A Novel Methodology For Crash Hotspot Identification And Network-Wide Safety Ranking

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Abstract

This study proposes a novel methodology for assessing road infrastructure safety across relatively large road networks based on historic crash data. The developed methodology aligns with existing road safety assessment frameworks that focus on the identification of crash hotspot locations as it addresses the identification of crash hotspots and so, it can be easily adopted by practitioners. In addition to crash hotspot identification, it also provides a framework for a safety ranking of the network. Therefore, the final outcome of the methodology is the critically unsafe locations plus a characterization of the safety level of the rest network. This paper presents a series of analyses that aim at demonstrating the differences among the alternative approaches of implementing the methodology. This study contributes to the existing literature by introducing the concept of network-wide safety ranking and is useful for road safety stakeholders who are interested in more effective yet user-friendly methodologies related to road safety management.

Keywords: *crash hotspot analysis; safety ranking; network-wide; road geometry; traffic data*

Η παρούσα μελέτη προτείνει μια νέα μεθοδολογία για την αξιολόγηση της ασφάλειας των οδικών υποδομών σε σχετικά μεγάλα οδικά δίκτυα με βάση ιστορικά δεδομένα ατυχημάτων. Η μεθοδολογία που αναπτύχθηκε ευθυγραμμίζεται με τα υφιστάμενα πλαίσια αξιολόγησης της οδικής ασφάλειας που επικεντρώνονται στον εντοπισμό των κρίσιμων σημείων σύγκρουσης και με αυτόν τον τρόπο μπορεί εύκολα να υιοθετηθεί από τους συμμετέχοντες. Εκτός από τον εντοπισμό των σημείων σύγκρουσης, παρέχει επίσης ένα πλαίσιο για την κατάταξη του δικτύου σε επίπεδο ασφάλειας. Ως εκ τούτου, το τελικό αποτέλεσμα της μεθοδολογίας είναι οι κρίσιμα επικίνδυνες θέσεις καθώς και ένας χαρακτηρισμός του επιπέδου ασφάλειας του υπόλοιπου δικτύου. Η παρούσα μελέτη παρουσιάζει μια σειρά αναλύσεων που αποσκοπούν στην ανάδειξη των διαφορών μεταξύ των εναλλακτικών προσεγγίσεων εφαρμογής της μεθοδολογίας. Η μελέτη αυτή συνεισφέρει στην υπάρχουσα βιβλιογραφία εισάγοντας την έννοια της κατάταξης της ασφάλειας σε επίπεδο δικτύου και είναι χρήσιμη για τους ενδιαφερόμενους φορείς οδικής ασφάλειας που ενδιαφέρονται για πιο αποτελεσματικές αλλά και φιλικές προς τον χρήστη μεθοδολογίες που σχετίζονται με τη διαχείριση της οδικής ασφάλειας.

Λέξεις-κλειδιά: *ανάλυση κρίσιμων σημείων σύγκρουσης; κατάταξη ασφάλειας; δίκτυο; γεωμετρία οδού; κυκλοφοριακά δεδομένα*

1. Introduction

Despite the efforts of transportation researchers and practitioners in order to improve road safety, road crashes constitute a major global societal problem with more than 1,25 million fatalities per year (first mortality cause for the ages 15-29). Accident Prediction Models (APMs), including Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) and other advanced statistical models are essential tools for transport authorities and highway agencies, mostly in developed countries, to predict crashes, analyze injury severity, identify hotspots and assess safety countermeasures. However, developing APMs requires a tremendous effort of data collection and data analysis, which could be potentially skipped by researchers and engineers if the models are transferable to conditions different from the ones they were developed for. Additionally, the issue of research findings transferability among various locations and most importantly among countries does not allow for generalization of results. Verifying the transferability of road safety research findings is essential for the development of a generic road safety management system which could be utilized worldwide and provide real-world solutions to everyday road safety problems. Thus, there is an imperative need for international scientific cooperation to identify and fully understand crash risk factors and respective measures, ultimately aiming at the development of an integrated international road safety management system.

