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RESEARCH ARTICLE

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A novel spatial analysis method to evaluate the safety impact of alternate road lighting

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ABSTRACT
The aim of this paper is to introduce a new method to assess the safety impact of road treatment that influences long sections of road network, such as alternate road lighting, i.e. switching off every other road light at selected roads. The new method used Spatial Traffic Accident Analysis (STAA) – a network-based GIS hotspot analysis method – to identify and map day-time and night-time road traffic accident (RTA) risk levels before and after the implementation of alternate road lighting along a study road. Using the change after treatment in day-time RTA risk levels as a comparison group, and the change after treatment in night-time RTA risk levels as a treatment group, the difference between the treatment change and the comparison change in RTA risk levels was evaluated and mapped along the study road. The spatial distribution of this difference resulted in three different levels of the safety impact of the alternate light treatment at different locations along the study road: no impact, possible impact and highly possible impact. Night-time RTA after the alternate light treatment at road locations with the last two safety impact levels were identified, and their contributory factors were found most likely related to the reduction in night-time sight distance linked to alternate road lighting, and thus validates the safety impact results from the new method.

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Alternate road lighting; spatial analysis; GIS; before-and-after study; traffic safety; road traffic accident

1. Introduction

In 2016, 1.35 million were killed in road traffic accident (RTA) which superseded the previous reported figure of 1.25 million in 2013 (WHO, 2015, WHO, 2018a). This now places death by RTA the eighth leading cause of death for all age group, where more people die from RTA injuries than from HIV/AIDS, tuberculosis or diarrhoeal diseases (WHO, 2018a). Children and young adults between age 5 to 29 are the largest group to die from road traffic injuries (WHO, 2018a). 93% of the world's RTA fatalities occurred in the low- and medium-income countries despite having only approximately 60% of the world's vehicles (WHO, 2018b). Low- and medium-income countries in Asia observed the highest rate of RTA fatality in the world (Tanaboriboon & Satiennam, 2005, Commission Internationale De L'eclairage, 2007). In most countries, RTA can cost between 3% to 5% of the country's gross domestic product (GDP) (Aghajani et al., 2017, WHO., 2018b, Febriani et al., 2020, Sholihah et al., 2018).

Haque (2011) attributed RTA occurrences to human error, vehicle defect, road design, environment condition and random influence, which concurred with earlier finding by Botha (2005) who attributed RTA occurrences to circumstantial elements – human, vehicle, roadway and environment. Botha (2005) highlighted that while the first three factors reflected the behaviour, attitude and performance of human and authority, the fourth factor – environment – could, to some extent, be regarded as being beyond the control of driver and/or road design. A very common situation where the road environment is beyond the control of driver but within the control of road design is the provision of adequate road lighting for night-time driving.

Road lighting was objectively introduced to serve as countermeasure (treatment) to reduce night-time RTA frequency and severity (Patel et al., 2014, Fotios & Price, 2017, Elvik et al., 2009). This is achieved by improving the drivers' and other road users' ability to see potential hazards not otherwise revealed by the vehicles' headlights and other environmental lighting (Fotios & Price, 2017, Elvik et al., 2009). Previous research carried out in the 1950s showed that the provision of road lighting could reduce RTA occurrences (Crabb & Crinson, 2008). However, Crabb and Crinson (2008) highlighted that the relationship between road lighting level and RTA rate remained ill-defined. So far, this claim still holds a significant level of validity. This is because there are many potential interactions between RTA contributory factors – human, vehicle, road design and random influence – which make the disconnection between the effect of road lighting and other factors extremely difficult. As a result, the relative effects/influences of other factors which affect RTA rate are not clearly defined. Schreuder (1989), in his pilot study, found that, contrary

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to the popular belief, there was no strong correlation between road's light level and its safety.

The expenditure, energy consumption and local accountability for climate change mitigation, associated with road lighting have become of national and international concerns (Patel et al., 2014, Steinbach et al., 2015, Hazair, 2018, Schreuder, 1989, Elvik et al., 2009), thus prompting many countries to search for energy conservation measures. Hazair (2018) reported that BND3.6 million (3.6 million Brunei Dollars) was saved annually just by switching off every other road light at selected road sections. Patel et al. (2014) recommended that road lighting level should be reduced to the minimum of what is required to ensure good traffic safety. Steinbach et al. (2015) indicated three different strategies for road lighting reduction in bid to save cost and energy and reduce greenhouse gas emissions: switch-off (i.e. switching lights off permanently), part-night lighting (i.e. reducing the number of hours that lights are on at night) and dimming (i.e. reducing the power or output of light intensity), which are commonly practised for the time being.

The associated risk of RTA occurring in darkness (unlit road) is about 1.5 to 2 times higher than that during the day (Elvik et al., 2009). Investigation by Owens and Sivak (1993) revealed that fatality per vehicle-miles averaged 3.5 times higher at night than that during the day and in 1991, day-time fatality rate was 1.2 per 100 million miles while night-time fatality rate was 4.4 per 100 million miles, i.e. 3.7 times higher. Plainis et al. (2006) also found that the number of fatalities per vehicle-miles was higher at night than that during the day, and night-time RTA occurrences generally declined following the installation of road lighting. For different road types, RTA severity, expressed by the average number of fatal collisions per hundred collisions, doubled at night after dimming road light. Isebrands et al. (2010a) reported that after the installation of lighting at isolated rural intersections, which was initially unlit, the expected night-time RTA occurrences was 37% lower than when no lighting was installed, which was statistically significant. The author further added that the change in day-time RTA occurrences before and after road lighting was only 4%, which was not statistically significant. Elvik et al. (2009), on the other hand, found that the provision of road lighting to previously unlit road can reduce fatal RTA by 60%, and injury and property-damage-only RTA by around 15%. The authors also found that reduction in road lighting, by turning off every other light, increased injury RTA by 17% and property-damage-only RTA by 27%. In contrast, when the level of road light was increased by two to five times the original level, the number of accidents occurring at night was reduced by 10%. Fotios et al. (2020) analysed the effect of road light on RTA occurrences in the UK. This study repeated the analysis method adopted by Raynham et al. (2020), and introduced three other methods of analysis based on the ratio of RTA count at night-time to that at daytime. The four methods resulted in large percentage differences in RTA counts between light and dark road conditions, showing a significant contribution of road lighting to RTA occurrences.

