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Mapping the knowledge domain of road safety studies: A scientometric analysis

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ABSTRACT

As a way of obtaining a visual expression of knowledge, mapping knowledge domain (MKD) provides a vision-based analytic approach to scientometric analysis which can be used to reveal an academic community, the structure of its networks, and the dynamic development of a discipline. This study, based on the Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) articles on road safety, employs the bibliometric tools VOSviewer and CitNetExplorer to create maps of author co-citation, document co-citation, citation networks, analyze the core authors and classic documents supporting road safety studies and show the citation context and development of such studies. It shows that road safety studies clustered mainly into four groups, whose we will refer to as “effects of driving psychology and behavior on road safety”, “causation, frequency and injury severity analysis of road crashes”, “epidemiology, assessment and prevention of road traffic injury”, and “effects of driver risk factors on driver performance and road safety”, respectively. Through our analysis, the core publications and their citation relationships were quickly located and explored, and “crash frequency modeling analysis” has been identified to be the core research topic in road safety studies, with spatial statistical analysis technique emerging as a frontier of this topic.

1. Introduction

Transportation is basic to national economic and social development, and ensuring safety is an essential element of its development. The frequent occurrence of road crashes and the large number of casualties resulting from them (over 1.35 million fatalities and an estimated 50 million injuries) constitute an important public-health and development problem with significant social and economic costs (World Health Organization, 2018). Road crashes lead to tremendous psychological trauma, including post-traumatic stress disorder (PTSD). PTSD following a road crash occurs as often as 45% of the time (Heron-Delaney et al., 2013), and heavy psychological, physiological and economical burdens are placed on individuals, families and society as a whole. In order to reduce the numbers of road crashes and improve road safety, a great deal of research has been carried out on it, and important contributions have been made to its development and understanding. Among them, the core authors have produced rich and high-impact research both independently and in teams. Who are these core authors, and what research topics attract they? What classic documents have they published? Which topic has attracted the most attention, and how has research developed and evolved? The search for answers to these questions offers two possible approaches:

- The first is the classic approach of research into the literature of road safety, that is, “partial literature sorting and selection → comprehensive comparison of models and theories → review and comment”. The reason for a partial literature review is that each scholar has limited time and energy, and no one can read all the literature thoroughly. There are plenty of brilliant review articles on road safety studies, such as Lin and Kraus (2009), Williamson et al. (2011); Savolainen et al. (2011); Theofilatos and Yannis (2014); Hughes et al. (2015). The research based on this approach on the one hand sorts and analyses the development processes of road-safety theories, while on the other hand it provides guidance to scholars engaged in applying such theories to real-world situations.
- The second is the scientometric and visualization method, that is, “collecting big data from document databases → exploring the relationships between citing and co-cited documents → visualizing the results of scientometric analysis (creating knowledge-domain maps) → discovering the research rules”. The scientometric method of document analysis has been widely applied in digital medicine (Fang, 2015), sustainable development (Zhu and Hua, 2017), synthetic biology (Shapira et al., 2017), information science (Hou et al., 2018), business economics (Castillo-Vergara et al., 2018), and health inequalities (Cash-Gibson et al., 2018). However,

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scientometric research on road-safety documents is just beginning.

Zou et al. (2018) first made use of a scientometrics-based approach to visually analyzing road safety studies, identifying main research topics and their most classical documents (knowledge bases) using document co-citation analysis. This study makes use of author co-citation analysis to identify authors from the same or similar research fields, while revealing the intellectual structure of road safety studies through the interpretation of the authors' representative works. The study also employs document citation analysis for creating a citation network map (historiograph) of road safety studies to identify core publications over a range of years.

The remainder of the paper is structured as follows. The data collection and analytical methods are described in Section 2. The results of author co-citation analysis and document citation analysis are presented and discussed in Sections 3 and 4, respectively. The final section, Section 5, summarizes the findings and concludes the paper.

2. Methodology

Separating the most important documents from the vast quantity of literature is very labor-intensive, and the amount is still growing rapidly, making it more and more difficult to track the development of the discipline through traditional approaches, especially in multi-disciplinary field. In this context, the mapping knowledge domain (MKD) is useful, providing a way of extracting the essence of a field from a mass of data. MKD research is a cross-disciplinary method involving applied mathematics, information science and computer science and is a new area of scientometrics.

MKD produces a graph showing the development processes and structural relationships within a field of scientific knowledge. It is an effective tool for tracking the frontiers of science and technology, showing the directions of scientific research, and assisting scientific and technological decision-making. By mapping what is known to science, its most notable elements can be visualized, helping researchers to mine, analyze and display the knowledge and interrelationships that exist within.

2.1. Data source and processing

The SCIE and SSCI citation index databases from the *Web of Science Core Collection* were retrieved as sources for this study. Retrieval topics included “road safety” OR (the Boolean operator) “road accident” OR “road crash” OR “traffic crash” OR “highway safety”. The time-span was “all years”, and the document types were “article” OR “review”. A total of 20,720 publications were collected, with the last update taking place on June 7, 2019. Retrieved results were saved in “plain text” with “full record and cited references”. Note that only the above-mentioned keywords were used in this study, and the number of publications could change given additional search keywords. Nevertheless, the methodology proposed herein remains unchanged and the findings in this paper are applicable to searches based on additional keywords.

2.2. Analytical methods and tools

2.2.1. Author co-citation analysis

Author co-citation analysis (ACA) was first proposed by White and Griffith (1981). It regards authors as the units of analysis in order to establish co-citation relationships among them, allowing many authors to be clustered into groups on the basis of their citations, forming a network that reflects the connections among them, as well as the relationships among the areas of study. ACA can be used to quantify scientific structures and to find scientific paradigms and communities; it has been widely used to locate the most important authors and intellectual structures in areas such as strategic management (Nerur et al., 2008), e-learning (Chen and Lien, 2011), bio-energy (Qian, 2013), hospitality management (García-Lillo et al., 2016), and big data (Hu et al., 2018). Combining ACA and MKD allows the structures and power distributions within a subject or research field to be visualized. Authors with closer relationships will be more concentrated, forming clusters that connect authors with different research directions and in different research fields, and give a visual demonstration of the structures of the discipline or research field and the corresponding academic groups within it. In this study VOSviewer (Visualization of Similarities Viewer), developed by van Eck and Waltman (2010), was used to build an author co-citation network for road safety studies. This software provides many common bibliometric-analysis functions, such as co-authorship, co-occurrence, bibliographic coupling, and co-citation analysis, and it has been widely used for scientometric analysis in many fields (Strozzi et al., 2017; Chandra, 2018; Galofré-Vilà, 2018; Homrich et al., 2018; Hosseini et al., 2018).