Within the above context, the core objective of the research project **i-safemodels - "International Comparative Analysis of Road Traffic Safety Statistics and Safety Modelling"** is the development of advanced road safety standardization models at both macroscopic and microscopic levels in developed and developing countries in the United Kingdom, Europe (UK). (Germany), Asia (China) and the USA. Exploring the possibility of transferability and comparing results will lead to valuable transfer of knowledge and experience to reduce road crashes in Greece, China and worldwide.

This paper aims to present project research activities and results from different countries, so as to compare them. In Chapter 1 there is an introduction to the main topic with general statistics about road crashes. Chapter 2 contains the literature review, in which the methodology was based. Chapter 3 describes the methodology followed to obtain the results. In chapter 4, results of the present research that emerged from the application of the methodology, are described. Chapter 5 summarises the conclusions of this study.

2. Background

By this step, the information known for each section (or junction) consist of the section start and end points, its total length, the total number of observed crashes during the analysis and if available, traffic volume information.

Using the Poisson method, an upper and lower threshold are estimated for the observed number of crashes of each section (or junction):

Lower confidence interval: $$chisquare[\frac{\alpha}{2}, 2 \times k] / 2 \quad \textbf{(1)}$$

Upper confidence interval: $$chisquare[1 - \frac{\alpha}{2}, 2 \times (k+1)] / 2 \quad \textbf{(2)}$$

Where:
k: is the observed number of crashes in a section/junction during the analysis period
α: confidence level. It is recommended to use 0.05.

Using the number of crashes defined by the upper and lower confidence intervals, two safety performance metrics are calculated per section (or junction): crash rate and crash density. It is noted that if traffic volume data is not available for the section/junction then, crash rate cannot be estimated. The crash rate is estimated as:

$$R_i = \frac{N_i * 10^8}{365.25 * AADTi * y * L_i} \quad \textbf{(3)}$$

Where:
N_i: number of crashes at road section/junction *i*, occurring in the analysis period
$AADT_i$: Average Annual Daily Traffic of the section/junction
y: analysis period (years)
L_i: length of section *i* (km)
The crash density is estimated as:

$$d_i = \frac{f_i}{L_i} \quad \textbf{(4)}$$

Where:
f_i: crash frequency at road section/junction *i*, that is the number of crashes (N_i) occurring per y which is the number of years in the analysis period
L_i = length of section/junction *i* (km)
Crash rate and crash density values are also estimated for each reference population group. These values serve as thresholds for assessing the safety level of each section (or junction).

3. Methodology

Data Collection

For the crash hotspot identification, a methodology has been developed with the objective to achieve a high level of flexibility and so, the same methodology can be applied to a diverse set of settings, e.g., different countries and different road types. This is achieved by proposing equivalent alternatives in various steps of the methodology, that vary in terms of data. Essentially, some alternatives are less data-intensive compared to others. A second objective of the methodology was not only to identify hotspots (i.e., unsafe parts of the network) but overall to rank the network and identify sections that are safe, less safe, etc.
It is noted that the methodology has been developed for motorways (urban and rural) and for rural roads that can be divided or undivided.

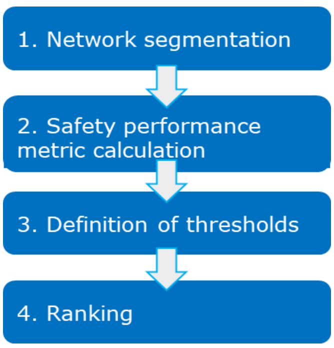

Figure 1: *Steps of the crash hotspot identification and network ranking methodology.*

It is important to highlight that the methodology requires three types of data:
1. Crash data
2. Traffic data
3. Road design/ road geometry data.

It is quite intuitive to understand the use of crash data in this context. Traffic data is used as an exposure metric with the objective to better understand how crashes occur based on the level of traffic. Road design and road geometry data are needed for segmentation purposes, i.e., for dividing the road in smaller parts.

Crash and traffic data are needed for (a) the road network under assessment and (b) for a set of roads with similar characteristics. The latter is known as the "reference population" and is used as a reference point for comparison. Essentially, this methodology assumes that the level of safety of road section is dependent upon the level of safety of the reference population. As this methodology has been developed for urban and rural motorways and primary rural (or other rural roads) that are either divided or undivided, four reference population groups are considered: urban motorways, rural motorways, primary divided roads and primary undivided roads.

