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Visualization and analysis of mapping knowledge domain of road safety studies

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ABSTRACT

Mapping knowledge domain (MKD) is an important application of visualization technology in Bibliometrics, which has been extensively applied in psychology, medicine, and information science. In this paper we conduct a systematic analysis of the development trend on road safety studies based on the Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) articles published between 2000 and 2018 using the MKD software tools VOSviewer and Sci2 Tool. Based on our analysis, we first present the annual numbers of articles, origin countries, main research organizations and groups as well as the source journals on road safety studies. We then report the collaborations among the main research organizations and groups using co-authorship analysis. Furthermore, we adopt the document co-citation analysis, keywords co-occurrence analysis, and burst detection analysis to visually explore the knowledge bases, topic distribution, research fronts and research trends on road safety studies. The proposed approach based on the visualized analysis of MKD can be used to establish a reference information and research basis for the application and development of methods in the domain of road safety studies. In particular, our results show that the knowledge bases (classical documents) of road safety studies in the last two decades have focused on five major areas of "Crash Frequency Data Analysis", "Driver Behavior Questionnaire", "Safety in Numbers for Walkers and Bicyclists", "Road Traffic Injury and Prevention", and "Driving Speed and Road Crashes". Among the research topics, the five dominant clusters are "Causation and Injury Severity Analysis of Road Accidents", "Epidemiologic Study and Prevention of Road Traffic Injury", "Intelligent Transportation System and Active Safety", "Young drivers' driving behavior and psychology", and "Older drivers' psychological and physiological characteristics". Finally, the burst keywords in research trends include Cycling, Intelligent Transportation Systems, and Distraction.

1. Introduction

Road crashes result in about 1.3 million fatalities and 50 million severely injuries worldwide every year. The number of road deaths is on the rise despite the continuing improvements in road safety (International Transport Forum, 2017). Road accidents put significant financial strain on families and the society. Many families fell into poverty due to the burden of long-term medical expenses, the loss of incomes, or the need to care for the disabled relative (Mohan et al., 2006). To this end, road safety research plays a significant role in the improvement of the socio-economic by reducing the occurrences and severities of road accidents.

Through a periodical review of research in road safety, it can be beneficial to understand the research status and identify gaps. However, the majority of literature reviews in this domain have been based on the summary of literatures with, and require a long-term accumulation, summarization and extraction of research activities in the domain. The existing reviewing approach thus often does not give the entire picture of road safety research which motivates the development of a new method in this paper. Using high-performance computers, more complete databases and information visualization technology, the mapping knowledge domain (MKD) methods provide a new way to conduct such a literature survey. In recent years, the MKD methods have been widely applied in exploring disciplinary development status, research frontiers, research hotspots, and systematic reviews (Zhu and Hua, 2017; van Nunen et al., 2017; Vega-Almeida et al., 2018; de la Hoz-Correa et al., 2018; Gaede and Rowlands, 2018). This paper proposes the use of MKD and employs bibliometric methods to proceed quantitative analyses, explores the research status in road safety research to objectively reveal the research development status, identify the research fronts and

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hotspots in the domain of road safety studies.

2. Methodology

Bibliometric analysis is a kind of document analysis methods which takes the advantage of bibliometric theory to analyze pertinent literatures through the use of mathematical and statistical approaches. It studies the distribution profiles, quantitative relations and clusters of the literatures. Within bibliometric analysis, MKD is a method to visually present the knowledge on a certain field of subject by means of data mining, information analysis, scientific measurement and graphic plotting. It has the function of knowledge navigation and belongs to the category of Scientometrics (Shiffrin and Börner, 2004). Bibliometric methods and MKD, with the advantages of comprehensive quantitative statistics, visual information display, objective description and evaluation, have become an important tool for global analysis and investigation in various scientific areas.

2.1. Data source and research process

The SCIE and SSCI citation index database in the Web of Science (WOS) Core Collection were retrieved as the source for this study. The retrieval topic was “Road Safety”, the timespan was “from 2000 to 2018”, and the document type was “Article”. A total of 9835 pertinent publications were collected, and the last update of the data was on May 9, 2018. The retrieved results were saved as a “Plain Text” with “Full Record and Cited References”. Note that only the “road safety” keyword was used in this study and the number might change with additional keywords added to the search. Nevertheless, the methodology proposed herein remains unchanged and the findings in this paper are applicable for multiple keywords search.