2.2.2. Document citation analysis

The co-authorship, co-citation, bibliographic coupling, and co-occurrence networks in MKD belong to the undirected network, and their chronological-order characteristics are not obvious. Therefore, it is difficult to see the dynamic process of knowledge development and new development trends from the results of the analysis. The citation network, however, is directed and has chronological-oder continuity. It is one-way loop-free, and the diffusion from early knowledge bases to the research fronts reflects changes in the knowledge paradigms and innovation process. This paper uses document citation analysis to explore the development of road safety studies over time, visualizes the most important publications, and displays the citation relationships among them to indicate their interrelationships. CitNetExplorer (Citation Network Explorer), developed by van Eck and Waltman (2014), was used to construct the citation network of road-safety publications. The software is embedded with the smart local moving (SLM) algorithm for clustering which provides superior results to those obtained through the Louvain algorithm (Waltman and van Eck, 2013). Moreover, CitNetExplorer offers sophisticated functionality for drilling down into a citation network containing the most essential publications on a particular topic (van Eck and Waltman, 2014).

3. Results of author co-citation analysis

Author co-citation analysis establishes co-citation relationships where the authors are basic units. By analyzing the situation when two authors are both cited by a third author, we can understand the degree of closeness among different authors in a certain research field and discover the important authors and research groups in this field. In this paper, the author co-citation analysis in VOSviewer was used to generate the author co-citation network of road safety studies (as shown in Fig. 1). It can be seen that the core authors identified have been divided into 4 clusters of different colors indicating the activities in this research field.

In order to analyze the main research topics, five core authors with high numbers of co-citations were selected from each cluster (Table 1). Based on the research findings of Zou et al. (2018), document co-citation analysis was used in VOSviewer to generate the density view of the document co-citation network, in order to discover the classic documents (knowledge bases) published by the prominent authors concerning road safety. By analyzing these documents, the developmental context and foundations of road safety research can be found which offers guidance to the research frontiers. In Fig. 2, the color of the area centered by a document depends on the number of co-citations. The larger the number is, the warmer (redder) the color is, while the smaller the number is, the cooler (bluer) the color. Details about these documents are given in Table 1.

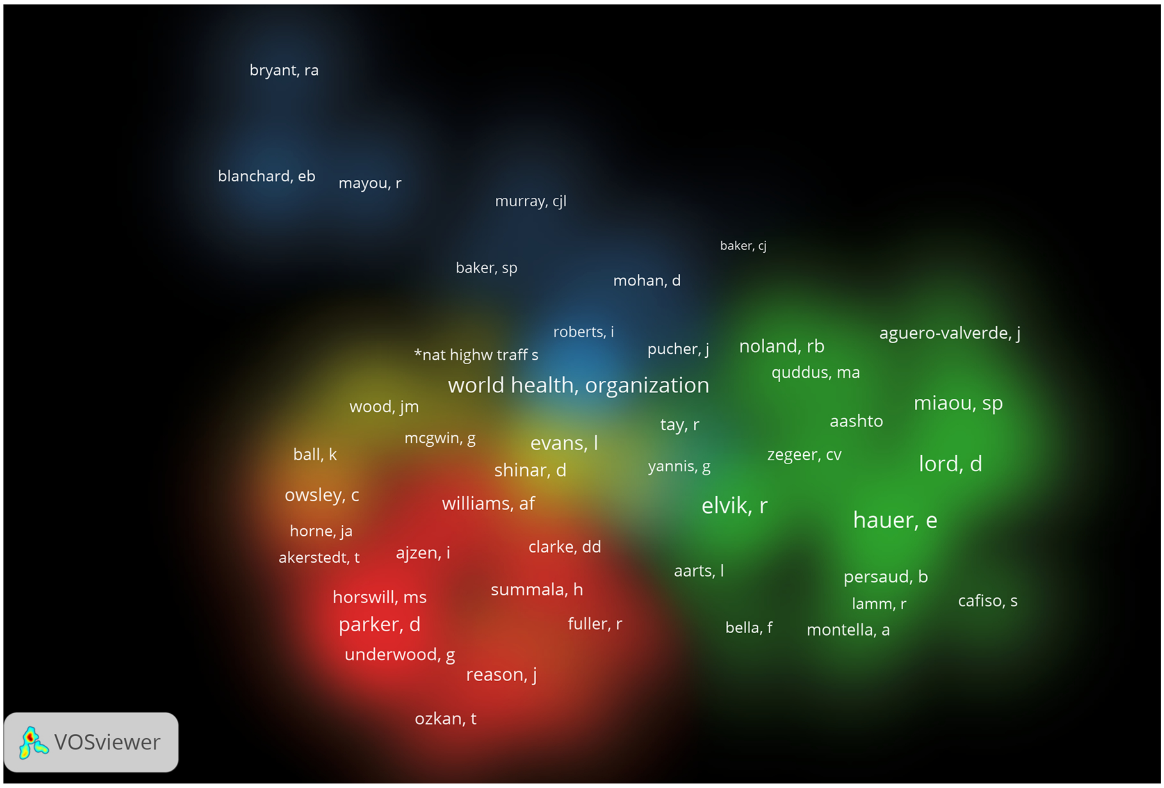

Fig. 1. Density view of author co-citation network.
Note: *Web of Science* data includes only the first author of a cited document.

