
2LS	69.9	2673	5.94	511	19%	69.6	2221	5.34	172	8%	69.8	2447	5.66	341	14%
2LR	75.8	3184				75.0	2393				75.4	2788			
3-lane Signal VS 3-lane Roundabout															
3LS	75.4	4744	-1.09	-647	-14%	73.3	3308	-1.25	-987	-30%	74.5	4026	-1.15	-817	-20%
3LR	74.3	4097				72.1	2321				73.3	3209			

5.3.6.1. Similar Intersection Types and Different Sizes

Comparison between sets of similar intersection types and different sizes (2-lane vs 3-lane signals and 2-lane vs 3-lane roundabouts) was done based on the hourly (see Figure 22) and the means of the 9 hourly traffic noise levels and volumes during the selected 9-hr weekday, 9-hr weekend, and overall (mean of weekday and weekend data) peak hour periods (see Figure 23, Figure 24, and Table 13). With a few exceptions, an overall positive relationship between the traffic noise levels and volumes was observed regardless of the intersection type and day.

5.3.6.1.1. 2-lane vs 3-lane signals

The range of weekday (around 4744 vph and 75.4 dB(A)) and weekend (around 3308 vph and 73.3 dB(A)) traffic volume and noise levels at 3-lane signals (3LS) were comparatively higher than the range of weekday (around 2673 vph and 69.9 dB(A)) and weekend (around 2221 vph and 69.6 dB(A)) traffic volume and noise levels observed at 2-lane signals (2LS) respectively. Overall (9-hr mean of weekday and weekend) results showed that traffic noise levels at the 3-lane signals (74.5 dB(A)) exceeded the mean value observed at the 2-lane signals (69.8 dB(A)) by 4.7 dB(A) due to a mean difference of 65% (1579 vehicles) more traffic volume at the 3LS.

Hence, most of the hourly and the overall 9-hr mean traffic volume and noise level at 3LS were higher than those at 2LS. In other words, in the case of signals, as expected the larger traffic intersection having larger volume capacity generated more traffic noise due to higher traffic volume.

5.3.6.1.2. 2-lane vs 3-lane roundabouts

The range of weekday (around 4097 vph and 74.3 dB(A)) and weekend (around 2321 vph and 72.1 dB(A)) traffic volume and noise levels at 3-lane roundabouts (3LR) were comparatively higher than the range of weekday (around 3184 vph and 75.8

dB(A)) and weekend (around 2393 vph and 75.0 dB(A)) traffic volume and noise levels observed at 2-lane roundabouts (2LR) respectively. The overall (9-hr mean of weekday and weekend) value of traffic noise level at the 2-lane roundabouts (75.4 dB(A)) exceeded the mean value at the 3-lane roundabouts (73.3 dB(A)) by 2.1 dB(A) although the overall 9-hr mean traffic volume at the 3LR was 15% (421 vehicles) more.

In the case of signals, larger size (3-lane) signals generated more noise due to more traffic volume as expected. However, the smaller size (2-lane) roundabouts were found to be noisier than the larger size roundabouts although the overall volume at the 2LR was about 1.2 times lower than that at the 3LR.

5.3.6.2. Different Intersection Types and Similar Sizes

Similarly, comparison between sets of different intersection types and similar sizes (2-lane signals vs roundabouts and 3-lane signals vs roundabouts) was done based on the hourly (see Figure 22) and the means of the 9 hourly traffic noise levels and volumes during the selected 9-hr weekday, 9-hr weekend, and overall (mean of weekday and weekend data) peak hour periods (see Figure 23, Figure 24, and Table 13).

5.3.6.2.1. 2-lane signals vs roundabouts

The range of weekday (around 3184 vph and 75.8 dB(A)) and weekend (around 2393 vph and 75 dB(A)) traffic volume and noise levels at 2-lane roundabouts (2LR) were comparatively higher than the range of weekday (around 2673 vph and 69.9 dB(A)) and weekend (around 2221 vph and 69.6 dB(A)) traffic volume and noise levels observed at 2-lane signals (2LS) respectively. Overall (9-hr mean of weekday and weekend) results showed that traffic noise levels at the 2-lane roundabouts (75.4 dB(A)) exceeded the mean value observed at the 2-lane signals (69.8 dB(A)) by 5.7 dB(A) due to a mean difference of 14% (341 vehicles) more traffic volume at the 2LR. Hence, in case of 2-lane intersections, 2LR generated perceivably higher (above 5 dB(A)) mean traffic noise level than 2LS even though the mean traffic volume at the roundabouts was only 1.1 times higher.

5.3.6.2.2. 3-lane signals vs roundabouts

The range of weekday (around 4744 vph and 75.4 dB(A)) and weekend (around 3308 vph and 73.3 dB(A)) traffic volume and noise levels at 3-lane signals (3LS) were comparatively higher than the range of weekday (around 4097 vph and 74.3 dB(A)) and weekend (around 2321 vph and 72.1 dB(A)) traffic volume and noise levels observed at 3-lane roundabouts (3LR) respectively. Likewise, the overall (9-hr mean of weekday and weekend) value of traffic noise level at the 3-lane signals (74.5 dB(A)) exceeded the mean value at the 3-lane roundabouts (73.3 dB(A)) by 1.2 dB(A) although the overall 9-hr mean traffic volume at the 3LR was 20% (817 vehicles) more. Hence, unlike 2-lane intersections, the mean noise level at 3LS was slightly higher (1.2 dB(A)) than the 3LR due to 1.3 times more mean traffic volume at the signals.

CHAPTER 6: TRAFFIC NOISE PREDICTION MODEL

6.1. Introduction

The main objective of the analysis in this chapter is to develop a general and intersection type (roundabout or signal) specific noise prediction models appropriate for the unique geographic, socio-economic, and traffic features of Qatar and other similar regions as a case study to investigate whether intersection type-specific models are better than calibrated generalized models to predict traffic noise levels at two very different intersection types – the signal and the roundabout. Besides, the calibrated models could be used to determine whether traffic noise levels at various traffic intersections in Doha, Qatar is within the WHO's acceptable daytime noise level threshold of 65 dB(A). Moreover, the customized models are expected to be especially advantageous in terms of predicting and comparing traffic noise levels at different intersection types so that governments, policymakers, and urban planners can better understand the noise contribution of the two intersection types and adopt noise management and mitigation plans and strategies accordingly.

6.2. Methodology

In this study, traffic noise level, volume, and site data at eight selected signalized intersections and roundabouts of two different sizes (2-lane and 3-lane) within Doha, Qatar were used to calibrate the general 1988 CORTN traffic noise prediction model as per the local site and traffic conditions in Doha, resulting in a general modified CORTN model appropriate for Doha and other similar cities in the Middle Eastern region.

Furthermore, the locally customized model was then customized based on the data collected at the two different intersection types namely signalized intersection and roundabout of two different sizes to develop intersection type-specific traffic noise predict models. Although the proposed models were calibrated to represent the local site and traffic conditions in Qatar, the methodology used in developing the customized models is expected to be applicable to other regions as well.

Additionally, a traffic noise prediction model developed for Doha, Qatar is expected to have the potential to predict traffic noise in other similar cities in the region with good reliability. As a result, the government and policy makers would be better equipped to plan a sustainable transport network and propose/modify land use for the surrounding areas.

6.2.1. The CORTN Traffic Noise Prediction Model

The CORTN is an empirical model that is based on traffic flow (Q) through a particular road section in an hour and the equivalent sound pressure level ($L_{Aeq.1hr.}$), a commonly used road traffic noise indicator (Quiñones-Bolaños et al., 2016). The model assumes a long line source of free-flowing homogenous rush hour traffic moving at a constant speed and radiating cylindrically at a reference distance from an observer (Steele, 2001). Consequently, the procedure to predict traffic noise using the CORTN model begins with the determination of a datum value of basic hourly noise level (Lo) in terms of total hourly traffic flow (Q) as follows:

$$Lo = Blog(Q) \tag{5.1}$$

where

Lo is the datum value of basic hourly noise level,

B is a constant which is equal to 10 in the original CORTN model, and

Q is the total hourly traffic flow.

Lo is calculated at a reference distance of 10 meters from the nearside edge of a carriageway, a reference mean hourly traffic speed of 75 km/hr, and heavy vehicle and gradient percentage of zero without considering the acceleration (Department of

Transport Welsh Office, 1988; Quiñones-Bolaños et al., 2016; Steele, 2001).

Next, to the datum Lo value (see Equation 5.1), a constant term A and various corrections such as adjustments for mean traffic speed and heavy vehicle percentage (Δf), gradient (Δg), pavement type (Δp), distance (Δd), shielding (Δs), angle of view (Δa), and reflection(Δs) are added to calculate the $L_{Aeq.1hr.}$ (see Equation 5.2). In the original CORTN model, the constant term A is equal to 42.2 (Department of Transport Welsh Office, 1988). Also, in the original CORTN model, the various correction factors, $\Delta f,\ \Delta g,\ \Delta p,\ \Delta d,\ \Delta s,\ \Delta a, and\ \Delta r,$ were derived based on curve fitting of datum basic noise level (Lo) values measured under a variety of possible conditions. As a result, the stratagem adopted by the model to calculate $L_{Aeq.1hr.}$ simplified the calculation and prediction of traffic noise, although it compromised the generality of the overall procedure (Steele, 2001).

The original equation for the CORTN Model (Department of Transport Welsh Office, 1988) developed in the UK in 1988 in which only heavy and total traffic flow is considered is as follows:

$$L_{Aeq.1hr.} = A + Blog(Q) + \ \Delta f + \Delta g + \Delta p + \Delta d + \Delta s + \Delta a + \Delta r \qquad (5.2)$$

where

A is a constant term equal to 42.2 in the original CORTN model,

B is a constant term equal to 10 in the original CORTN model,

Q is the total hourly traffic flow,

$Blog(Q)$ is the datum value of basic hourly noise level,

Δf is the heavy vehicle adjustment,

Δg is the gradient adjustment,

Δp is the pavement type adjustment,

Δd is the distance adjustment,

Δs is the shielding adjustment,

Δa is the angle of view adjustment, and

Δr is the angle of reflection adjustment.

