Heliyon 10 (2024) e28391

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Systematic review, evaluation and comparison of different approaches for the implementation of road network safety analysis

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A R T I C L E I N F O

Keywords:
Road network safety analysis
Network-wide road safety assessment
Network safety ranking
Road safety
Road infrastructure management

A B S T R A C T

Introduction: Road safety is still a major issue all around the world. The capability to analyze the road network and identify high risk sections is crucial in road safety management. Therefore, it is essential for road administrations, practitioners, and researcher to have a clear and practical framework of the available road network safety analysis procedures. The aim of this study is to provide such a framework by carrying out an exhaustive analysis of the main procedures available all around the world.
Method: The proposed literature review has started considering a web search on Web of Science (WoS). Then, a systematic review of each publication has been carried out using the Bibliometrix software, to identify the main characteristics of the publications within the specific topic. Then, the most relevant and widespread safety analysis procedures have been considered and the following aspects have been analyzed: the type of approach (crash analysis, crash prediction models procedures, based on road safety inspections, etc.), which and how many data are required (crashes, traffic, visual inspections, geometrical data, etc.), which is the effectiveness of the procedure, and which are the segmentation criteria used (fixed length, variable length based on geometry, traffic, etc.).
Results: Ten different procedures for road network safety analysis have been considered for detailed analysis. The research findings highlight that each procedure has its own pros and cons.
Conclusions: The choice of the best procedure to use is highly related to the characteristics of the road network that need to be analyzed, to the availability of data, and to the main elements the Road Authorities (RA) wants to give priority to.
Practical applications: This collection and review of different procedures will be of great interest for RAs, practitioners, and researchers in the process of selecting the most useful procedure to use to carry out a road network safety analysis.

1. Introduction

Road safety analysis is a process that allows to investigate the level of safety of a specific road or road network. Road safety analysis can be of different nature and can be carried out following different processes. Consequently, road safety analysis may differ and may be called by different names. For example, network screening (NS) is a process that considers a statistical analysis of the crashes

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https://doi.org/10.1016/j.heliyon.2024.e28391
Received 27 September 2023; Received in revised form 8 March 2024; Accepted 18 March 2024
Available online 30 March 2024
2405-8440/

occurred in a specific road section, into a whole road, or into a road network. It considers both the number of crashes and their characteristics. Elvik [1] describes the NS objective as "*to identify road sections that have safety problems – either in the form of an abnormally high number of accidents, a high share of severe accidents or a high share of a particular type of accident*". Such type of analysis, which considers the occurred number of crashes, is defined as "reactive approach", which means an approach that reacts to something already happened (i.e., crashes). On the other hand, since the first years of the 21st century, another approach has spread across the world, which can be defined as a "proactive approach". This type of approach aims at identifying hazardous locations before crashes occur. Proactive road safety analysis are, for example, Road Safety Inspections (RSIs). The definition of RSI given by Elvik [1] is "*road safety inspection is a systematic assessment of the safety of an existing road. Road safety inspections are […] applied to a road that has already been constructed and open to traffic for some time. The aim is to identify problem features which are not yet apparent from the accident history, or new problems introduced by engineering changes to the road or by modifications in the way it is used*". RSIs are generally carried out through visual investigation of the road and the outcomes of the inspections (e. g., identification of hazardous location or the network safety ranking) are made by the road safety inspector. Based on the RSI procedure chosen, the degree of subjectivity of the judgment may vary, but overall, RSIs are always affected by subjectivity. Another approach to road safety analysis, which overcomes the subjectivity issue, and standardizes and fastens their implementation, is based on Crash Prediction Models (CPMs, or Accidents Prediction Models, APMs). A CPM is used to link the number of expected crashes of a site to its specific geometric, cross-sectional, and environmental characteristics. CPMs are usually developed based on statistical analysis [2]. The geometric, cross-sectional, and environmental characteristics of the road may be included in a database that will be used to apply the CPM. The drawbacks of CPMs are mainly two: (I) the statistical analysis is carried out with data of only specific characteristics and this may cause to neglect relevant peculiarities of specific sites, and (II) they are developed considering data of a specific country, but the influence of some factors may vary from a country to another, reducing the transferability of the model. In the last decade some other procedures have been developed to carry out road safety analysis. Some of them try to bring together the efficiency of the CPMs and the higher level of details of the standard RSI. One example is the iRAP methodology [3,4] and the Australian National Risk Assessment Model "ANRAM" [5].

All the approaches that have been mentioned, differ in many elements: they can be reactive or proactive, they may be based on visual inspections or not, they may have different segmentation criteria, they may analyze different factors, and they may consider different approach for the analysis (e.g., statistical and visual analysis).

Moreover, with the update of the directive 2008/96/EC [6], the European Commission (EC) asks all member states to carry out a Network-Wide Road Safety Assessment (NWRSA), which must be based on: (I) "*primarly, a visual examination, either on site or by electronic means, of the design characteristics of the road (in-built safety)*", and (II) "*an analysis of sections of the road network which have been in operation for more than three years and upon which a large number of serious accidents in proportion to the traffic flow have occurred*". This implies that this new procedure required by the EC must include a safety analysis based on crashes (e.g., NS), and an analysis based on visual inspection and evaluation of the in-built safety (e.g., RSIs and APMs).

For all these reasons, it has been decided to investigate the characteristics of the main road network safety analysis used all around the world with an emphasis on the most innovative ones. This has been done starting with a massive search on a scientific search engine and a bibliometric analysis of the results. Bibliometric analysis has gained wide popularity in recent years because, as highlighted by Donthu et al., "*it is useful for deciphering and mapping the cumulative scientific knowledge and evolutionary nuances [..] by making sense of large volumes of unstructured data in rigorous ways*" [7].

The proposed literature review has started considering a web search on Web of Science (WoS) and Scopus. Then, a first manual screening of the items founded has been carried out in order to be sure that only the documents were considered that are relevant to the topic described above. Then, a systematic review of each publication has been carried out using the Bibliometrix software [8]. Such a review allows to identify the main characteristics of the publications, mainly considering emerging topics and identifying the most discussed and widespread type of safety analysis, following the approach used by Scarano et al. [9]. Finally, the most relevant and widespread safety analysis procedures have been considered and their characteristics analyzed in detail.

The objective of this paper is to provide an exhaustive review of approaches aiming at analyzing road safety at a network level. Moreover, this paper provides researchers, technicians, and practitioners with information about the different procedures (the data required to carry out the procedures, the effectiveness of the procedure, and the main segmentation criteria used, etc.) that will support them in the selection of the most appropriate procedure for their specific application.

2. Method

Considering the worldwide availability of hundreds of thousands of papers, it is essential to carry out a first massive search of papers that have a high possibility of addressing the topic of interest. Many scientific literature search engines are available online, like Scopus (https://www.scopus.com) or Web of Science (WoS, http://www.webofknowledge.com). In this literature review a first online massive search has been carried out on WoS and Scopus search engines, followed by a bibliometric analysis of the data identified. The bibliometric analysis provides a macroscopic overview of research literature throughout a statistical analysis of some relevant papers data (such as keywords, references, titles, publication frequency, etc.). Such analysis may highlight the trends in the investigated field and identifies papers which has been of reference for a wide range of researchers (and, talking about road safety analysis, also practitioners). However, even if a massive search on online search engines is an instrument that fastens the identification of relevant documents, sometimes other relevant documents may be missed. This happens for many reasons. Two of them are, for example, because some documents are not scientifically referenced (technical reports are an example), or because some search criteria are missing, or the search filters are too much and force the exclusion of some documents. For this reason, it has been decided to include in the analysis and discussion of the different procedures also some documents that have been considered of interest by the authors of this paper, which were not included in the massive search results. Those documents, together with some of the most cited, consistent, and innovative papers coming from the bibliometric analysis, have been deeply analyzed. The main characteristics of those procedures are then described and compared to each others, highlighting the main characteristics of each one. Fig. 1 shows a conceptual scheme of the adopted methodological approach. The following paragraph provide the description of each of the step implemented.

2.1. Massive literature search with the online search engine

To ensure the validity of the review process, it is essential that the considered publications (journals, reports, conferences proceedings, books, and book series) are of high quality. WoS and Scopus have been chosen to carry out the massive search due to their wide database.

The search criteria must address the scope of the research, that is to identify road network safety analysis procedures that can be of interest for the implementation of the European directive [6].

The search for this study was conducted on November 30th, 2023 considering the following search criteria.

2.1.1. WOS

1 year published: 2014–2023;
2 title: road safety analysis OR road safety inspection OR road network OR road safety assessment OR road safety evaluation OR road safety estimation;
3 language: English;
4 document type: article, book, book chapter, discussion, proceedings paper, review;
5 authors' keywords: "road network" OR "highway administration" OR "network analysis" OR "road safety" OR "risk assessment" OR "accident prevention"
6 Limit to: Transportation Science Technology or Transportation or Engineering Civil or Engineering Multidisciplinary (Web of Science Categories)

2.1.2. SCOPUS

7 year published: 2014–2023;
8 title: {road safety analysis} OR {road safety inspection} OR {road network} OR {road safety assessment} OR {road safety evaluation} OR {road safety estimation};
9 language: English;
10 document type: article, book chapter, review paper, conference paper;
11 Keywords: {road network} OR {highway administration} OR {network analysis} OR {road safety} OR {risk assessment} OR {accident prevention}
12 Subject area: engineering

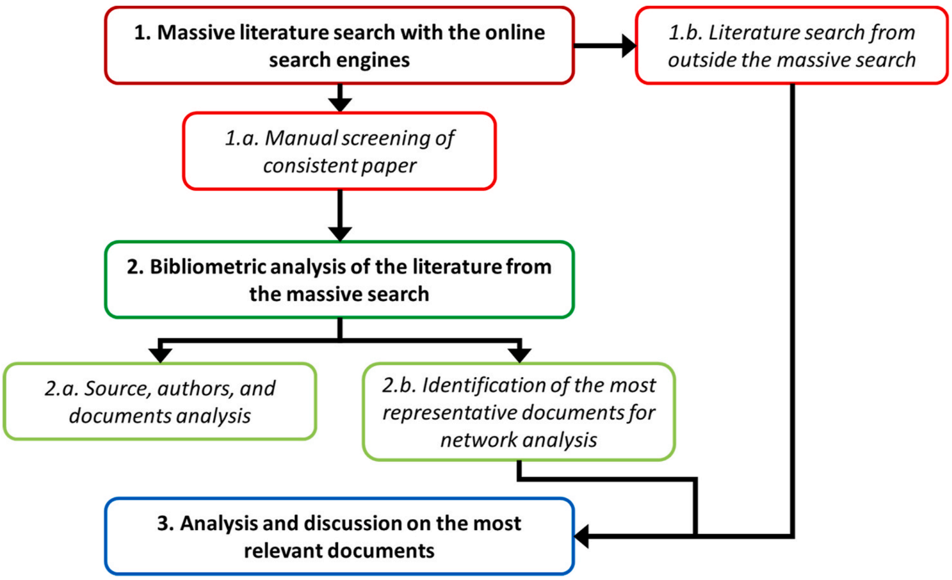

Fig. 1. Methodological approach scheme.

In both the considered search engines the Boolean operator "OR" is used to find records that contain either one of the concepts defined in the search. All the six listed criteria must occur simultaneously, thus the Boolean operator "AND" has been used to contain them in a single search code.

332 documents have been identified with WoS and 499 with Scopus, for a total of 831 documents. The results from the massive search were carefully analyzed and the papers that were not relevant with the topic of road safety (i.e., occurrence of road crashes) were excluded. This has been done by the authors by looking at the title, at the authors' keywords and, if necessary, at the abstract. Excluded papers include, for example, safety risk related to anomalous event, such as floods or earthquakes. Such a procedure was made manually, because the inclusion of other keywords in the filters during the massive search could cause the exclusion of consistent papers. Moreover, double results have been canceled (which are obtained because the paper is present both in the WoS and Scopus databases).

2.2. Bibliometric analysis of literature from the massive search

The considered bibliometric review is carried out through the use of the Biblioshiny software [8] and it covers three different level metrics: sources and interest, authors, and documents, as suggested in many other bibliometric analysis [7,9–11].

The source and interest level, represents an analysis of the publishing journals and a trend of the topic. The number of paper published by a specific journal about the topic of interest, will highlight if the journal effectively deals with such topic and/or is chosen by authors to publish papers of the relevant topic (i.e., road safety analysis).

The author's analysis is useful to identify the authors who have been the most productive in the topic of interest, to investigate the evolution of their research and to identify experts in the field. This will also include authors affiliations.

The documents level metric considers how much it is cited. As defined by Garfield [12], the citation count measures the utility rather than the importance or impact of a document. However, these two characteristics are highly related because a highly cited document indirectly provide a measure also of the scientific importance of a work: even if it has low scientific relevance, it will assume a high relevance because of its use, and will influence another research consequently. Thus, the number of citations is a parameter that, even if not crucial to prove the quality of a document, should be considered as an index of its effectivness.

2.3. Analysis and discussion of the most relevant documents

The last part of this study provides a specific analysis and discussion of the most relevant and innovative documents found. It must be clarified that definition of "relevant documents" reflects the point of view of the authors of this paper. This means that, even if the bibliometric analysis provides objective results, they are not always consistent with the topic of interest or may not consider some specific aspects that must be accounted for, or some relevant paper may have been excluded from the results because of some limitations on the search parameters from the massive search. For this reason, authors manually included also other documents they know from their experience, or they found in a different way from that of the massive search. Once all the documents have been defined, a specific analysis has been carried out considering the following aspects of the road network safety assessments procedures proposed in

Table 1
Statistics on the main information of the documents found with the massive search.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2014:2023
Sources (Journals, Books, etc)	105
Documents	164
Annual Growth Rate %	8.59
Document Average Age	3.96
Average citations per doc	11.52
References	6292
DOCUMENT CONTENTS	
Keywords Plus (ID)	710
Author's Keywords (DE)	569
AUTHORS	
Authors	466
Authors of single-authored docs	11
AUTHORS COLLABORATION	
Single-authored docs	11
Co-Authors per Doc	3.4
International co-authorships %	17.68
DOCUMENT TYPES	
article	108
article; proceedings paper	2
conference paper	16
proceedings paper	32
review	6

each relevant document.