2.2. Analytical tool and method

The main method in this study is based on Scientometrics, and the analysis software used include VOSviewer and Sci2 (Science of Science) Tool. VOSviewer, developed by van Eck and Waltman (Leiden University) in Netherlands, is a literature knowledge unit visualization software based on Visualization of Similarities (VOS) technology, which has unique advantages in the display of mapping knowledge domains, especially in the aspect of clustering (van Eck and Waltman, 2010). The layer label display technology of VOSviewer enables the node of dense network to be clearly displayed through interactions, therefore, it is especially suitable for analyzing large-scale data and constructing complex networks. In the latest VOSviewer version 1.6.6, the co-occurrence network, citation network and coupling network can be constructed using file formats such as. net,. mat and. txt. The Sci2 Tool, developed by the research team of Börner (Indiana University) and Boyack (SciTech Strategies) in USA, is a modular toolset specifically designed for the study of science (Sci2 Team, 2009). The Sci2 Tool, embedded with a variety of database functions, can load data sets in the different formats to conduct fundamental analysis on Scientometrics, such as co-occurrence analysis, citation analysis, coupling analysis and burst detection analysis. The maps of knowledge domains can also be created by a variety of visualization algorithms built in the Sci2 Tool.

Mapping the knowledge domain is a kind of image which shows the development process and structural relationship on the scientific knowledge. It has the dual nature and characteristics of “graph” and “genealogy”, which means it is not only a visual knowledge graph but also a serialized knowledge genealogy, showing many implied complex relationships including network, structure, interaction, intersection, evolution, or derivative among knowledge units or knowledge clusters. Understanding these complex knowledge relationships can thus produce a new knowledge. The drawing (or creating) of mapping knowledge domains includes co-citation analysis, co-occurrence analysis and burst detection analysis as explained below.

- ***Document co-citation analysis***: In Scientometrics, citing documents form the research frontier in a certain field, and the cited documents form a knowledge base in that field. The document co-citation analysis is based on the statistics of the number of two documents being cited by one or more documents at the same time, so as to conduct the network analysis and cluster analysis for the cited documents and thus analyze the knowledge base of the certain subject represented by these documents.
- ***Keywords co-occurrence analysis***: The keywords in academic publications are the natural language words that express the thematic concepts of documents. The keywords condense authors’ academic viewpoints, making it an important indicator in bibliometrics. Keywords co-occurrence analysis is based on the statistics of the number of a pair of keywords being cited in the same document, so as to conduct the network analysis and cluster analysis for these words and thus reveal the knowledge structure and research frontier of a certain subject.
- ***Burst detection analysis***: Burst detection analysis takes into account the change of keyword frequencies and identifies the keywords with burst growth characteristics in a certain time period on a certain research sector, which can be used to study the development trend of a certain topic. It is different from the burst detection analysis based on threshold values, although each keyword may be used relatively less frequently, the burst keywords can be found according to the change of keyword frequencies over time, and thus the latest research trend can be predicted through such keywords.

2.3. Construction of co-word similar matrix

The construction of the keywords co-occurrence matrix is the basis of conducting cluster analysis. Counting the number of times of any two keywords appearing in the same documents, and n keywords can build a $n \times n$ co-occurrence matrix, which defines the similarity matrix S:

$$S = (s_{ij}) \tag{1}$$

where $s_{ij} \geq 0$ is a similarity measure defined below and $s_{ij} = s_{ji}$, $i, j \in \{1, 2, \cdots, n\}$

The idea of using the association strength in VOS to express the relationship between two objects is to cluster the objects with high similarity as much as possible, while the objects with low similarity should be separated as far as possible (van Eck and Waltman, 2007). VOSviewer uses association strength method to calculate the similarity s_{ij} between the objects i and j in a map as:

$$s_{ij} = \frac{c_{ij}}{W_i W_j} \tag{2}$$

where s_{ij} denotes the similarity between the objects i and j,

c_{ij} denotes the co-occurrence times of the objects i and j,

W_i and W_j denote the occurrence times of the objects i and j respectively.

Note that van Eck and Waltman (2009) specially discussed the advantages of this measure comparing to other similarity measures (such as the cosine, the inclusion index, and the Jaccard index).