The developed methodology was tested using data from the Olympia Odos motorway which is a rural motorway. The length of the road used for the analysis is equal to 50,6km and starts right after the Elefsina Toll Station. This part of the motorway has a cross-section that consist of 2 or 3 lanes per direction of traffic plus emergency lane, central median with concrete barrier. There are 6 grade-separated junctions, while it is noted that tunnels that have been excluded from the assessment as they are not addressed by the developed methodology. Figure 2 illustrates the part of the Olympia Odos motorway where the developed methodology was implemented.

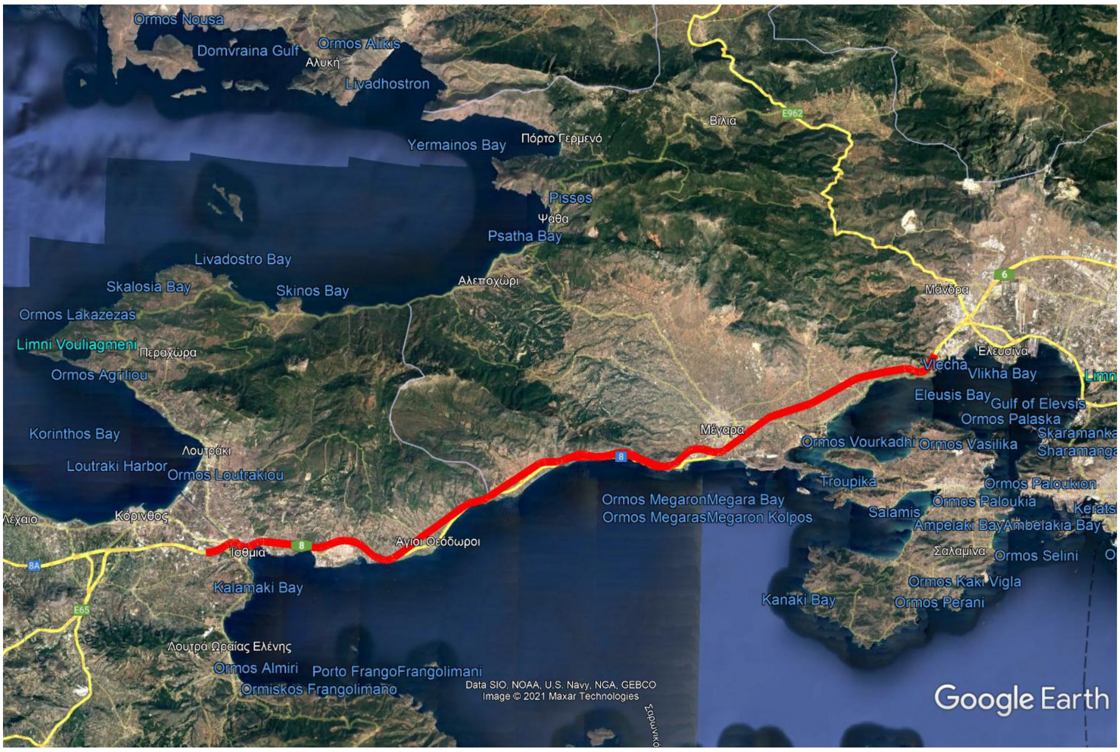

Figure 2: *Location of examined segment of Olympia Odos motorway (Source: Google Earth).*

Crash data were used for a 5-year period namely, 2015 to 2019. While data for 2020 were available it was decided not to include these records in the analysis as they were likely affected by the COVID-2019 pandemic. The road operator provided the total number of and the location of injury related single-vehicle crashes, property damage-only single vehicle crashes, injury related multi-vehicle crashes, and property damage-only multi vehicle crashes. Based on this information, the total number of injury crashes and the total number of all crashes were estimated for the 5-year period.
For the examined part of the motorway and for both directions of traffic, 56 injury-related crashes were recorded between 2015-2019. The same number of all crashes is equal to 1.038, meaning that this motorway is mostly subject to property damage-only crashes and the injury-related ones are rather rare. Traffic volume data were used for the same period and for the analysis, the 5-year average was used.
Remarkable is that the developed crash hotspot identification methodology relies on the concept of the reference population in order to define thresholds for crash density based on which a section is classified as low or high risk (or unsure). For the period of analysis, average crash density and average crash rate are not readily available for rural motorways in Greece. Therefore, for the implementation at the Olympia Odos motorway it is assumed that the total sections (or junctions) form the reference population. This means that a section (or junction) is compared against average statistics estimated across the 50,6km part of Olympia Odos.
Lastly, the geometric data was used for the network segmentation. Road curvature, number of lanes, location and size of interchanges were the data types that were used.