A simple before-after analysis method was developed by Box and Alroth (1976) to evaluate the safety impact of alternate road lighting on a major urban road. They computed two ratios of night to day RTA counts before and after switching off alternate road lights: R-before and R-after. They indicated the safety impact of alternate road lighting by comparing R-before to R-after. A negative safety impact was indicated by R-after greater than R-before. Long-term changes in RTA-contributory factors, such as traffic volume, weather and driver trends that could influence RTA count, from before to after the implementation of alternate road lighting were not considered in this analysis method. Hauer (1997a) developed an observational before-and-after comparison group (C-G analysis) method to analyse the safety impact of road treatment, which was adopted subsequently by Gross et al. (2010) for the development of crash modification factors for various traffic safety treatment measures. The C-G analysis method uses 2 groups: treatment group, e.g. night crashes before and after switching off alternate road lights, and comparison group, e.g. day crashes before and after switching off alternate road lights, to compute a Crash Modification Factor (CMF). CMF was computed as the ratio of crash count with the treatment in place to expected crash count without the treatment. Using night crashes before switching off alternate road lights and crash ratio of the comparison group, e.g. the ratio of day crashes after to those before switching off alternate road lights, the expected night crash count without the treatment could be estimated. If CMF was greater than 1, this would indicate a negative safety impact of alternate road lighting. Elvik et al. (2009) consolidated research that used C-G analysis to study the effects of reduced road lighting for energy- and cost-saving purpose on RTA while Isebrands et al. (2010a) used the method to determine the safety benefits of road lighting at rural intersections. The use of comparison group in C-G analysis allowed the implicit consideration of other factors apart from the treatment being investigated that could cause all or part of the observed change in RTA occurrence (Sayed et al., 2008). It also allowed the implicit consideration of time-trend effects, such as changing seasons, weather conditions, shift in demographics and/or driving behaviours (Autey, 2012). However, it does not account explicitly for the effects caused by the regression-to-the-mean and long-term trend effects of crash contributory factors, apart from the treatment being investigated, on the RTA counts (Gross et al., 2010, Sayed et al., 2008).

Hauer (1997b) developed the Empirical-Bayes (EB) method to analyse the safety impact of highway and traffic engineering measures. This method explicitly addressed changes in traffic volume, and other factors that affected RTA count, from before to after the implementation of road treatments, such as alternate road lighting. This was done via the development of a multivariate regression model, known as Safety Performance Function (SPF) or Crash Prediction Model (CPM), to relate RTA count to the aforementioned factors. Goh et al. (2012) used SPF to compute the expected crash count without the treatment, and thus CMF. However, CMF only uses RTA count, excluding RTA severity, to evaluate the safety impact of road treatment. Therefore, Full Bayes (FB) before-after study has been recently introduced to extend the EB method for the evaluation of safety impacts of road treatment (EL-Basyouny & Sayed, 2011, Li et al., 2008). The FB method accounts for all uncertainties related to parameters of the CPM by considering the probability distribution of each model parameter, which allows inferences at hierarchical levels such as various RTA severity levels and crash types. For developing CPM, the EB method uses a single assumption of a negative binomial distribution for RTA counts while the FB method can consider other distributions, such as hierarchical Poisson-Gamma and Poisson-LogNormal distributions (Persaud et al., 2010). In addition, the FB method combines crash prediction and treatment effects into a single model, and thus data requirements for the FB method are less than those for the EB method. Guo and Sayed (2020) used the FB method to evaluate the safety impact of extending the left-turn lane at 3 signalised intersections. They used multivariate Poisson-LogNormal linear intervention models for their analysis. They evaluated the safety impact of the treatment for two crash types by computing the reduction percentage in rear-end and sideswipe RTA counts after extending the left-turn lane at the treated intersections. They also evaluated the safety impact of the treatment for two RTA severity levels by computing the reduction percentage in injuries and fatalities count, as well as in property damage only RTA count, after extending the left-turn lane at the treated intersections. Although the safety impact analysis computed the reduction in RTA count for two RTA severity levels, it did not integrate RTA count and severity into a single risk level while evaluating the safety impact of the treatment. For any of the 2 considered RTA severities or crash types, the safety impact analysis predicted a single safety impact of the treatment for all the 3 treated intersections. For road treatment that affects long road section, for example alternate road lighting, both EB and FB methods fall short of capturing the variation in the safety impact of this treatment that may happen due to the variation in road conditions along the road section.

RTA occurrences seldom happen randomly in space and time (Aghajani et al., 2017, Xie & Yan, 2013) but in spatial and temporal clusters, which become more evident when the accident frequency/rate is greater than a specific threshold (Tan, 2018). This statement, nonetheless, contradicts with Botha (2005) who stated that RTA occurrences are random events or incidents. As RTA occurrences form spatial clusters, it is therefore easy to capture their spatial extent by performing RTA hotspot analysis (HSA) using Geographic Information Systems (GIS). Türe Kibar and Tuydes-Yaman (2020) used RTA hotspot analysis in GIS to evaluate the safety impact of the increase in speed limit from 70 to 82 km/hr on 7 urban arterials in Ankara, Turkey. They used the nearest neighbour hierarchical clustering to map the spatial clusters of RTA points along the 7 arterials for 3 years of RTA data before, and another 3 years of RTA data after, the speed limit increase. They used the count of RTA points within each cluster to rank the RTA hotspot clusters. For each of the 7 arterials, they used the hit rate, predictive accuracy index and recapture rate index to evaluate the spatial shift of RTA hotspots from before to after the speed limit increase. This only indicated the spatial change in RTA hotspot distribution along the arterial after the treatment, but did not identify the magnitude and location of the safety impact of the treatment. In addition, the study did not use a comparison group to exclude the safety impact of other factors apart from the speed limit increase, which might have changed from the time before to after the increase in the speed limit.