2.4. Construction of knowledge domain maps

In order to make the clustering effect more obvious, the main idea of VOS is to minimize the sum of the weighted Euclidean distances of all the objects in each cluster, where the distance of each cluster can be determined with following equation:

$$E(X; S) = \sum_{i<j} s_{ij} \, || x_i - x_j ||^2 \tag{3}$$

where | • | denotes the Euclidean norm. In order to avoid all similar objects appearing in the same position, the following constraint condition is used:

$$\sum_{i<j} \|x_i - x_j\| = 1 \quad (4)$$

In density view, the color of a point in a map is determined by the point density, the average distance between two points is represented by a distance d as follow:

$$d = \frac{2}{n(n-1)} \sum_{i<j} \|x_i - x_j\| \quad (5)$$

$D(X)$ represents the density of point $X(x_i, x_j)$ given by:

$$D(X) = \sum_{i<j}^{n} W_i k\left\{\frac{\|x_i - x_j\|}{dh}\right\} \quad (6)$$

where $k \in [0, \infty)$ denotes kernel function,

$h > 0$ denotes kernel width parameter,

W_i denotes the weight of object i, namely the total frequency that i appears,

The kernel function shall be non-increasing, and VOS uses the Gaussian kernel function $k(t) = e^{-t^2}$.

After calculating the densities of objects, the color of a point in the map is determined by two steps:

Step 1: Calculating the weighted average of object colors in cluster to obtain the color of the cluster, and the weight of one color is equal to the object density of the corresponding cluster.

Step 2: Blending the color obtained in *Step 1* with the background color of the cluster density view, of which the background color is black or white.

3. Document statistical analysis

3.1. Yearly quantitative distribution of literature

The quantity variations of academic papers on a subject is a vital indicator of the development trend in that research area, and a reflection of change in the extent of the subject knowledge. By plotting the quantity of literatures over time and conducting multivariate statistical analysis, one can understand the research level and future development trend in a certain field. The earliest research article on road safety retrieved from the Wed of Science was published in 1976, and 10,258 pertinent articles have been included by 2017. It can be seen from Fig. 1 that the quantities of documents of road safety studies have been through four stages which are “Initial”, “Primary Development”, “Consolidation and Stabilization”, and “Rapid Development” explained below.

- ***Initial stage (1967–1990)***: From the first article of road safety studies published in 1967 to the 1990s, there were few of related research results in this field, and the maximum annual number of published papers was only 7, which means a complete document system had not yet been formed.
- ***Primary development stage (1991–1999)***: The number of pertinent documents in this stage started to rise significantly with an average annual growth of 8 articles. It can be considered that the field of research for road safety was initially formed during this period.
- ***Consolidation and stabilization stage (2000–2009)***: With the increasing emphasis on road safety from various countries, there had been a steady-growth with an average annual growth of 30 articles during this period.
- ***Rapid development stage (2010–2017)***: The pertinent documents in this stage have an average annual growth of 80 articles. It indicates that the research on road safety continues to increase and has entered the phase of rapid development.

3.2. Quantitative analysis of productive countries

According to the retrieved results, the documents on road safety studies come from 124 countries (or territories), and Table 1 lists the Top–10 productive countries with a total number of 7923 articles which accounts for 80.56% of the total publications. Most of the articles published by the developed countries in North America and Europe including two in North America, six in Europe, one in East Asia and one in Oceania. As expected, USA is the most active country in road safety research with a dominant output of 2347 articles, accounting for 23.86% of the total; As one of the emerging science forces (Rogers Hollingsworth et al., 2008), China ranks second with 972 articles accounting for 9.88%; while Australia ranks third with 948 articles accounting for 9.64%. Rank at 4th and 5th places, Canada and England (UK) accounted for 8.06% and 7.32%, respectively; Countries ranks between 6th and 10th accounting for about 4% on average. These productive countries are either economically developed or in at a rapid development stage which take road safety a higher priority than other countries.