The cases that were developed are the following:

- Case 1: Homogenous road sections & injury crashes

The examined section of Olympia Odos motorway was divided into homogeneous sections. Sections included junctions in addition to road segments and they were defined considering the traffic volume and horizontal curvature changes. It is noted that the entire road lies along the same terrain type and has three-lane segments and so, terrain type as well as number of lanes were not used as criteria for the segmentation. Segmentation resulted in 13 sections in the direction from Athens to Korinthos (coded as "T") and in 13 sections in the directions from Korinthos to Athens (coded as "E"). While the number of sections is the same, their starting and ending points per direction of traffic do not necessarily align.
For this implementation of the crash hotspot identification methodology, crashes with fatalities and injuries were used (i.e., the total number of injury-related crashes). Their total number is equal to 52.

Table 1: *Summary of the data used for the assessment of the Athens to Korinthos direction ("T") in Case 1.*

Reference data - Road sections	
Data on the road under assessment:	
Time period of accident data (years)	5
Total n. accidents	23
Total length of all road sections (km)	46
Data on the Reference Population to which the road sections belong:	
Total km of roads	95
Total n. accidents	46
Average AADT	9,969
Average accident density - calculated *(acc./km)*	0.10
Average accident density - input *(acc./km)*	
Average accident rate - calculated *(acc./veh.*km)*	2.66
Average accident rate - input *(acc./veh.*km)*	
Average AADT - calculated	-

Table 2: *Summary of the data used for the assessment of the Athens to Korinthos direction ("T") in Case 1.*

Reference data - Road sections	
Data on the road under assessment:	
Time period of accident data (years)	5
Total n. accidents	29
Total length of all road sections (km)	49
Data on the Reference Population to which the road sections belong:	
Total km of roads	95
Total n. accidents	56
Average AADT	9,969
Average accident density - calculated *(acc./km)*	0.12
Average accident rate - calculated *(acc./veh.*km)*	3.24
Average AADT - calculated	-

- Case 2 : Homogenous road sections & all crash types

In this implementation of the crash hotspot identification methodology, the network segmentation remains the same as in Case 1 and the modification of the original methodology entails the use of all crashes, i.e., injury-related ones and property damage-only ones. The addition of the latter significantly and greatly changes the previous values as the number of the property damage-only crashes is very much higher. Tables 3 and 4 present the summary of the data used for the assessment of each direction of traffic.

Table 3: *Summary of the data used for the assessment of the Athens to Korinthos direction ("T") in Case 1.*

Reference data - Road sections	
Data on the road under assessment:	
Time period of accident data (years)	5
Total n. accidents	489
Total length of all road sections (km)	46
Data on the Reference Population to which the road sections belong:	
Total km of roads	95
Total n. accidents	1,122
Average AADT	9,969
Average accident density - calculated *(acc./km)*	2.36
Average accident rate - calculated *(acc./veh.*km)*	64.87

Table 4: *Summary of the data used for the assessment of the Athens to Korinthos direction ("T") in Case 1.*

Reference data - Road sections	
Data on the road under assessment:	
Time period of accident data (years)	5
Total n. accidents	633
Total length of all road sections (km)	49
Data on the Reference Population to which the road sections belong:	
Total km of roads	95
Total n. accidents	1,122
Average AADT	9,969
Average accident density - calculated *(acc./km)*	2.36
Average accident rate - calculated *(acc./veh.*km)*	64.87
Average AADT - calculated	-

- Case 3 : Homogenous road sections & injury crashes – different alpha

This implementation of the methodology aims to assess its sensitivity with respect to the alpha parameter:

- α = 0,10
- α = 0,01

It is noted that all other values and parameters used in the methodology remain the same as in Case 1.
α = 0,10

- Case 4: Traffic volume-based sections & injury crashes

In this implementation of the crash hotspot identification methodology the objective is to modify the segmentation criteria. Removing segmentation criteria can allow the formulation of longer sections and so, the performance of the methodology can be then tested in the setting of network-wide setting.