- main data required (crashes, traffic, visual inspections, geometrical data, etc.)
- effectiveness of the procedure (considering the results presented in the analyzed studies);
- main segmentation criteria (fixed length, variable length based on geometry, traffic, etc.).

Such type of analysis will help researcher, technicians, and practitioners to identify the procedure that most comply with their scopes. Finally, a discussion of the main characteristics of the relevant documents will be provided.

3. Results

3.1. Bibliometric analysis of the massive search results

A total of 831 documents have been identified from the massive search on WoS and Scopus. After a careful reading of each title, keywords and, if necessary, abstracts, a total of 164 documents have been found to be relevant with the considered topic. Those documents are related to road safety analysis that considers causing factors, consequences, surrogate measures, etc., related to crashes. Documents that consider other types of risk but are still related to roads and safety (e.g., safety risk due to floods or earthquakes), are excluded, together with those documents that do not deal with safety but are related to road network (e.g., how to identify the geometry of a road network from GIS information). Review documents are included at this stage, because even if they do not provide any procedure to implement a road network safety assessment, they help to identify the interest trend, the major source for the topic, and influencing authors. An overview of the main characteristics and information of the identified documents are provided in Table 1.

These results have been then analyzed with the Biblioshiny software, to highlight the trend and the statistics concerning three different metrics: sources and interest, authors, and documents.

3.1.1. Source and interest analysis

Firstly, it may be useful to look at the trend over the last ten years. Fig. 2 shows the annual documents publication over the last ten years. Considering the 164 documents analyzed, a general increase in the number of published documents can be observed between 2018 and 2021, with a small reduction in 2022 and an increased production in 2023. This highlights an increased average interest in the topic by the scientific world during the last 6 years. It must be noted that the massive search has been done in the end of November 2023, thus it is not possible to know how many articles will be published within the end of 2023. An estimation of the number of possible articles production in 2023 has been made considering that for the whole 2023, the same production rate of the first eleven months will be present (because eleven months out of twelve have been considered, the number can be considered as representative of the expected 2023 production). Fare clic o toccare qui per immettere il testo.

The literature search highlights a total of 105 different sources, thus the average production in this topic is about 1.56 document in 10 years per source. Table 2 shows the list of the sources that had a production over the average production rate (that is, with at least 2 published documents matching the search criteria). In the same table the Scimago Journal Ranking index and the H-index are also provided for each journal. The SJR is an index that measures the degree of scientific influence of any academic journal; it considers the number of citations received from a journal and the relevance of the journals from which those citations come. The H-index (Hirsch index) is used to quantifying the scientific impact of an author (or journal). The H-index considersboth the number of citations received and the number of publications made by the author. This means that an author has a index of “n” if at least “n” of their published papers has been cited at least “n” times each. The same criteria are applied to journals ranking.

The source with the highest number of articles in this topic is Accident Analysis and Prevention (AAP), with 17 articles. AAP also shows a high H-index and a high SJR compared to other journals. Sources listed in Table 2 with at least 3 published documents, belong to the “Core Sources” Zone according to the Bradford’s Law [13].

Overall, it can be concluded that the topic is not an exclusive of a single journal. Authors published on many different sources.

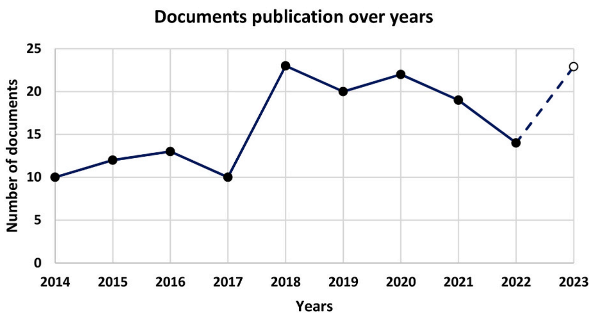

Fig. 2. Articles publication over the last 10 years.

Table 2
Most relevant sources (those with at least 2 articles).

Sources	Articles	SJR[a]	H_index[a]
ACCIDENT ANALYSIS AND PREVENTION	17	1.96	177
SAFETY	7	0.39	16
TRANSPORT RESEARCH ARENA TRA2016	6	–	–
IOP CONFERENCE SERIES: MATERIALS SCIENCE AND ENGINEERING	4	0.20	54
SAFETY SCIENCE	4	1.43	140
SUSTAINABILITY	4	0.66	136
INTERNATIONAL JOURNAL OF INJURY CONTROL AND SAFETY PROMOTION	3	0.58	43
KSCE JOURNAL OF CIVIL ENGINEERING	3	0.53	54
TRANSPORT MEANS 2018, PTS I-III	3	–	–
TRANSPORT POLICY	3	1.85	113
TRANSPORTATION RESEARCH RECORD	3	0.62	141
ADVANCES IN TRANSPORTATION STUDIES	2	0.19	19
APPLIED SCIENCES	2	0.49	101
BALTIC JOURNAL OF ROAD AND BRIDGE ENGINEERING	2	0.28	25
EUROPEAN TRANSPORT-TRASPORTI EUROPEI	2	0.25	23
IEEE ACCESS	2	0.93	204
IET INTELLIGENT TRANSPORT SYSTEMS	2	0.68	58
INTERNATIONAL CONFERENCE ON TRAFFIC AND TRANSPORT ENGINEERING	2	–	–
INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH	2	0.83	167
JOURNAL OF TRANSPORTATION SAFETY & SECURITY	2	0.72	26
NEURAL COMPUTING & APPLICATIONS	2	1.17	111
ROADS AND BRIDGES-DROGI I MOSTY	2	0.25	13
SCIENTIFIC JOURNAL OF SILESIAN UNIVERSITY OF TECHNOLOGY-SERIES TRANSPORT	2	0.17	7
SUSTAINABLE CIVIL INFRASTRUCTURES	2	0.14	10

[a] SJR= Scimago Journal Ranking. These data are taken from the Scimago Journal & Country Rank (https://www.scimagojr.com) and refers to December 01, 2023.

3.1.2. Authors analysis

The authors analysis comprehends both authors, affiliations, and countries. Table 3 shows the most relevant authors together with the produced articles, and the articles fractionalized coefficient. The number of articles and the local citations refer to the sample derived from the massive search procedure. The authors listed in Table 3 are those that have at least three articles. Fractional authorship quantifies an individual author's contribution to a published set of papers. The articles fractionalized coefficient, represents how much the author published and if they published alone or in group. The coefficient is the sum of the contribution to each paper, which is in turn, one divided by the number of authors.

Considering the production over countries, Table 4 shows the ten countries with the highest number of documents (eleven are shown because the last three has the same number). China confirms to be a leading country concerning road safety analysis, followed by Italy, Iran and Poland.

The results shown in Table 4 are graphically represented in Fig. 3: the darker the color blue, the higher the number of published

Table 3
Most relevant authors.

Authors	Articles	Articles Fractionalized
Carta M.	4	1.33
Fancello G.	4	1.33
Ganji Ss	4	1.50
Rassafi Aa	4	1.50
Zheng L.	4	1.25
Ren G.	4	1.17
Ambros J.	4	1.12
Fadda P.	3	1.00
Shen Yj	3	0.67
Sayed T.	3	0.92
Elvik R.	3	1.64
Borucka A.	3	1.33
Kiec M.	3	1.25
Grdinic-Rakonjac M.	3	1.00
Pajkovic V.	3	1.00
Li H.	3	0.92
Budzynski M.	3	0.83
Jamroz K.	3	0.83
Kustra W.	3	0.83
Cafiso S.	3	0.78
Pappalardo G.	3	0.78

Table 4
Most relevant countries.

Country	Articles
China	46
Italy	32
Iran	20
Poland	20
Canada	10
Spain	10
Australia	9
Usa	9
Belgium	7
India	7
Lithuania	7

documents. The grey indicates that no documents have been published in that country. Fig. 3 highlights that mainly high-income countries are interested in the topic, together with the main growing economy (China, India, and Brazil). In the same figures collaborating countries are linked with a colored line. The thickness of the line is proportional to the number of documents published together by the two linked countries.

3.1.3. Documents analysis

Documents analysis has been carried out considering at first the twenty most global cited (GC) documents. The documents are listed in Table 5 together with their authors, the document "type", a brief description of the contents of the document, their DOI, the publication year, and the number of global citations per year (GCY). The document "type" has been chosen to identify both the aim and the methodology adopted in the document, and it has been selected from the following.

- literature review: a literature review on a specific topic;
- data analysis and modelling: analysis of data considering statistics, correlation analysis, and other statistical approaches, and definition of models based on analyzed data;
- analysis based on Road Safety Inspections (RSI): road safety analysis that accounts for visual on-site inspections of the road.

The 20 most globally cited documents listed in Table 5 are split in 5 literature review documents, 14 data analysis and modelling documents, and 1 analysis based on RSI. The most two cited papers are both literature reviews, confirming the need, among researchers and practitioners, of papers providing a systematization of procedures and studies as this one.

However, not all the considered documents are strictly related to road safety analysis that accounts for road network risk assessments based on the analysis of road characteristics. For example, the interesting paper from Zheng et al. [15] considers surrogate safety measures to analyze the potential conflicts at four different signalized intersections in Canada. The specific focus on a single type of intersection is not in line with the concept of network risk assessment. Moreover, many papers are also reviews, which can be a

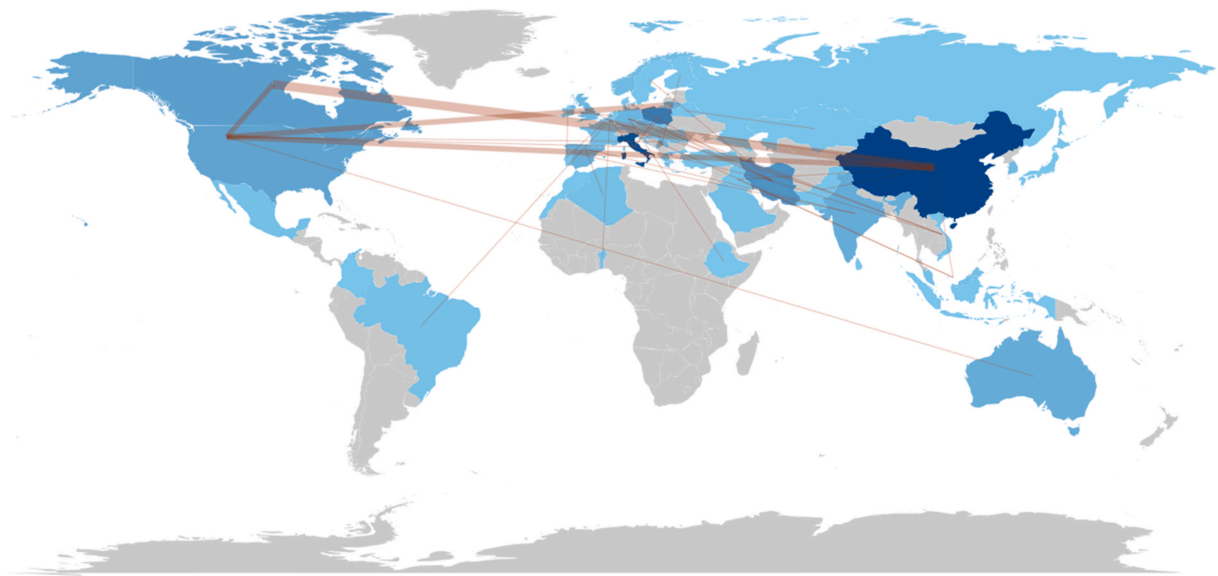

Fig. 3. Production and collaboration among different countries.

Table 5
The twenty most global cited documents.

Title	Type	Description	Reference	Year	GC	GCY
Modeling traffic conflicts for use in road safety analysis: A review of analytic methods and future directions	Literature Review	A comprehensive review of studies that use traffic conflicts indices in road safety analysis	[14]	2021	108	36
Visualization and analysis of mapping knowledge domain of road safety studies	Literature Review	Literature review on road safety studies	[10]	2018	173	28.3
Validating the bivariate extreme value modeling approach for road safety estimation with different traffic conflict indicators	Data analysis and modeling	Bivariate extreme value models that considers several conflict indicator combinations	[15]	2019	82	16.4
Road safety assessment and risks prioritization using an integrated SWARA and MARCOS approach under spherical fuzzy environment	Data analysis and modeling	Analysis and contribution of different risk factors to accidents occurrence (including driver, vehicle, road and environmental factors)	[16]	2022	15	15
Traffic conflict techniques for road safety analysis: open questions and some insights	Literature Review	Literature review on traffic conflict techniques	[17]	2014	149	14.9
Road safety research in the context of low- and middle-income countries: Macro-scale literature analyses, trends, knowledge gaps and challenges	Literature Review	Literature review on road safety with specific emphasis in LMIC literature.	[18]	2022	24	12
A Novel CRITIC-Fuzzy FUCOM-DEA-Fuzzy MARCOS Model for Safety Evaluation of Road Sections Based on Geometric Parameters of Road	Data analysis and modeling	Integrated model to predict possible accidents based on geometric and functional road parameters. Two-lane roads.	[19]	2020	46	11.5
Bivariate extreme value modeling for road safety estimation	Data analysis and modeling	Bivariate extreme value model for road safety analysis	[20]	2018	59	9.83
Road safety risk evaluation by means of improved entropy TOPSIS–RSR	Data analysis and modeling	Analysis of the “level of safety” of a province based on different factors ((including driver, vehicle, road and environmental factors)	[21]	2015	78	8.67
An integrated group best-worst method – Data envelopment analysis approach for evaluating road safety: A case of Iran	Data analysis and modeling	Analysis of network safety based on population and driving data (such as The average number of passenger along 100 km road)	[22]	2020	34	8.50
Road network safety evaluation using Bayesian hierarchical joint model	Data analysis and modeling	A Bayesian hierarchical joint model for road network safety analysis, considering some physical and functional road characteristics	[23]	2016	1	47
Deep neural network-based predictive modeling of road accidents	Data analysis and modeling	Deep neural networks (DNN) model for prediction of road accidents considering road geometrical and functional characteristics.	[24]	2020	27	6.75
The common road safety approaches: A scoping review and thematic analysis	Literature Review	Comparison of effective road safety approaches with those of relatively similar countries	[25]	2020	27	6.75
Propensity score methods for road safety evaluation: Practical suggestions from a simulation study	Data analysis and modeling	Propensity score (PS) method to evaluate the effectiveness of safety treatments.	[26]	2021	20	6.67
Large-scale automated proactive road safety analysis using video data	Data analysis and modeling	Implementation of an automated, video-based traffic-analysis system, for safety and behavior analysis	[27]	2015	58	6.44
A Comprehensive Approach Combining Regulatory Procedures and Accident Data Analysis for Road Safety Management Based on the European Directive 2019/1936/EC	Analysis based on Road Safety Inspections (RSI)	Study of mathematical models on the contribution of multiple infrastructure-related variables to accident occurrence	[28]	2021	18	6
Application of evidential reasoning approach and OWA operator weights in road safety evaluation considering the best and worst practice frontiers	Data analysis and modeling	Considerations and studies on data envelopment analysis (DEA)	[29]	2020	23	5.75
Estimating heterogeneous treatment effects in road safety analysis using generalized random forests	Data analysis and modeling	generalized random forests (GRF) method to evaluate the effectiveness of safety treatments.	[30]	2022	10	5
Road Safety Assessment under Uncertainty Using a Multi Attribute Decision Analysis Based on Dempster–Shafer Theory	Data analysis and modeling	Multi Attribute Decision Analysis (MADA) to implement road safety assessment	[31]	2018	29	4.83
Event-based road safety assessment: A novel approach towards risk microsimulation in roundabouts	Data analysis and modeling	Event-based microsimulation safety assessment for roundabouts using VISSIM	[32]	2020	19	4.75

useful source to find other methodologies, but do not provide any methodology by themselves [14].