The equation for the adjustment factors in Equation 5.2 are as follows (Department of Transport Welsh Office, 1988):

Heavy vehicle adjustment,

$$\Delta f = 33 \log\left(v + 40 + \frac{500}{v}\right) + 10 \log\left(1 + \frac{5p}{v}\right) - 68.8 \tag{5.3}$$

where

v is traffic velocity and

p is the heavy vehicle flow.

In Equation 5.3, p is expressed as rate of the no. HV (f) per total traffic flow, that is,

$$p = \frac{\text{Number of of HV}}{\text{Total Traffic Flow, Q}} \tag{5.4}$$

Mean traffic speed (km/h), v in Equation 5.3 at road junctions are estimated based on class of road with a required speed correction (Δv) of,

$$\Delta v = 0.73 + \left(2.3 - \frac{1.15p}{100}\right)\left(\frac{p}{100}\right) G \tag{5.5}$$

where

v is traffic velocity,

p is the heavy vehicle flow, and

g is the percent gradient.

However, Δv is not applicable to downward flows in case of separately treated carriageway or for one-way traffic schemes.

Gradient adjustment,

$$\Delta g = 0.3G \tag{5.6}$$

where

G is the gradient expressed in %.

Distance adjustment,

$$\Delta d = -10\log\left(\frac{d'}{13.5}\right) \tag{5.7}$$

where

d' is the shortest distance between the effective source and receiver; it is the correction required when receiver point is located at distance d ≥ 4 m from the edge of the nearest carriageway.

Pavement type adjustment for impervious bituminous road surfaces when traffic velocity is < 75km/hr is as follows:

$$\Delta p = -1 \text{ dB(A)} \tag{5.8}$$

Shielding adjustment when there is no barrier between receiver and noise source affecting field noise measurements is as follows:

$$\Delta s = 0 \tag{5.9}$$

Angle of view adjustment,

$$\Delta a = 10\log\left(\frac{\theta}{180°}\right) \tag{5.10}$$

where

θ is the view angle.

Angle of reflection adjustment,

$$\Delta r = +1.5\gamma \tag{5.11}$$

where

ɣ is the proportion of the constructed façade

Besides, all the adjustment factors (Equations 5.3 to Equation 5.11) for a road scheme can be lumped into a single parameter Δm as follows:

$$\Delta m = \Delta g + \Delta p + \Delta d + \Delta s + \Delta a + \Delta r \tag{5.12}$$

where

Δg is the gradient adjustment,

Δp is the pavement type adjustment,

Δd is the distance adjustment,

Δs is the shielding adjustment,

Δa is the angle of view adjustment, and

Δr is the angle of reflection adjustment.

Then, Equation 5.2 can be rewritten as follows:

$$L_{Aeq.1hr.} = A + Blog(Q) + \Delta f + \Delta m \tag{5.13}$$

where

A is a constant term equal to 42.2 in the original CORTN model,

B is a constant term equal to 10 in the original CORTN model,

Q is the total hourly traffic flow,

$Blog(Q)$ is the datum value of basic hourly noise level,

Δf is the heavy vehicle adjustment, and

Δm is the sum of gradient adjustment, pavement type adjustment, distance adjustment, shielding adjustment, angle of view adjustment, and angle of reflection adjustment.

To calibrate Equation 5.13 to conform to local conditions, besides considering the various noise adjustments, the constants A and B need to be fitted to the available noise level measurement data. Consequently, using the available field data, the parameters A and B can be estimated by applying the generalized reduced gradient (GRG) method (Abadie and Carpentier, 1969) while minimizing the root mean square error of the data set (Equation 5.14).

The GRG method is considered to be a precise and accurate method for solving nonlinear programming problems in which the non-linear objective along with the constraint functions are linearized at a local solution based on the Taylor expansion equation (Abadie & Carpentier, 1969; Lee, H.-T., Chen, S.-H., Kang, 2003; Quiñones-Bolaños et al., 2016).

Besides, to check the fit of the prediction models, root means square error (RMSE) is calculated as follows:

$$\text{Root Mean Square Error, } RMSE = \sqrt{\frac{(MSE)^2}{n}} \tag{5.14}$$

where

$$\text{Mean Square Error, } MSE = (Residual)^2 \tag{5.15}$$

and

$$Residual = (Predicted\ Noise) - (Observed\ Noise) \tag{5.16}$$

Additionally, to check whether the calibrated models provide a satisfactory and decent fit to the measured data, residual plots can be used in which the predicted noise levels are plotted with respect to standardized residuals. A model can be considered to provide a good fit if about 95% of the standardized residuals are within 2 dB(A). Standardized residuals are calculated using the following equation:

$$Standardized\ Residual = \frac{Residual}{Standard\ Deviation\ of\ Residuals} \tag{5.17}$$

Besides, the general procedures for the CORTN prediction method outlines 5 main steps to predict or calculate traffic noise levels namely (1) dividing the road scheme into one or more segments to reduce noise variation within a segment, (2) calculating the basic noise level for each segment at a reference distance of 10 meters away from the nearside edge of carriageway, (3) considering distance attenuation and screening of source line of traffic noise to assess noise level at the reception point for each segment, (4) taking into account site layout features such as noise reflections due to presence of buildings and facades and the size of source segment, and (5) finally combining noise contribution from all segments to obtain the predicted noise level at the reception point for the entire road scheme (Department of Transport Welsh Office, 1988). For predicting noise at a complex traffic junction, the stated procedure could be further simplified by not dividing the road scheme at a junction into smaller segments and calculating the traffic noise for the entire road scheme using mean values of the recommended corrections obtained separately for the different approaches of a junction (Quiñones-Bolaños et al., 2016).

Accordingly, Equation 5.13, is the traffic noise prediction model that was calibrated in this study using Equation 5.3 to Equation 5.11 to conform to the local site and traffic characteristics found at traffic intersections in Doha, Qatar. The customized model was further calibrated to develop a set of intersection type-specific CORTN models. Equation 5.14 to Equation 5.17 were used to check the improvement and accuracy of the proposed modified and intersection type-specific CORTN models.

6.2.2. Variables

$L_{Aeq.}$ (A-weighted equivalent continuous noise level) and traffic volume (with the vehicle type) were the main variables required for the development of the CORTN noise prediction models (see Chapter 3 for more details). In addition, other site and traffic data such as gradient, distance from the receiver (noise level meter), shielding, angle of view, and angle of reflection due to facades or obstructions, heavy vehicle percentage, and traffic speed were also observed at each of the eight intersections. The additional data were necessary to make adjustments to the noise level data recorded in order to calibrate the CORTN model to local site and traffic conditions.

6.2.3. Field Measurements

Traffic noise, volume, and weather data were recorded at the eight intersections at 5-min intervals on 8 weekdays and 8 weekends from 6 AM until 10 PM (16 hours). The corresponding 9 peak hours traffic flow volumes and characteristics at all approaches were then extracted at 5-min intervals from the recorded 16 hourly video data. At the same time, other factors such as speed limit, total number of lanes, slope, and pavement surface texture (good or excellent) for each approach were also observed at each of the eight intersections (see Chapter 3 for more details).

6.3. Analysis

Based on the two main variables – traffic volume (divided into two vehicle categories – light vehicle and heavy vehicle) and noise level data – collected at the eight traffic intersections (of 2 different types and 2 different sizes) in Doha, Qatar, a modified general (CORTN-M) traffic noise level prediction model was developed by modifying the original 1988 CORTN model (CORTN-O) in order to calibrate the model to local conditions. Next, the modified general model was further customized into intersection type-specific models to represent two of the most common intersection types – signals and roundabouts of two of the most common sizes (2-lane and 3-lane) – found in urban areas. The specific models were developed using various combinations of data sets to check if and which intersection type-specific models improved traffic noise level predictions compared to the modified general model.

Besides, during model development, adjustments for heavy vehicle percentage, traffic speed, gradient, distance from the receiver, shielding, angle of view, and angle of reflection due to facades or obstructions were also incorporated into the models as per the local site and vehicle conditions. In other words, the models were calibrated for the intersection types, traffic characteristics, geometric layout of roads, and other road and site conditions found in Doha, Qatar. Consequently, the first section of the analysis summarized and discussed the various adjustment values used for developing the models (see Table 14, Table 15, and Table 16).

Second, the root mean square error (RMSE) for nine different models developed using various combinations of data sets representing all sites (CORTN-M), 3-lane signals (CORTN-S-3LS), 2-lane signals CORTN-S-2LS), 3-lane roundabouts (CORTN-S-3LR), 2-lane roundabouts (CORTN-S-2LR), signals (CORTN-S-S), roundabouts (CORTN-S-R), 3-lane intersections (CORTN-S-3L), and 2-lane intersections (CORTN-S-2L) respectively were summarized in Table 17 and plotted together using bar charts (see Figure 25) to identify the combination of data sets that provided the least errors. Based on this, besides the general (CORTN-M) model, the customized intersection type-specific models namely CORTN-S-2LS for 2-lane signals, CORTN-S-3LS for 3-lane signals, CORTN-S-2LR for 2-lane roundabouts, and CORTN-S-3LR for 3-lane roundabouts provided comparatively lower RMSE. Consequently, the general and these four specific models were further analyzed and discussed in the analysis. Furthermore, RMSE of each of the 8 locations using these models were also tabulated in Table 18 and plotted (see Table 16) for comparison purposes.

Third, the measured and the predicted noise levels with respect to the corresponding traffic volumes were plotted on scatter charts (see Figure 27) using the original and the modified general noise prediction models. Additionally, residual analysis (see Figure 28) was done for the modified noise prediction model to check the data fitting capability of the CORTN-M model with respect to the measured noise levels.