3.1. Author cluster 1 (red): effects of driving psychology and behavior on road safety

The main purpose of research into the psychology of driving is to find the rules governing driver actions, analyze the factors contributing to road crashes, and to modify aberrant driving, prevent road crashes, and improve safety. Driver psychology is closely related to driving behavior, and aberrant driving is an important cause of road crashes. Reason et al. (1990) constructed the original driver behavior questionnaire (DBQ), investigating 520 drivers and concluding that three fundamental factors relate to aberrant driving: violations, dangerous errors, and harmless lapses. Parker et al. (1995) reduced the original 50-item DBQ to 24 items and conducted an investigation. The results of their factor analysis affirmed the earlier three-factor structure, but also found that a self-reported tendency to commit violations had an obvious predictive effect on crash involvement. The proposal of DBQ and the classifications of aberrant driving laid a solid foundation for further research on the causes of road crashes (Lajunen et al., 2004; Bener et al., 2008; Martinussen et al., 2013; Cordazzo et al., 2014; Stephens and Fitzharris, 2016). Ajzen (1991) formally proposed a theory of planned behavior (TPB) to describe rational human behavior. The TPB holds that human behavior is mainly caused by behavioral intention, which is subject to the influence of individual attitudes, subjective norms, and perceived behavioral control. In addition, perceived behavioral control can affect behavior directly or by influencing behavioral intention. The TPB has been widely used in causal studies of intentional driving violations such as speeding (Warner and Åberg, 2006; Paris and Broucke, 2008), drunk driving (Chan et al., 2010), aggressive driving (Efrat and Shoham, 2013), and texting while driving (Benson et al., 2015; Bazargan-Hejazi et al., 2017). Deffenbacher et al. (1994) designed 53 driving-related situations that could lead to anger, and investigated 1500 college students. Cluster analysis was used to obtain a 33-item driving anger scale (DAS) consisting of six subscales, and including hostile gestures, illegal driving, police presence, slow driving, discourtesy, and traffic obstructions. DAS is the basis of research on driver anger, and scholars have conducted research on it in relation to the national conditions and cultural traits of different countries, such as New Zealand (Sullman, 2006), Sweden (Björklund, 2008), Turkey (Yasak and Esiyok, 2009), Japan (McLinton and Dollard, 2010), and Malaysia (Sullman et al., 2014). Lajunen and Summala (1995) developed the extended version of the driver skill inventory (DSI) to assess self-reported perceptual-motor and safety skills. Their research results suggested that experienced drivers judged their skills as higher but their safety concern as lower than inexperienced ones, and skill-oriented drivers actually like driving, but also get aggressive more easily in heavy traffic. DSI has been widely used in subsequent studies, and shown to be effective (Özkan et al., 2006; Shi et al., 2011; Öz et al., 2013; Martinussen et al., 2017; Bıçaksız et al., 2018). Over the years, the DSI and DBQ have become two of the most frequently applied measures of self-reported driving skill and driving style, notable among them being an excellent study by Lajunen et al. (1998) on aggressive driving behavior that used both along with the DAS.

3.2. Author cluster 2 (green): causation, frequency and injury severity analysis of road crashes

Causation, frequency and injury severity analysis of road crashes studies the overall distribution and trends in road crashes, and the role of risk factors in them to gain a quantitative and macroscopic understanding of the nature of and rules governing the crashes. It aims to improve road design, propose road safety measures, formulate policy and regulations, and achieve the objectives of reducing both crashes and the severity of injuries. Miaou (1994) examined the impacts of roadway geometrics on truck-crash frequencies using the Poisson, zero-inflated Poisson (ZIP), and negative binomial (NB) regression models, and suggested that the NB and ZIP regression models could be employed if the overdispersion of crash data is found to be moderate or high. In overcoming the problem of Poisson overdispersion, Abdel-Aty

Table 1

Core authors and their representative works with high co-citations in road safety studies (Abdel-Aty, 2003, Abdel-Aty and Keller, 2005, Ajzen and Fishbein, 1980, Ball et al., 2006, Baker et al., 1992, Ball et al., 1998, Baker et al., 1987, Deffenbacher et al., 2002, Elvik and Vaa, 2004, Evans, 2004, Hauer, 2001, Hauer et al., 2002, Lajunen and Summala, 2003, World Health Organization (WHO), 2009, World Health Organization (WHO), 2013, Strayer & Johnston, 2001, Strayer & Drew, 2004, Shinar & Compton, 2004, Shinar, 2007, Reason, 1990, Parker et al., 1995, Parker et al., 1998, Owsley et al., 1991, Owsley et al., 1999).

Cluster (color)	Core author	Affiliation	Country	Highly co-cited document (representative work)		
				Year	Title	Co-citations
1 (red)	Dianne Parker	Safety Culture Associates Limited	UK	1995	Driving errors, driving violations and accident involvement	1420
				1995	Behavioural characteristics and involvement in different types of traffic accident	753
				1998	Attitudinal predictors of interpersonally aggressive violations on the road	605
	Timo J. Lajunen	Norwegian University of Science and Technology	Norway	2003	Can we trust self-reports of driving? Effects of impression management on driver behaviour questionnaire responses	833
				2004	The Manchester Driver Behaviour Questionnaire: a cross-cultural study	793
				1995	Driving experience, personality, and skill and safety-motive dimensions in drivers' self-assessments	523
	James T. Reason	University of Manchester	UK	1990	Errors and violations on the roads: a real distinction?	2174
				1990	*Human Error*	486
	Icek Ajzen	University of Massachusetts Amherst	USA	1991	The theory of planned behavior	864
				1980	*Understanding Attitudes and Predicting Social Behavior*	279
	Jerry L. Deffenbacher	Colorado State University	USA	1994	Development of a driving anger scale	919
				2003	Anger, aggression, and risky behavior: a comparison of high and low anger drivers	607
				2002	The Driving Anger Expression Inventory: a measure of how people express their anger on the road	537
2 (green)	Rune Elvik	Institute of Transport Economics	Norway	2009	*The Handbook of Road Safety Measures (Second Edition)*	794
				2004	*The Handbook of Road Safety Measures (First Edition)*	647
	Ezra Hauer	University of Toronto	Canada	1997	*Observational Before—After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*	1329
				2001	Overdispersion in modelling accidents on road sections and in empirical Bayes estimation	664
				2002	Estimating safety by the empirical Bayes method: a tutorial	489
	Dominique Lord	Texas A&M University	USA	2010	The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives	4342
				2005	Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory	2210
				2006	Modeling motor vehicle crashes using Poisson-gamma models: Examining the effects of low sample mean values and small sample size on the estimation of the fixed dispersion parameter	1006
	Shaw-Pin Miaou	Texas A&M Transportation Institute	USA	1994	The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions	2092
				1993	Modeling vehicle accidents and highway geometric design relationships	1268
				2005	Bayesian ranking of sites for engineering safety improvements: decision parameter, treatability concept, statistical criterion, and spatial dependence	1097
	Mohamed A. Abdel-Aty	University of Central Florida	USA	2000	Modeling traffic accident occurrence and involvement	2127
				2003	Analysis of driver injury severity levels at multiple locations using ordered probit models	1938
				2005	Exploring the overall and specific crash severity levels at signalized intersections	875
3 (blue)	World Health Organization (WHO)	United Nations Economic and Social Council	United Nations	2004	*World Report on Road Traffic Injury Prevention*	2189
				2013	*Global Status Report on Road Safety 2013: Supporting a Decade of Action*	1392
				2009	*Global Status Report on Road Safety 2009: Time for Action*	1254
	Richard A. Mayou	University of Oxford	UK	1993	Psychiatric consequences of road traffic accidents	223
	Edward B. Blanchard	State University of New York at Albany	USA	1995	Psychiatric morbidity associated with motor vehicle accidents	105
	Dinesh Mohan	Indian Institute of Technology Delhi	India	2002	Road safety in less-motorized environments: future concerns	252
	Susan P. Baker	Johns Hopkins Bloomberg	USA	1974	The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care	376