Thus, in order to identify only high consistent documents, an analysis of all the 164 documents resulting from the first screening has been carried out. The selection has been made by the authors considering documents that are no review documents and that account for these specific aspects: crash analysis, or crash prediction models (using different model-ling approaches), or road safety analysis based on visual inspections, or procedures that combine two or more of the previous approaches. The procedures must be developed for application on a network level, and they must consider rural roads (motorways, primary roads, or secondary roads). Therefore, predictive models accounting only for too specific conditions are not considered (such as predictive models for rear-end crashes at signalized three-leg intersections), because even if they help to identify hazardous locations, they are too specific for network analysis. Moreover, to consider documents which have been found of utility by other researchers, those with at least 2 GC have been considered, with the exception of years 2021, 2022, and 2023. In this case, also those with 1 citation (2021) and those with 0 citations (2022 and 2023) have been considered because of the reduced time to be cited.

The results are shown in Table 6. Table 6 is organized as Table 5 except for the "Description" column, which has been removed. The description and discussion of the documents in Table 6 are presented in the following paragraph. A total of 35 papers have been identified.

In the list of papers in Table 6 there are many papers that develop CPMs with a statistical approach similar to those proposed by the worldly known Highway Safety Manual (HSM) [63,64]. Among those papers there are those from Wang et al. [33], Kustra et al. [50], Bonera et al. [52], Llopis-Castellò et al. [37], and many works from Ambros et al. [41,46,47,49,50,65,66].

The document with the highest number of GC is that from Wang et al. [33]. The method used in the paper is based on data analysis and modelling. The paper compares three different models (hierarchical joint model, joint model, NB model) to evaluate the risk of crashes accounting both for road characteristics (e.g., segment length), and for area characteristics (e.g., region). It suggests an interesting way to bring together both the macro level CMFs associated with the safety of a traffic zone [67] and micro level CMFs related to the safety of a road element [63].

Kustra et al. [50], propose a CPM based on the method described by Jamroz [68]. They consider very long sections from 10 to 50 km, which are homogeneous considering both the cross section and the average daily traffic. Geometrical, environmental, cross-sectional, and traffic data were all used in the model.

Bonera et al. [52] developed their own CPM based on the HSM approach but using the data from the Province of Brescia (Northern

Table 6
List of the documents that are most consistent with the topic of road network safety analysis, which has at list one citation.

Title	Reference	Year	GC
Road Network Safety Evaluation Using Bayesian Hierarchical Joint Model	[33]	2016	57
Road Safety Assessment Under Uncertainty Using a Multi Attribute Decision Analysis Based on Dempster-Shafer Theory	[34]	2018	28
Deep Neural Network-Based Predictive Modeling of Road Accidents	[24]	2020	27
Road Safety Risk Evaluation Using Gis-Based Data Envelopment Analysis-Artificial Neural Networks Approach	[35]	2017	23
A Decision Support System Based on Electre III for Safety Analysis in a Suburban Road Network	[36]	2014	21
New Consistency Model Based on Inertial Operating Speed Profiles for Road Safety Evaluation	[37]	2018	21
A Comprehensive Approach Combining Regulatory Procedures and Accident Data Analysis for Road Safety Management Based on the European Directive 2019/1936/EC	[38]	2021	18
Road Safety Evaluation Through Automatic Extraction of Road Horizontal Alignments from Mobile Lidar System and Inductive Reasoning Based on A Decision Tree	[39]	2018	15
A Decision Support System for Road Safety Analysis	[40]	2015	13
Identification of Hazardous Locations in Regional Road Network – Comparison of Reactive and Proactive Approaches	[41]	2016	13
Road Safety Analysis Using Multi Criteria Approach: A Case Study in India	[42]	2017	13
Safety Inspection and Management Tools for Low-Volume Road Network	[43]	2015	12
Using Low-Cost Smartphone Sensor Data for Locating Crash Risk Spots in A Road Network	[44]	2016	7
Dijkstra's-Dbscan: Fast, Accurate, And Routable Density Based Clustering of Traffic Incidents on Large Road Network	[45]	2018	6
Safety assessment of Czech motorways and national roads	[46]	2019	6
A Comparative Analysis of Identification of Hazardous Locations in Regional Rural Road Network	[47]	2014	5
A Comparison Between Prediction Power of Artificial Neural Networks and Multivariate Analysis in Road Safety Management	[48]	2015	5
How To Simplify Road Network Safety Screening?	[49]	2018	5
Injury Prediction Models for Onshore Road Network Development	[50]	2019	4
Modeling Conflict Risk with Real-Time Traffic Data for Road Safety Assessment: A Copula-Based Joint Approach	[51]	2022	4
Road Network Safety Screening of County Wide Road Network. The Case of The Province of Brescia (Northern Italy)	[52]	2022	4
Application of a Crash-predictive Risk Assessment Model to Prioritise Road Safety Investment in Australia	[53]	2016	3
Optimizing Road Safety Inspections on Rural Roads	[54]	2023	3
Road Safety Analysis of High-Risk Roads: Case Study in Baja California, México	[55]	2020	3
Road Safety Analysis on Achmad Yani Frontage Road Surabaya	[56]	2017	2
Application and Evaluation of a Non-Accident-Based Approach to Road Safety Analysis Based on Infrastructure-Related Human Factors	[57]	2022	1
Application of an Innovative Network Wide Road Safety Assessment Procedure Based on Human Factors	[58]	2022	1
A Proactive Decision Support Tool for Road Safety Audit of New Highway Projects Based on Crash Modification Factors and Analytical Analysis: Algeria as a Case Study	[59]	2023	0
Assessment Of the Transferability of European Road Safety Inspection Procedures and Risk Index Model to Egypt	[60]	2024[a]	0
Safety Risk Assessment of Low-Volume Road Segments on The Tibetan Plateau Using Uav Lidar Data	[61]	2023	0
Spatial Analysis of Road Traffic Accidents: Identifying Hotspots for Improved Road Safety In Addis Ababa, Ethiopia	[62]	2023	0

[a] the journal issue will be published in 2024, but the paper is available online since October 2023.

Italy). Only few significant variables were finally included in the model to obtain the crash frequency values. Based on those values risk maps have been produced.

Llopis-Castellò et al. [37], proposed a network analysis based on operating speed. The model was developed considering the difference between the inertial operating speed profile (V_i) and the operating speed profile (V_{85}). V_i represents drivers' expectations and it is calculated considering the speed held in the previous road segment; V_{85} is calculated considering the operating speed model from Marchionna & Perco [69]. A speed consistency parameter has been calculated accounting for the difference between V_i and V_{85} and the length of the segment. The higher the value of the consistency parameter, the higher the crash rate because it means that driver's expectations are violated. Expectations violations have been found to be an important crash contributing factors by many other studies [39,58,70,71] and the introduction of their influence in speed is an interesting topic that should be further investigated in future research. Antonio Martin-Jiménez et al. [39] proposed a procedure to reconstruct the road geometry. After the reconstruction, it considers some speed consistency parameters based on the Lamm criteria [72,73]. Another network safety assessment procedure based on speed is the procedure developed in Czech Republic [74] in the SAMO project. The method relies on speed prediction models. The procedure is divided into four steps: (1) road network segmentation into horizontal curves and tangents; (2) speed calculation from FCD (Floating Car Data); (3) estimation of speed using multivariate speed models; and (4) evaluation of speed consistency.

Ambros and their group focus their research on road network safety analysis, investigating also the use of crash prediction models both for motorways [46] and two-lanes two-ways rural roads [47,65]. The latter research underlines an interesting point that seems to be obvious, but it really isn't: road network safety analysis (and so NWRSA) are time consuming and resource consuming procedures that require to account for road and road furniture's characteristics (in a higher or lower number based on the procedure adopted), but to those characteristics that do not change over time (except after road modifications). Inspections for maintenance purposes are not part of the NWRSA. For this reason, the only variable that changes every year is traffic. Consequently, the most resource and time consuming activities of a NWRSA procedure (i.e., visual inspections) can be carried out after many years (it is not necessary a yearly update of the data). Ambro et al. focused also on the optimization of existing procedures, mainly on that proposed by HSM [63]. In one of their works [49] they investigate the possibilities of using a minor number of intersections belonging to the network as representative of all the intersections in the network. Such a procedure highly reduces the time required to collect all the necessary data. After implementing different road safety analysis procedures, Ambros et al. also investigate the difference between three different approaches [41]: (1) identification of black-spots, which is the traditional reactive accident-based approach; (2) accident prediction model with empirical Bayes, which allow to identify both real and potential black spots; (3) Proactive "preliminary" RSI. They concluded that traditional reactive accident-based approach does not perform always well, especially in low-volume road network with scattered accident occurrence. Instead, both RSIs and empirical Bayes approaches work well, and the application of one or another is recommended (by Ambros et al.).

Road safety analysis based on RSI have been considered also by Vaiana et al. [38], Cafiso et al. [43], Domenichini et al. [57], Erieba et al. [60], and Cantisani et al. [54]. Vaiana et al. compared the outcomes of an RSI carried out on a two-lanes two ways rural state road to the outcomes from crashes analysis. Based on this comparison they identified the most relevant road features for safety and developed five different models that allows to transform the qualitative analysis derived from RSIs to quantitative results. The most performing model is finally selected using Akaike's Information Criterion. Cafiso et al. considered the inclusion of RSI-based model in a road maintenance process. The road safety analysis procedure considered is better explained in a previous work from the authors [75]. In this work the authors calculated the quantitative Safety Index (SI) which allows for a network safety ranking, based on many different road features which contribute to the exposure of road users to road hazards, the probability of a vehicle being involved in a crash, and the resulting consequences of a crash. The SI is a very interesting approach that allows to deeply analyze the road and its features. The drawback of this procedure is that is highly time consuming. The same procedure has been applied by Erieba et al. [60] to 100 km of rural single carriageway roads in Egypt. Again, it shows great concordance with the expected crash frequency calculated with the HSM calibrated model [63]. Another interesting approach to road safety analysis based on RSI is that proposed from Domenichini et al. [57], which consider human factors as the main factors influencing the occurrence of a crash. Domenichini et al. investigated the PIARC approach to human factors analysis [76,77] comparing the outcomes of an analysis carried out with the PIARC Human Factors Evaluation Tool (HFET) to the observed crashes occurred in a five years period on two regional two-lanes two-ways rural roads. The same research was then carried forward and deepened in the works from Paliotto [78] and Paliotto et al. [58,79]. The research highlighted the relationship between human factors-related road deficiencies and road crashes and the effectiveness of the proposed procedure. However, as most of the RSI-based approaches, this procedure is also time consuming. Cantisani et al. [54] proposed a methodology to improve currently used inspection procedures and let them be applicable also to secondary and local rural roads. They found a good consistency between the observed accident index (accident rate) and the outcomes from the inspection form. Visual inspections are also at the core of the research from Rassafi et al. [34] and Kanuganti et al. [42]. The former authors proposed a methodology to put together the different ratings of a road stretch proposed both by experts and by road users. The judgements are put together through the use of an Evidential Reasoning (ER) approach, which belongs to the multi-criteria analysis approaches. Kanuganti et al. [42] consider three different multi-criteria decision making analysis tools and compare their results: Simple Additive Weightage (SAW), Analytical Hierarchy Process (AHP) and Fuzzy AHP methods. The multi-criteria analysis are based on ratings from experts of some infrastructural properties (e.g., sight distance, presence of a sharp curve, shoulder width, drainage provision). The second most global cited document in Table 6 also belongs to the multi-criteria analysis groups, and it is from Fancello et al. [36]. The proposed model applies to motorway and aims at ranking different motorway segments based on multicriteria analysis using the Electre III model. The model builds a concordance matrix which provides different weights for the considered parameters. A second paper from Fancello et al. illustrates another part of the same research [40].

Zhang et al. [61] propose a methodology based on the reconstruction of road geometry from LiDAR and assignment of rating based on geometrical parameters. The rating concurred to generate a risk index. Natural disasters and environment characteristics are also considered.