Fourth, the measured and the predicted noise levels using CORTN-O, CORTN-M and CORTN-S (2LS, 3LS, 2LR, and 3LR) models were plotted in four separate scatter charts (see Figure 29) representing the four different intersection types respectively. Residual analysis for these specific models was also illustrated in Figure 30 to observe if the model provided a decent fit to the measured data.

Fifth, the measured and the predicted noise levels using CORTN-O, CORTN-M and CORTN-S (2LS, 3LS, 2LR, and 3LR) models were plotted with respect to time on two separate scatter charts (see Figure 31) representing weekday and weekend data respectively. These charts illustrated how the predicted noise level values fitted the measured values over weekday and weekend respectively.

Finally, the varying coefficients of the models were tabulated in Table 19 and discussed followed by listing and discussing the newly proposed equations for the modified and the calibrated CORTN noise prediction models (see Figure 32).

6.3.1. Adjustments for CORTN Model

For calibrating the CORTN model as per the local road, traffic, and site conditions at the eight traffic intersections in Doha, Qatar, a number of adjustments were required to be incorporated into the models such as adjustments for heavy vehicle percentage (p = heavy vehicle flow expressed as rate of the number of heavy vehicle flow per total traffic flow), traffic speed, gradient (Δg), distance from receiver (Δd), shielding (Δs), angle of view (Δa), and angle of reflection (Δr) due to facades or obstructions. Consequently, in this sub-section, the various adjustment values used for calibrating the models were summarized and discussed (see Table 14, Table 15, and Table 16).

At first, the slope per approach (EB, WB, SB, and NB) at each intersection were tabulated along with the mean slope per intersection (see Table 14) in order to analyze if noise adjustments were required for extra noise due to uphill flowing traffic on a gradient (+G%) (Department of Transport Welsh Office, 1988). Accordingly, gradient adjustments, Δg were required only for 2LS-1 and 2LR-1 3LS-1 and 3LR-1), and the rest of the downhill intersections had zero gradient correction.

Table 14. Calculation of Mean Slope and Slope Adjustment for each Location

Location	**Site ID**	**Slope, G(%) = (Rise/Run) X 100%**				**AVG.**	**Δg = 0.3G(%),**
		EB	WB	SB	NB	**G(%)**	**dB(A)**
1	3LS-1	-1.6	-5.5	-1.3	1.9	-1.6	0
2	3LR-1	-1.6	-5.5	-1.3	1.9	-1.6	0
3	2LS-1	0.8	0.5	0.9	0.6	0.7	0.2
4	2LR-1	2.1	1.6	-0.7	1.2	1.1	0.3
5	3LS-2	0.6	-1.0	-1.3	0.7	-0.3	0
6	3LR-2	-0.8	-0.6	-0.7	-1.1	-0.8	0
7	2LS-2	-0.6	-1.8	-0.5	-0.7	-0.9	0
8	2LR-2	-1.6	1.1	-1.5	0.6	-0.4	0

Secondly, since all the intersection were road junctions, estimated traffic speeds were used based on the class of roads instead of the actual traffic speed at the intersections (see Table 15). Accordingly, when the estimated speed was less 75 km/hr, impervious bituminous road surface correction of -1 dB(A) was required as tabulated in Table 15. (Department of Transport Welsh Office, 1988)

Table 15. Estimated Speed at the Intersections based on Road Classification and Speed Adjustment for each Location

Site	**Speed Limit; km/h**	**Speed Limit; km/h**	**V, Mean traffic speed estimated from class of road; km/h**	**ΔV; Mean Traffic Speed Correction due to Heavy Vehicle Percentage (p) and Upward Gradient (+G); km/h**	**Δp; Pavement Surface Correction of -1dB(A) if the estimated mean traffic speed is less than 75 km/h**
3LS-1	80	80	80	f(p, G)	0
3LR-1	80	80	80	f(p, G)	0
2LS-1	50	50	50	0	-1
2LR-1	(80 , 50)	65	60	0	-1
3LS-2	80	80	80	f(p, G)	0
3LR-2	80	80	80	f(p, G)	0
2LS-2	(80, 60)	70	60	f(p, G)	-1
2LR-2	50	50	50	f(p, G)	-1

Other noise adjustments applied to the noise measurements observed at the intersections were namely distance, shielding, angle of view, and angle of reflection, tabulated in Table 16.

Table 16. Other Noise Adjustments for the Sites

Adjustment	**dB(A)**
Distance, Δd	2.5
Shielding, Δs	0
Angle of view, Δa	0
Angle of reflection, Δr	1.5

6.3.2. RMSE of Various Noise Prediction Models

At first, using data at all the eight intersections, the original general CORTN-O model was calibrated for local site conditions and vehicle flow characteristics by incorporating the required noise adjustments identified in the previous sub-section, resulting in a calibrated general CORTN-M model. The RMSE of the two models, the original and the modified, were then tabulated and compared (see Table 17). Although the modified model calibrated for local conditions reduced the RMSE by 5.2 dB(A), 8 more intersection type-specific models were calibrated using various combinations of data sets representing 3-lane signals (CORTN-S-3LS), 2-lane signals CORTN-S-2LS), 3-lane roundabouts (CORTN-S-3LR), 2-lane roundabouts (CORTN-S-2LR), signals (CORTN-S-S), roundabouts (CORTN-S-R), 3-lane intersections (CORTN-S-3L), and 2-lane intersections (CORTN-S-2L) respectively. These were developed to compare their respective RMSE with the RMSE of the general model (see Table 17) to check if and which intersection type-specific models resulted in lower RMSE compared to that of the general modified model.

Accordingly, it was observed that the RMSE of CORTN-S-R (3.2 dB(A)) and CORTN-S-3L (2.4 dB(A)) were much higher than the other seven calibrated models. In other words, combining 2-lane and 3-lane roundabouts increased RMSE and combining 3-lane signals with roundabouts especially increased the RMSE. Although the RMSE of their counterparts, CORTN-S-S (1.0 dB(A)) and CORTN-S-2L (1.5 dB(A)) respectively, were comparatively low, they produced a combined higher RMSE.

Table 17. RMSE of Various Combinations of Data Sets

Model	**Location**	**Intersection Type**	**N**	**A***	**B***	**RMSE**, dB(A)**		**ΔRMSE***, dB(A)**
						(CORTN-O)	(CORTN-M/ CORTN-S)	
CORTN-M	All	2-lane and 3-lane Signals and Roundabouts	172	40.6	8.0	8.3	1.0	-7.3
CORTN-S-3LS	1, 5	3-lane Signals	50	39.1	8.5	8.6	1.1	-7.5
CORTN-S-3LR	2 ,6	3-lane Roundabouts	50	24.5	12.3	10.0	1.4	-8.6
CORTN-S-2LS	3, 7	2-lane Signals	36	44.2	7.0	8.0	0.7	-7.3
CORTN-S-2LR	4, 8	2-lane Roundabouts	36	22.0	14.8	4.2	1.3	-2.9
CORTN-S-S	1, 3, 5, 7	2-lane and 3-lane Signals	86	40.9	7.9	8.3	1.0	-7.3
CORTN-S-R	2, 4, 6, 8	2-lane and 3-lane Roundabouts	76	22.6	13.6	8.1	3.2	-4.9
CORTN-S-2L	3, 4, 7, 8	2-lane Signals and Roundabouts	72	27.6	12.6	6.4	2.4	-4.0
CORTN-S-3L	1, 2, 5, 6	3-lane Signals and Roundabouts	100	33.0	9.9	9.3	1.5	-7.8

* see Equation 5.13: $L_{Aeq.1hr.} = A + \ Blog(Q) + \Delta f + \Delta m$; where A and B are constant terms (A=42.2 and B=10 in the original CORTN Model, CORTN-O), Q is the total hourly traffic flow (light vehicle and heavy vehicle), Δf is the heavy vehicle adjustment (see Equation 5.3), and Δm is the sum of gradient adjustment, pavement type adjustment, distance adjustment, shielding adjustment, angle of view adjustment, and angle of reflection adjustment (see Equation 5.12).

**see Equation 5.14: $RMSE = \sqrt{\frac{(MSE)^2}{n}}$; where $RMSE$ is root mean square error, MSE is mean square error, and n is the sample size.

***Δ $RMSE$ = (CORTN-O) – (CORTN-M/CORTN-S)

Next, the root means square error (RMSE) for the nine different models developed using various combinations of data sets were plotted together using bar charts (see Figure 25) to visually identify the combination of data sets that provided the least RMSE compared to the original general model. Based on this, besides the general (CORTN-M) model, the customized intersection type-specific models namely CORTN-S-2LS for 2-lane signals, CORTN-S-3LS for 3-lane signals, CORTN-S-2LR for 2-lane roundabouts, and CORTN-S-3LR for 3-lane roundabouts provided comparatively lower RMSE.

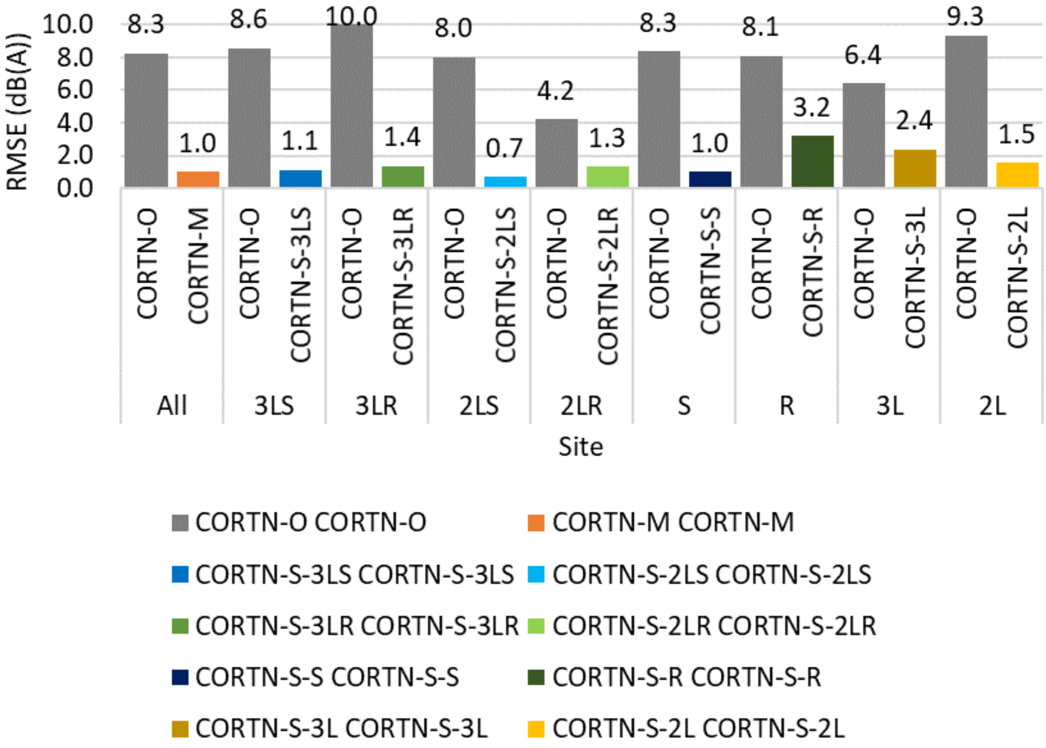


Figure 25. RMSE chart for various combinations of data sets.