(*continued on next page*)

Table 1 (*continued*)

		School of Public Health		1987	Geographic Variations in Mortality from Motor Vehicle Crashes	133
				1992	*The Injury Fact Book (Second Edition)*	110
4 (yellow)	Leonard Evans	Science Serving Society	USA	1991	Traffic Safety and the Driver	1010
				2004	*Traffic Safety*	823
	David Shinar	Ben-Gurion University of the Negev	Israel	2004	Aggressive driving: an observational study of driver, vehicle, and situational variables	539
				1998	Aggressive driving: the contribution of the drivers and the situation	458
				2007	*Traffic Safety and Human Behavior*	291
	Cynthia Owsley	University of Alabama at Birmingham	USA	1998	Visual processing impairment and risk of motor vehicle crash among older adults	983
				1991	Visual/cognitive correlates of vehicle accidents in older drivers	809
				1999	Older drivers and cataract: driving habits and crash risk	405
	Karlene K. Ball	University of Alabama at Birmingham	USA	1993	Visual attention problems as a predictor of vehicle crashes in older drivers	1036
				2006	Can high-risk older drivers be identified through performance-based measures in a department of motor vehicles setting?	678
				1998	Driving avoidance and functional impairment in older drivers	603
	David L. Strayer	University of Utah	USA	2003	Cell phone-induced failures of visual attention during simulated driving	612
				2001	Driven to distraction: dual-task studies of simulated driving and conversing on a cellular telephone	535
				2004	Profiles in driver distraction: effects of cell phone conversations on younger and older drivers	531

and Radwan (2000) used the NB regression model to analyze the relationship between crash frequency and risk factors in road segments. The results indicated that factors including heavy traffic, speeding, narrow lane contribute to the likelihood of road crashes. In addition, crash types correlate with driver gender and age. The research findings not only enrich the crash prediction methodologies, but also provide important research perspectives, and starting points for subsequent research (Chin and Quddus, 2003; Noland and Quddus, 2004a; Ma et al., 2008; Huang and Abdel-Aty, 2010; Chiou and Fu, 2013; Lao et al., 2014; Cai et al., 2016). Hauer (1997) published a book titled *Observational Before—After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety* which provides an extensive discussion of traditional before-after studies concerning road safety. In particular, a empirical Bayes (EB) approach and a comparison group were employed and discussed in great details. Based on his research, the EB method has been widely used in further research (Abdel-Aty et al., 2009; Shin and Washington, 2012; Elvik, 2013; Høye, 2015; Naznin et al., 2016; Khattak et al., 2018). Another important book is *The Handbook of Road Safety Measures (Second Edition)* by Elvik et al. (2009), which describes the effects of 128 road safety measures in 10 different areas, such as road design, equipment and maintenance, as well as traffic control. In particular, the handbook discusses the risk factors contributing to crashes and the severity of injuries associated with them, and assesses the relative importance of these factors. The handbook has become a classic of road safety, and is cited as many as 1935 times in Google Scholar (recorded on June 7, 2019). Lord and Mannering (2010) conducted a comprehensive review of the characteristics of crash-frequency data (such as over-dispersion, under-reporting, and omitted-variables bias) and the methodological alternatives (such as NB, ZIP, and neural networks) and limitations for

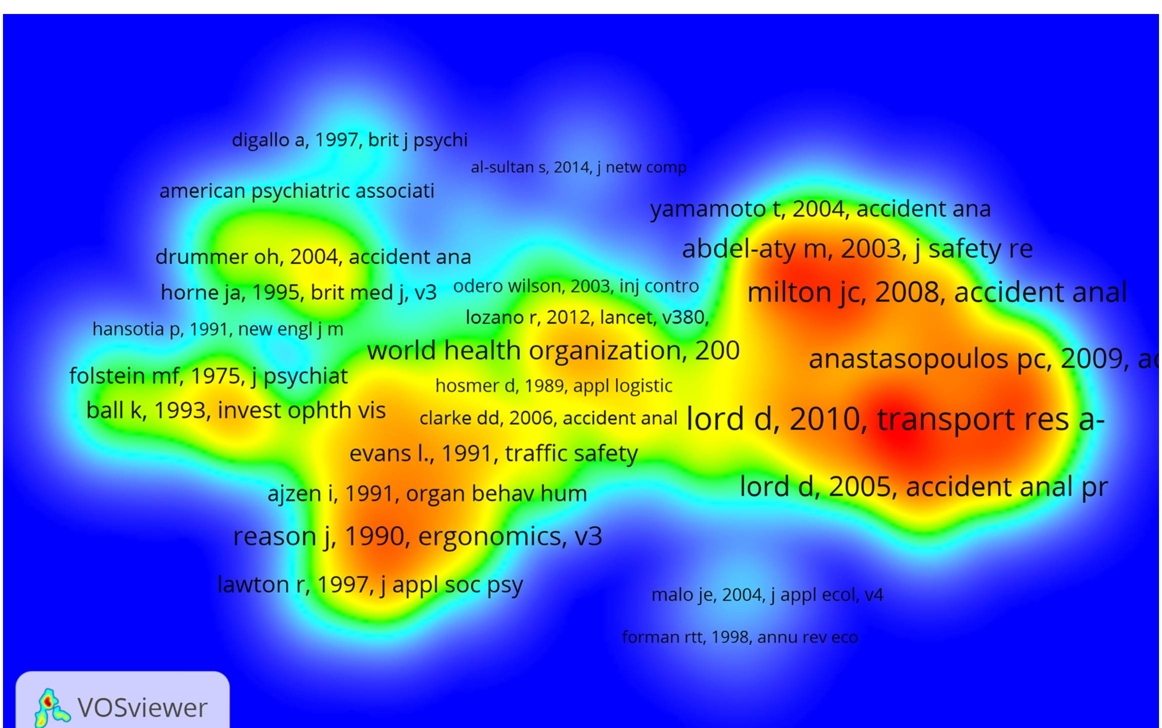

Fig. 2. Density view of the document co-citation network.

examining such data. Through its systematic analysis and summary of existing approaches, this excellent review has provided many insights into crash frequency modeling and analyses (Meng and Qu, 2012; Chiou and Fu, 2013; Dong et al., 2015; Jonathan et al., 2016; Wang et al., 2017).