Another interesting approach that starts from the concept of statistical inference, like CPMs, but differently from statistical approaches are based on neural networks, are those from Singh et al. [24], Shah et al. [35], De Luca [48]. Singh et al. [24] use a DNN model for prediction of road crashes, considering different road features. The research from Shah et al. [35] provides a two-stage framework consisting of data envelopment analysis DEA in combination with artificial neural networks ANNs, considering road features. The study from De Luca [48] shows the results of prediction road accidents comparing Multi-Variate Analysis technique (MVA) and ANN technique. De Luca stated that comparing the two models, ANN is better than MVA because it has a lower total residual, although MVA perform better to identify the most dangerous black spots.

The work from Jurewicz et al. [53] illustrates a very interesting procedure that tries to synthesize two different approaches: CPMs and iRAP approach [80]. The paper shows how the Australian National Risk Assessment Model (ANRAM) works. ANRAM is used by the road administrations to predict the possibility of future severe crashes across the road networks. The method relies on the Star Rating Score outcome and locally developed accident prediction models. A report is also available where the procedure is widely described [5]. Another procedure based on iRAP is that from Oulha et al. [59]. The methodology adopted consists of combining a multiple linear regression method with the International Road Assessment Program (iRAP).

Montoya-Alcaraz et al. [55] considers a semi-qualitative approach. The procedure considers pavement surface condition data, geometric design performances, analysis of traffic signals, and road safety devices, and compares the deficiencies of one or more of the cited aspects to the road crashes history.

The work from Aichinger et al. [44], shows an alternative approach considering the use of data from smartphones. Using a speed-dependent threshold, they collected data about situations of near-miss accidents. The threshold is calculated considering quantile regression (QR) model, the euroFOT threshold, and a parametrized weight function to incorporate the available information about the driver. A spatial clustering technique is than applied to identify potential high-risk locations. Similar research is proposed by Hu et al. [51] and Stipancic et al. [81]. The study from Hu et al. [51] proposes to associate conflict frequency and severity with short-term traffic characteristics. A severity index (SeI) is proposed considering the time-to-collision (TTC). The method used in the paper from Stipancic et al. [81] is based on data analysis and modelling. The proposed research is innovative because it investigates the possibilities of using GPS-derived surrogate safety measures (SSMs) as predictive variables of crash frequency and severity in urban environment. The GPS-derived SSMs are taken from smartphones. The network is divided between intersections and links. The model validation shows diverging results: link level model has a poor prediction capability, while intersection level model perform better.A similar approach is considered also by Orsini et al. [82], which investigates the risk of different road sections analyzing SSMs like TTC using the Extreme Value Theory (EVT). However, the paper investigates only the possible occurrence of motorway rear-end collisions. SSMs studies demonstrated an increasing research interest in the last years, as demonstrated also by the review article from Nikolaou et al. [83].

Finally, it can be observed that only four works are based only on crash analysis (e.g., black spots identifications) and three of them belongs to low-income countries. The work from Machsus et al. [56], uses the crash rate in order to identify hazardous locations, while Zhang et al. [45] propose a new algorithm to cluster together spatially closer crashes located on linked segments of the road. Berhanu et al. [62] also provide an example of standard crash data analysis based on crash rate, crash types and crash severity.

The limited interest in the last ten years on procedures that accounts only for crashes, highlights that overall, an integrated approach based not only on crashes is now currently preferred. Mainly because tools are necessary, which are able to identify hazardous locations even where crash data are not available.

3.2. Documents outside the massive search

Some additional documents that have not been included in the list of the documents resulting from the massive search must be considered in our literature review. These documents are of interest for the research on the road network safety analysis field, because of their innovation, their diffusion, or their approach. These documents are hence listed: the American HSM [63,64], the iRAP procedure [4], the Network Wide Road Safety Assessment - Methodology and Implementation Handbook [84], and the crash prediction model from PRACT [85]. The HSM and PRACT provide CPMs based on safety performance functions and crash modification factors. PRACT models are developed on European countries implementing the HSM approach. iRAP (International Road Assessment Program) approach to road safety safety assessment is the Star Rating (SR), which reflects the risk related to an individual road user. 1-Star roads have the highest risk and 5-Star roads the lowest risk. SR can be produced without detailed crash data and refer to road features that should be catalogued based on visual analysis carried out in person (like RSI) or through the use of fast automatic devices (such as mobile mapping vehicles). HSM and iRAP procedure has been developed before the period of analysis considered in this paper, however are two procedures largely used all around the world. For this reason it is essential to include also them in the analysis. The methodology developed by the research group commissioned by the European Commission [84] focuses exactly in developing a NWRSA procedure based on the requirements from the European Directive on road safety [6]. Thus, it proposes a two level analysis: one based on the evaluation of in-built safety through considering some road features that mainly influence crash occurrence, and one based on accident analysis. The data needed to carry out the in-built safety analysis depends on the road type. Some of those data are: lanes width and number, roadside composition, curvature, accesses density, conflict points, shoulders type and width, signs and markings.

4. Discussions

Among the reviewed documents, it has been decided to focus the attention on those listed in Table 7, which have been found to be more representative of the four main different approaches illustrated in the introduction of this paper and which are of interest considering the implementation of the NWRSA request by the European directive [6]. These approaches are: crash analysis approach (CA), crash prediction models (CPM) approach, RSI-based approach, and a hybrid approach between the last two (CPM/RSI). The hybrid approach implements models that are not derived directly from statistical models; moreover, the hybrid approaches results are often not in the form of the expected number of crashes, but in the form of a safety index/parameter. In addition, also the multi-criteria/qualitative approach (MCQ) and those papers that include the use of new technologies (NT) have been considered. Procedures accounting only for standard crash analysis without any kind of innovation have not be included in Table 7. If different papers among those listed in Table 6 propose similar procedures, they have been grouped together and listed in the "Reference" column of Table 7, and the main representative has been considered in the detailed analysis.

All those papers listed in column "Reference paper" of Table 7, are deeply analyzed in the next section, starting with a general discussion on the different types of approach.

4.1. Type of approach

4.1.1. Crash analysis

Approaches relying on crash data are recommended when the data are both accessible, available and reliable, as crashes can offer valuable insights about road safety issues. However, visual safety inspections offer the possibility to identify some peculiarities of the site, and better understand which can be the causes of crashes. Crash data often fail to comprehensively identify all contributing factors

Table 7
Documents considered for discussion.

Reference paper	References	Approach Type	Main focus	Outputs	Apply to
Highway Safety Manual	[63,64,85] and papers that propose procedures that are very close to HSM ([46,47,49,50,52])	CA CPM	Main road geometrical and functional features	Crash frequency (all severity expected crashes)	All road types
Safety Index for Evaluation of Two-Lane Rural Highways	[43,60,75]	CPM/RSI	Main road geometrical and functional features	Numerical index	Primary undivided roads Secondary undivided roads
Network Wide Road Safety Assessment - Methodology and Implementation Handbook	[84]	CA CPM/RSI	Main road geometrical and functional features	Safety levels	Motorways Primary divided roads Primary undivided roads
A Decision Support System Based on Electre III for Safety Analysis in a Suburban Road Network	[36,40]	MCQ CA	Road traffic and crashes	Numerical index	Motorways
iRAP procedure	[4,59,80]	CPM/RSI	Main road geometrical and functional features	Safety levels	All road types
Application of a Crash-predictive Risk Assessment Model to Prioritise Road Safety Investment in Australia	[5,53]	Crash analysis CPM/RSI	Main road geometrical and functional features	Crash frequency (severe expected crashes) Safety levels	All road types
New Consistency Model Based on Inertial Operating Speed Profiles for Road Safety Evaluation	[37]	CPM	Operating Speed	Crash frequency (fatal predicted crashes)	Primary undivided roads Secondary undivided roads
Application of an Innovative Network Wide Road Safety Assessment Procedure Based on Human Factors	[57,58]	RSI	Human Factors	Safety levels	Primary undivided roads Secondary undivided roads
Using Low-Cost Smartphone Sensor Data for Locating Crash Risk Spots in A Road Network	[44,51]	NT	Surrogate Safety Measures	Number of potential conflicts at specific location	All roads (not specified the road environment)
Road Safety Risk Evaluation Using GIS-Based Data Envelopment Analysis —Artificial Neural Networks Approach	[24,35,48]	CA NT	Artificial Neural Networks (ANN)	Numerical index	Motorway
Safety Risk Assessment of Low-Volume Road Segments on The Tibetan Plateau Using Uav Lidar Data	[39,61]	NT MCQ	Main road geometrical features and environmental characteristics	Numerical index	Secondary rural roads

to crashes. Additionally, crash data may encounter reliability issues that affect the analysis: possible false negative, that is a site with few crashes in the observed period can be instead a high risk location (and crashes will occur in the future); crashes are a stochastic parameter influenced by the phenomenon of regression to the mean (RTM); the relationship between traffic and crashes is not linear; and the frequent unavailability of crash data, particularly evident in Low- and Medium-Income Countries (LMICs). To mitigate some of these challenges associated with crash data, methods such as Crash Prediction Models (CPMs) with Empirical Bayes (EB) adjustments or data analysis utilizing Artificial Neural Networks (ANN) have been implemented.

4.1.2. Crash prediction models with Empirical Bayes (EB) adjustments

CPMs are developed analyzing the historical crash number and type occurring on similar road sites by means of statistical procedures. These models relate the geometric and environmental characteristics of the road to the number of crashes expected on that road [2]. Elvik provided an exhaustive description of CPMs [1]. CPMs are a potent tool for assessing the safety level of roads but their considerable reliability is accompanied by the need for a substantial amount of available data and reliable models. In some cases, a straightforward calibration procedure like the one outlined in the Highway Safety Manual (HSM) may not be sufficient, and the use of specific Safety Performance Functions (SPFs) becomes necessary, especially when the baseline conditions significantly diverge from standard conditions [86–88]. Gross et al. [89] and Bonneson et al. [90] highlighted that the same countermeasure leads to different effects if applied in different regions, highlighting once more the importance of specific site conditions. Furthermore, CPMs can only partially address the issues related to the perception of the road, because most of time they do not account for the environment where the road develops. Empirical Bayes help to reduce this gap, because they allow to consider both the predicted crashes from the model and the observed crashes from the reality. However, in order to use Empirical Bayes methodologies, crash data must be available. Some CPMs consider also the use of Crash Modification Factors (CMF), like the HSM from AASHTO [63]. A CMF is a multiplicative factor used to compute the predicted number of crashes after implementing a given countermeasure at a specific site. Many studies are present about CMFs. While sometimes the influence of a CMF is confirmed in different studies, sometimes the results clearly diverge based on the specific characteristics of a site.

Finally, it must be highlighted that defining which factors influence the occurrence of crashes is a difficult task [91]. Moreover, as underlined by Schlögl & Stütz [92], while issues related to methodological approaches have been subject to a wide discussion, and effective models have been developed, uncertainties regarding data quality are still to be solved. For this reason, RSI may be a crucial support to NWRSA procedures.

4.1.3. Road safety inspections

PIARC defines RSI as "*a systematic, on-site review, conducted by road safety expert(s), on an existing road or section of road to identify hazardous conditions, faults and deficiencies that may lead to serious crashes*" [93]. RSIs allow to deeply analyze a road segment, accounting for specific characteristics and peculiarities and combination of factors that may be hidden within a statistical analysis based only on some main data. On the opposite RSI have two main drawbacks: they are subjective because they relay on the experience of the auditor, and they are time consuming. The latter issue causes that often RSI are used to carry out specific analysis of location that have been found to be hazardous during an NS. RSI are most of time complementary to NS procedures based on crashes analysis or CPMs, because an on-field analysis is always useful to identify the factors influencing crash occurrence. For this reason, RSI are often used not as an instrument to carry out road network safety analysis, but an instrument to deeply investigate risky location, defined as "risky" on the basis of previous NS or CPMs analysis.

4.1.4. Approaches based on new technologies

New technologies are of great interest for road safety. The review carried out highlights that new technologies can be applied at different stage of safety analysis procedures and with different scopes. One possibility is to use them as an alternative to CPMs. Deep learning and machine learning techniques based on ANNs can provide additional models for crash predictions. Furthermore, new technologies and their diffusion can help to obtaining a large number of important data that can be used to identify dangerous location. This is the case of surrogate safety measures observed by smartphones data or floating car data, as also highlighted in the study from Stipancic et al. [81], and in the two interesting literature review papers made by Grimberg et al. [94] and Eskandari Torbaghan et al. [95]. Finally, new technologies can be used to carry out in an easier way already existing procedures based both on RSI or on CMPS that account for road geometrical features that are easily measurable by radar/LiDAR instruments [96–98].

4.1.5. Parameters considered

Road agencies and practitioners involved in network safety analysis must consider three main parameters to choose the best procedure to adopt: effectiveness, data availability, and resources (mainly time). While the last parameter cannot be effectively commented and discussed without applying all the proposed procedures to the same road network (or at least stretch), it is instead possible to provide information on the data required to correctly apply the different procedures, and their effectiveness. This last parameter is given on the basis of the results presented in the documents listed in Table 7. Finally, an overview of the criteria adopted for the segmentation are provided. Indeed, segmentation is always a crucial and not trivial issue in order to define a road network safety analysis [99,100].

4.1.6. Resources

As stated before, it is not possible to effectively discuss the difference among the procedures concerning resources and time required to carry out the procedure without applying all the proposed procedures to the same road network (or at least road section). However,

Table 8
Quantity of required data.