Consequently, the general and these four specific models were further analyzed and discussed in the later sub-sections of the analysis. Accordingly, the RMSE of each of the eight locations using these five models were tabulated in Table 18 along with the

RMSE of respective CORTN-O values. Based on comparison of the residuals of modified RMSE and specific RMSE (the difference of RMSE of CORTN-O model and RMSE of CORTN-M or CORTN-S model respectively), at most of the sites, the specific models generated lower RMSE than the modified model except for 3LS-2 and 2LR-2, for which the residuals of the modified CORTN-M model were comparatively lower. Nevertheless, the specific models provided an overall better prediction than the general modified models.

Table 18. RMSE of each Location

Location	**Site ID**	**N**	**CORTN -O**	**CORTN-M**	**CORTN-S**	**ΔRMSE (M)**	**ΔRMSE (S)**
1	3LS-1	32	8.5	1.1	1.1	-7.4	-7.4
2	3LR-1	32	10.9	3.2	1.4	-7.7	-9.5
3	2LS-1	18	7.5	0.8	0.7	-6.7	-6.8
4	2LR-1	18	2.9	6.1	1.4	3.2	-1.5
5	3LS-2	18	9.0	1.2	1.2	-7.8	-7.8
6	3LR-2	18	8.3	0.7	1.2	-7.6	-7.1
7	2LS-2	18	8.5	0.7	0.7	-7.9	-7.9
8	2LR-2	18	5.2	3.1	1.2	-2.1	-4.1

Moreover, the CORTN-O, CORTN-M, and CORTN-S RMSE of each of the locations were also plotted with bar charts (see Figure 26) for visually comparing the RMSE. Similar to the conclusions drawn from Table 18, it was observed that the specific models contributed to much lower RMSE than the general modified model with the exception of locations 4, 6 and 8 (2LR-1, 3LS-2 and 2LR-2) for which the specific model residuals were either almost zero (in case of 2LR-1) or lower (in case of 3LS-2 and 2LR-2) compared to the general modified model residuals.

However, in spite of the small drawbacks noticed in these 3 locations, the RMSE at location 2LR-1 was significantly improved with the intersection type-specific model (1.4 dB(A)) compared to the general modified model (6.1 dB(A)). Only at this particular site, the general modified model instead of significantly decreasing the RMSE of the CORTN-O model (2.9 dB(A)) had significantly increased the RMSE to 5 dB(A).

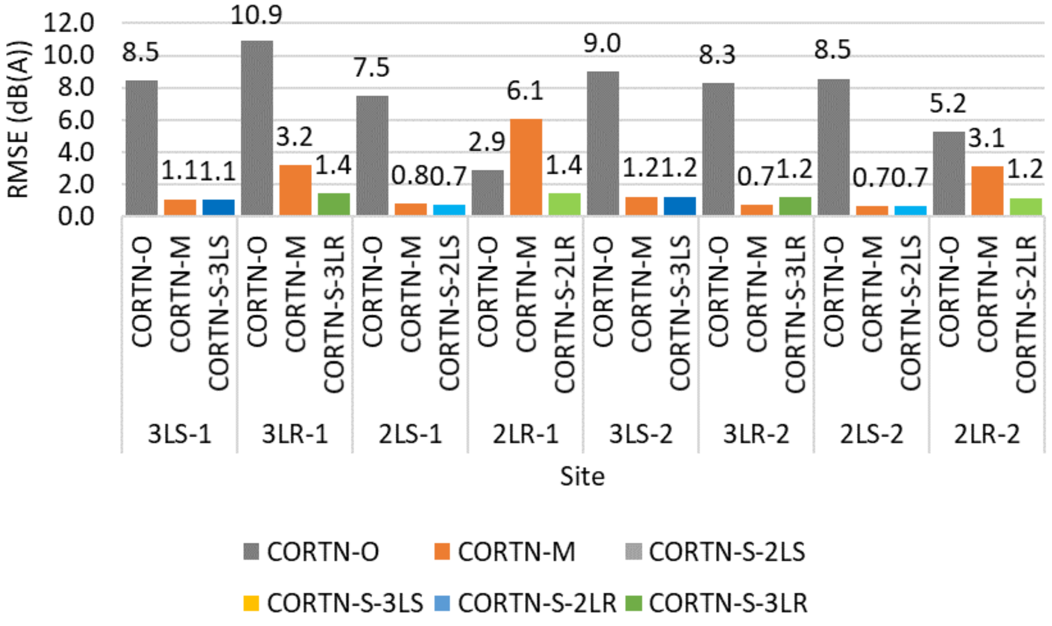


Figure 26. RMSE chart for each location.

As a result, based on an overall comparison of the RMSE obtained from the CORTN-O, CORTN-M, and CORTN-S models, the use of intersection type-specific models were recommended instead of the general models which increase the RMSE due to mixing of traffic intersections that are essentially different in terms of geometric layout, control type, vehicle flow patterns, size and so on. Nonetheless, the general modified model also gave comparatively good results except for one of the 2-lane roundabouts (2LR-1). Hence, both the general modified model and the intersection type-specific models were further analyzed in this study.

6.3.3. General Noise Prediction Model, CORTN-M

Using the original and the modified general noise prediction models, the measured and the predicted noise levels with respect to the corresponding traffic volumes were plotted on scatter charts as illustrated in Figure 27. From this chart, it was clearly observed that the CORTN-O model was over-estimating the noise level measurements obtained at the sites. However, the calibrated general model provided a closer and better estimation of the traffic noise levels obtained at the eight locations.

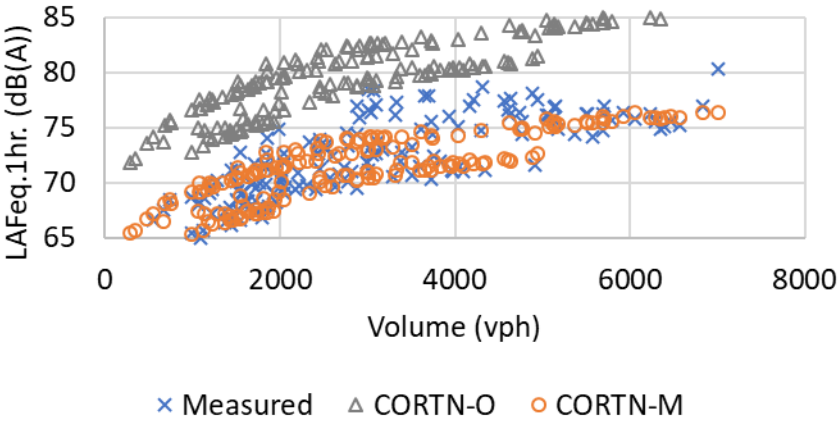


Figure 27. Noise levels vs volumes based on general original CORTN and modified CORTN models.

Additionally, residual analysis (see Figure 28) was done for the modified noise prediction model to check the data fitting capability of the CORTN-M model with respect to the measured noise levels. The random gunshot pattern of the standardized residuals with respect to the predicted noise level values indicated that the calibrated general model provided a decent fit (Quiñones-Bolaños et al., 2016). In other words, traffic noise levels could be satisfactorily predicted using the general modified model.