3.3. Author cluster 3 (blue): epidemiology, assessment and prevention of road traffic injury

Road traffic injury (RTI) is a worldwide public-health concern, and leads to more than 3000 fatalities every day (World Health Organization (WHO, 2004b). Many scholars have conducted epidemiological, assessment and prevention research on RTI. In applying the abbreviated injury scale (AIS), Baker et al. (1974) found that both the degree of injury and death rate have linear relations with the quadratic sum of AIS grades, with or without multiple injuries. Based on this, the injury severity score (ISS) was proposed, and became an essential aspect of assessing the severity of RTIs, finding wide clinical use in every regard. In particular, the ISS is useful for assessing the relationship between severity of injury and probability of survival (Sahdev et al., 1994; Rosman et al., 1996; Sciortino et al., 2005; Leijdesdorff et al., 2012; Kenardy et al., 2015). Moreover, Baker et al. (1974) laid the foundation for the establishment of follow-up trauma-scoring systems, including the trauma and injury severity score (TRISS) (Boyd et al., 1987), the ICD-9 injury severity score (ICISS) (Osler et al., 1996), and the new injury severity score (NISS) (Osler et al., 1997). In addition to physical injuries, road crashes can also lead to a variety of psychiatric disorders, especially post-traumatic stress disorder (PTSD), with symptoms including irritability, emotional anesthesia and hyper-vigilance. By following up with 188 road-crash victims in Oxford, Mayou et al. (1993) conducted an epidemiological study of the incidence of PTSD resulting from road crashes. 19 (11%) victims were diagnosed with PTSD over the course of the year, and their PTSD was not associated with neuroticism, previous psychological problems, or baseline depression. In a subsequent study by Blanchard et al. (1995), PTSD was found to have co-morbidity with a variety of disorders (including panic disorder, social phobia and avoidant-personality disorder). The results showed that 62 (39.2%) victims met the criteria for PTSD, and that 53% of this group also met the criteria for current major depression, while 50% of those who developed PTSD had a history of previous major depression. Therefore, early intervention, including psychological counseling, should be given to vulnerable groups to enhance their ability to cope with PTSD. The research results of Mayou et al. (1993) and Blanchard et al. (1995) provide a good theoretical basis for road-crash-related PTSD assessment, prediction and intervention (Holeva and Tarrier, 2001; Hamanaka et al., 2006; Beck and Coffey, 2007; Bryant et al., 2012; Guest et al., 2016). Mohan (2002) conducted an epidemiological study of RTIs in less-motorized countries. He found that due to the different traffic and RTI patterns, the road-safety policies of high-income countries do not have the same effects in such countries. Therefore, the risk factors and potential solutions there were analyzed with a special focus on vulnerable road users. The findings of Mohan (2002) have inspired a great deal of RTI research in medium- and low-income countries (Zhang et al., 2011; Miranda et al., 2014; Rodríguez et al., 2015). This research also provided valuable insights for another important document: the *World Report on Road Traffic Injury Prevention* (World Health Organization (WHO, 2004a). The WHO named the World Health Day (WHD) of 7 April 2004 as “WHD 2004: Road Safety”, promoting it with the slogan “Road Safety Is No Accident” (WHO, 2003) in order to call for global action to prevent RTIs; a landmark publication, *World Report on Road Traffic Injury Prevention* (World Health Organization (WHO, 2004a), was also released. The report was written by a number of renowned scholars who analyzed in great detail the global impact of RTIs and their risk factors and interventions; this has attracted extensive attention, and provided an important reference for RTI research. All in all, the WHO (2004a) emphasizes prevention as the most effective measure. Governments should formulate and strictly implement comprehensive road-traffic laws and regulations. At the same time, transportation law-enforcing should increase the scope of its investigation and the punishment of aberrant driving, improving the efficiency of law enforcement.

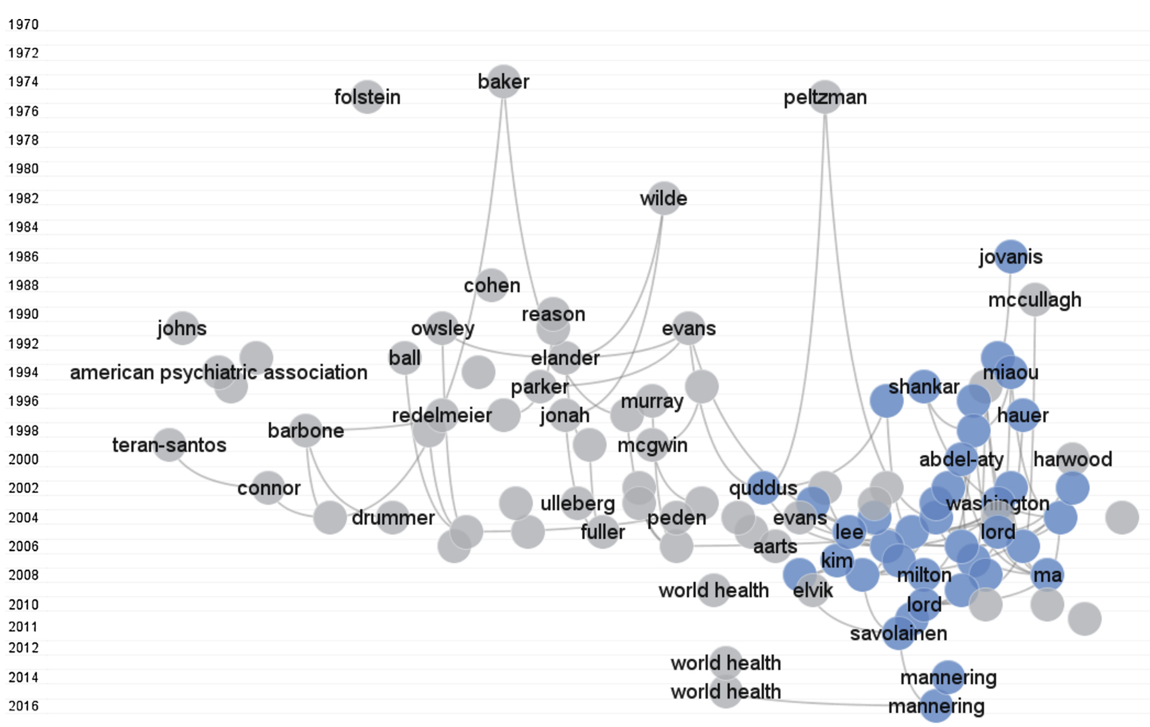

Fig. 3. Citation network map (historiograph) of the publications on road safety.
Note: The blue nodes are core publications that have at least 21 (incoming or outgoing) citation links with other core publications.