#	Document Title	Crash data	Traffic Data	Geometrical Data	Cross-sectional data	Margins dangerousness	Environment composition	Functional Data	Signs and markings	Conflict points	Intersections and interchanges	Pavement conditions
1	Highway Safety Manual	M	M	M	M	M		F		F	M	
2	Safety Index for Evaluation of Two-Lane Rural Highways		M	M	M	F		M	M	F		F
3	Network Wide Road Safety Assessment - Methodology and Implementation Handbook	M	M	F	M	M		F	F	F	F	
4	A Decision Support System Based on Electre III for Safety Analysis in a Suburban Road Network	M	M		F							
5	iRAP procedure		M	M	M	M	F	M	F	M	M	M
6	Application of a Crash-predictive Risk Assessment Model to Prioritise Road Safety Investment in Australia	M	M	M	M	M	F	M	M	F	M	M
7	New Consistency Model Based on Inertial Operating Speed Profiles for Road Safety Evaluation		F	M								
8	Application of an Innovative Network Wide Road Safety Assessment Procedure Based on Human Factors			F	F		M	F	F	M	F	
9	Using Low-Cost Smartphone Sensor Data for Locating Crash Risk Spots in A Road Network							M				
10	Road Safety Risk Evaluation Using GIS-Based Data Envelopment Analysis —Artificial Neural Networks Approach	F	M	F				F				
11	Safety Risk Assessment of Low-Volume Road Segments on The Tibetan Plateau Using Uav Lidar Data			F	F		F					

the following considerations can be made: (a) some procedures are quite fast to be applied once the database has been prepared (e.g., HSM, iRAP and ANRAM methodologies, ANN), however the construction of a well-built database with all the data required is not a trivial task and it is often the most time-consuming activity; consequently, it may happen that (b) RSI procedures that do not require too many detailed data (for examples they do not require the exact geometry and cross section data) may be most easy to be implemented when detailed data are not available.

4.1.7. Data required

The data required by each procedure are listed in Table 8. Because some data are very specific and some procedures need a very wide set of data, data have been grouped into different categories and for each category it will be stated if the procedure require few (F = few or with low level of detail) or many data of that category (M = many or with high level of detail). If no data of the specific group are needed, the cell is left empty. The group of data considered are the following: crash data, traffic data (e.g., AADT, percentage of heavy good vehicles, peak hour traffic), geometrical data (both planimetric and altimetric data), cross-sectional data (e.g., number of lanes, lanes and shoulders width), margins dangerousness (e.g., dangerous terminals and transitions, trees, clearzones), environment composition (e.g., layout of road margins, field of view composition, land use), functional data (e.g., operating speed, environmental speed, speed limits, surrogate safety measures, visibility), signs and markings (including VMS), conflict points (e.g., driveways/accesses, bus stops, pedestrian crossings, work zones), intersections and interchanges (e.g., presence, intersection types and layout, intersections elements) and pavement conditions. Moreover, some procedures need different data with reference to the road type considered. Table 8 shows the list of data required by each procedure considering each group.

To quantitatively evaluate the amount of data for each procedure, it has been decided to assign a weight of 1 to all "F" votes and a weight of 2 to all the "M" votes. Substituting the votes and adding the results for each document, the results are those presented in Fig. 4. The graph shows that the most data-requiring procedure is the Australian ANRAM (6), which is based on iRAP procedure (5) that is the second most data-demanding procedure. These two procedures need data concerning all the categories groups identified. (1), (2) and (3) are following. Among those three procedures it can be observed that no or only few data about the environment composition and the pavement conditions are necessary. Moreover, procedure (2) doesn't require crash data. Crash data are also not required by (5), (7), (8), (9), (11). Procedure (8) needs data from many different categories but it needs a low number of them or with a low level of detail. Finally, procedure (9) needs very few data, but they are very specific data that are not easy to be found (data from smartphones).

Similarly, it is possible to understand which type of data are the most required, as shown in Fig. 5. Traffic data are the most required, followed by geometrical data (planimetric and altimetric), cross-sectional data (cross-section composition), and functional data. However, often functional data are required with a low level of detail. Environment composition and pavement conditions are the less required data. Crash data, when required, are required with a high level of detail (at least position, year, severity, and number of vehicles involved).

The results from Fig. 5 also provide an overview of the data which indirectly are considered more relevant for road safety.

4.1.8. Procedures effectiveness

The effectiveness of each procedure can be evaluated based only on the results presented in the analyzed documents or other documents which apply to the same procedures. As a matter of fact, many researches are presented, investigated, or analyzed under different points of view, in more documents, not only one. For this reason, when necessary, it has been searched on the web for other documents applying or analyzing the procedure as the one presented in each document listed in Table 7.

The Highway Safety Manual has proven to be a reliable instrument if applied on USA roads and mainly on motorways or roads with very simple and homogeneous sections. However, its transferability to other countries has been demonstrated to be not easy and it requires additional actions to adapt the model to specific countries [2,86–88,101–104]. A wide literature is present on HSM and its transferability. An example is PRACT project [105]. HSM accounts for many road features (the main ones) but cannot account for all road features or specific situations (like all other methodologies that do not rely on visual inspections of the site where the inspector has a certain flexibility on what to look at). Moreover, sometimes it can be hard to schematize a road with the geometric data required for the application of the HSM procedure.

The Safety Index (SI) for the Evaluation of Two-Lane Rural Highways [75] has been demonstrated to be an effective instrument. The authors highlighted that the correlation between SI values and EB safety estimates is highly significant ($t = 9.64$, p-value <0.001), with 77% of the variation in the estimated number of crashes explained by the SI value. Moreover, the results from the Spearman's rank correlation analysis provide further validation for the SI, indicating that the ranking from the SI and the EB estimate agree at the 99.9% level of significance with a correlation coefficient of 0.87.

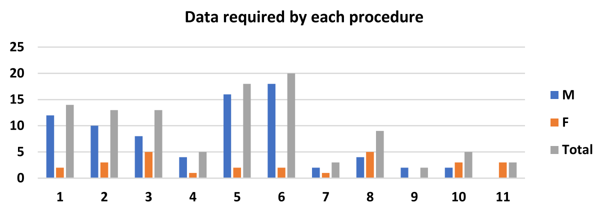

Fig. 4. Data required by each procedure counting "M" votes as double the value of "F" votes.

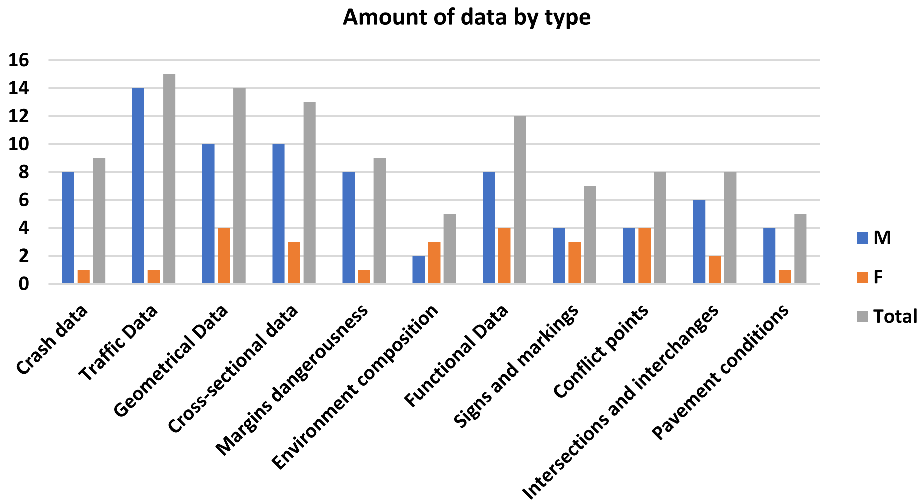

Fig. 5. Amount of data required by data type counting “M” votes as double the value of “F” votes.

The Network Wide Road Safety Assessment methodology [84] has been tested on a motorway segment and primary road segment in Greece. The results prove the robustness of the procedure, however it cannot be compared to actual level of road safety based on crashes, because it includes itself accidents. Other scientific reviews of this methodology are not present because of its recent publication.

The procedure from Fancello et al. [36] also includes crash data so a comparison between its results and crash data is not significant. However, authors stated that sensitivity analyses showed that the obtained ranking has proven to be a stable solution when varying the weights of the criteria without significant changes.

The comparison of the iRAP procedure to crash data received quite low interest in the scientific world considering to the worldwide diffusion of such a procedure. A report from iRAP concerning the comparison between crash rates and star ratings (SRs) has been published in 2011 [106]. The report shows a relationship between crash rate and SR, and therefore the iRAP procedure could be an effective procedure to identify road safety level. However, the same report underlines that sometimes the results are discordant and that the relationship between crash rate and SR is not always clear. Moreover, iRAP has been widely improved in the last decade, thus some updated comparison between crash rate and SR is desirable. However, the iRAP methodology is a procedure widely used around the world that demonstrated its reliability many times considering experts opinions [107,108].

The paper from Jurewicz and Excel [53] showed how the ANRAM hybrid risk assessment and crash prediction methodology is applied to estimate individual and collective severe crash risk. ANRAM methodology incorporates the Star Rating assessment method (with all its qualities and drawbacks) and accident risk estimations. Because of the incorporation of crash data through an EB procedure (like that used by HSM), the effectiveness of ANRAM methodology can be evaluated mainly comparing the predicted number of crashes (which are obtained before the application of the EB procedure) to the observed number of crashes. No specific studies have been found on this, but some information can be derived from the works of Jurewicz et al. [5,53]. Looking at the results from the cited works, the correspondence between observed and predicted crashes is moderate. This highlights once more that considering models developed from statistical analysis of data from a specific region/country, does not assure a good prediction for other sites with different characteristics.

The innovative model based on operating speed consistency proposed by Llopis-Castellò et al. [37] is a model developed to evaluate the consistency of a road, which also provides the predicted number of crashes. Thus, it can be easily applied also during a NWRSA. The methodology has been derived and then tested, on a set of 71 homogeneous two-lane rural road segments, with a total length of approximately 550 km. The coefficient of determination of the linear model considered to evaluate the effectiveness of the methodology, was 60%. CURE plots were also considered, which show good results. However, the test has been carried out on the data used for its development. Application on different road segments is suggested to confirm the validity of the model.

The procedure proposed by Paliotto et al. [58,78,79] and Domenichini et al. [57] has been developed based on the PIARC approach [77], modified to be suitable for application to NWRSA. Human factors are crucial factors in crash occurrence. The procedure refers to human factors that are “standard” and common to all human beings (and so it does not consider difference in gender, age, or altered status of the driver, such as alcohol, stress, and similar). It provides 4 different level of safety. The procedure is based on RSI, and it has been developed from the PIARC Human Factors Evaluation Tool [77]. It has been tested on several two-lanes two-ways rural roads for a total length of approximately 80 km. The validation of the procedure has been carried out comparing the risk level obtained from the procedure to that obtained from the crash analysis (the accident rate index has been considered), using both Freeman-Halton extension of Fisher’s test with contingency table, and the Kendall’s W. The results have shown an overall concordance of 56%. Kendall’s W was 0.78.

The procedure from Aichinger et al. [44] combines the well-established euroFOT [109,110] threshold for critical driving situations with a speed-dependent driving-style-adaptive threshold able to reflect individual differences between drivers (and even vehicles). The study does not provide a validation of the procedure effectiveness, which is postponed to successive works. It must be underlined that other studies accounting for similar data, demonstrate the effectiveness of the approach, like that from Ryder et al. [111]. A similar research from Stipancic et al. [81] also considers SSMs. The ranked lists generated by the mixed multivariate model and the ranked lists based on crash data had a correlation of 0.47 for links (segments) and 0.63 for intersections. Still, the covariates chosen by the authors are able to explain 32% of the variation in crash cost for links and 45% of the variation for intersections. Thus, the model may be improved. Authors stated that additional validation using larger datasets is expected to improve the accuracy of the results, especially for low-volume sites.

The paper from Zhang et al. [61] does not provide any validation. The same for the paper from Shah et al. [35], which in addition, includes in the required data the crash data, therefore the results cannot be compared with crash indices (like crash frequency or crash rate).

4.2. Segmentation

As highlighted by several authors [99,100], segmentation is a crucial step in a network safety analysis. Segmentation allows to divide the network in shorter road elements which can be easily analyzed, and which generally have homogeneous characteristics (e.

Table 9
Summary of segmentation criteria.

#	Document Title	Different segmentation for analysis and results	Based on length (fixed length)	Homogeneous segments based on segment characteristics	Intersections as separated segment	Main parameters considered for homogeneous segments
1	Highway Safety Manual			X	x	All those required for the application of the procedure
2	Safety Index for Evaluation of Two-Lane Rural Highways			X	[d]	Geometric alignment, traffic volume
3	Network Wide Road Safety Assessment - Methodology and Implementation Handbook	x	x	X	X	Curvature[a], traffic volume[b], number of lanes[a,b], terrain type[b] and speed limit[b]
4	A Decision Support System Based on Electre III for Safety Analysis in a Suburban Road Network			X	X	All those required for the application of the procedure
5	Highway and Road Probabilistic Safety Assessment Based on Bayesian Network Models			X		All those required for the application of the procedure
6	iRAP procedure	x	Analysis	Results		Carriageway type, area type, not continuous consecutive segments, change in speed limit, section length
7	Application of a Crash-predictive Risk Assessment Model to Prioritise Road Safety Investment in Australia	x	Analysis	Analysis[c]/Results		Carriageway type, area type, not continuous consecutive segments, change in speed limit, section length
8	New Consistency Model Based on Inertial Operating Speed Profiles for Road Safety Evaluation			X		Traffic volume, cross-section variations, major intersections, and curvature change rate (CCR)[e]
9	Application of an Innovative Network Wide Road Safety Assessment Procedure Based on Human Factors	x	Results	Analysis		Road type, curvature change rate (CCR), perception of possible interaction (PPI)
10	Using Low-Cost Smartphone Sensor Data for Locating Crash Risk Spots in A Road Network					Spatial clustering (precise measure not defined). No segmentation of the network.
11	Road Safety Risk Evaluation Using GIS-Based Data Envelopment Analysis —Artificial Neural Networks Approach			X		Segmentation is up to the analyst (it seems to not influence the results)
12	Safety Risk Assessment of Low-Volume Road Segments on The Tibetan Plateau Using Uav Lidar Data			X		Segmentation is up to the analyst (it seems to not influence the results)

[a] considered for the reactive methodology.
[b] considered for the proactive methodology.
[c] these sections are considered for the crash prediction module.
[d] does not consider intersection.
[e] the segment must be proceeded by at least 600 m of road in both directions to apply the methodology.

g., the same lane width, the same traffic, etc.). Table 9 presents a summary of the main segmentation characteristics. For each procedure the following segmentation aspects are considered ("x" means that the specific aspect is considered).

a) Whether the procedure uses different segmentations within the analysis process and to provide the final results.
b) The segmentation is based on fixed length segments.
c) The segmentation is based on segment with homogeneous characteristics.
d) The intersections are considered in different segments as compared to road links.
e) If the segmentation is based on homogeneous segments, the list of the road characteristics considered is provided.