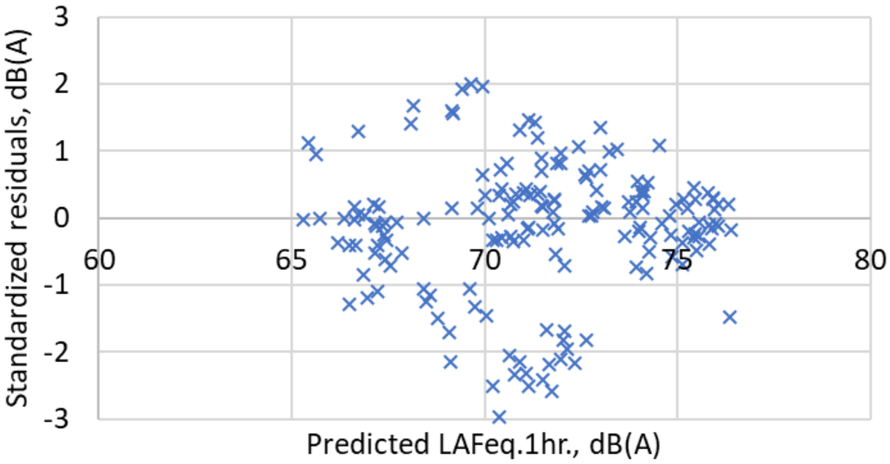


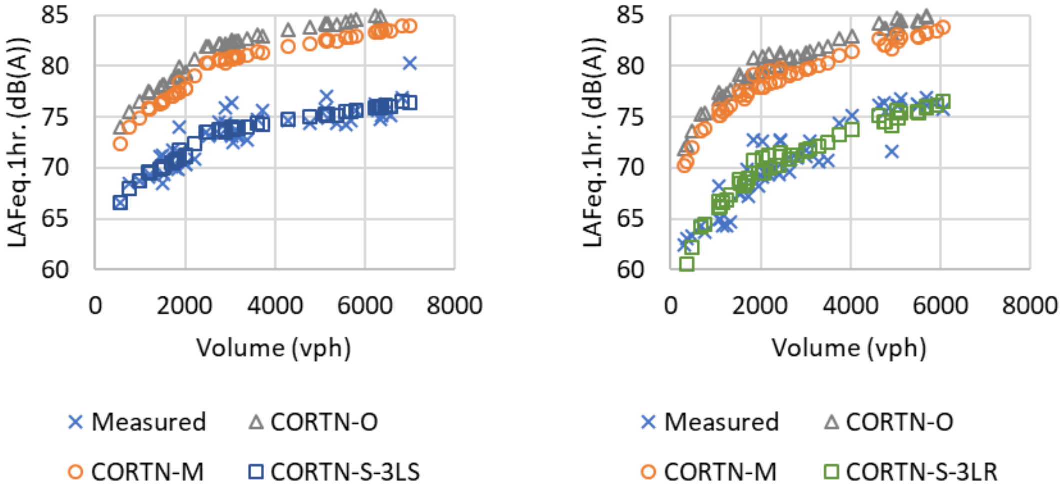
Figure 28. Residual analysis of general modified CORTN model, CORTN-M.

Nevertheless, in Figure 28, some outliers were observed due to one site in particular, the 2LR-1. The intersection type-specific models were, hence, expected to provide a better fit for all sites since it separated the intersections based on intersection type and size, reducing the probability of having outliers as observed in Figure 28.

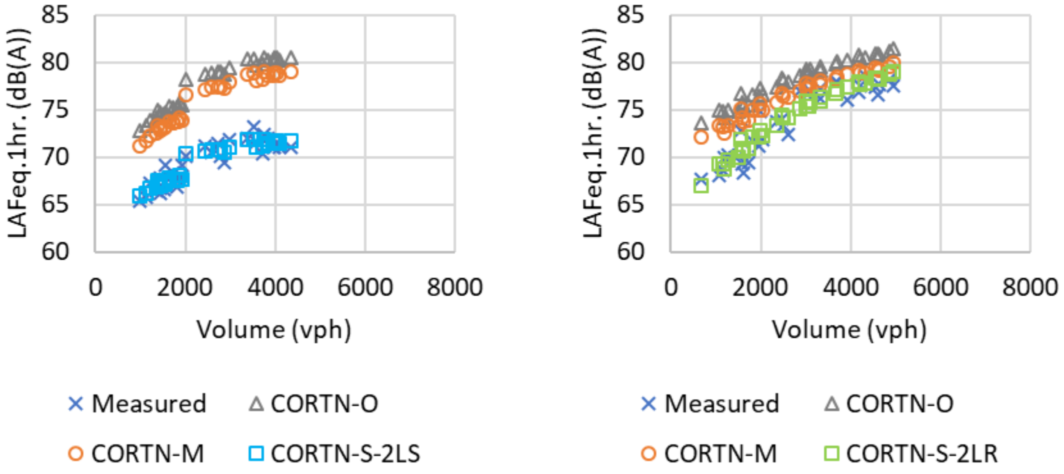
6.3.4. Specific Noise Prediction Models, CORTN-S

In this sub-section, the measured and the predicted noise levels using CORTN-O, CORTN-M and CORTN-S (2LS, 3LS, 2LR, and 3LR) models were plotted in four separate scatter charts, representing the four different intersection types respectively, as illustrated in Figure 29. From these charts, it was observed that the general CORTN-O model over-estimated the noise levels obtained at all intersection types especially the 3LS, 3LR, and 2LS. The general modified model estimated the traffic noise levels comparatively better than the original model except in the case of 2LR.

In the case of 2-lane roundabouts, noise levels due to higher traffic volumes (around 4000 vph) were predicted better by the original CORTN-O model, whereas noise levels due to lower traffic volumes (around 2000 vph) were fitted more closely with the general modified model. In other words, the CORTN-M model provided a good estimation when traffic conditions were under-saturated at the 2LR. However, the four intersection-type specific models provided an overall better fit for the four different intersection types respectively.



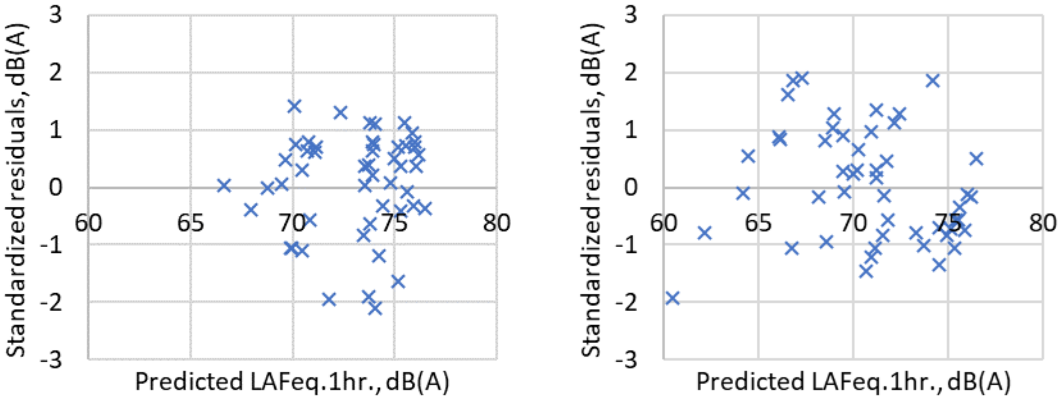
(a) CORTN-S-3LS (b) CORTN-S-3LR



(c) CORTN-S-2LS (d) CORTN-S-2LR

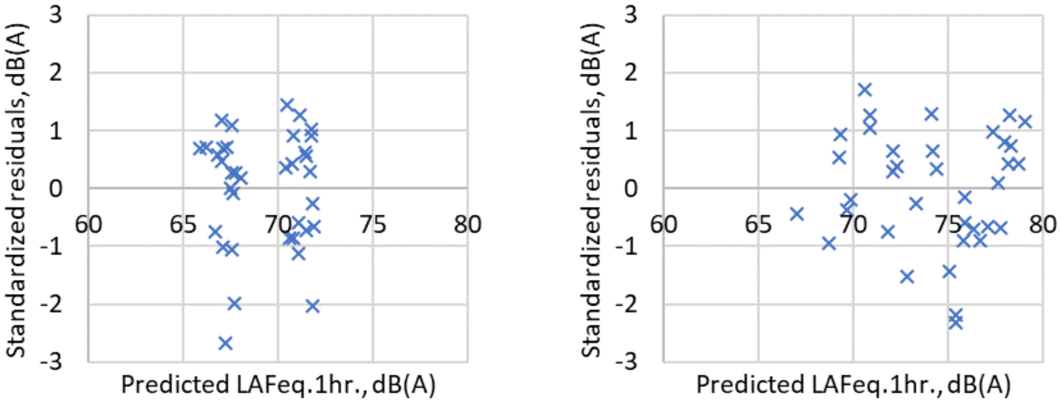
Figure 29. Noise levels vs volumes based on general and specific CORTN models.

Similar to the general modified model, residual analysis for the four specific models was also done separately as illustrated in Figure 30. The standardized residual values with respect to the predicted noise level values were found to be within 2 dB(A) in all cases.



(a) CORTN-S-3LS

(b) CORTN-S-3LR



(c) CORTN-S-2LS

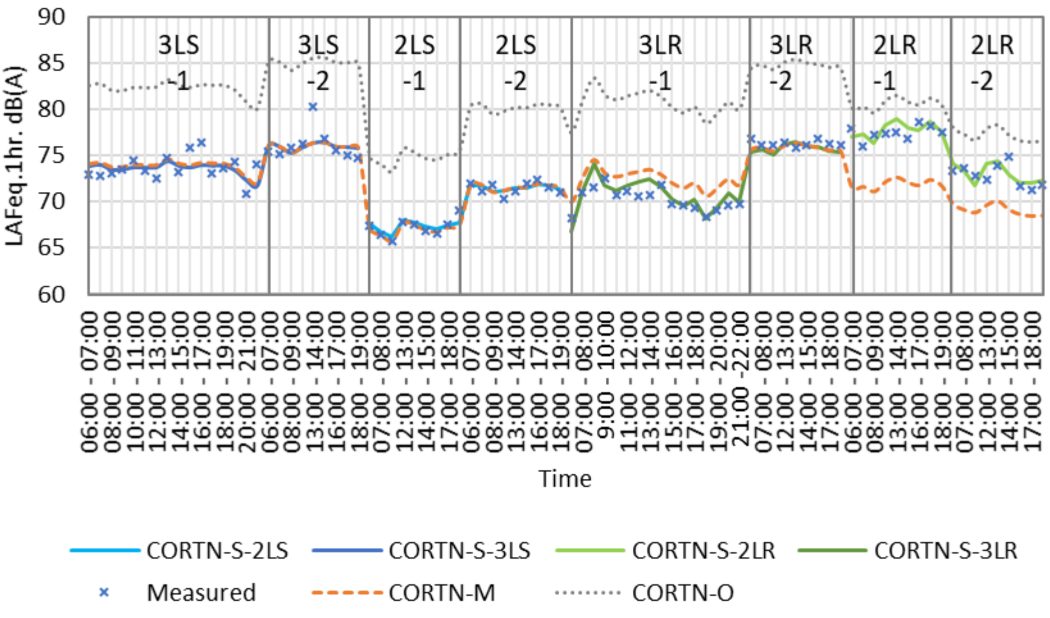
(d) CORTN-S-2LR

Figure 30. Residual Analysis of Specific CORTN Models, CORTN-S.