Tan (2018) has presented a review of various planar and network spatial analyses of RTA hotspots. The methods and tools discussed in the paper primarily used historical/past RTA data to observe the safety performance of selected study roads. Tan (2018) concluded that network spatial analysis is the most appropriate for RTA hotspot analysis as it significantly reduces false conclusion/impression of spatial distribution of RTA occurrences. Zahran et al. (2021) validated 3 network-based and 1 planar-based RTA hotspot analysis methods, Network KDE by SANET, KDE+, Spatial Traffic Accident Analysis (STAA) and Getis-Ord Gi* respectively, using risk levels from road safety audit. Getis-Ord Gi* failed to identify RTA hotspots along the study road. Network KDE by SANET mistakenly estimated risk levels at road sections free of RTA. The predicted risk levels by KDE + deviated the most from the risk levels observed by the road safety audit. STAA method, which considers both RTA count and severity for computing risk levels, predicted the most consistent risk levels with those observed by the road safety audit. In addition, unlike other RTA HSA methods such as KDE+, STAA was applicable to RTA at both intersections and straight sections of road network without the need for segmentation.

Zahran et al. (2019c) employed STAA method to investigate the safety impact of alternate road lighting along a study road. Using STAA, they produced four RTA hotspot maps: 'before implementation-day-time RTA', 'before implementation-night-time RTA', 'after implementation-day-time RTA' and 'after implementation-night-time RTA'. RTA hotspots in each of the four maps were assigned four hierarchical risk levels. The change in the lengths of RTA hotspots before and after the implementation of alternate road lighting was computed for each risk level of the day-time RTA hotspots. The four changes constituted a comparison group. For each risk level of the night-time RTA hotspots, the same was computed resulting in four changes that constituted a treatment group. For each risk level, if the treatment group's change in RTA hotspot lengths was greater than that of the comparison group, this would indicate an overall increase in the extents of RTA hotspots with this particular risk level after the implementation of alternate road lighting, which would imply a negative safety impact of the treatment at this particular risk level. Despite implying the safety impact of the road treatment for various risk levels, the results from this approach did not show the exact locations of the safety impact of alternate road lighting along the study road. This approach could not also consider the change in risk level of a particular location from before to after the implementation of alternate road lighting. Therefore, STAA is used in this paper in a different way that can help identify the variation in risk level and exact locations of the safety impact of alternate road lighting on a long road section. This is achieved by comparing the spatial distribution of the change in day-time RTA risk level (comparison group) to that of the change in night-time RTA risk level (treatment group) from before to after alternating road lights. The difference between these two spatial distributions results in the spatial distribution of the safety impact levels of alternate road lighting along the road section.

2. Study road

A road section in Brunei Darussalam referred herein as the 'study road', has been chosen for this research. In recent years, the road lighting system along the study road has been switched from full-lighting to alternate-lighting at non-intersections and perceived lower-risk road sections. The alternate-lighting system is an initiative to reduce energy consumption, environmental impact and expenditure.

Figure 1 illustrates the adopted mode of alternate lighting for the study road. The yellow bulbs indicate light-on while the black bulbs indicate light-off. As a result of such implementation, there was reduced lighting along the road. The road also experienced a 'zebra' effect, where there was a combination of partially dark and well-lit sections of the road.

Anonymised RTA reported to the police during the study period were collected. The analysis in this paper used two groups of RTA data along the study road that happened during two equal periods – 26 months before and after alternating road lights on October 27, 2016. RTA that happened from 6:01am to 7.00 pm were considered daytime RTA, and those that happened from 7.01 pm to 6.00am were considered as night-time RTA. With reference to Figure 2, RTA took place along the study road both during day- and night-times of the whole study period, and peaked during traffic peak hours in the morning, afternoon and evening at 8.00-9.00 am, 12.00-1.00 pm, 4.00-5.00 pm, 7.00-8.00 pm and 10.00 to 11.00 pm.

The length of the study road section was 4.1 km, which was a dual carriageway as shown in Figure 3. Along this study road section, there were 3 traffic light-controlled junctions, 85 uncontrolled, stop- or yield-controlled junctions, 6 U-turns and 4 right-turns. The study road was bounded on two sides by densely populated residential and commercial zones. Although the speed limit of the study road was 65 km/hr, the operating speed of this road, i.e. the 85th percentile of observed spot speeds, was measured as 87 km/hr using a radar speed gun.

3. Analysis and results

STAA was briefly introduced in the Introduction, and this section provides a brief methodology on the application of STAA to identify RTA hotspots along the study road and prioritise them using four hierarchical risk levels. The details of STAA methodology was thoroughly presented in Zahran et al. (2016), Zahran et al. (2017), Zahran et al. (2019) and Zahran et al. (2021).