4. Results

This section summarizes the findings of the previous analyses in a comparative manner with the objective to illustrate the implications of choosing one approach over the other. The aggregated outcome of all four cases (Case 1 to 4) are summarized in Tables 5 and 6. The difference between the two tables is that the former displays total values and the other percentages.

On average, across the different approaches to implement the methodology the majority of the sections, approximately 8 sections which correspond to approximately to 35,5km out of the total length per direction of traffic (equal to 46km for the "T" direction and 49km for the "E" direction), are ranked as "Unsure". "Low Risk" sections for the Olympia Odos motorway are mostly the sections that have zero crashes. Exemptions to the latter statement can be found in Case 2 where all crash types are considered and so, there are no sections with zero crashes and "Low Risk" sections have crashes. Across the different cases, "High Risk" sections correspond on average to 11,7% of the total length in Direction "T" and to 18% of the total length in Direction "E".

Table 5: *Aggregated results across Cases 1 to 4.*

		Direction "T"		Direction "E"	
		Total Length (Km)	No. sections	Total Length (Km)	No. sections
Case 1	High Risk	8.20	3	5.20	2
	Unsure	31.20	8	36.20	8
	Low Risk	6.60	2	7.40	3
Case 2	High Risk	3.40	1	20.00	4
	Unsure	36.60	10	28.80	9
	Low Risk	6.00	2	0.00	0
Case 3 - a=0,01	High Risk	4.80	2	5.20	2
	Unsure	34.60	9	36.20	8
	Low Risk	6.60	2	7.40	3
Case 3b - a=0,10	High Risk	8.20	3	10.60	3
	Unsure	31.20	8	30.80	7
	Low Risk	6.60	2	7.40	3
Case 4	High Risk	2.20	1	3.00	1
	Unsure	43.80	7	45.80	7
	Low Risk	0.00	0	0.00	0

Table 6: *Aggregated results in percentage form across Cases 1 to 4.*

		Direction "T"		Direction "E"	
		% of total Length	% of tot. sections	% of total Length	% of tot. sections
Case 1	High Risk	17.83	23.08	10.66	15.38
	Unsure	67.83	61.54	74.18	61.54
	Low Risk	14.35	15.38	15.16	23.08
Case 2	High Risk	7.39	7.69	40.98	30.77
	Unsure	79.57	76.92	59.02	69.23
	Low Risk	13.04	15.38	0	0
Case 3 - a=0,01	High Risk	10.43	15.38	10.66	15.38
	Unsure	75.22	69.23	74.18	61.54
	Low Risk	14.35	15.38	15.16	23.08
Case 3b - a=0,10	High Risk	17.83	23.08	21.72	23.08
	Unsure	67.83	61.54	63.11	53.85
	Low Risk	14.35	15.38	15.16	23.08
Case 4	High Risk	4.78	12.5	6.15	12.5
	Unsure	95.22	87.5	93.85	87.5
	Low Risk	0	0	0	0

Table 7 presents an illustrative comparison between Case 1 and Case 2. In Case 1 the analysis relies on injury-related crashes to identify crash hotspots and rank the network while in Case 2 all crash types are used for the same purpose. The findings indicate the relying of different crash types affects the identification of crash hotspots and the safety ranking, too. Section 11 is found as “High Risk” across all cases and directions of traffic. Section 12 is found as “Low Risk” in Direction “T” in both Cases 1 and 2. In other sections, there is no correspondence between “High Risk” and “Low Risk” sections across Cases 1 and 2.

