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Conference Paper · September 2019

DOI: 10.1109/ICITE.2019.8880263

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***Abstract*—The aim of this paper is to investigate the impact of alternate road lighting (i.e. switching off every other road light at selected roadways) on road traffic accident (RTA) hotspots using Spatial Traffic Accident Analysis (STAA) – a GIS hotspot analysis method that takes into account RTA frequency and socio-economic impact. STAA was used to identify and rank into four hierarchical risk levels day-time and night-time RTA hotspots before and after the implementation of alternate road lighting along a study road. Using the day-time RTA hotspots as a comparison group and night-time RTA hotspots as treatment group, the changes to the length of RTA hotspots of the four hierarchical risk levels were evaluated. There was an overall increase in the lengths of RTA hotspots with moderate and serious risk levels, while there was an overall reduction in the lengths of RTA hotspots with minor and significant RTA risk levels. Some of the limitations of the current study were identified and further research is recommended to validate the current findings.**

Keywords-road safety impact; hotspot identification; hotspot ranking; Spatial Traffic Accident Analysis; alternate road lighting

I. INTRODUCTION

In 2016, deaths by road traffic accident (RTA) climbed to 1.35 million [1]. Low- and medium-income countries in Asia observed the highest rate of RTA fatality [2, 3] and in most countries, RTA can cost between 3% to 5% of the country's gross domestic product [4]. Reference [5] attributed RTA to human error/negligence, vehicle defects, poor road design, environmental condition and random influence. For an RTA to occur, two or more causal factors normally have to be present concurrently. A common scenario where safety performance is occasionally investigated is night-time RTA under reduced lighting condition. Road lighting is objectively introduced to serve as countermeasure to reduce the frequency and severity of night-time RTA [6] as reduced lighting impairs visibility and decreases sight distance. The decision to reduce road lighting is mainly driven by the need to save energy and cost as well as reduce local impacts on climate change [7]. References [8] and [9] motioned that the road lighting level can be reduced to the minimum of what is required to ensure good traffic safety. Past researchers have previously concluded that unlit or partially-lit roads resulted in more serious injuries and fatalities despite the frequency being much less compared to day-time RTA. The risk of RTA occurring on unlit road is about 1.5 to 2 times higher than that during the day [10] while fatality per vehicle-miles is 3.5 times higher at night than that during the day [11].

Reference [12] developed a simple before-after method to analyse the safety impact of alternate road lighting on a major urban road. For the same road, they compared the ratio of night to day RTA counts before switching off alternate road lights (R-before) to the ratio of night to day RTA counts after the implementation of alternate road lighting (R-after). If R-after was greater than R-before, this would indicate a negative safety impact of alternate road lighting. This analysis method did not take into account many factors that might influence RTA count, such as traffic volume, weather and driver trends. In addition, Reference [13] stated that this method does not address possible regression-to-the-mean and long-term trend effects on the RTA counts. Therefore, Reference [13] pioneered the Empirical-Bayes (EB) method to evaluate the safety impact of alternate road lighting. This method addresses the regression-to-the-mean of RTA counts and properly accounts for changes in traffic volume and other factors affecting RTA count. In the EB method, a multivariate regression model, known as a safety performance function, is used to compute the expected crash frequency at the locations of alternate road lighting had this not been made. A Crash Modification Factor (CMF) is computed using this expected crash frequency and the observed crash frequency at the locations of alternate road lighting. A CMF value of less than 1 indicates an RTA reduction due to alternate road lighting, and vice versa. Even though the CMF indicates the safety impact of alternate road lighting, it does not indicate the location and risk level of this impact.

RTA seldom occur randomly in space and time [14, 15]. They usually form spatial and temporal hotspots/clusters in a road network, which can be identified and ranked using Geographic Information Systems (GIS) [16]. Reference [16] has reviewed various GIS hotspot analysis methods of historical RTA data, and the author concluded that a network-based spatial analysis is the most appropriate method of RTA hotspot analysis. Reference [17] concluded that Spatial Traffic Accident Analysis (STAA) method is a promising method to identify and prioritise RTA hotspots on urban arterials with high density of junctions. STAA is a risk-based hotspot analysis method that accounts for RTA frequency, severity and socio-economic impact [17]; an advantage over the simple before-after and EB methods that normally only consider RTA frequency. Furthermore, using STAA hotspot analysis method, spatial locations of safety impacts of alternate road lighting can be mapped.