3.1. Rta hotspot analysis using STAA

RTA map locations along the study road were modelled as points and were split into four GIS maps: 'before implementation-daytime RTA' and 'after implementation-daytime RTA' that constitute the comparison group of this paper's analysis, and 'before implementation-night-time RTA' and 'after implementation-night-time RTA' that constitute the treatment group of this paper's analysis. Each RTA point had many data fields, including the count of fatality, serious injury, minor injury and no injury cases. For each of the four maps, circular buffers were created around the RTA points of a radius equalled the stopping sight distance (SSD) along the study road. Zahran et al. (2019c), (Zahran et al., 2019, Zahran et al., 2021) estimated SSD along the study road as 78 m using Equation (1) from American Association of State and Transportation (2018), as reproduced below.

$$SSD = 0.278Vt + \frac{V^2}{254f}(1)$$

Where V: 65 km/hr (posted speed limit)t: 1.5 sec (perception-reaction time) (Ladi et al., 2009, Zahran et al., 2017)f: 0.33 (longitudinal friction coefficient between vehicle tyres and road surface) (Ladi et al., 2009, Zahran et al., 2017)

In each of the four maps, the overlapping circular polygons were merged together into a small number of big-sized polygons, which represented RTA hotspots, as shown in Figure 3 representing the daytime RTA hotspots before alternating the road lights of the study road. The three other maps of RTA hotspots were created the same. The sum of RTA points, and their attribute data, within each

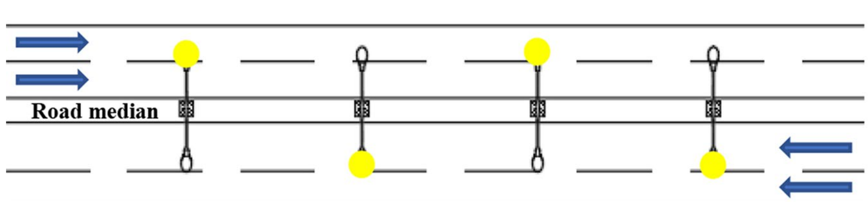

Figure 1. Alternate road lighting along the study road.

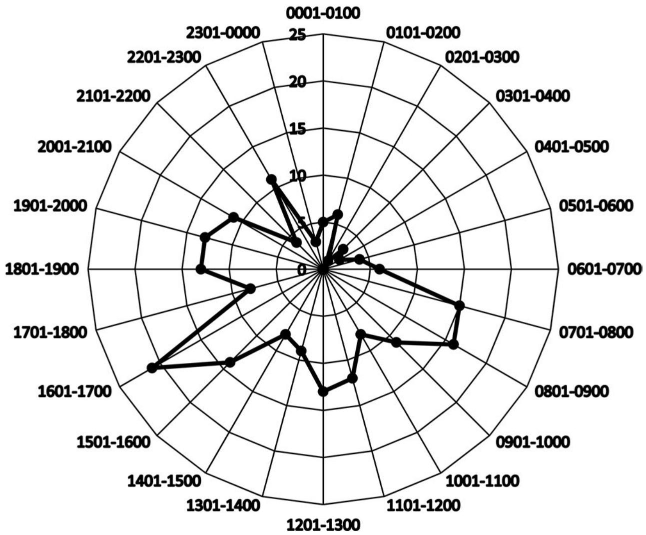

Figure 2. Hourly frequency of RTA along the study road for the whole study period.

hotspot polygon was computed using the 'Join Data' function, so that each polygon stored the count of RTA points and the sum of their fatality, serious injury, minor injury and no injury cases. Using this data, the normalised frequency (NF) and normalised socio-economic impact (NSEI) of RTA within each hotspot polygon were computed and appended to the table of attributes of that polygon. NF corresponded to the count, and NSEI corresponded to the severity, of RTA points located within each RTA hotspot polygon. Equations (2) (3) and (4) from Zahran et al. (2017), reproduced below, were used for the computation of NF and NSEI.

$$NF = RTA \times \frac{SSD}{L} \times \frac{1}{N} (2)$$

Where NF: Average annual number of RTA cases within each hotspot polygon per SSD

RTA: RTA count within the hotspot zone

SSD: Stopping sight distance (m)

L: Length of hotspot zone along the road centreline (m)

N: Number of years of data.

$$SEI = (Fatality \times USD1{,}419{,}639) + (Serious\ injury \times USD70{,}205) + (Slight\ injury \times USD9{,}119) + (No\ injury \times USD3{,}300)\ (3)$$

Where SEI: Socio-economic impact

$$NSEI = SEI \times \frac{SSD}{L} \times \frac{1}{N} (4)$$

Where NSEI: Normalised socio-economic impact (SEI per SSD length per year)

The costs in USD for Equation (3) were acquired from previously published costs of RTA in Brunei Darussalam