If two different types of segmentation (fixed length or homogeneous segments) are used during two different phases of application of the procedure (i.e., analysis and results), this is specified in the table cell.

It can be noted that three different procedures use different segmentation criteria during the analysis process. These procedures are iRAP (5), ANRAM (6), which is based on the iRAP procedure, and the Human Factors evaluation Procedure (HFEP) (8). iRAP and ANRAM use short segment of fixed length to carry out the analysis (100 m long) and then group them into homogenous segments (defined as sections) of longer variable length. The HFEP does the opposite: it considers homogeneous segments to carry out the analysis and then groups those segments into longer ones (defined as sections) of fixed length (about 1 km[1]). ANRAM allows also for crash prediction. The crash prediction module applies to the sections (longer) and not to the segment of 100 m (shorter). The NWRSA methodology (3) is divided into two parts: reactive methodology, which considers the number of crashes, and proactive methodology, which considers the road in-built safety. In both cases it allows for different segmentation criteria: it may be based on fixed length, or on homogeneous segments. However, homogeneous segments are defined with different criteria for each methodology, as shown in Table 9. The outcomes from the two methodologies are combined considering another different segmentation for the results, which is simply to set a segment limit where a limit from one of the two previous segmentations is present. Finally, the Consistency Model Based on Inertial Operating Speed Profiles (7) calculates V_i considering the previous 600 m of road, thus the considered segments must be preceded at least by 600 m of road in both directions.

It must be highlighted also the role of intersections. Intersections are very specific points of the road because in intersections many conflict points are present (depending on the intersection type). For this reason, many procedures analyze intersections as a separate element, different from a road link. Some others exclude them from the analysis (implicitly highlighting their difference from road segments), and some other include them in the analysis of roadway segments. In the first two groups, intersections influence the segmentation, while in the last they do not influence the segmentation, but they may still influence the segment evaluation, as shown in Table 8.

A very interesting results derive from the use of SSMs (10), that does not consider any information from the infrastructure neither from traffic. This allows to exclude the necessity of a segmentation (with all the possible issues listed above concerning the segmentation process).

The segmentation is not considered an influential factor also in the work from Shah et al. [35]. They took the segmentation from the work of Janssens et al. [112], who segmented the network considering traffic analysis (not road safety analysis). The same for the work of Zhang et al. [61], where they considered seventeen road segments without specifying the criteria the use for the selection.

Overall, it must be noted that different procedures consider different segmentation types, because segmentation is always strictly related to the procedure itself. Some procedures introduce a second segmentation to provide global results of the application of the procedure. This second segmentation usually considers longer segments or a combination of segments, which are called "sections". In this case, the use of the term segment or sections is clear, but many times the difference between the two terms is not defined.

5. Choice of the best procedure

This chapter proposes a practical flow chart to help RAs and practitioners choosing the most fitting procedure considering the RAs available resources. The flow chart in Fig. 6 should be used as a guide that is not exhaustive or mandatory, but that may help in the decision process. The flow chart proposes six different requirements concerning the amount and type of available data, interest of RA in having highly formed and trained personnel, objectives of the screening procedure and available time. The numbers in brackets refer to the number of the procedures as listed in Table 9. The flow chart is not continuous because it could have been too much complex to read. Instead, practitioners may answer each single question and look at the procedure's number that is present in all of the answers. Doing so, they will find out the most suitable procedure to use.

It can be observed that time consuming procedures are mainly those that comprise RSIs. However, it must be also noted that data collection for these procedures is mainly done during the inspections. Thus, few data are required before the implementation of the procedure. If a RA wants to implement a procedure that require many data and it is not based on RSI, a large amount of time should be spent in data collection.

[1] The length of these sections is not completely fixed. Indeed, it must be around 1 km, but it must integrate the entire lengths of the segments, thus sometimes sections can be shorter or longer than 1 km.

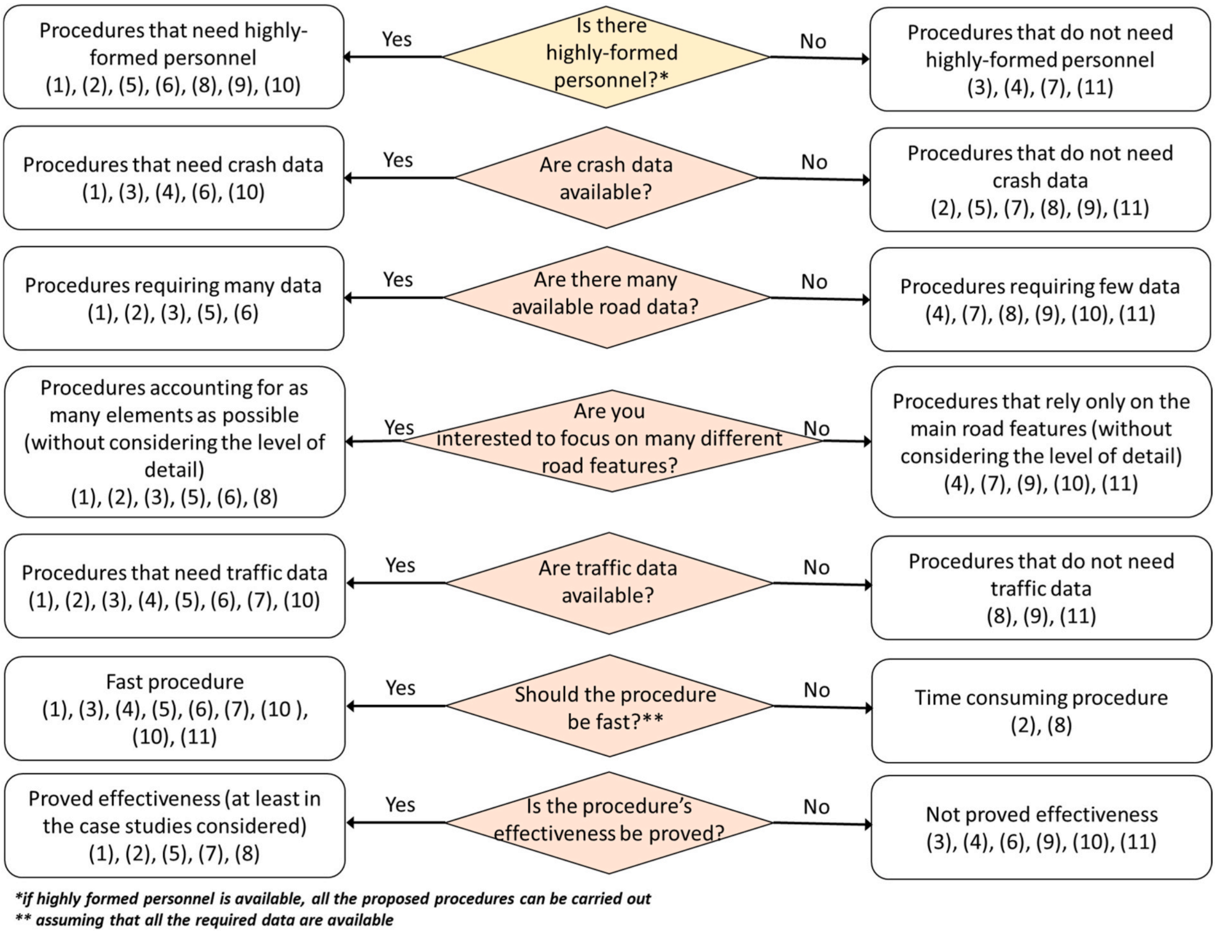

Fig. 6. Summary of the possible procedures choice based on the resources and scopes of the RA.

6. Conclusions

The aim of this literature review was to investigate which are the most innovative, common and/or used procedures to carry out road safety analysis, discussing their approach and their main characteristics, like required data, time for application, and effectiveness. Road safety analysis are processes that allow to investigate the level of safety of a specific road or road network. At first, it has been decided to carry out a massive search and a fast bibliometric analysis. The massive search has been carried out through the WoS database aiming at identifying as many as possible scientific documents dealing with road network safety analysis. A total of 237 documents resulted from the massive search and their bibliometric statics have been analyzed through the use of the Biblioshiny software. The bibliometric analysis aims at identifying the trends in this research field, the primary sources and the authors mostly involved in the topic, and which documents demonstrated to be the most relevant in the scientific world (considering the list of documents derived from the massive search). The results show that during the last years, the interest in the topic is higher. Accident Analysis and Prevention journal is the journal most involved in the topic with 17 articles, followed by Safety with 7 articles. The topic is considered mainly in high-income countries with very few countries in South America and Africa. Among the analyzed documents those from Zou et al. [10] and from Zheng et al. [14] are those with the highest number of global citations (respectively 173 and 108). However, both these papers, like many others, are literature review papers. Using massive search procedures on search engines like WoS and Scopus, demonstrated to greatly help the research, however, some drawbacks are present. Many documents of interest related to the topic may be left outside of the list because they are not present in the search engine (inn this case WoS or Scopus), or they do not fit for some reasons the searching criteria adopted. For this reason, all the documents included in the bibliometrix analysis have been evaluated and those really relevant for the topic and which include innovative approaches for road network safety analysis, have been considered together with other documents outside the list from the literature search. These additional documents have been included considering the experience of the authors. Thus, a total of 11 documents have been deeply analyzed and their main characteristics have been listed and discussed considering three aspects: data required, procedure effectiveness, and segmentation criteria. The results have shown that different procedures require different types and amount of data. The data needed by a procedure may guide the choice of road administrations (RAs). Procedure effectiveness evaluation have been based on the results claimed by the authors of the analyzed documents and considering other studies about the same procedure (when available). Each procedure has its own pros and cons, and it is not possible to clearly state if one procedure is better than another in an absolute way. The choice of the best procedure to use is inevitably related to the characteristics of the road network that need to be analyzed, to the availability of data, and to the main elements the RA wants to give priority to. This literature review may provide a great help to all those RAs that wants to implement a road network safety analysis and to researcher aiming at improving or developing new procedure for road network safety analysis.

Further development of this research is of applying the considered methodology to a road stretch to better understand how they work, how long it takes for their application, and compare the results to understand if they are able to identify the same critical sections of a road, or not. Once this has been clarified, a step forward in this field should be the definition of a framework to instruct RAs and practitioners on when and why to use different procedures, how they can be used together when complementary, and investigates the possibility to incorporate some specific aspects of a procedure into other.

8. Statements

PRISMA 2020 considerations: the present review is composed by both a systematic review part, and a review article part. Moreover, as stated in the paper, many aspects concerning road safety evaluations and analysis can be hardly compared only looking at literature and without applying the specific procedure on the same site. For these reasons, it must be considered that some items from the PRISMA 2020 cannot be applied to this paper and the paper itself does not want to be a full systematic review and meta-analysis paper. The items that are not considered at all or only partially addressed in the paper are (referring to the PRISMA 2020 checklist): 11, 12, 13c-e, 14, 15, 20c-d, and 21.

Moreover, it must be stated that: review was not registered (item 24a), protocol was not prepared (item 24b), no amendments are present for registration or protocol (item 24c), authors have no competing interest (item 26), the required data to carry out the review can be found considering the references, no specific database have been created (item 27).

Data availability

no data associated with this study has been deposited into a publicly available repository. The paper is a review paper, and the considered data are related to those contained in the analyzed papers. Thus, all data are referenced in the article to the related papers.

CRediT authorship contribution statement

Andrea Paliotto: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Monica Meocci:** Writing – review & editing, Supervision, Project administration, Formal analysis, Data curation. **Alessandro Terrosi:** Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis, Data curation. **Francesca La Torre:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7 List of recurring acronyms

AADT	Average Annual Daily Traffic
AAP	Accident Analysis and Prevention
ANRAM	Australian National Risk Assessment Model
BN	Bayesian Network
CA	Crash Analysis
CCR	Curvature Change Rate
CMF	Crash Modification Factor
CPM	Crash Prediction Models
CURE	CUmulative REsiduals
DOI	Digital Object Identifier
EB	Empirical Bayes
EC	European Committee
EVT	Extreme Value Theory
GC	Global Citation
GPS	Global Positioning System
HFEP	Human Factors Evaluation Procedure
HFET	Human Factors Evaluation Tool
HSM	Highway Safety Manual
IRAP	Internation Road Assessment Programme

(continued on next page)

(*continued*)

AADT	Average Annual Daily Traffic
MCQ	Multicriteria Qualitative
NS	Network Screening
NT	New Technologies
NWRSA	Network-Wide Road Safety Assessment
PIARC	World Road Association
PPI	Perception of Possible Interaction
QS	Quacquarelli Symonds
RA	Road Authorities
RSI	Road Safety Inspections
RTM	Regression To the Mean
SI	Safety Index
SJR	Scimago Journal Ranking
SPF	Safety Performance Function
SR	Star Rating
SSM	Surrogate Safety Measure
TTC	Time To Collision
USA	United States of America
VMS	Variable Message Sign