Table 7: *Comparison of the outcomes of Case 1 and Case 2.*

Direction "T"			Direction "E"		
Length (km)	Case 1 - Injury Crashes	Case 2 - All Crashes	Length (km)	Case 1 - Injury Crashes	Case 2 - All Crashes
	Ranking	Ranking		Ranking	Ranking
3.0	Unsure	Unsure	1.4	High Risk	Unsure
3.6	Unsure	Unsure	2.6	Low Risk	Unsure
5.4	Unsure	Unsure	5.8	Unsure	High Risk
2.4	Unsure	Unsure	1.8	Low Risk	Unsure
3.4	High Risk	Low Risk	5.0	Unsure	Unsure
4.0	Low Risk	Unsure	2.4	Unsure	Unsure
3.0	Unsure	Unsure	3.0	Low Risk	Unsure
4.2	Unsure	Unsure	2.4	Unsure	Unsure
5.2	Unsure	Unsure	4.0	Unsure	Unsure
4.4	Unsure	Unsure	5.4	Unsure	High Risk
3.4	High Risk	High Risk	3.8	High Risk	High Risk
2.6	Low Risk	Low Risk	5.0	Unsure	High Risk
1.4	High Risk	Unsure	6.2	Unsure	Unsure

In Case 2, in Direction "E" there are no "Low Risk" sections while four sections are found as "High Risk" and so, in Case 2 this direction of traffic is found quite unsafe. The visualization of the crash distribution per section and per direction of traffic assists in understanding why there is a difference in the safety ranking between Case 1 and Case 2. Figure 3 presents the crashes per section for Case 1 while Figure 4 presents the same information for Case 2.

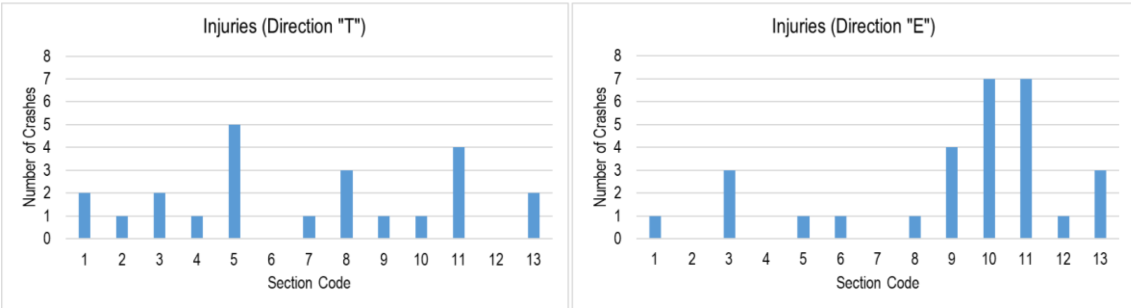

Figure 3: *Crash distribution per section (Case 1).*

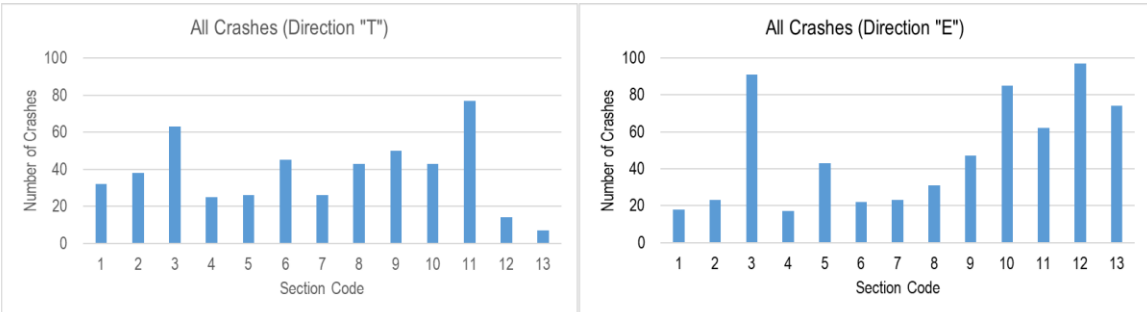

Figure 4: *Crash distribution per section (Case 2).*

Overall, the differences between Case 1 and Case 2 stand as an indication that injury-related hotspots do not necessarily align with hotspots that include crashes of all severity levels (injury-related and property damage-only).

From Table 8 it can be seen that for the specific implementation of the methodology, the impact of alpha parameter in the Poisson method is very small. Essentially, only one or two sections are affected per direction of traffic across the different cases.