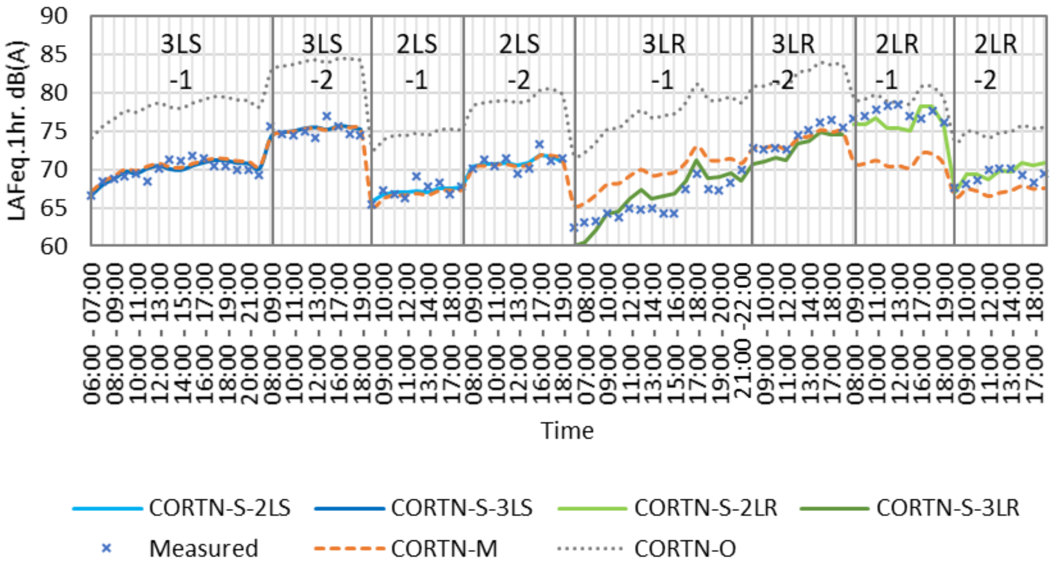
Moreover, the residual values in Figure 30 were all scattered in random gunshot patterns. This further indicated that the separate models provided a better fit to the observed noise level data (Quiñones-Bolaños et al., 2016). Hence, the intersection type-specific models were able to satisfactorily predict the noise level at the different intersection types due to roadway traffic volumes.

6.3.5. Measured and Predicted Noise Levels Based on Various Models

The measured and the predicted noise levels based on CORTN-O, CORTN-M and CORTN-S (2LS, 3LS, 2LR, or 3LR) models were plotted with respect to time on two separate scatter charts (see Figure 31) representing weekday and weekend data respectively for each site. The two charts illustrated how the predicted noise level values fitted the measured values over the weekday and weekend noise level periods measured at each of the sites. Weekday and weekend noise levels at locations 1 and 2 (3LS-1 and 3LR-1) were shown for the entire measured 16-hr daytime period. Whereas for other sites, the noise levels were shown over the selected 9-hr weekday and weekend peak hour (morning, afternoon, and evening) periods respectively.



(a) Weekday



(b) Weekend

Figure 31. Measured and predicted weekday and weekend noise levels vs time.

An overall observation of the measured and the predicted noise levels illustrated in Figure 31 showed that the CORTN-O model mostly over-estimated the noise levels observed at all the eight sites regardless of the day and time. On the other hand, the calibrated general CORTN-M model provided a comparatively much better fit to the measured data (Quiñones-Bolaños et al., 2016). However, the CORTN-S models provided an excellent fit between the weekday and weekend measured data and the predicted noise levels at all the sites regardless of the time of the day.

6.3.6. Modified and Specific Noise Prediction Model Equations

The main difference in the equations of the calibrated models and the original model is in the value of the basic noise level coefficient. In the case of the original model, the basic noise level coefficient, A was equal to 42.2 dB(A) which mainly contributed to the noise level over-estimation observed at all the sites (see Figure 27, Figure 29, and Figure 31). Hence, in the calibrated models, this coefficient was reduced so that the least possible RMSE could be obtained for the selected data set. Accordingly, in the modified and the specific models, parameter A was reduced by a reduction coefficient that produced the least RMSE for that particular data set. The resulting varying coefficients of the models were tabulated in Table 19 and discussed in this sub-section followed by listing and discussing the newly proposed calibrated equations for the general modified and the intersection type-specific CORTN noise prediction models (see Figure 32).

An observation of the basic noise level coefficients corresponding to the various CORTN models showed that the basic noise level coefficient, A in the original CORTN-values required the least reduction for 2LR followed by 3LS, 3LR, and 2LS ranging between 82% and 92% reduction (see Table 19). The A value was reduced by 84% for the modified CORTN-M model. The RMSE of the calibrated models (ranging between 0.7 dB(A) to 2 .0 dB(A)) were always lower than the corresponding CORTN-O RMSE (ranging between 4.0 dB(A) and 7.5 dB(A)).

Table 19. Coefficients and RMSE of Various Models

Model	**Locations**	**N**	**Coefficient, A**	**Coefficient, B**	**RMSE**
CORTN-O	All	172	42.2	10	8.3
	4, 8	36			4.2
	1, 5	50			8.6
	2 ,6	50			10.0
	3, 7	36			8.0
	All	172	40.6	8.0	1.0
CORTN-S-2LS	3, 7	36	44.2	7.0	0.7
CORTN-S-3LS	1, 5	50	39.1	8.5	1.1
CORTN-S-2LR	4, 8	36	22.0	14.8	1.3
CORTN-S-3LR	2 ,6	50	24.5	12.3	1.4

Next, all the measured and the predicted noise level values using all the CORTN models were plotted on the same scatter graph with respect to the corresponding traffic volumes observed at the respective sites (see Figure 32). The original and the calibrated equations were also included on this chart based on descending values of basic noise level coefficients (see Table 19). Measured and all predicted noise level values (belonging to each CORTN model) followed a logarithmic growth with traffic volume as expected since the CORTN models were logarithmic functions.

Besides, based on this chart, overall trends of noise levels measured and predicted at the different intersection types based on the intersection type-specific models were observed. Accordingly, 2LR generated comparatively higher traffic noise levels followed by 3LS, 3LR, and 2LS. Hence, the noise level at traffic intersections was both a function of intersection type and size.

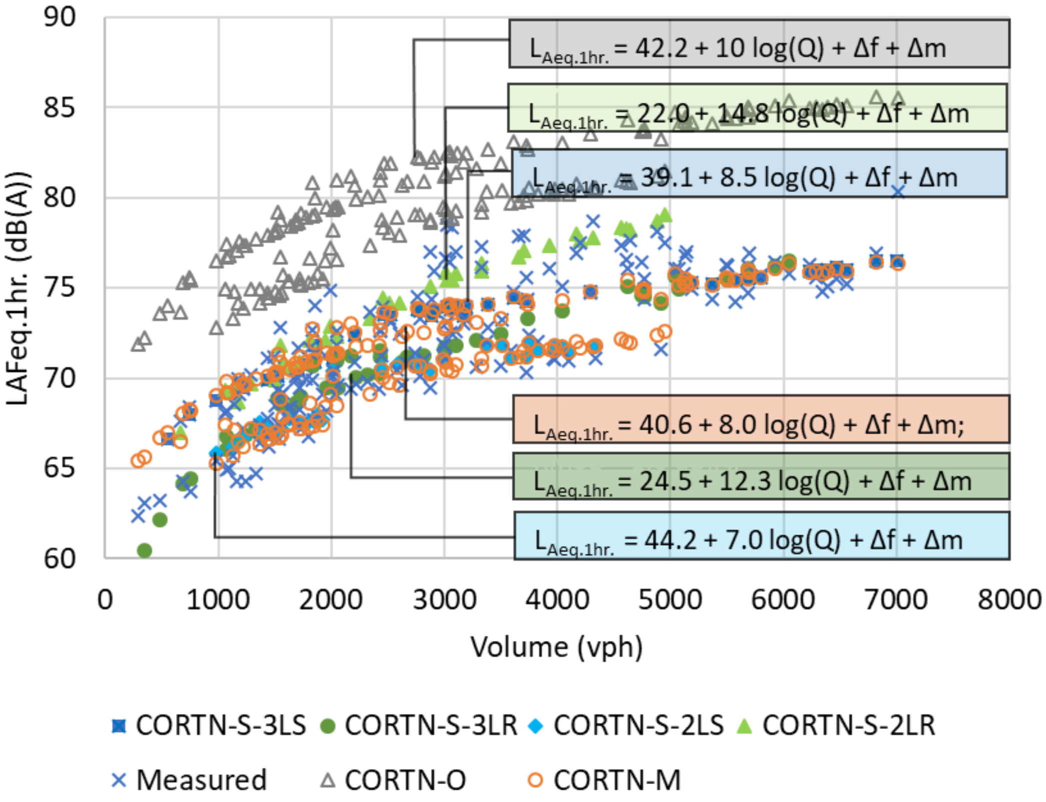


Figure 32. Measured and predicted noise levels vs volumes using various models.

Finally, the original and the proposed calibrated CORTN models are listed along with their respective RMSE. The equations for the original CORTN model and the calibrated general CORTN-M model and their RMSE are as follows:

CORTN: $L_{Aeq.1hr.} = A + B \log(Q) + \Delta f + \Delta m;$ (5.18)

where

A is a constant term equal to 42.2 in the original CORTN model,

B is a constant term equal to 10 in the original CORTN model,

Q is the total hourly traffic flow (light vehicle and heavy vehicle),

$Blog(Q)$ is the datum value of basic hourly noise level,

Δf is the heavy vehicle adjustment (see Equation 5.3), and

Δm is the sum of gradient adjustment, pavement type adjustment, distance adjustment, shielding adjustment, angle of view adjustment, and angle of reflection adjustment (see Equation 5.12).