3.4. Author cluster 4 (yellow): effects of driver risk factors on driver performance and road safety

Road traffic is a dynamic and complex system consisting of people, vehicles, roads and the environment. Every such element establishes its own subsystem and interacts with others. Road crashes are caused by problems in the subsystems themselves or imbalances in the interactions among them. In general, road crashes take place as a result of combinations of various factors. Very few road crashes are caused by a single factor, but driver behavior has been recognized as the main cause of road crashes by many authorities (National Highway Traffic Safety Administration (NHTSA), 2015; Transport for NSW, 2017; Department for Transport, 2018). Driving under the influence of alcohol is a major cause of casualties, and in *Traffic Safety and the Driver*, Evans (1991) gives a detailed analysis of the role of alcohol in road crashes, and suggests that drinking not only increases blood-alcohol content (BAC), and degrades driver performance, but also significantly increases crash severity. Among the countermeasures he suggests are criminal sanctions, server intervention and social norms. Driving is a continuous process consisting of perception, judgment, decision-making, and operations, and it requires a high degree of coordination of hands, eyes and brain. With aging, the physiological functions gradually decline, leading to lower driving ability. In order to find out what elements of vision are related to crash involvement in older drivers, Ball et al. (1993) assessed variables including the size of the useful field of view (UFOV), eye-health status, and visual sensory function using a sample of 294 older drivers in Jefferson County, Alabama. The results suggested that the UFOV test is superior to typical acuity tests in predicting crashes in older drivers. In a follow-up study by Owsley et al. (1998), the authors adopted the same sample Ball et al. (1993) had, and also found that deficits in the UFOV were correlated with crash involvement, and that older drivers with UFOV impairment were 2.2 times more likely to be involved in a crash during the three years of the follow-up. Their research provides valuable information as a basis for further study of the UFOV test in assessing driver performance and its relation to crashes (Bédard et al., 2008; Wood et al., 2012; Matas et al., 2014; Gracitelli et al., 2015; Kosuge et al., 2017). Driver emotions are also important in their effect on safety, with rage being a common emotion. Shinar (1998) believes that aggressive driving is a symptom of frustration; that is, the aggressive behavior is a way for the driver to achieve a goal. The aggression is intended to resolve frustration, and once the frustration is eliminated, it comes to an end. It involves ignoring or interfering with other road users, or putting others at risk in order to save time. Shinar (1998) also listed inconsiderate or deliberate driver aggressive actions, including tailgating, running red lights, and honking at other drivers, but not speeding. He believes that, although speeding is a risky behavior, it is not motivated by traffic conditions or the behavior of other road users. Based on Shinar's findings, many scholars have conducted studies of the factors contributing to aggressive driving, such as gender (Björklund, 2008; González-Iglesias et al., 2012), personality (Deffenbacher et al., 2003; Jovanović et al., 2011), passengers (Hu et al., 2012), environmental conditions (Harris and Houston, 2010), and loud music in other cars (Sagar et al., 2013). Driver distraction is common, and one of the major factors in road crashes. The inattention-blindness hypothesis states that, while the driver is watching the road, a shift in his or her attention, such as to a cell-phone conversation, leads to a neglect of traffic and road conditions. To verify this hypothesis, Strayer et al. (2003) conducted an experiment via an eye tracker, with the subjects divided into two groups. The experimental group performed a dual-task operation by using a cell phone while driving, while the control group only drove. Billboards were set up at random along the road, and after the test was completed,

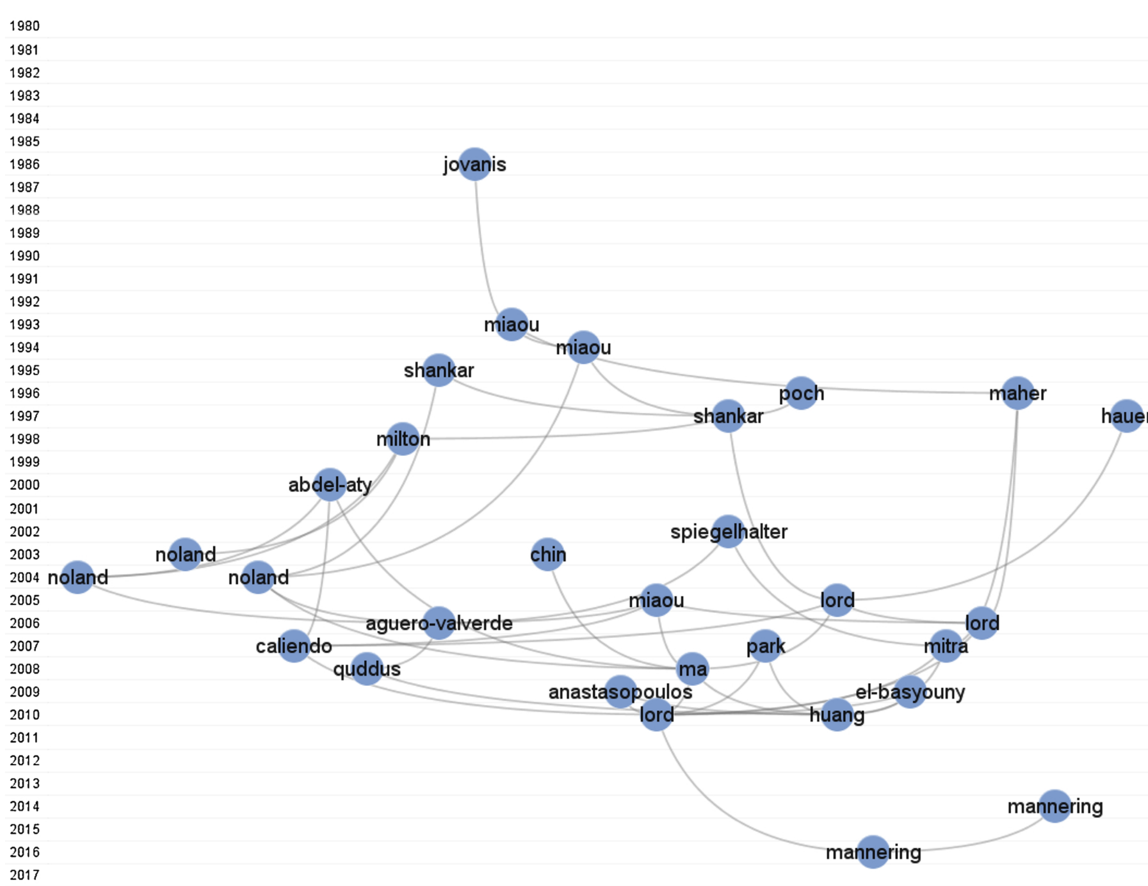

Fig. 4. Citation sub-network of the core publications on road safety.