Table 8: *Comparison of the outcomes of Case 1 and Case 3.*

Direction "T"				Direction "E"			
Length (km)	Case 1 Poisson method: alpha = 0,05	Case 3 Poisson method: alpha = 0,01	Case 3 Poisson method: alpha = 0,10	Length (km)	Case 1 Poisson method: alpha = 0,05	Case 3 Poisson method: alpha = 0,01	Case 3 Poisson method: alpha = 0,10
	Ranking	Ranking	Ranking		Ranking	Ranking	Ranking
3.0	Unsure	Unsure	Unsure	1.4	High Risk	High Risk	High Risk
3.6	Unsure	Unsure	Unsure	2.6	Low Risk	Low Risk	Low Risk
5.4	Unsure	Unsure	Unsure	5.8	Unsure	Unsure	Unsure
2.4	Unsure	Unsure	Unsure	1.8	Low Risk	Low Risk	Low Risk
3.4	High Risk	High Risk	High Risk	5.0	Unsure	Unsure	Unsure
4.0	Low Risk	Low Risk	Low Risk	2.4	Unsure	Unsure	Unsure
3.0	Unsure	Unsure	Unsure	3.0	Low Risk	Low Risk	Low Risk
4.2	Unsure	Unsure	Unsure	2.4	Unsure	Unsure	Unsure
5.2	Unsure	Unsure	Unsure	4.0	Unsure	Unsure	Unsure
4.4	Unsure	Unsure	Unsure	5.4	Unsure	Unsure	High Risk
3.4	High Risk	Unsure	High Risk	3.8	High Risk	High Risk	High Risk
2.6	Low Risk	Low Risk	Low Risk	5.0	Unsure	Unsure	Unsure
1.4	High Risk	High Risk	High Risk	6.2	Unsure	Unsure	Unsure

The final comparison concerns Case 1 and Case 4. In Case 4 the segmentation approach is simplified and so, it allows for larger sections to be formed. This influences both "Low Risk" and "High Risk" sections in the following ways. In Olympia Odos motorway, the great majority of "Low Risk" sections in the previous cases happened to be those sections that had zero crashes. By extending the section length, the "zero-crash" sections were eliminated as they included parts of the road with crashes. This along with the reference population characteristics led to the creation of more "Unsure" sections (compared to Case 1). By extending the section length, "High Risk" sections are affected too, as length is incorporated in the denominator of crash density and crash rate and lowers these values for each section.

5. Conclusions

Research conclusions that can be drawn from the methodological analysis are as follows:

1. The applied methodology results in road sections being classified as "low risk" (i.e. statistically significant result below the estimated threshold), "high risk" (i.e. statistically significant result above the estimated threshold), or "unsure" (i.e. not statistically significant result). In all tested variations (as well as in most methodologies based on recorded crash data), a considerable percentage of the analyzed road network, is characterized as "unsure". For these sections, useful insights for road safety can be gained only through the application of proactive microscopic road safety analysis.
2. As expected, the change of the alpha parameter of the Poisson distribution used in the statistical analysis impacts on the classification of sections, with a lower alpha indicating a greater degree of certainty in the classification, thus resulting in more "Unsure" results.

However, the choice of alpha parameter is not a critical factor for the classification, as only one or two sections are affected per direction of traffic across the different cases.

3. A further comment that can be drawn from this analysis is that injury crash hotspots do not necessarily align with hotspots that include crashes of all severity levels (injury-related and property damage-only).
4. Finally, interesting conclusions can be drawn with regard to the segmentation method: In Case 4 the segmentation approach is simplified and so, it allows for larger sections to be formed. This influences both “Low Risk” and “High Risk” sections in the following ways: In Olympia Odos motorway, the great majority of “Low Risk” sections in the previous cases happened to be those sections that had zero crashes. By extending the section length, the “zero-crash” sections were eliminated as they included parts of the road with crashes. This along with the reference population characteristics led to the classification of more sections as "Unsure" (compared to Case 1). By extending the section length, “High Risk” sections are affected too, as length is incorporated in the denominator of crash density and crash rate and lowers these values for each section.

Overall it can be concluded that although the examined variations of the crash hotspots identification methodology lead to some variation in the segments classified as "High Risk", the results do not differ dramatically, the most prominent hazardous sections are identified in all variations and the methodology is appropriate for efficient identification of hazardous segments, provided of course that historic crash data of adequate quality, quantity (i.e. number of years) and accuracy (i.e. location of crash) are available.

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