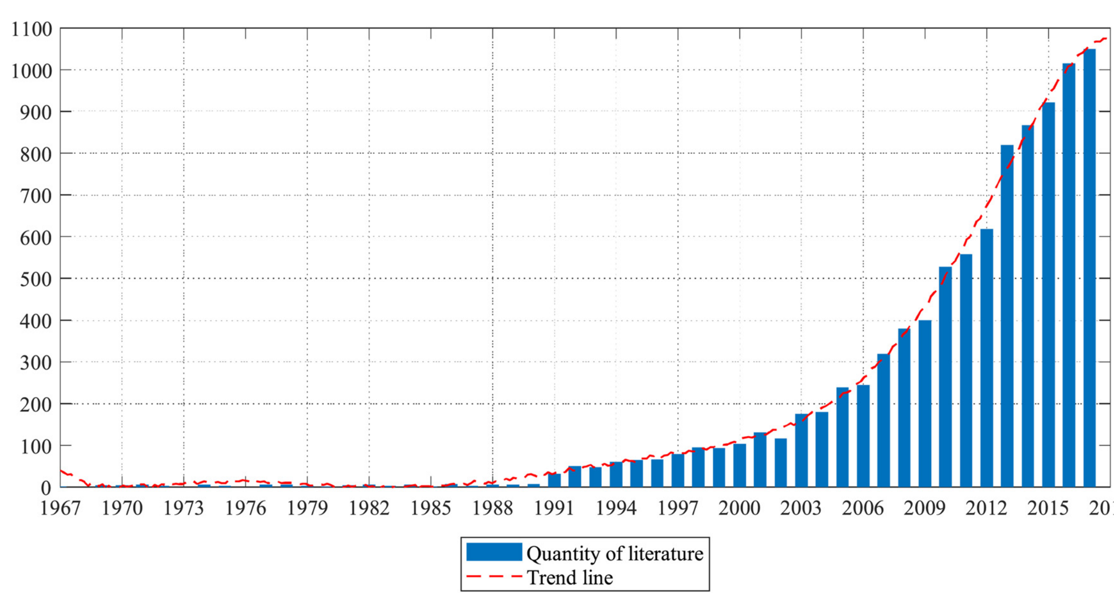

Fig. 1. Quantitative distribution of published articles in road safety studies, 1967–2017.
Note: As the data in 2018 is still updating, it is not included in this figure.

Table 1
Top–10 productive countries in road safety studies, 2000–2018.

Rank	Countries/ Territories	Region	Quantity	Percentage	Citations
1	USA	North America	2347	23.864%	33,069
2	China	East Asia	972	9.883%	7,783
3	Australia	Oceania	948	9.639%	14,721
4	Canada	North America	793	8.063%	9,520
5	England, UK	Western Europe	720	7.321%	10,306
6	Italy	Southern Europe	486	4.942%	5,042
7	France	Western Europe	475	4.830%	5,354
8	Spain	Southern Europe	446	4.535%	4,331
9	Germany	Central Europe	385	3.915%	4,008
10	Sweden	Northern Europe	351	3.569%	4,904

In VOSviewer, Citation Analysis was used to generate the knowledge domain map of main research countries in road safety area. Fig. 2 is a density heat map which visually displays the occurrence of high-frequency and related words in road safety research and its publications. The data in Fig. 2 is displayed as labels and the corresponding heat map area. The color of the area centered by the corresponding label (country) which depends on the number of articles published by that country. The larger the number is, the warmer (redder) the color is. While the smaller the number is, the cooler (bluer) the color is. Concentric color blocks have close links, while non-concentric color blocks also have a certain link if they are connected by blocks with different colors from the mazarine background. As shown in Fig. 2, the countries with larger nodes are at the central positions of blocks in this density view.

Observe that USA, China and Australia are in the central positions (reddish) of the map. Yuasa (1962), a Japanese science historian, defined countries that claimed more than 25% of the major scientific achievements of the entire world as the centers of scientific activity. In accordance with the statistical data in Table 1, USA occupies almost one fourth of the total number of published papers and exhibits the largest density (also the reddest) in the map which indicates that USA is indeed the international scientific center in road safety studies. China, despite having started the road safety research program later with the increase of car ownership, is in the second place in terms of the number of articles. This fact demonstrates that China has become more and more active in the international academic publications including the road safety area. Australia, which has been committed to the betterment of road safety since the 1970s, ranks third in road safety research in terms of publications. Through decades of endeavors, Australia has become one of the countries with the most satisfying situation with regard to road safety. Moreover, it has produced many scientific and practical outputs in all the aspects of road safety design, safety auditing and law enforcement (Austroads, 2009). Some European countries, such as the UK, France, Italy and Netherlands, have also been prominent in the road safety studies as shown in Fig. 2.