II. AIM AND OBJECTIVES

This study employs STAA to investigate the impact of alternate road lighting on RTA hotspots on a section of Jalan Tutong in Brunei Darussalam. This particular road section was selected as the study road as the lighting on this road was switched from full to alternate basis since October 2016 while RTA data before and after the implementation of alternate lighting was available. The two objectives of the study are to:

- Apply STAA to identify RTA hotspots and rank them using four risk levels – minor, moderate, significant and serious; and
- Evaluate the impact of alternate road lighting for each risk level of the RTA hotspots.

There was a shortcoming encountered in this investigation. Only RTA reported to the police were available for the STAA analysis. As of 31 July 2017, non-injury RTA and RTA that do not involve damage to government properties were no longer reported to the police. This would result in a reduced number of non-injury RTA after this date in the dataset. To account for this effect, as will be explained later in this paper, the day-time RTA will be used as a comparison group in this investigation.

III. HISTORICAL RTA DATA AND ROAD PROFILE

RTA that occurred during two equal periods – 26 months before and after the implementation of alternate road lighting on 27 October 2016 – were used in the investigation. The day-time RTA were considered as those that happened between 6:01am to 7.00pm while the night-time RTA were those that happened between 7.01pm to 6.00am. As shown in Fig. 1, most of the RTA occurred during peak hours in the morning, afternoon and evening at 7.00-9.00am, 12.00-1.00pm, 4.00-5.00pm, 6.00-9.00pm and 10.00-11.00pm.

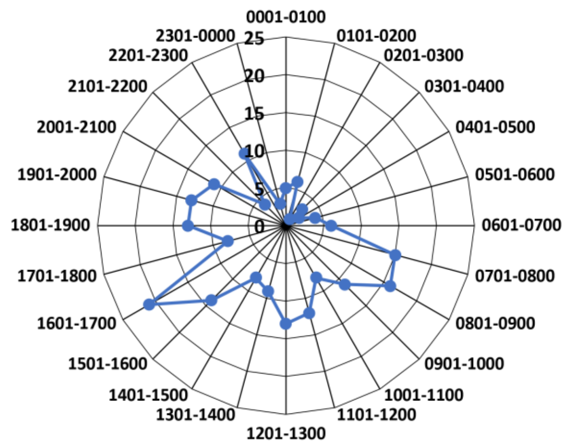

Figure 1. Number of RTA occurrences, on an hourly basis, during the study period for Jalan Tutong

The study section of Jalan Tutong has a length of approximately 4.1 km and comprises dual carriageway carrying traffic northeast towards Gadong, southeast towards Bandar Seri Begawan, north towards Jerudong and south-west to the Tutong district (see Fig. 3). There are 3 signalised junctions, 85 unsignalised junctions, 6 U-turns, 4 right-turns and several stop- or yield-controlled intersections. On both sides of Jalan Tutong, there are high concentrations of residential and commercial areas. The posted speed along this road is 65km/hr but the operating speed, i.e. the 85th percentile of observed speeds, was found to be 87km/hr. Alternate road lighting was implemented along Jalan Tutong by extinguishing one of the two luminaires on opposing lanes, which are mounted on lighting poles in the central median, as shown graphically in Fig. 2.

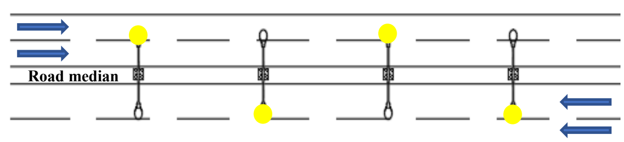

Figure 2. Alternate road lighting along Jalan Tutong

IV. METHODOLOGY

The STAA is a network- and risk-based spatial analysis method established to identify and rank RTA hotspots. This method has been thoroughly presented in detail by authors in References [17], [18] and [19], and its application in this study is explained below.