References

[1] R. Elvik, Assessment and Applicability of Road Safety Management Evaluation Tools: Current Practice and State-Of-The-Art in Europe, 2010, p. 349.
[2] G. Yannis, et al., Use of accident prediction models in road safety management - an international Inquiry, Transport. Res. Procedia (2016), https://doi.org/10.1016/j.trpro.2016.05.397.
[3] iRAP Methodology fact sheets - iRAP [Online]. Available: https://irap.org/methodology/.
[4] EuroRAP, Star Rating Roads for Safety, The EuroRAP methodology, 2009.
[5] C. Jurewicz, L. Steinmetz, B. Turner, M. Cammack, Australian National Risk Assessment Model, AP-R4vols. 51–14, Sydney NSW 2000 Australia: Austroads Ltd, Level 9, 287 Elizabeth Street, 2014 [Online]. Available: www.austroads.com.au.
[6] European Parliament and European Council, Directive 2008/96/CE of the European Parliament and of the Council of 19 November 2008 on Road Infrastructure Safety Management, Amended by Directive (EU) 2019/1936, 2019.
[7] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, W.M. Lim, How to conduct a bibliometric analysis: an overview and guidelines, J. Bus. Res. 133 (2021) 285–296, https://doi.org/10.1016/J.JBUSRES.2021.04.070. Sep.
[8] M. Aria, C. Cuccurullo, bibliometrix: an R-tool for comprehensive science mapping analysis, J Informetr 11 (4) (2017) 959–975, https://doi.org/10.1016/J.JOI.2017.08.007. Nov.
[9] A. Scarano, M. Aria, F. Mauriello, M.R. Riccardi, A. Montella, Systematic literature review of 10 years of cyclist safety research, Accid. Anal. Prev. 184 (May 2023), https://doi.org/10.1016/j.aap.2023.106996.
[10] X. Zou, W.L. Yue, H. Le Vu, Visualization and analysis of mapping knowledge domain of road safety studies, Accid. Anal. Prev. 118 (2018) 131–145, https://doi.org/10.1016/J.AAP.2018.06.010. Sep.
[11] A. Mirhashemi, S. Amirifar, A. Tavakoli Kashani, X. Zou, Macro-level literature analysis on pedestrian safety: bibliometric overview, conceptual frames, and trends, Accid. Anal. Prev. 174 (2022) 106720, https://doi.org/10.1016/J.AAP.2022.106720. Sep.
[12] E. Garfield, Is citation analysis a legitimate evaluation tool? Scientometrics 1 (4) (May 1979) 359–375, https://doi.org/10.1007/BF02019306/METRICS.
[13] S.C. Bradford, Sources of information on specific subjects, J. Inf. Sci. 10 (4) (1985) 173–180.
[14] L. Zheng, T. Sayed, F. Mannering, Modeling traffic conflicts for use in road safety analysis: a review of analytic methods and future directions, Anal Methods Accid Res 29 (2021) 100142, https://doi.org/10.1016/J.AMAR.2020.100142. Mar.
[15] L. Zheng, T. Sayed, M. Essa, Validating the bivariate extreme value modeling approach for road safety estimation with different traffic conflict indicators, Accid. Anal. Prev. 123 (2019) 314–323, https://doi.org/10.1016/J.AAP.2018.12.007. Feb.
[16] S. Jafarzadeh Ghoushchi, S. Shaffiee Haghshenas, A. Memarpour Ghiaci, G. Guido, A. Vitale, Road safety assessment and risks prioritization using an integrated SWARA and MARCOS approach under spherical fuzzy environment, Neural Comput. Appl. 35 (6) (2023) 4549–4567, https://doi.org/10.1007/S00521-022-07929-4/FIGURES/5. Feb.
[17] L. Zheng, K. Ismail, X. Meng, Traffic conflict techniques for road safety analysis: open questions and some insights 41 (7) (2014) 633–641, https://doi.org/10.1139/CJCE-2013-0558. *10.1139/cjce-2013-0558*.
[18] M. Haghani, A. Behnood, V. Dixit, O. Oviedo-Trespalacios, Road safety research in the context of low- and middle-income countries: macro-scale literature analyses, trends, knowledge gaps and challenges, Saf. Sci. 146 (2022) 105513, https://doi.org/10.1016/J.SSCI.2021.105513. Feb.
[19] J.M. Simić, Ž. Stević, E.K. Zavadskas, V. Bogdanović, M. Subotić, A. Mardani, A novel CRITIC-fuzzy FUCOM-DEA-fuzzy MARCOS model for safety evaluation of road sections based on geometric parameters of road, Symmetry 12 (2020) 2006, https://doi.org/10.3390/SYM12122006, vol. 12, no. 12, p. 2006, Dec. 2020.
[20] L. Zheng, K. Ismail, T. Sayed, T. Fatema, Bivariate extreme value modeling for road safety estimation, Accid. Anal. Prev. 120 (2018) 83–91, https://doi.org/10.1016/J.AAP.2018.08.004. Nov.
[21] F. Chen, J. Wang, Y. Deng, Road safety risk evaluation by means of improved entropy TOPSIS–RSR, Saf. Sci. 79 (2015) 39–54, https://doi.org/10.1016/J.SSCI.2015.05.006. Nov.
[22] H. Omrani, M. Amini, A. Alizadeh, An integrated group best-worst method – data envelopment analysis approach for evaluating road safety: a case of Iran, Measurement 152 (2020) 107330, https://doi.org/10.1016/J.MEASUREMENT.2019.107330. Feb.
[23] J. Wang, H. Huang, Road network safety evaluation using Bayesian hierarchical joint model, Accid. Anal. Prev. 90 (May 2016) 152–158, https://doi.org/10.1016/J.AAP.2016.02.018.
[24] G. Singh, M. Pal, Y. Yadav, T. Singla, Deep neural network-based predictive modeling of road accidents, Neural Comput. Appl. 32 (16) (2020) 12417–12426, https://doi.org/10.1007/S00521-019-04695-8/TABLES/7. Aug.
[25] H. Safarpour, D. Khorasani-Zavareh, R. Mohammadi, The common road safety approaches: a scoping review and thematic analysis, Chin. J. Traumatol. 23 (2) (2020) 113–121, https://doi.org/10.1016/J.CJTEE.2020.02.005. Apr.
[26] Y. Zhang, H. Li, N.N. Sze, G. Ren, Propensity score methods for road safety evaluation: practical suggestions from a simulation study, Accid. Anal. Prev. 158 (2021) 106200, https://doi.org/10.1016/J.AAP.2021.106200. Aug.
[27] P. St-Aubin, N. Saunier, L. Miranda-Moreno, Large-scale automated proactive road safety analysis using video data, Transp Res Part C Emerg Technol 58 (2015) 363–379, https://doi.org/10.1016/J.TRC.2015.04.007. Sep.

[28] R. Vaiana, G. Perri, T. Iuele, V. Gallelli, A comprehensive approach combining Regulatory procedures and accident data analysis for road safety management based on the European directive 2019/1936/EC, Saf. Now. 7 (2021) 6, https://doi.org/10.3390/SAFETY7010006, 7, no. 1, p. 6, Jan. 2021.
[29] S.S. Ganji, A.A. Rassafi, S.J. Bandari, Application of evidential reasoning approach and OWA operator weights in road safety evaluation considering the best and worst practice frontiers, Socioecon Plann Sci 69 (2020) 100706, https://doi.org/10.1016/J.SEPS.2019.04.003. Mar.
[30] Y. Zhang, H. Li, G. Ren, Estimating heterogeneous treatment effects in road safety analysis using generalized random forests, Accid. Anal. Prev. 165 (2022) 106507, https://doi.org/10.1016/J.AAP.2021.106507. Feb.
[31] A.A. Rassafi, S.S. Ganji, H. Pourkhani, Road safety assessment under uncertainty using a multi Attribute decision analysis based on Dempster–Shafer theory, KSCE J. Civ. Eng. 22 (8) (2018) 3137–3152, https://doi.org/10.1007/S12205-017-1854-5/METRICS. Aug.
[32] L.A. Bulla-Cruz, A. Laureshyn, L. Lyons, Event-based road safety assessment: a novel approach towards risk microsimulation in roundabouts, Measurement 165 (2020) 108192, https://doi.org/10.1016/J.MEASUREMENT.2020.108192. Dec.
[33] J. Wang, H. Huang, Road network safety evaluation using Bayesian hierarchical joint model, Accid. Anal. Prev. 90 (May 2016) 152–158, https://doi.org/10.1016/J.AAP.2016.02.018.
[34] A.A. Rassafi, S.S. Ganji, H. Pourkhani, Road safety assessment under uncertainty using a multi Attribute decision analysis based on Dempster–Shafer theory, KSCE J. Civ. Eng. 22 (8) (2018) 3137–3152, https://doi.org/10.1007/S12205-017-1854-5/METRICS. Aug.
[35] S.A.R. Shah, T. Brijs, N. Ahmad, A. Pirdavani, Y. Shen, M.A. Basheer, Road safety risk evaluation using GIS-based data envelopment analysis—artificial neural networks approach, Appl. Sci. 7 (2017) 886, https://doi.org/10.3390/APP7090886, vol. 7, no. 9, p. 886, Aug. 2017.
[36] G. Fancello, M. Carta, P. Fadda, A decision support System based on Electre III for safety analysis in a Suburban road network, Transport. Res. Procedia 3 (2014) 175–184, https://doi.org/10.1016/J.TRPRO.2014.10.103. Jan.
[37] D. Llopis-Castelló, F. Bella, F.J. Camacho-Torregrosa, A. García, New consistency model based on inertial operating speed profiles for road safety evaluation, J Transp Eng A Syst 144 (4) (2018) 04018006, https://doi.org/10.1061/JTEPBS.0000126. Apr.
[38] R. Vaiana, G. Perri, T. Iuele, V. Gallelli, A comprehensive approach combining Regulatory procedures and accident data analysis for road safety management based on the European directive 2019/1936/EC, Saf. Now. 7 (2021) 6, https://doi.org/10.3390/SAFETY7010006, 7, no. 1, p. 6, Jan. 2021.
[39] J. Antonio Martín-Jiménez, S. Zazo, J.J. Arranz Justel, P. Rodríguez-Gonzálvez, D. González-Aguilera, Road safety evaluation through automatic extraction of road horizontal alignments from Mobile LiDAR System and inductive reasoning based on a decision tree, ISPRS J. Photogrammetry Remote Sens. 146 (2018) 334–346, https://doi.org/10.1016/J.ISPRSJPRS.2018.10.004. Dec.
[40] G. Fancello, M. Carta, P. Fadda, A decision support System for road safety analysis, Transport. Res. Procedia 5 (2015) 201–210, https://doi.org/10.1016/J.TRPRO.2015.01.009. Jan.
[41] J. Ambros, P. Havránek, V. Valentová, Z. Křivánková, R. Striegler, Identification of hazardous locations in regional road network - comparison of reactive and proactive approaches, Transport. Res. Procedia 14 (April) (2016) 4209–4217, https://doi.org/10.1016/j.trpro.2016.05.392.
[42] S. Kanuganti, R. Agarwala, B. Dutta, P.N. Bhanegaonkar, A.P. Singh, A.K. Sarkar, Road safety analysis using multi criteria approach: a case study in India, Transport. Res. Procedia 25 (2017) 4649–4661, https://doi.org/10.1016/J.TRPRO.2017.05.299. Jan.
[43] S. Cafiso, A. Di Graziano, G. Pappalardo, *10.3141/2472-16*, Safety Inspection and Management Tools for Low-Volume Road Network 1 (2472) (2015) 134–141, https://doi.org/10.3141/2472-16. Jan.
[44] C. Aichinger, P. Nitsche, R. Stütz, M. Harnisch, Using low-cost smartphone sensor data for locating crash risk spots in a road network, Transport. Res. Procedia 14 (2016) 2015–2024, https://doi.org/10.1016/J.TRPRO.2016.05.169. Jan.
[45] Y. Zhang, L.D. Han, H. Kim, *10.1177/0361198118796071*, Dijkstra's-DBSCAN: Fast, Accurate, and Routable Density Based Clustering of Traffic Incidents on Large Road Network 2672 (45) (2018) 265–273, https://doi.org/10.1177/0361198118796071. Sep.
[46] J. Ambros, R. Turek, M. Brich, J. Kubeček, Safety assessment of Czech motorways and national roads, European Transport Research Review 11 (1) (2019) 1–15, https://doi.org/10.1186/S12544-018-0328-2/TABLES/5. Dec.
[47] V. Valentová, J. Ambros, Z. Janoška, A comparative analysis of identification of hazardous locations in regional rural road network, Advances in Transportation Studies an international Journal Section B 34 (2014) 57.
[48] M. De Luca, A comparison between prediction power of artificial neural networks and multivariate analysis in road safety management, Transport 32 (4) (2017) 379–385, https://doi.org/10.3846/16484142.2014.995702. Oct.
[49] J. Ambros, J. Sedoník, Z. Křivánková, How to simplify road network safety screening? Adv. Transport. Stud.: an international Journal Section B 44 (2018) 151.
[50] W. Kustra, J. Ukowska, M. Budzyński, K. Jamroz, Injury prediction models for Onshore road network development, Pol. Marit. Res. 26 (2) (2019) 93–103, https://doi.org/10.2478/POMR-2019-0029. Jun.
[51] Y. Hu, Y. Li, C. Yuan, H. Huang, Modeling conflict risk with real-time traffic data for road safety assessment: a copula-based joint approach, Transportation Safety and Environment 4 (3) (2022), https://doi.org/10.1093/TSE/TDAC017. Sep.
[52] M. Bonera, B. Barabino, G. Maternini, Road network safety screening of county wide road network. The case of the Province of Brescia (Northern Italy), Sustainable Civil Infrastructures (2022) 525–541, https://doi.org/10.1007/978-3-030-79801-7_38/FIGURES/3.
[53] C. Jurewicz, R. Excel, Application of a crash-predictive risk assessment model to Prioritise road safety Investment in Australia, Transport. Res. Procedia 14 (2016) 2101–2110, https://doi.org/10.1016/J.TRPRO.2016.05.225. Jan.
[54] G. Cantisani, C.C. Borrelli, G. Del Serrone, P. Peluso, Optimizing road safety inspections on rural roads, Infrastructures 8 (2023) 30, https://doi.org/10.3390/INFRASTRUCTURES8020030, 8, no. 2, p. 30, Feb. 2023.
[55] M. Montoya-Alcaraz, A. Mungaray-Moctezuma, J. Calderón-Ramírez, L. García, C. Martinez-Lazcano, Road safety analysis of high-risk roads: case study in Baja California, México, Saf. Now. 6 (2020) 45, https://doi.org/10.3390/SAFETY6040045, 6, no. 4, p. 45, Oct. 2020.
[56] I. Prayogo Machsus, Chomaedhi, D.W. Hayati, A. Utanaka, Road safety analysis on Achmad Yani frontage road Surabaya, IOP Conf. Ser. Mater. Sci. Eng. 267 (1) (2017) 012027, https://doi.org/10.1088/1757-899X/267/1/012027. Nov.
[57] L. Domenichini, A. Paliotto, M. Meocci, V. Branzi, Application and evaluation of a Non-accident-based approach to road safety analysis based on infrastructure-related human factors, Sustainability 14 (2) (May 2022) 662, https://doi.org/10.3390/su14020662.
[58] A. Paliotto, M. Meocci, V. Branzi, Application of an Innovative Network Wide Road Safety Assessment Procedure Based on Human Factors, Springer, Cham, 2022, pp. 493–510, https://doi.org/10.1007/978-3-030-79801-7_36.
[59] R. Oulha, A. Derras, A proactive decision support tool for road safety audit of new highway projects based on crash modification factors and analytical analysis: Algeria as a case study, Int J Inj Contr Saf Promot 30 (3) (2023) 455–469, https://doi.org/10.1080/17457300.2023.2210558.
[60] O. Erieba, G. Pappalardo, A. Hassan, D. Said, S. Cafiso, Assessment of the transferability of European road safety inspection procedures and risk index model to Egypt, Ain Shams Eng. J. 15 (3) (2024) 102502, https://doi.org/10.1016/J.ASEJ.2023.102502. Mar.
[61] Y. Zhang, X. Dou, H. Zhao, Y. Xue, J. Liang, Safety risk assessment of low-volume road segments on the Tibetan plateau using UAV LiDAR data, Sustainability 15 (2023) 11443, https://doi.org/10.3390/SU151411443, 15, no. 14, p. 11443, Jul. 2023.
[62] Y. Berhanu, D. Schroeder, B. Teklu, E. Alemayehu, Spatial analysis of road traffic accidents: identifying hotspots for improved road safety in Addis Ababa, Ethiopia, Cogent Eng 10 (2) (2023), https://doi.org/10.1080/23311916.2023.2269655. Dec.
[63] AASHTO, Highway Safety Manual, first ed., American Association of State Highway Transportation Professionals, 2010.
[64] AASHTO, Highway Safety Manual, Supplement 2014, American Association of State Highway and Transportation Officials, 2014.
[65] J. Ambros, V. Valentová, J. Sedoník, *10.3141/2583-01*, Developing Updatable Crash Prediction Model for Network Screening: Case Study of Czech Two-Lane Rural Road Segments 2583 (2016) 1–7, https://doi.org/10.3141/2583-01. Jan.
[66] P. Šenk, J. Ambros, P. Pokorný, R. Striegler, Use of accident prediction models in identifying hazardous road locations, Transactions on Transport Sciences 5 (4) (2012) 223–232, https://doi.org/10.2478/V10158-012-0025-0.
[67] A. Hadayeghi, A.S. Shalaby, B.N. Persaud, *10.3141/2019-27*, Safety Prediction Models (2019) (2007) 225–236, https://doi.org/10.3141/2019-27. Jan.
[68] K. Jamroz, Method of Risk Management in Highway Engineering, Gdansk University of Technology, Gdansk, 2011.
[69] A. Marchionna, P. Perco, Operating speed-profile prediction model for two-lane rural roads in the Italian context, Adv. Transport. Stud. 14 (14) (2008) 57–68.