3.3. Quantitative analysis of main research organizations

Through the analysis of organization cooperation, the information on the most productive organizations and groups that are specialized in a certain theme within the discipline can be identified. According to the retrieved results, the documents on road safety studies come from 6166 organizations, and the Top–10 organizations with the largest number of published papers are listed in Table 2.

Often the research strength of universities is an indicator of the country's abilities in scientific research and innovation. It can be seen in

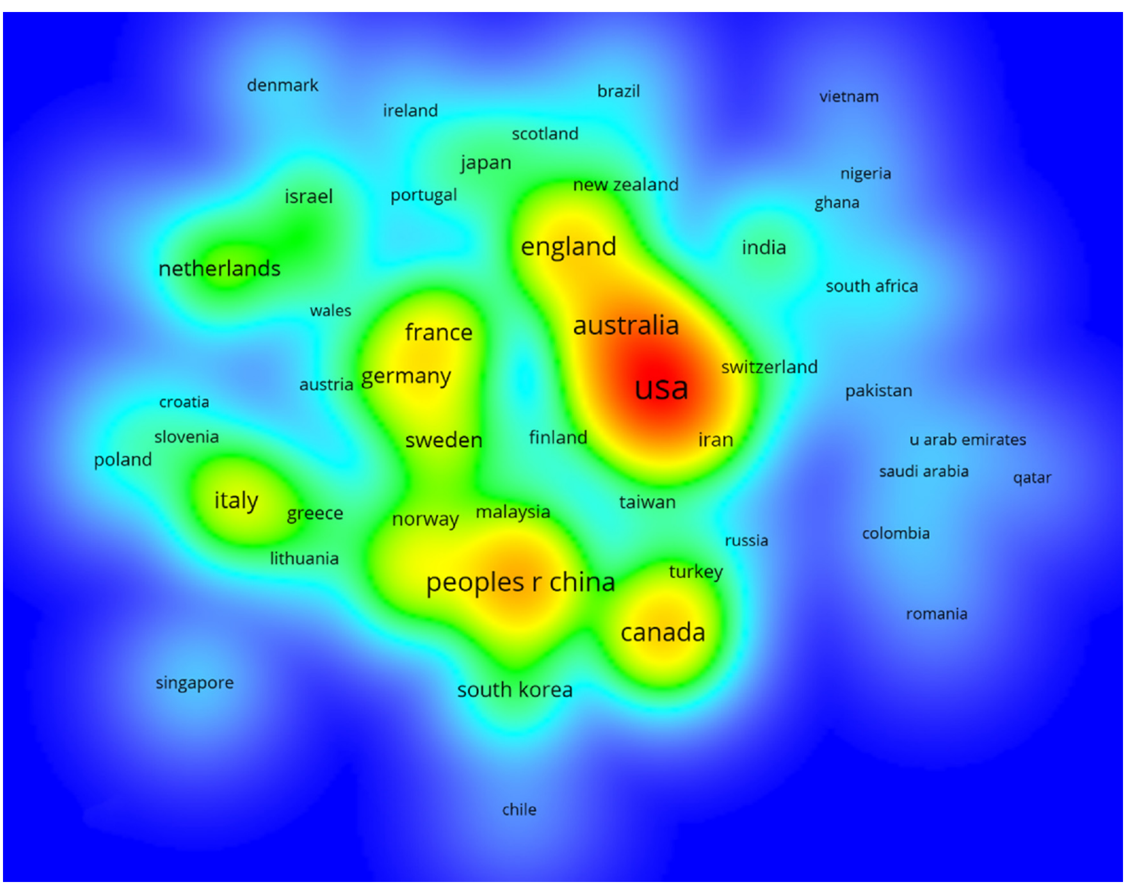

Fig. 2. Density of main research countries in road safety studies.

Table 2
Top–10 productive organizations in road safety studies, 2000–2018.

Rank	Organization	Country	Quantity	Percentage
1	Monash University	Australia	220	2.237 %
2	Queensland University of Technology	Australia	215	2.186 %
3	University of British Columbia	Canada	121	1.230 %
4	Delft University of Technology	Netherlands	96	0.976 %
5	Tongji University	China	95	0.966 %
6	National Technical University of Athens	Greece	90	0.915 %
7	Institute of Transport Economics	Norway	84	0.854 %
8	Tsinghua University	China	84	0.854 %
9	University of Sydney	Australia	83	0.844 %
10	University of Central Florida	USA	78	0.793 %

Table 2 that there are 9 universities who have contributed a total of 1082 papers accounting for 11% of the total publications in road safety. Table 2 also shows that universities and institutes in Australia, China, USA and some selected European countries are the main contributors on road safety studies. These organizations have published 1166 papers, which occupies 11.86% of the total. Of the 6166 organizations, 5813 organizations, which occupies 94.28% of the total, have published less than 10 papers. The results show that the published documents are highly concentrated in a few organizations only.