A. Identification of RTA Hotspots Using STAA

The RTA GIS points for Jalan Tutong were segregated into four maps consisting of 'before implementation-day-time RTA', 'before implementation-night-time RTA', 'after implementation-day-time RTA' and 'after implementation-night-time RTA'. For the first map, the RTA points were buffered by circular polygons of diameter equal to the stopping sight distance (SSD) along Jalan Tutong. According to Reference [17], the SSD for Jalan Tutong is 78m. Fig. 3

illustrates the overlay of the RTA hotspots on the study road obtained from the 'before implementation-day-time RTA'. The process was repeated for the other three maps. The next step was to use the "Join Data" function from the RTA hotspot polygons to consolidate the RTA data into the polygons – thus, each polygon stored the sum of fatality, serious injury, minor injury and no injury cases.

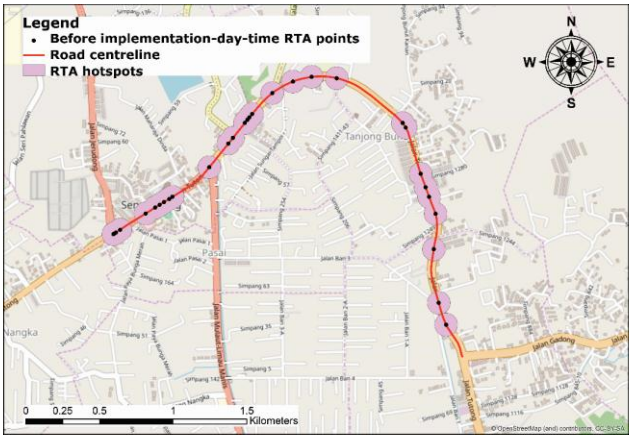

Figure 3. RTA locations and hotspots along Jalan Tutong for the 'before implementation-day-time RTA'.

B. *Quantifying RTA Hotspot Risk*

Equations (1), (2) and (3) from Reference [19], developed for the STAA method and reproduced below, were used to calculate the normalised frequency (NF) and normalised socio-economic impact (NSEI) of RTA within each hotspot polygon.

$$\mathrm{NF} = \mathrm{RTA} \times \frac{\mathrm{SSD}}{\mathrm{L}} \times 1/\mathrm{N} \qquad (1)$$

Where NF: Average annual number of RTA count within each hotspot polygon per SSD.
RTA: RTA count within the hotspot zone.
SSD: Stopping sight distance (78m).
L: Length of hotspot zone along the road centreline.
N: Number of years of data (2⅙ years).

$$\mathrm{SEI} = (\mathrm{fatal} \times \mathrm{USD1{,}419{,}639}) + (\mathrm{serious\ injury} \times \mathrm{USD70{,}205}) + (\mathrm{slight\ injury} \times \mathrm{USD9{,}119}) + (\mathrm{no\ injury} \times \mathrm{USD9{,}119}) \qquad (2)$$

Where SEI: Socio-economic impact.

$$\mathrm{NSEI} = \mathrm{SEI} \times \frac{\mathrm{SSD}}{\mathrm{L}} \times 1/\mathrm{N} \qquad (3)$$

Where NSEI: Normalised socio-economic impact.

The values of NF and NSEI of the RTA hotspots in the four maps were aggregated to give the range of NF and NSEI respectively. The NF and NSEI were then classified based on equal quantiles, i.e., $0 \leq q_1 \leq 0.25$, $0.25 < q_2 \leq 0.50$, $0.50 < q_3 \leq 0.75$ and $0.75 < q_4 \leq 1.00$. In percentile, they could be represented as $Q_1 \leq 25^{th}$ percentile, 25^{th} percentile $< Q_2 \leq 50^{th}$ percentile, 50^{th} percentile $< Q_3 \leq 75^{th}$ percentile and 75^{th} percentile $< Q_4$.