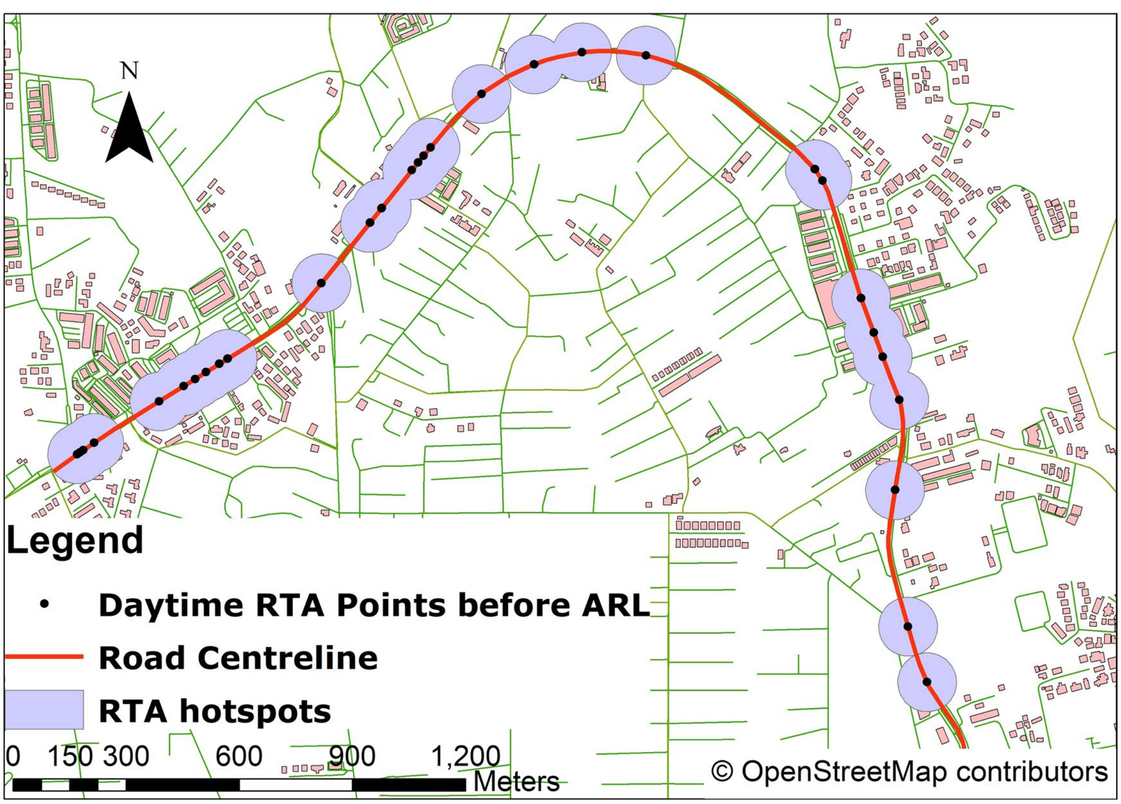

Figure 3. The study road hotspots of daytime RTA before alternating road lights.

(Melhuish et al., 2005, Zahran et al., 2017). The polygons (RTA hotspots) in each of the four maps had a range of NF values and range of NSEI values. The analysis range of NF was identified by combining the four NF ranges from the four maps into a single range. Likewise, the analysis range of NSEI was identified by combining the four NSEI ranges from the four maps into a single range. A quantile data classification was applied to split each of the ranges of NF and NSEI into four equal quantiles. To rank RTA hotspot polygons in the four maps, a composite risk level was identified for each polygon based on its respective NF and NSEI quantiles, as shown in Table 1. The ranking scheme was composed of four hierarchical risk levels, namely 'minor', 'moderate', 'significant' and 'serious'. A colour scheme composed of four colours, one for each of the four composite risk levels as shown in Table 1, was assigned to the RTA hotspot polygons in the four maps. Figures 4 and 5 show the RTA hotspots and their hierarchical ranks for both the comparison and treatment groups.

3.2. Safety impact of alternate road lighting

The centreline of the study road section was clipped for four times using the RTA hotspot polygons in the four maps in Figures 4 and 5. This resulted in four maps of road centreline segments that are only located within the RTA hotspot polygons in Figures 4 and 5. Using the Spatial Join tool of ArcGIS 10.2, each of these road centreline segments acquired the quantitative risk level of the RTA hotspot polygon within which it was located, such as 1 for Minor, 2 for Moderate, 3 for Significant and 4 for Serious.

The change in risk levels of daytime RTA from before to after the implementation of the alternate light treatment was computed as the comparison group of the safety impact assessment. The risk levels of road centreline segments related to the daytime RTA before the alternate light treatment (A) were subtracted from the risk levels of those segments related to the daytime RTA after the treatment (B). Since the two sets of road centreline segments A and B were not co-located as shown in Figure 4 by mismatching A and B RTA hotspots, the Identity Overlay spatial analysis of ArcGIS 10.2 was used to overlay these two sets of road centreline segments, and produced an output layer (C) that contained all road centreline segments B and only those portions of road centreline segments A that overlapped road centreline segments B. The risk levels for the output layer contained the risk levels of road segments B and the risk levels of road segments A that overlapped road segments B. For road segments B that did not overlap with road segments A, the output road segment in layer C had zero for the risk level of road segments A. Erase Overlay spatial analysis of ArcGIS 10.2 was used to erase portions of road segments B that overlapped with road segments A from road segments A, resulting in output layer (D). Merge tool of ArcGIS 10.2 was used combine layers C and D, resulting in output layer (E) that had road segments with the risk levels of either both road segments A and B, road segments A and zero from road segments B or road segments B and zero from road segments A. Identity Overlay spatial analysis of ArcGIS 10.2 was used to overlay the whole centreline of the study road section with

Table 1. Composite risk levels of RTA hotspots along the study road.

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

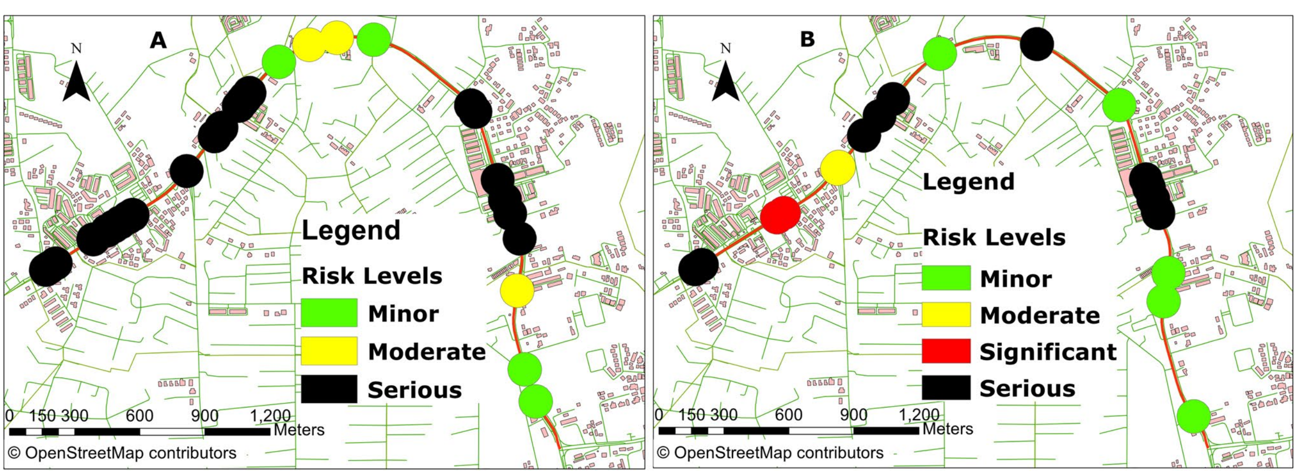

Figure 4. Day-time RTA hotspots along the study road before (A) and after (B) the implementation of alternate road lighting (comparison group).