In VOSviewer, Co-Authorship Analysis was adopted to generate the knowledge domain map of main research organizations in order to demonstrate the collaboration network among the research organizations in road safety studies. The distribution of research strength can be found through collaboration network analysis, as shown in Fig. 3.

In Fig. 3, each node represents an organization, and the node sizes indicate the number of published articles. The links between nodes represent the collaborations where the greater width of the link (namely link strength) means the closer collaborations. In the course of generating the knowledge domain map of collaboration among main research organizations, 82 items, 8 clusters and 352 links were displayed and selected through automatic clustering. The collaboration knowledge domain map shows an obvious "locally centralized but globally discrete" type, indicating not very close collaborations among these organizations. This map also shows that Monash University has the most articles, followed by Queensland University of Technology and University of British Columbia. In terms of the number of links, Monash University also has the highest number (links = 28), followed by Queensland University of Technology (links = 26) and University of British Columbia (links = 17), indicating that these organizations are key nodes in the collaboration network. In terms of the link strength, two organizations with high link strength are usually in the same city, for example, the node that has the highest link strength with Monash University is the University of Melbourne (Link strength = 19), where both are located in Melbourne, Australia; the node that has the highest link strength with Tongji University is Shanghai Jiao Tong University (Link strength = 9), and both are in Shanghai, China.

3.4. Co-authorship analysis of main research groups

Because of the highly interdisciplinary nature of road safety studies, researchers are coming from different domains, such as traffic engineering, transport planning, mathematics, psychology, computer science, medicine, and statistics etc., where complementary advantages could be achieved through cooperation. Creating and analyzing the knowledge maps of co-authorship network of productive authors can provide valuable information for research organizations to develop cooperation groups, for individual researchers to seek cooperation