[70] J. Theeuwes, Self-explaining roads: what does visual cognition tell us about designing safer roads? Cogn Res Princ Implic 6 (1) (2021) 15, https://doi.org/10.1186/S41235-021-00281-6.
[71] M. Green, Roadway Human Factors: from Science to Application, 2017.
[72] R. Lamm, B. Psarianos, S. Cafiso, Safety evaluation process for two-lane rural roads: a 10-year review, Transport. Res. Rec.: J. Transport. Res. Board 1796 (1) (May 2002) 51–59, https://doi.org/10.3141/1796-06.
[73] R. Lamm, A. Beck, T. Ruscher, T. Mailaender, S.D. Cafiso, G. Lacava, How to Make Two-Lane Rural Roads Safer: Scientific Background and Guide for Practical Application, undefined, 2006.
[74] J. Ambros, V. Valentová, O. Gogolín, R. Andrášik, J. Kubeček, M. Bíl, Improving the Self-explaining performance of Czech national roads, Transport. Res. Rec.: J. Transport. Res. Board 2635 (1) (2017) 62–70, https://doi.org/10.3141/2635-08. Jan.
[75] S. Cafiso, G. La Cava, A. Montella, Safety index for evaluation of two-lane rural highways, Transport. Res. Rec.: J. Transport. Res. Board 2019 (1) (2007) 136–145, https://doi.org/10.3141/2019-17.
[76] PIARC, Human Factors Guidelines for a Safer Man-Road Interface (2016) 78p [Online]. Available: http://www.piarc.org/en/order-library/25370-en-Human.
[77] PIARC, Road safety evaluation based on human factors method, World Road Association (PIARC), (2019) 2019R27EN.
[78] A. Paliotto, Development of a Human Factors Evaluation Procedure for Network-wide Road Safety Assessments, 2023, https://doi.org/10.26083/TUPRINTS-00022962.
[79] A. Paliotto, M. Meocci, Development of a network-level road safety assessment procedure based on human factors Principles, Infrastructures 9 (2024) 35, https://doi.org/10.3390/INFRASTRUCTURES9020035, 9, no. 2, p. 35, Feb. 2024.
[80] iRAP, iRAP Methodology fact sheets - iRAP [Online]. Available: https://irap.org/methodology/.
[81] J. Stipancic, L. Miranda-Moreno, N. Saunier, A. Labbe, Network screening for large urban road networks: using GPS data and surrogate measures to model crash frequency and severity, Accid. Anal. Prev. 125 (2019) 290–301, https://doi.org/10.1016/J.AAP.2019.02.016. Apr.
[82] F. Orsini, G. Gecchele, M. Gastaldi, R. Rossi, Large-scale road safety evaluation using extreme value theory, IET Intell. Transp. Syst. 14 (9) (2020) 1004–1012, https://doi.org/10.1049/IET-ITS.2019.0633. Sep.
[83] D. Nikolaou, A. Ziakopoulos, G. Yannis, A review of surrogate safety measures Uses in historical crash investigations, Sustainability 15 (2023) 7580, https://doi.org/10.3390/SU15097580, 15, no. 9, p. 7580, May 2023.
[84] European Commission, Network Wide Road Safety Assessment Methodology and Implementation Handbook, 2023.
[85] PRACT, PRACT Predicting Road ACcidents - a Transferable Methodology across Europe, Deliverable D - Development of New Crash Modification Factors/Functions Per Key Safety Treatments CEDR Call 2013, 2015.
[86] F. Moraldi, F. La Torre, S. Ruhl, Transfer of the Highway Safety Manual predictive method to German rural two-lane, two-way roads 12 (8) (2019) 977–996, https://doi.org/10.1080/19439962.2019.1571546. *10.1080/19439962.2019.1571546*.
[87] F. La Torre, L. Domenichini, V. Branzi, M. Meocci, A. Paliotto, N. Tanzi, Transferability of the highway safety manual freeway model to EU countries, Accid. Anal. Prev. 178 (2022) 106852, https://doi.org/10.1016/j.aap.2022.106852.
[88] F. La Torre, M. Meocci, L. Domenichini, V. Branzi, N. Tanzi, A. Paliotto, Development of an accident prediction model for Italian freeways, Accid. Anal. Prev. 124 (January) (May 2019) 1–11, https://doi.org/10.1016/j.aap.2018.12.023.
[89] F. Gross, P.P. Jovanis, K. Eccles, Safety effectiveness of lane and shoulder width combinations on rural, two-lane, undivided roads, Transp Res Rec 2103 (2009) 42–49, https://doi.org/10.3141/2103-06.
[90] J.A. Bonneson, M.P. Pratt, Roadway Safety Design Workbook, 2009 [Online]. Available: https://rosap.ntl.bts.gov/view/dot/16831.
[91] R. Elvik, Why are there so few experimental road safety evaluation studies: could their findings explain it? Accid. Anal. Prev. 163 (2021) 106467 https://doi.org/10.1016/J.AAP.2021.106467. Dec.
[92] M. Schlögl, R. Stütz, Methodological considerations with data uncertainty in road safety analysis, Accid. Anal. Prev. 130 (2019) 136–150, https://doi.org/10.1016/J.AAP.2017.02.001. Sep.
[93] PIARC, Road safety inspection guidelines for safety checks of existing roads 83 (2012) [Online]. Available: https://www.piarc.org/en/order-library/18265-en-Road.
[94] E. Grimberg, A. Botzer, O. Musicant, Smartphones vs. in-vehicle data acquisition systems as tools for naturalistic driving studies: a comparative review, Saf. Sci. 131 (2020) 104917, https://doi.org/10.1016/J.SSCI.2020.104917. Nov.
[95] M. Eskandari Torbaghan, M. Sasidharan, L. Reardon, L.C.W. Muchanga-Hvelplund, Understanding the potential of emerging digital technologies for improving road safety, Accid. Anal. Prev. 166 (2022) 106543, https://doi.org/10.1016/J.AAP.2021.106543. Mar.
[96] Y. Wang, et al., Framework for geometric information extraction and digital modeling from LiDAR data of road Scenarios, Rem. Sens. 15 (2023) 576, https://doi.org/10.3390/RS15030576, 15, no. 3, p. 576, Jan. 2023.
[97] M. Soilán, A. Sánchez-Rodríguez, P. Del Río-Barral, C. Perez-Collazo, P. Arias, B. Riveiro, Review of laser Scanning technologies and their applications for road and Railway infrastructure Monitoring, Infrastructures 4 (2019) 58, https://doi.org/10.3390/INFRASTRUCTURES4040058, 4, no. 4, p. 58, Sep. 2019.
[98] L. Barazzetti, M. Previtali, M. Scaioni, Roads Detection and Parametrization in integrated BIM-GIS using LiDAR, Infrastructures 5 (2020) 55, https://doi.org/10.3390/INFRASTRUCTURES5070055, 5, no. 7, p. 55, Jul. 2020.
[99] S. Cafiso, C. D'Agostino, B. Persaud, Investigating the influence of segmentation in estimating safety performance functions for roadway sections, J. Traffic Transport. Eng. 5 (2) (May 2018) 129–136, https://doi.org/10.1016/j.jtte.2017.10.001.
[100] S.R. Elagamy, S.M. El-Badawy, S.A. Shwaly, Z.M. Zidan, U.E. Shahdah, Segmentation effect on the transferability of international safety performance functions for rural roads in Egypt, Saf. Now. 6 (3) (2020) 1–24, https://doi.org/10.3390/SAFETY6030043.
[101] F. Martinelli, F. La Torre, P. Vadi, Calibration of the highway safety Manual's accident prediction model for Italian secondary road network, Transport. Res. Rec.: J. Transport. Res. Board 2103 (1) (May 2009) 1–9, https://doi.org/10.3141/2103-01.
[102] F. La Torre, L. Domenichini, F. Corsi, F. Fanfani, Transferability of the highway safety manual freeway model to the Italian motorway network, Transport. Res. Rec.: J. Transport. Res. Board 2435 (1) (May 2014) 61–71, https://doi.org/10.3141/2435-08.
[103] F. La Torre, et al., Development of a Transnational accident prediction model, Transport. Res. Procedia 14 (2016) 1772–1781, https://doi.org/10.1016/J.TRPRO.2016.05.143.
[104] F. Cunto, L. Sobreira, S. Ferreira, Assessing the transferability of the highway safety manual predictive method for urban roads in Fortaleza City, Brazil, J Transp Eng 141 (1) (2015) 04014072, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000734/ASSET/965D7AB3-C46B-40C3-992F-B08C4ADAFA3F/ASSETS/IMAGES/LARGE/FIGURE6.JPG. Jan.
[105] Niovi Karathodorou, J. Graham Daniel, Thomas Richter, Stephan Ruhl, La Torre Francesca, Domenichini Lorenzo, Yannis George, Dragomanovits Anastasios, Laiou Alexandra, Swedish National Road and Transport Research Institute (VTI), Development of a crash modification factors model in Europe, in: Road Safety on Five Continents (RS5C): 17th International Conference, Rio de Janeiro, Brazil, 2016 [Online]. Available: http://vti.diva-portal.org/smash/get/diva2:926147/FULLTEXT01.pdf.
[106] iRAP and EuroRAP, Crash Rate-Star Rating Comparisons, 2011 [Online]. Available: www.eurorap.org.
[107] A.F.M. Murozi, S.Z. Ishak, F.N.M. Nusa, A.P.W. Hoong, S. Sulistyono, The application of international road assessment Programme (iRAP) as a road infrastructure risk assessment tool, in: 2022 IEEE 13th Control and System Graduate Research Colloquium, ICSGRC 2022 - Conference Proceedings, 2022, pp. 237–242, https://doi.org/10.1109/ICSGRC55096.2022.9845149.
[108] A. Derras, K. Amara, R. Oulha, Application of the IRAP method combined with GIS to improve road safety on new highway projects in Algeria, Period. Polytech. Transp. Eng. 50 (4) (2022) 414–425, https://doi.org/10.3311/PPTR.19026. Aug.
[109] euroFOT//The first large-scale European Field Operational Test on Active Safety Systems" Accessed: December. 13, 2023. [Online]. Available: https://www.eurofot-ip.eu/.

[110] A. Christoph Kessler et al., "Deliverable D11.3 Version 1.1 Ii Final Report".
[111] B. Ryder, A. Dahlinger, B. Gahr, P. Zundritsch, F. Wortmann, E. Fleisch, Spatial prediction of traffic accidents with critical driving events – insights from a nationwide field study, Transp Res Part A Policy Pract 124 (2019) 611–626, https://doi.org/10.1016/J.TRA.2018.05.007. Jun.
[112] D. Janssens, G. Wets, H.J.P. Timmermans, T.A. Arentze, Modelling Short-Term Dynamics in Activity-Travel Patterns: Conceptual Framework of the Feathers Model, 2007.