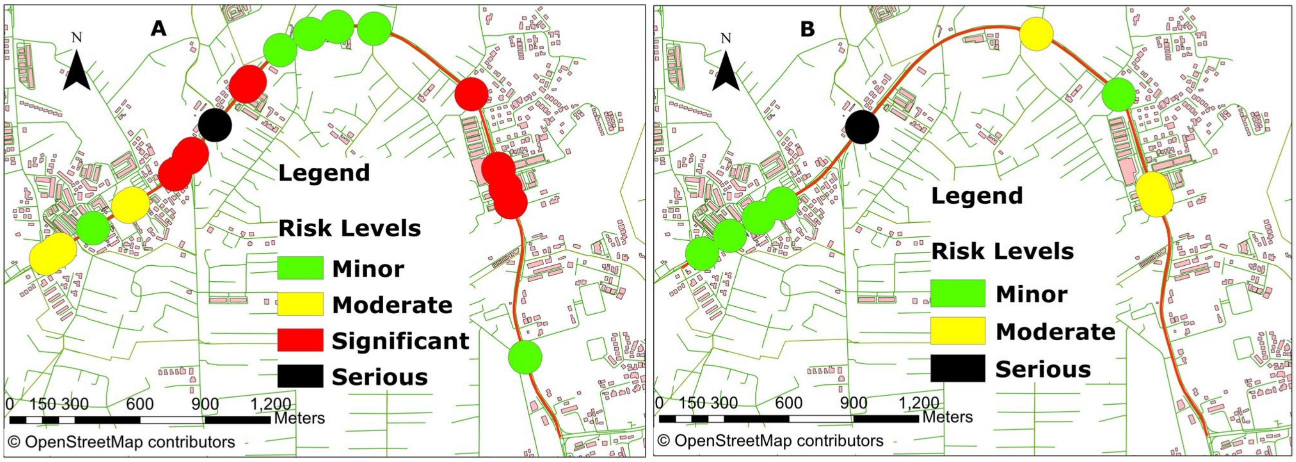

Figure 5. Night-time RTA hotspots along the study road before (A) and after (B) the implementation of alternate road lighting (treatment group).

layer E, resulting in the comparison group layer, in which the daytime RTA risk level before the implementation of the alternate light treatment was subtracted from the daytime RTA risk level after the treatment for every road centreline segment. The difference between these two daytime RTA risk levels for all road centreline segments provided the spatial distribution of the change in risk levels of daytime RTA from before to after the implementation of the alternate light treatment, as shown in Figure 6.

The aforementioned steps in the former paragraph were repeated using the road centreline segments located within the night-time RTA hotspots before and after the alternate light treatment in Figure 5. This resulted in the treatment group layer of the safety impact assessment, in which the night-time RTA risk level before the implementation of the alternate light treatment was subtracted from the night-time RTA risk level after the treatment for every road centreline segment. The difference between these two night-time RTA risk levels for all road centreline segments provided the spatial distribution of the change in risk levels of night-time RTA from before to after the implementation of the alternate light treatment, as shown in Figure 7.

Identity Overlay spatial analysis of ArcGIS 10.2 was used to overlay the treatment group layer in Figure 7 with the comparison group layer in Figure 6. This resulted in the safety impact assessment layer of the alternate light treatment, in which road centreline segments had attributes for both the comparison and treatment risk level changes. For every road centreline segment in the safety impact assessment layer, the comparison change in RTA risk level was subtracted from the treatment change in RTA risk level.