C. *Ranking of RTA Hotspots Using STAA*

The ranking was accomplished by assigning each RTA hotspot polygon in the four maps a composite risk level based on their respective NF and NSEI quantiles, as shown in Table I. Four composite risk levels were used to rank hierarchically RTA hotspots, known as 'minor', 'moderate', 'significant' and 'serious'. The colour scheme illustrated in Table I was assigned to the RTA hotspot polygons, in order to display their hierarchical risk levels.

TABLE I. COMPOSITE RISK LEVLES OF RTA HOTSPOTS ALONG JALAN TUTONG

NSEI VERSUS NF		NORMALISED FREQUENCY (NF)			
		$0 < NF \leq 25^{th}$ Percentile	25^{th} Percentile $< NF \leq 50^{th}$ Percentile	50^{th} Percentile $< NF \leq 75^{th}$ Percentile	$NF > 75^{th}$ Percentile
NORMALISED SOCIOECONOMIC IMPACT (NSEI)	$0 < NSEI \leq 25^{th}$ Percentile	Minor	Minor	Minor	Moderate
	25^{th} Percentile $< NSEI \leq 50^{th}$ Percentile	Minor	Minor	Moderate	Significant
	50^{th} Percentile $< NSEI \leq 75^{th}$ Percentile	Minor	Moderate	Significant	Serious
	$NSEI > 75^{th}$ Percentile	Moderate	Significant	Serious	Serious

D. *Impact of Alternate Road Lighting Using STAA*

For each risk level of the day-time RTA hotspots, the difference between the lengths of RTA hotspots before and after the implementation of alternate road lighting was computed. This resulted in 4 differences, one for each of the 4 RTA hotspot risk levels. These 4 differences were used as a comparison group. The same was computed for each risk level of the night-time RTA hotspots, resulting in 4 differences that were used as a treatment group. A negative difference value indicated a reduction in the length of RTA hotspots of a particular risk level after the implementation of alternate road lighting, and vice versa. For each RTA hotspot risk level, if the increase in the length of night-time RTA hotspots was greater than that of the day-time RTA hotspots, this would indicate a negative safety impact of alternate road lighting.

V. RESULTS AND DISCUSSION

Fig. 4 shows the results of STAA method for the day-time RTA hotspots along the study road before (A) and after (B) the implementation of alternate road lighting. Fig. 5 shows the results of STAA method for the night-time RTA hotspots along the study road before (A) and after (B) the implementation of alternate road lighting.

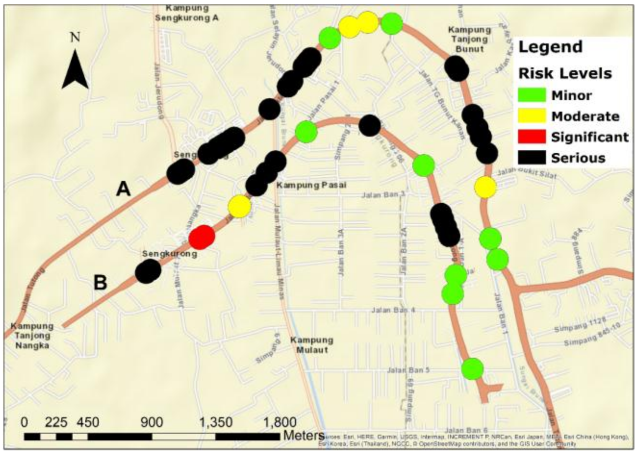

Figure 4. Day-time RTA hotspots along Jalan Tutong before (A) and after (B) the implementation of alternate road lighting.

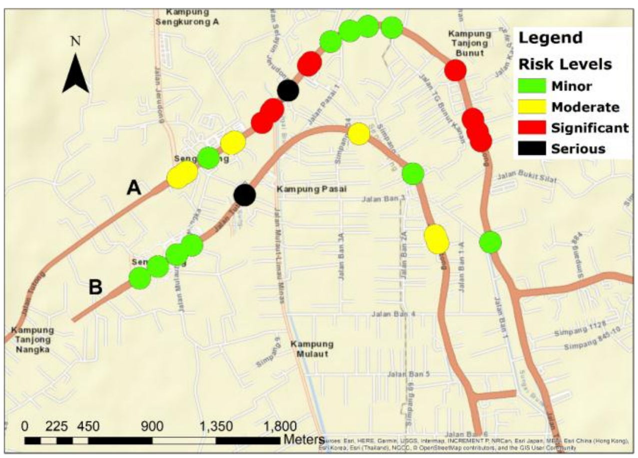

Figure 5. Night-time RTA hotspots along Jalan Tutong before (A) and after (B) the implementation of alternate road lighting.