Table 2
Core publications visualized in the core citation sub-network.

Year	Author(s)	Title	Published in	Internal citation score
1986	Jovanis and Chang	Modeling the relationship of accidents to miles traveled	*Transportation Research Record*	120
1993	Miaou and Lum	Modeling vehicle accidents and highway geometric design relationships	*Accident Analysis & Prevention*	143
1994	Miaou	The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions	*Accident Analysis & Prevention*	213
1995	Shankar et al.	Effect of roadway geometrics and environmental factors on rural freeway accident frequencies	*Accident Analysis & Prevention*	224
1996	Poch and Mannering	Negative binomial analysis of intersection-accident frequencies	*Journal of Transportation Engineering*	155
	Maher and Summersgill	A comprehensive methodology for the fitting of predictive accident models	*Accident Analysis & Prevention*	91
1997	Hauer	Observational before—after studies in road safety: estimating the effect of highway and traffic engineering measures on road safety	*(Book)*	415
	Shankar et al.	Modeling accident frequencies as zero-altered probability processes: An empirical inquiry	*Accident Analysis & Prevention*	101
1998	Milton and Mannering	The relationship among highway geometrics, traffic-related elements and motor-vehicle accident frequencies	*Transportation*	162
2000	Abdel-Aty and Radwan	Modeling traffic accident occurrence and involvement	*Accident Analysis & Prevention*	216
2002	Spiegelhalter et al.	Bayesian measures of model complexity and fit	*Journal of the Royal Statistical Society: Series B (Statistical Methodology)*	152
2003	Chin and Quddus	Applying the random effect negative binomial model to examine traffic accident occurrence at signalized intersections	*Accident Analysis & Prevention*	111
	Noland	Traffic fatalities and injuries: the effect of changes in infrastructure and other trends	*Accident Analysis & Prevention*	86
2004	Noland and Oh	The effect of infrastructure and demographic change on traffic-related fatalities and crashes: a case study of Illinois county-level data	*Accident Analysis & Prevention*	106
	Noland and Quddus	A spatially disaggregate analysis of road casualties in England	*Accident Analysis & Prevention*	106
2005	Lord et al.	Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory	*Accident Analysis & Prevention*	213
	Miaou and Song	Bayesian ranking of sites for engineering safety improvements: Decision parameter, treatability concept, statistical criterion, and spatial dependence	*Accident Analysis & Prevention*	86
2006	Aguero-Valverde and Jovanis	Spatial analysis of fatal and injury crashes in Pennsylvania	*Accident Analysis & Prevention*	139
	Lord	Modeling motor vehicle crashes using Poisson-gamma models: Examining the effects of low sample mean values and small sample size on the estimation of the fixed dispersion parameter	*Accident Analysis & Prevention*	105
2007	Caliendo et al.	A crash-prediction model for multilane roads	*Accident Analysis & Prevention*	105
	Mitra and Washington	On the nature of over-dispersion in motor vehicle crash prediction models	*Accident Analysis & Prevention*	99
	Park and Lord	Multivariate Poisson-Lognormal Models for Jointly Modeling Crash Frequency by Severity	*Transportation Research Record*	92
2008	Quddus	Modelling area-wide count outcomes with spatial correlation and heterogeneity: an analysis of London crash data	*Accident Analysis & Prevention*	122
	Ma et al.	A multivariate Poisson-lognormal regression model for prediction of crash counts by severity, using Bayesian methods	*Accident Analysis & Prevention*	111
2009	Anastasopoulos and Mannering	A note on modeling vehicle accident frequencies with random-parameters count models	*Accident Analysis & Prevention*	197
	El-Basyouny and Sayed	Collision prediction models using multivariate Poisson-lognormal regression	*Accident Analysis & Prevention*	86
2010	Lord and Mannering	The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives	*Transportation Research Part A: Policy and Practice*	426
	Huang and Abdel-Aty	Multilevel data and Bayesian analysis in traffic safety	*Accident Analysis & Prevention*	87
2014	Mannering and Bhat	Analytic methods in accident research: Methodological frontier and future directions	*Analytic Methods in Accident Research*	180
2016	Mannering et al.	Unobserved heterogeneity and the statistical analysis of highway accident data	*Analytic Methods in Accident Research*	121

memory of these billboards was tested. The study found that the number of objects identified by the control group was significantly higher than that identified by the experimental group, which means that using a cell phone impaired recognition memory. In addition, analysis of eye-movement data showed that there were no significant differences in fixation probability and duration between the groups, which means that even if the subjects of the experimental group looked directly at items in the driving environment, they were unlikely to create durable explicit memories of them. The eye-movement data gave a degree of support to the inattention-blindness hypothesis. Based on the research findings of Strayer et al. (2003), the effects of cell phones on driver performance have become a research hotspot (Rakauskas et al., 2004; Rosenbloom, 2006; Caird et al., 2008; Liu and Ou, 2011; Saifuzzaman et al., 2015; Papadakaki et al., 2016).

4. Results of document citation analysis

In this paper, CitNetExplorer was used to carry out document citation analysis of road safety studies. After generating the citation network, the "core publications" function of the software was used to identify such publications in the network. Here we define a core publication as a publication that has citation relations with at least 21 other core publications (21 is the maximum threshold value, and no core publication will have a value of higher than 21). In the end, 360 core publications were identified (the blue nodes in Fig. 3).

In Fig. 3, each node labelled with the last name of the first author represents a publication; the lines between nodes indicate citation relations, and publication years are on the left. The 100 publications (display limit in the software) with the highest internal citation scores (the number of citations of the publication within the citation network being analyzed) are displayed (grey and blue nodes in Fig. 3). The "drill down" and "clustering" functions were used to identify the citation subnetwork of the core publications on road safety, and to provide a clear visualization of the network, while the "transitive reduction" function was used to remove non-essential citation relations (van Eck and Waltman, 2014), as shown in Fig. 4.