Accordingly,

CORTN-O: $L_{Aeq.1hr.} = 42.2 + 10 \log(Q) + \Delta f + \Delta m;$ RMSE = 8.3 dB(A) (5.19)

where

Q is the total hourly traffic flow (light vehicle and heavy vehicle),

Δf is the heavy vehicle adjustment (see Equation 5.3), and

Δm is the sum of gradient adjustment, pavement type adjustment, distance adjustment, shielding adjustment, angle of view adjustment, and angle of reflection adjustment (see Equation 5.12).

The equation for the modified CORTN-O model, CORTN-M and its RMSE is as follows:

CORTN-M: $L_{Aeq.1hr.} = 40.6 + 8.0 \log(Q) + \Delta f + \Delta m;$ RMSE = 1.0 dB(A) (5.20)

where

Q is the total hourly traffic flow (light vehicle and heavy vehicle),

Δf is the heavy vehicle adjustment (see Equation 5.3), and

Δm is the sum of gradient adjustment, pavement type adjustment, distance adjustment, shielding adjustment, angle of view adjustment, and angle of reflection adjustment (see Equation 5.12).

Additionally, the recommended intersection type specific CORTN-S models and their RMSE are as follows:

CORTN-S-2LS: $L_{Aeq.1hr.} = 44.2 + 7.0 \log(Q) + \Delta f + \Delta m$; RMSE = 0.7 dB(A) (5.21)

CORTN-S-3LS: $L_{Aeq.1hr.} = 39.1 + 8.5 \log(Q) + \Delta f + \Delta m$; RMSE = 1.1 dB(A) (5.22)

CORTN-S-2LR: $L_{Aeq.1hr.} = 22.0 + 14.8 \log(Q) + \Delta f + \Delta m$; RMSE = 1.3 dB(A) (5.23)

CORTN-S-3LR: $L_{Aeq.1hr.} = 24.5 + 12.3 \log(Q) + \Delta f + \Delta m$; RMSE = 1.4 dB(A) (5.24)

where

Q is the total hourly traffic flow (light vehicle and heavy vehicle),

Δf is the heavy vehicle adjustment (see Equation 5.3), and

Δm is the sum of gradient adjustment, pavement type adjustment, distance adjustment, shielding adjustment, angle of view adjustment, and angle of reflection adjustment (see Equation 5.12).

In the modified equations (Equation 5.20 to Equation 5.24), the value of parameter A and parameter B were selected such that they generated the least RMSE for that specific data set.

In a similar study done in Tehran, Iran (Givargis & Mahmoodi, 2008), the value of A and B were around 52.7 and 5.6 respectively. Whereas, in the Columbian study, the value of A was 29.5 and the value of B was 10. However, this model considered motorcycles as the third vehicle category besides considering the light vehicle and heavy vehicle type; as such, Δf was also modified in this model (Quiñones-Bolaños et al., 2016). Hence, considering more vehicle categories could further improve the calibrated model proposed here.

CHAPTER 7: CONCLUSION

This study presents a comparative traffic noise study done between signals and roundabouts in Doha, Qatar. To do this, equivalent sound pressure level, ambient temperature, humidity, and wind speed data at four signalized intersections (S/I) and four roundabouts (R/A) were recorded at 5-minute intervals during morning, afternoon, and evening (n=16) hours of eight weekdays and eight weekends from 6 AM to 11 PM. Other relevant factors such as site characteristics, traffic speed limits, pavement surface texture, slope and number of lanes were also observed. Then, analysis of the collected data focused on meeting four main objectives.

The first aim was to determine whether the equivalent traffic noise levels in the city of Doha city were below or above the local and the WHO’s acceptable daytime noise thresholds of 55 dB(A) and 65 dB(A) respectively for residential areas. Results showed that the mean (16-hr) weekday and weekend noise levels at all the sites exceeded both the allowable noise thresholds. In addition, the mean weekday noise levels mostly exceeded the mean weekend noise levels indicating that the usually higher weekday traffic volumes in the city were most likely to be the cause (Quiñones-Bolaños et al., 2016).

The second aim was to identify which of the two most common intersection types found in urban areas – the roundabout or the signal – generated higher traffic noise levels and why. For this, as a case study, 16-hr weekday and weekend traffic noise level and volume data collected at a three-lane roundabout in Doha, Qatar just before and six months after it was converted to a three-lane signalized intersection were analyzed.

On weekday, the 16-hr mean equivalent traffic noise levels at both the roundabout and the signal were found to exceed the allowable daytime noise threshold of 65 dB(A) by 5.4 dB(A) and 8.9 dB(A) respectively. Likewise, on the weekend, the 16-hr mean noise levels exceeded by 1.2 dB(A) and 5.0 dB(A) respectively. Moreover, based on noise pollution indices, $L_{A90,1hr.}$ the weekday and weekend background noise levels at the roundabout, the quieter of the two intersections, were 68.2~68.8 dB(A) and 63.5~64.9 dB(A) respectively. On the other hand, the weekday and the weekend annoyance noise levels due to $L_{A10,1hr.}$ at the signal, the noisier intersection was 73.0~78.2 dB(A) and 71.4~71.7 dB(A) respectively.

Finally, based on the comparison of the two main variables – 5-min and hourly traffic noise level and the corresponding volume, as expected, largely positive relationship between the variables was identified. That is, the equivalent noise levels were higher when the mean traffic volumes were higher and vice versa. Furthermore, the mean 16-hr traffic noise level corresponding to the mean 16-hr traffic volume at the signal exceeded the roundabout by 3.5 dB(A), the traffic volume at the signal is 8% more (207 vehicles). Similarly, on the weekend, the mean 16-hr traffic noise level corresponding to the mean 16-hr traffic volume at the signal exceeded the roundabout by 3.7 dB(A) due to 23% more (279 vehicles) traffic volume at the signal.

Hence, the traffic flow and the intersection type had a significant effect on the noise level observed at the roundabout and the signal (Calixto et al., 2003; Chevallier, Leclercq, Lelong, & Chatagnon, 2009; De Coensel et al., 2006; Gardziejczyk & Motylewicz, 2016; Li et al., 2017; Quiñones-Bolaños et al., 2016). The observed 16-hr mean noise levels on weekdays exceeded the weekend noise levels for both the intersection types. As expected, the mean 16-hr weekend traffic volumes were lower at the intersections than the weekday traffic volumes, and the maximum mean 16-hr traffic volumes were observed at the signal on both weekday and weekend (Quiñones-Bolaños et al., 2016). Furthermore, the weekday and the weekend noise level increments from

65 dB(A) at the signal were more readily perceivable than that at the roundabout.

Moreover, on the working day, the afternoon and the evening mean values were mostly the highest and the lowest respectively at both the signal and the roundabout due to trip patterns of commuters (Mehdi et al., 2011). Whereas the pattern changed on the weekend seemingly due to higher mean traffic volumes during the evening and lower volumes during the morning period. Also, during early morning hours (6:00-7:00) or late evening hour (20:00-22:00), the noise level and the traffic volume were the minimum. On the other hand, the values were maximum between late morning and early evening hours (8:00-18:00). Nevertheless, the relationship between the traffic noise and traffic volume was not always found to be directly positive indicating factors other than the traffic volume such as traffic composition and flow, traffic control type, pavement surface texture, and intersection layout could be contributing to the discrepancies observed (Chevallier, Can, et al., 2009; Gardziejczyk & Motylewicz, 2016; Guarnaccia, 2010; Li et al., 2017; Obaidat, 2011).

The third aim was to compare the noise between four major signalized intersections and four major roundabouts in Doha, Qatar of two different sizes (2-lane and 3-lane) to identify the traffic noise level contributions of each intersection type. The intersections were selected so that at least two of them belonged to the same intersection type. Comparative traffic noise level analysis between the intersections was done based on measured traffic noise levels and extracted traffic volume data during 9 peak traffic hours instead of the entire 16 hours period.

As a result, traffic volume data (divided into 7 vehicle types) were extracted at 5-min intervals corresponding to two different sets of 9 hourly (morning, afternoon, and evening) peak traffic periods selected for weekdays (6:00-9:00, 12:00-15:00, and 16:00-19:00) and weekends (8:00-11:00, 11:00-14:00, and 16:00-19:00) respectively based on 16-hr weekday and weekend traffic volume data extracted at the first site, a busy 3-lane signalized intersection (3LS-1) at the heart of the city. In other words, the peak traffic count intervals at this site were assumed to be a reflection of the peak hours at the other sites. Also, 9 hours of peak traffic count data per site per day was expected to be more critical in comparing the traffic noise levels at the intersections, similar to other noise level studies which also investigated noise levels observed during morning, afternoon, and evening peaks hours in their respective cities (Obaidat, 2011; Quiñones-Bolaños et al., 2016).

The mean 16-hr daytime weekday traffic noise levels at each of the eight traffic intersections were found to exceed the WHO's acceptable daytime noise level threshold of 65 dB(A) by 2.6 dB(A) and 12.5 dB(A) at 2LS-1 (location 3) and 2LR-1 (location 4) respectively. On weekends, the minimum and the maximum mean noise levels exceeded by 1.2 dB(A) and 11.9 dB(A) at 3LR-1 (location 2) and 2LR-1 (location 4) respectively. In other words, 2LS-1-WD and 3LR-1-WE generated the least traffic noise and 2LR-1 generated the most traffic noise on both days compared to the other 6 traffic intersections. Similarly, the background noise levels at 2LS-1 (location 3) - the quietest site - was between 65.7 dB(A) and 66.4 dB(A) on weekday based on $LA_{90,1hr}$ data. On the other hand, the annoyance noise levels due to traffic at the noisiest site, 3LS-2 (location 5) was between 78.6 dB(A) and 80.6 dB(A) due to $L_{A10,1hr.}$ noise data. Likewise, from the weekend statistical distribution it was observed that the background noise levels at the quietest site, 3LR-1 (location 2) was between 62.4 dB(A) and 63.2 dB(A). On the contrary, the annoyance noise levels at the noisiest site, 2LR-1 (location 4) was between 78.1 dB(A) and 78.5 dB(A). That is, the 2LS-1 or the 3LR-1 seemed to be the quietest and the least annoying on weekday and weekend respectively, whereas the 2LR-1 was found to be both the loudest and the most annoying on both days. This indicates that background and annoyance noise levels varied with traffic volume, number of lanes, and the control type.