With reference to Figs. 4 and 5, the risk level of many road sections has either increased or decreased inconsistently for day-time and night-time RTA after the implementation of alternate road lighting. This impeded the visual inspection of the changes in the risk levels by visually comparing RTA hotspots before and after the implementation of this lighting scheme. To provide a more objective comparison, the RTA hotspots in Figs. 4 and 5 were further interpreted quantitatively to analyse the impact on safety, as explained in Section D. Table II shows the results of this quantitative analysis.

With reference to Table II, for minor and significant risk levels, the length of night-time RTA hotspots decreased after the implementation of alternate road lighting. For the same risk levels, the length of day-time RTA hotspots increased after the implementation of alternate road lighting. This indicate that the reduction in hotspot length of the minor and significant risk levels at night is confirmed by the comparison with the day-time results.

Also with reference to Table II, for moderate and serious risk levels, the length of night-time RTA hotspots increased after the implementation of alternate road lighting. For the same risk levels, the length of day-time RTA hotspots decreased after the implementation of alternate road lighting. Hence, the comparison with the day-time results confirmed that there were increases in the hotspot length of the moderate and serious risk levels.

TABLE II. QUANTITATIVE SAFETY IMPACT ANALYSIS OF ALTERNATE ROAD LIGHTING

Jalan Tutong	**Before implementation, day-time RTA**
	Hotspot Length (m)
Minor	624.1
Moderate	443.1
Significant	0
Serious	1707.3

Jalan Tutong	**Before implementation, night-time RTA**
	Hotspot Length (m)
Minor	909.8
Moderate	336.3
Significant	941.8
Serious	155.8

Jalan Tutong	**After implementation, day-time RTA**
	Hotspot Length (m)
Minor	757.3
Moderate	166.1
Significant	193.6
Serious	967.6

Jalan Tutong	**After implementation, night-time RTA**
	Hotspot Length (m)
Minor	704.6
Moderate	372.4
Significant	0
Serious	159.2

Risk Level	**Difference of day-time RTA hotspot lengths (m)**
Minor	133.2
Moderate	-277.0
Significant	193.6
Serious	-739.8

Risk Level	**Difference of night-time RTA hotspot lengths (m)**
Minor	-205.3
Moderate	36.1
Significant	-941.8
Serious	3.3

VI. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated the application of STAA to analyse and identify the changes in the lengths of RTA hotspots of four hierarchical risk levels after the implementation of alternate road lighting on a section of Jalan Tutong. Based on the quantitative analysis of the STAA results, there was an overall increase in the extents of RTA hotspots with moderate and serious risk levels, while there was an overall reduction in the extents of RTA hotspots with minor and significant RTA risk levels.

The results in Table II did not indicate the exact location, nor the size, of the hotspots affected after implementation of the alternate road lighting. It also cannot account for the change in risk level from one hierarchy to another. Other factors in addition to alternate road lighting, such as reduction in the efficiency of luminaires and changes to night-time traffic characteristics, may also contribute to the changes in risk levels after implementation of alternate road lighting. Hence, the current results are considered as indicative and they cannot conclusively confirm the safety impact of alternate road lighting.

Further research is recommended to address these limitations. The identified locations of the safety impact can be validated by measuring and comparing ambient illuminance at these locations to ambient illuminance at other locations with no safety impact. Road safety audit during night-time should also be conducted once these locations are validated to determine the role of reduced lighting.

Acknowledgment

The authors are grateful to the Brunei National Road Safety Council and Insurans Islam TAIB General Takaful for their support and the Royal Brunei Police Force and Department of Electrical Services for providing the necessary road safety data and information.

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