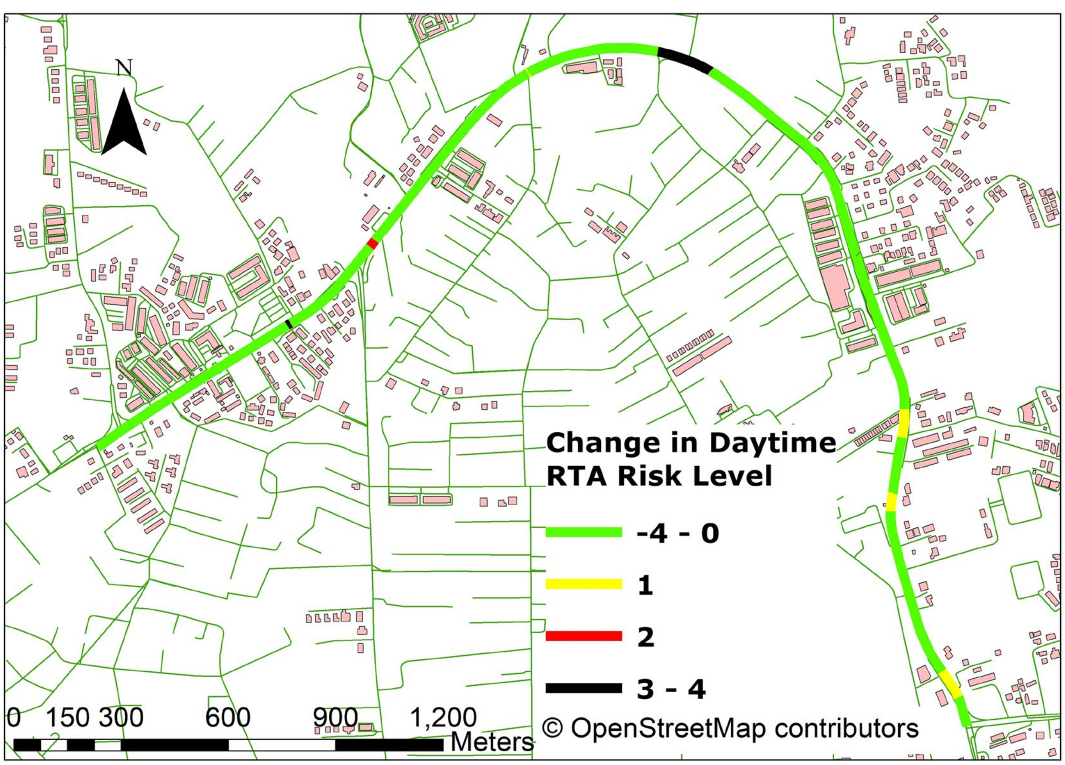

Figure 6. Comparison group of the safety impact of alternate road lighting.

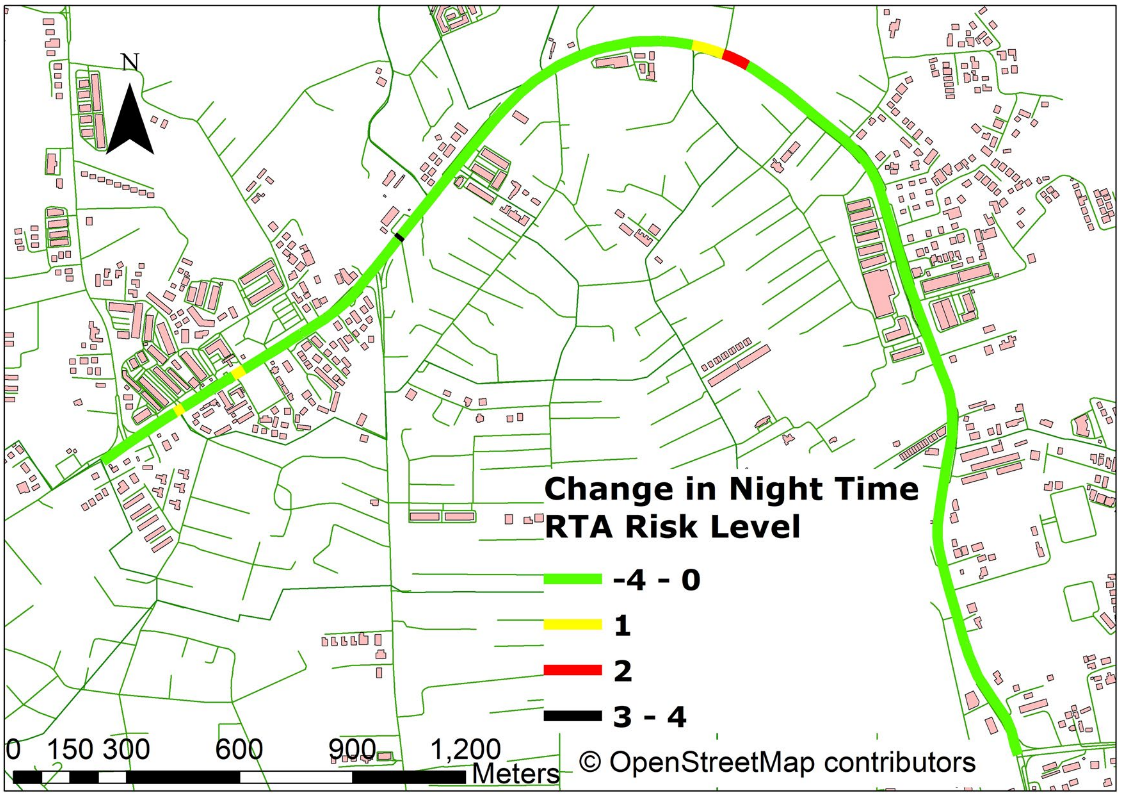

Figure 7. Treatment group of the safety impact of alternate road lighting.