Next, comparisons were made between the four different intersection types (2LS, 2LR, 3LS, and 3LR) based on the overall (9-hr mean of weekday and weekend) traffic noise level and volume data. Accordingly, in case of signals, the overall noise level at 3LS (74.5 dB(A)) exceeded the overall noise level at 2LS (69.8 dB(A)) by 4.7 dB(A) due to overall traffic volume that was 1.6 times (1579 vehicles) more at the 3-lane signals. In other words, as expected the larger traffic intersection with larger volume capacity generated more traffic noise due to higher traffic volume (Quiñones-Bolaños et al., 2016). Contrary to signals but in line with comparative literature, the smaller size (2-lane) roundabouts were found to be noisier (75.4 dB(A)) than the larger size (3-lane) roundabouts (73.3 dB(A)) by 2.1 dB(A) although the overall traffic volume at the 3LR was 1.2 times (421 vehicles) more (Gardziejczyk & Motylewicz, 2016). This was most likely due to the concentration of vehicles within a comparatively smaller inscribed circle area of 2-lane roundabouts compared to the 3-lane roundabouts (Gardziejczyk & Motylewicz, 2016).

In case of 2-lane intersections, contrary to the simulation literature, 2LR generated perceivably higher (about 5.7 dB(A)) mean traffic noise level (75.4 dB(A)) than 2LS (69.8 dB(A)) even though the mean traffic volume at the 2-lane roundabouts was only 1.1 times (341 vehicles) higher (Gardziejczyk & Motylewicz, 2016; Quiñones-Bolaños et al., 2016). In contrast and in line with comparison and simulation literature, the mean noise level at 3LS (74.5 dB(A)) was slightly higher (by 1.2 dB(A)) than the 3LR (73.3 dB(A)) due to 1.3 time (817 vehicles) more mean traffic volume at the signals (Chevallier, Leclercq, et al., 2009; De Coensel et al., 2006; Gardziejczyk & Motylewicz, 2016; Guarnaccia, 2010; Li et al., 2017; Quiñones-Bolaños et al., 2016).

The fourth aim was to develop a prediction noise model based on the data collected. Since traffic noise level data are not always available, traffic noise prediction models have been developed by governments and researchers to predict traffic noise levels at roadways, sections of highway, and traffic intersections to deal with traffic noise originating from roadways. These noise models are usually developed as a factor of expected or measured traffic volume and other vehicle and site characteristics. Recent studies have focused on either statistically developing new generalized traffic noise prediction models (Ahmed et al., 2016; Calixto et al., 2003; Hamad et al., 2017) or customizing the established models such as the CORTN for different countries such as Australia (Samuels & Saunders, 1982; Saunders et al., 1983), Columbia (Quiñones-Bolaños et al., 2016), Iran (Givargis & Mahmoodi, 2008) and so on based on region-specific site and traffic characteristics. Nevertheless, intersection type-specific noise prediction models that can be used to predict varying traffic noise levels as expected at the two very geometrically and operationally different traffic intersection types - signals and roundabouts - separately have not yet been developed.

In addition, no traffic noise prediction model has been developed or customized for use in Qatar or other similar countries within the Middle Eastern region which have different weather, site, pavement, and vehicle type characteristics compared to other regions. Hence, developing a customized general traffic noise prediction model for Qatar or a set of intersection type-specific model, whichever provides a better prediction of traffic noise levels at signals and roundabouts in Qatar or in general, has become indispensable. Such a noise prediction model could be utilized in planning future land use or modifying current land use based on newly developed noise risk zones. In addition, the results of the prediction model could serve as a factor in determining speed limits on roadways and highways to limit or mitigate current and future traffic noise pollution levels based on intersection type. In short, it could be used to design a more sustainable urban transport network based on anticipated land use of the surrounding areas.

Based on the findings, intersection type-specific noise prediction models in which 2-lane roundabouts and 3-lane roundabouts are combined gives higher errors than the customized general CORTN-M model. The same was found to be true when 2-lane signals were combined with 2-lane roundabouts. Also, combining 3-lane signals and roundabout increases the RMSE. However, using separate models for 2-lane signals, 2-lane roundabouts, 3-lane signals, and 3-lane roundabouts decreases the RMSE. Overall, both the calibrated general and the intersection type-specific models reduce the RMSE significantly compared to the original CORTN-O model.

Hence, the proposed models could be used to determine whether traffic noise levels at various traffic intersections in Doha, Qatar is within the WHO's acceptable daytime noise level threshold of 65 dB(A). Moreover, the customized models are expected to be especially advantageous in terms of predicting and comparing traffic noise levels at different intersection types so that governments, policymakers, and urban planners can better understand the noise contribution of the two intersection types and adopt noise management and mitigation plans and strategies accordingly.

7.1. Limitations

The traffic noise levels and volumes in this case study were recorded for 16 consecutive daytime hours (6:00-22:00) per day. This was done to evaluate the mean 16-hr traffic noise level with respect to the WHO's allowable noise level threshold of 65 dB(A) for the 16-hour daytime period. Furthermore, since the peak morning, afternoon, and evening traffic hours for Doha city, like most other cities, were expected to fall within this time period, the comparative analysis was done based on daytime data alone. In addition, traffic noise levels due to comparatively much lower traffic volume in the city during the nighttime period (22:00 – 6:00) were also assumed to be not critical for the before-and-after comparison. As a result, analysis of the mean 16-hr noise level and volume data was expected to provide a reasonable conclusion. Also, only two vehicle categories were considered in the model, although traffic streams in urban areas are much more complex.

7.2. Future Work

In future, a larger scale noise level study could be conducted in Doha city with more data points taken around major city blocks, intersections, and road sections during daytime and nighttime to further validate the findings of this study and compare the noise level differences based on the time of the day. The findings of such a study could also help determine the main reasons behind the excessive traffic noise levels found in Doha city with respect to the WHO's allowable noise level thresholds. In addition, the data could be used to generate a detailed traffic noise map of the city. This would aid in the identification of high noise risk zones within the city so that present and future land-use could be modified and planned accordingly.

To further validate the findings of the before-and-after study, similar case studies at more about-to-be-converted traffic intersections in Qatar and around the world could be explored. Also, using data obtained from such case studies, existing noise prediction models used for different traffic intersections could be modified to improve the models.

To further validate the findings of the comparative study, similar case studies at more traffic intersections in Qatar and around the world could be explored. Also, using data obtained from such case studies, existing noise prediction models used for different traffic intersections could be modified to improve the models. In addition, larger-scale comparative noise level studies could be undertaken in order to find the relative traffic noise impact of pavement surface texture, number of lanes, traffic speed, meteorological conditions, traffic volume and composition, and other contributing factors. Consequently, using the resulting values, customized models to predict noise at different types of traffic intersections could be developed as future work.

Lastly, to further validate the findings of the prediction study, especially the validity of the intersection type-specific models, the proposed models could be further calibrated based on data collected at more signals and roundabouts in Qatar or other regions. The model could be further improved by including additional vehicle categories that are more representative of traffic stream observed in Qatar.

7.3. Recommendations

The first step towards reducing noise pollution levels in Doha city could be through discouraging and limiting the main source of excessive traffic noise levels in the city: use of automobiles. To do this, the government needs to introduce public awareness campaigns regarding the adverse environmental and health effects of excessive traffic noise generated due to heavy dependence on this mode of travel. At the same time, more sustainable alternatives such as public bus, metro, cycling, and walking need to be made more attractive and accessible to the population by urban planners and policymakers.

Besides, noise mitigation strategies need to be applied through the introduction of noise-reducing vegetation zones in the city and the installation of noise barriers where needed. Furthermore, better urban and land-use planning combined with the implementation of more efficient traffic management schemes such as diverting traffic from heavily congested road networks using the latest technologies could also help reduce excessive traffic noise generated in the adjacent areas.

Hence, in order to reduce excessive traffic noise levels in Doha city, sustainable urbanization that incorporates traffic noise reducing policies and strategies need to be implemented in Qatar. This could be achieved by prioritizing public health and welfare in urban planning combined with implementing nation-wide traffic noise awareness campaigns. Likewise, other cities in the region facing similar urbanization and noise pollution challenges could also benefit from these recommendations.

Also, based on this study, the traffic flow and the intersection type had a significant effect on the noise level observed at the roundabouts and the signals. Hence, before converting from a roundabout to a signal or vice versa, the noise contribution of the selected intersection type must be taken into consideration to avoid creating noise pollution issues at major traffic intersections. In case the traffic situation warrants the selection of the noisier option, appropriate noise management and mitigation policies and strategies need to be implemented to address noise pollution problems associated with the expected higher levels of traffic noise.

For instance, controlling and limiting vehicle usage by creating environmental awareness, diverting traffic from heavily congested road networks using latest technologies, encouraging use of more sustainable means of transport such as public transit, walking or cycling, stipulating traffic noise management guidelines for designing roadways, planning land-use for areas that are noise-sensitive, introducing noise-reducing vegetation zones near traffic intersections, and installing noise barriers where needed are some is crucial for cities facing noise pollution challenges due to road traffic (Burgess & Macpherson, 2016).

That is, in order to reduce excessive traffic noise levels in urban areas, especially at urban intersections, sustainable urbanization that incorporates traffic noise reducing policies and strategies need to be implemented by the government, environment protection agencies, policymakers, transport engineers and urban planners alike. This could be achieved by prioritizing public health and welfare in urban planning and intersection selection combined with wide-spread traffic noise awareness campaigns.

Finally, the proposed prediction model is expected to serve as a deciding factor in determining speed limits on roadways and highways to limit or mitigate noise pollution. It could also be incorporated into the Qatar Highway Design Manual to aid in selecting an intersection type. Additionally, the finding of this study is also expected to aid policymakers in modifying current and planning future land use for Doha city.

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