In Fig. 4, the 30 publications with the highest internal citation scores are shown, with detailed publication information provided in Table 2. It can be seen that this citation sub-network mainly covers the topic of "crash frequency modeling analysis", which indicates that this sub-field of road safety studies is the most important, and has attracted the most attention in the academic circles. As shown in Table 2, the majority of core publications (21/30) appear in the journal *Accident Analysis & Prevention* (*AA&P*), indicating that this is the leading journal on the topic.

Road crashes are random events with a low probability. Their occurrences are distributed in non-negative, discrete and abnormal forms. Starting from the assumption that crash frequency is governed by a Poisson process (Jovanis and Chang, 1986), research on crash prediction models has made considerable progress. First, Miaou and Lum (1993) proposed using the Poisson regression model to analyze the relationship between road crashes and the factors. As a limitation of using this model, the variance and mean are forced to be equal, and if crash-frequency data show over-dispersion (variance greater than the mean), the model may produce false estimates of crash likelihood (Shankar et al., 1995; Maher and Summersgill, 1996). In order to reduce or even eliminate such adverse effects, some authors suggested applying negative binomial (NB) models which introduce an error term to deal with the over-dispersion of crash data (Shankar et al., 1995; Poch and Mannering, 1996; Milton and Mannering, 1998; Abdel-Aty and Radwan, 2000; Noland, 2003; Noland and Oh, 2004; Noland and Quddus, 2004b; Lord, 2006). When statistical intervals are shorter or road-usage rates are lower, the numbers of crashes for certain sections of road may be zero. Therefore, some researchers have proposed the use of zero-inflated Poisson (ZIP) and zero-inflated negative binomial (ZINB) models to deal with "excess" zeros (Miaou, 1994; Shankar et al., 1997). In their opinions, the models can account for the over-dispersion of crash data and lead to better results; however, other researchers have criticized their use since it does not accurately reflect the fundamental principles of the crash process (Lord et al., 2005; Lord and Geedipally, 2018). In addition, due to limitations in both Poisson and NB models in terms of requiring the crash data to be uncorrelated in time, Chin and Quddus (2003) employed the random effect negative binomial (RENB) model, treating the data in a time-series cross-section panel. At the same time, Lord et al. (2005) have stated that crash data are best characterized as Bernoulli trials with independence. Based on research on NB and generalized estimating equations (GEE) models (Abdel-Aty and Radwan, 2000; Lord et al., 2005), Caliendo et al. (2007) conducted a longitudinal study on crash frequencies and proposed a negative multinomial (NM) model which was superior to the Poisson and NB models in terms of over-dispersion and explanatory power. Additionally, the multivariate Poisson-lognormal (MVPLN) models, first introduced by Park and Lord (2007), have been applied to overcome correlation issues among crash frequencies at different levels of injury severity (Ma et al., 2008; El-Basyouny and Sayed, 2009), which can also address over-dispersion and a fully general correlation structure. Those studies were focusing on crashes over time while spatial feature (i.e. where the crashes happen) also plays an important role. Spatial correlation has a tangible effect on regression analysis. Neglect of spatial distribution, structure and heterogeneity may lead to estimate deviations and mistakes in regression diagnostics. The Bayesian methods, which has a flexible hierarchy and favorable response to spatial-correlation random variables, can reflect accurately the factors affecting road safety (Hauer, 1997; Miaou and Song, 2005; Aguero-Valverde and Jovanis, 2006; Mitra and Washington, 2007; Quddus, 2008). When it comes to evaluating Bayesian models, Spiegelhalter et al. (2002) proposed a deviance information criterion (DIC) which comprehensively quantifies the degree of fitting and complexity of Bayesian models. Additionally, attempting to go beyond fixed-parameters models, Anastasopoulos and Mannering (2009) constructed a random-parameters negative binomial regression to study the factors determining crash frequency. This new approach correctly accounts for heterogeneity in a variety of factors and leads to a more comprehensive understanding of the factors contributing to crashes. Finally, Lord and Mannering (2010) conducted a comprehensive and systematic review of above-mentioned approaches. In order to accommodate heterogeneity among different groups and spatiotemporal correlation due to multilevel data structure, Huang and Abdel-Aty (2010) introduced a Bayesian hierarchical approach showing higher model goodness-of-fit and predictive performance when compared to conventional models. Two recent works by Mannering and Bhat (2014) and Mannering et al. (2016) further explored the evolution of methodological approaches in crash frequency research, highlighting the importance of addressing unobserved heterogeneity in crash analysis.

These core publications occupy central positions in the citation network, and play a crucial role in road safety studies. However, as a complex spatial distribution exists in safety data, the neglect of spatial characteristics will have a great impact on the accuracy and robustness of the estimates. Our above findings point to a new, emerging crash frequency models developed recently that take into account spatial correlations and heterogeneity. This frontier research includes the Bayesian spatial joint model (Zeng and Huang, 2014), semi-parametric geographically weighted Poisson regression (S-GWPR) model (Xu and Huang, 2015), MVPLN spatial model (Jonathan et al., 2016), Bayesian spatial random parameters Tobit model (Zeng et al., 2017), and multivariate hierarchical Poisson-lognormal (HPLN) spatial joint model (Alarifi et al., 2018).

5. Conclusion and future work

As the quantity of road-safety research continues to grow, big data is becoming more and more relevant to the field, leading to new challenges and providing new opportunities. In this paper, we proposed the use of co-citation and document citation analyses (i.e. VOSviewer and CitNetExplorer) to conduct scientometric analysis of the vast literature body relating to road safety studies.

Our co-citation analyses identified several main research topics within the road safety studies including the “effects of driving psychology and behavior on road safety”, “causation, frequency and injury severity analysis of road crashes”, “epidemiology, assessment and prevention of road traffic injury”, and “effects of driver risk factors on driver performance and road safety”.

Through our document citation analysis, the core publications and their citation relationships have been located and explored. These publications constituted the largest and the most important citation sub-network where we found that “crash frequency modeling analysis” was the core research topic in road safety studies. Starting from the assumption that crash frequency is governed by a Poisson process, it was found that the development of crash frequency models mainly based on Poisson, NB, ZIP, ZINB, RENB, NM, MVPLN, Bayesian, and random-parameters count models. Moreover, we found that the spatial statistical analysis technique is emerging as a frontier in this area.

Future studies may consider using different document databases and other bibliometric methods (such as bibliographic coupling analysis) to explore other aspect of road safety research. In addition, Altmetrics, a new and comprehensive bibliometric method for evaluating the academic and social influences of research outputs, can also be applied in combination with scientometric analysis to better understand the trends and new areas of research in the field.

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.

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