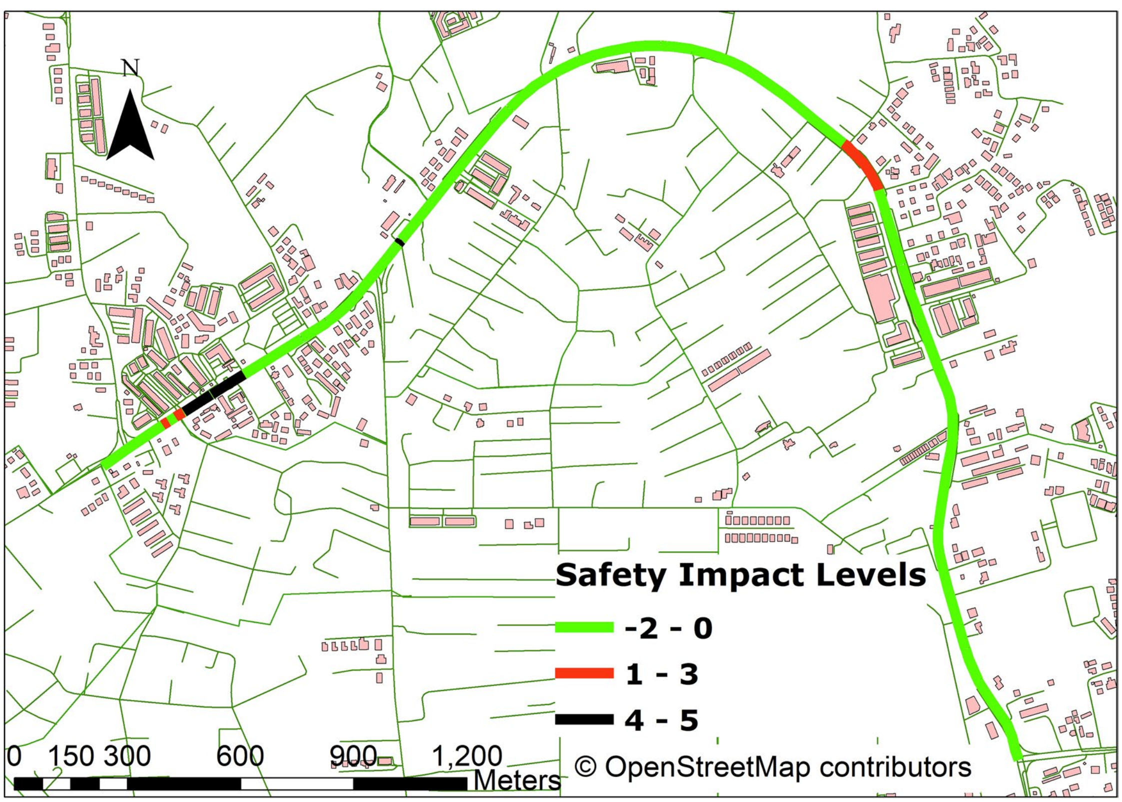

Figure 8. Spatial distribution of the levels of the safety impact of alternate road lighting.

The difference between these two changes in RTA risk level (Δ change in RTA risk level) for all road centreline segments was computed and appended to their table of attributes. For road centreline segments with 0 risk level at nigh time after the alternate light treatment, Δ change in RTA risk level was set to 0 in the safety impact assessment layer. Δ change in RTA risk level indicated the safety impact of alternate road lighting along the study road section. In contrast to EB and FB, the safety impact assessment method of this investigation was able to identify the spatial distribution of the safety impact of the alternate light treatment along the study road section, as shown in Figure 8.

4. Discussion

Figures 4 and 5 show that the changes in both daytime and night-time RTA risk levels were inconsistent from one segment to another of the study road from the time before the alternate light treatment to the time after the implementation of alternate road lighting. Therefore, the visual comparison of RTA hotspots before and after the alternate light treatment was not enough to give the correct visual impression of the changes in risk levels of both daytime and night-time RTA from before to after the treatment. Figures 6 and 7 provided the spatial and quantitative distribution of the changes in daytime and night-time RTA risk levels after the alternate light treatment in the range from −4 to 4. −4 to 0 denoted a reduction or no change in RTA risk level, while the three levels from 1 to 4 denoted three different rise levels in RTA risk level, after the alternate light treatment. In contrast to the simple before-after analysis method that was developed by Box and Alroth (1976), the consideration of the change in daytime RTA risk level from before to after the alternate light treatment as a comparison group allowed the consideration of long-term changes in RTA-contributory factors other than the road treatment being evaluated.

Figure 8 shows that the changes in RTA risk level between treatment and comparison from one segment to another of the study road were in the range of −2 to 5 risk levels. For road segments with Δ change in RTA risk level with a value of −2 to 0, the treatment change was less than or equal to the comparison change in RTA risk level. For road segments with Δ change in RTA risk level with a value of 1 to 5, the treatment change was higher than the comparison change in RTA risk level. The higher the value of Δ change in RTA risk level, the higher the difference between the two changes in RTA risk level.

Road centreline segments with 0 risk level at night-time after the alternate light treatment experienced no night-time RTA after, and thus have no safety impact of, the treatment. However, for some of these road centreline segments, the reduction in the treatment change was higher than the reduction in the comparison change in RTA risk level. After subtracting the comparison change from the treatment change in RTA risk level, this resulted in a positive value of Δ change in RTA risk level, which mistakenly implied adverse safety impact of the treatment, for these road centreline segments. Setting Δ change in RTA risk level to 0 for these road centreline segments corrected this mistake.

An investigation was undertaken into the night-time RTA after the alternate light treatment that took place along the road centreline segments with a positive value for Δ change in RTA risk level. The road type of these RTA was either a curve or a junction. It is well known that inadequate driver's sight distance on these road types can easily lead to RTA if available sight distance gets less than the SSD. The implementation of alternate road lighting may have reduced the night-time sight distance below the SSD at these road segments, leading to the rise in Δ change in RTA risk level at these road segments. Some of these RTA were rear collisions when a car from a slip road used a very short gap in the traffic stream on the study road to join it. Some of the other RTA were due to loss of control when a car dodged another car making a U-turn or changing lane abruptly. This further supported the assumption that the implementation of alternate road lighting may have reduced the night-time sight distance below the SSD at these road segments, leading to the occurrence of these RTA.

5. Conclusions and recommendations

This research developed a new method for the safety impact assessment of road treatment that influences long sections of road network, and may have different levels of the safety impact, such as alternate road lighting. The new method applied STAA to analyse and identify the changes in RTA risk levels, based on both RTA frequency and severity in the form of RTA socio-economic impact, after the implementation of alternate road lighting along a section of the study road. With reference to Figure 8, the results from this method identified road segments with 3 different levels of the safety impact. For the first level, Δ change in RTA risk level was less than or equal to 0, indicating no impact. For the second level, Δ change in RTA risk level ranged from 1 to 3, which indicated a possible safety impact of the road treatment. For the third level, Δ change in RTA risk level was from 4 to 5, which indicated a possible high safety impact of the road treatment. For road segments with the last two levels of the safety impact, night-time RTA after the alternate light treatment may be related to the reduction in night-time sight distance, which is possibly linked to alternating road lights, and is validating the safety impact results from the new method. It is recommended to conduct a road light survey to measure and compare the light luminance and consistency at road segments with adverse safety impact to those at road segments with no impact. This can further validate the safety impact results from the new method.

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