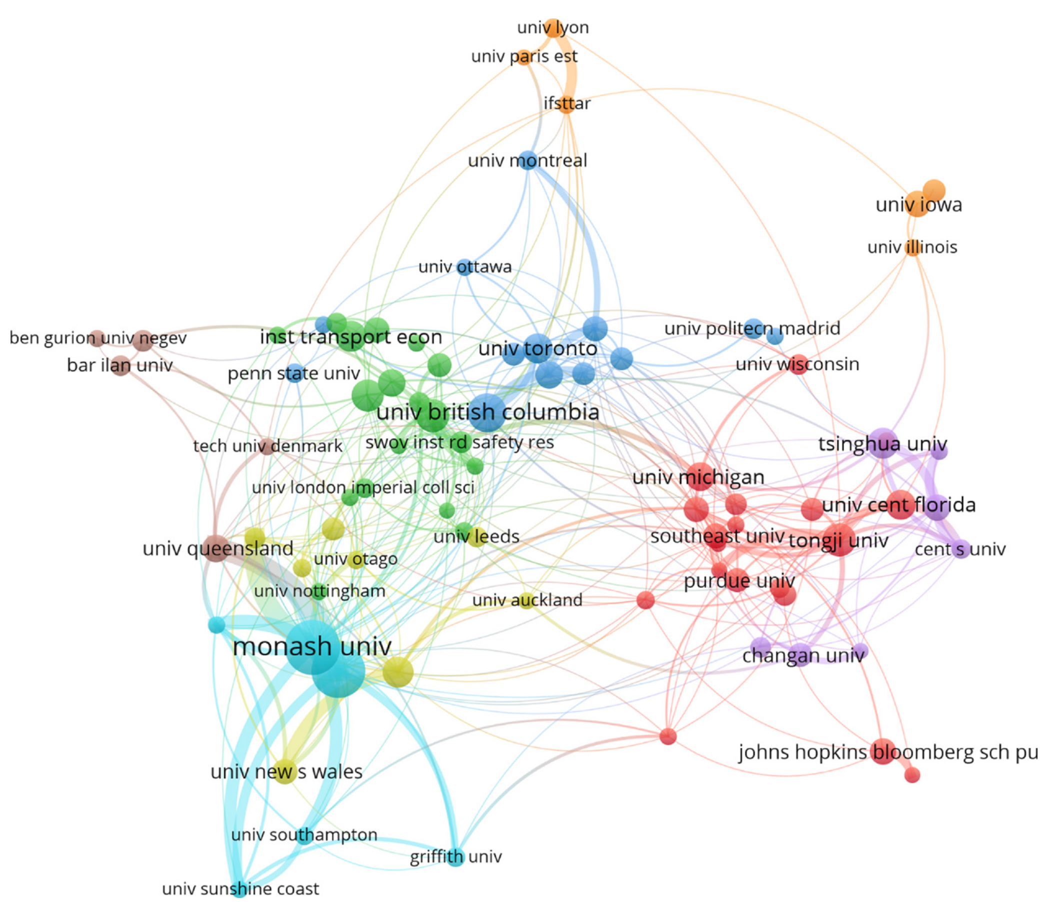

Fig. 3. Collaboration network among main research organizations.

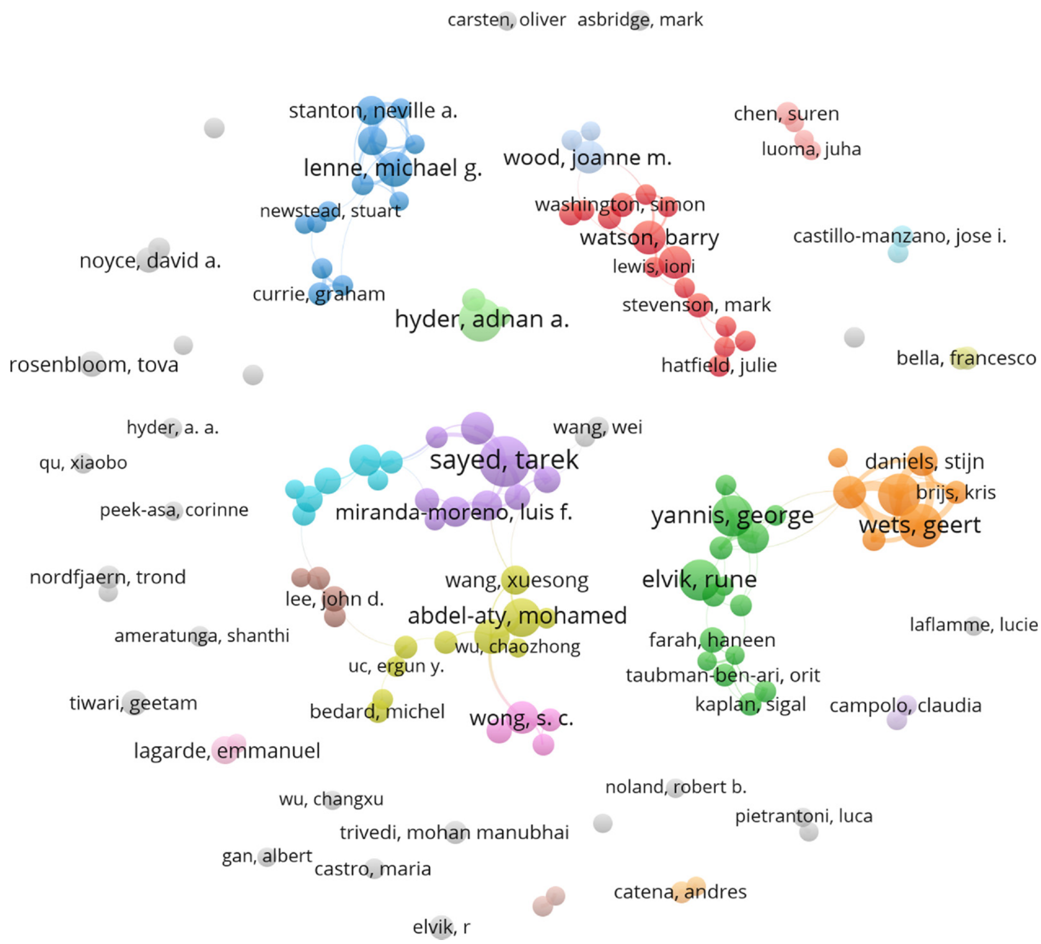

Fig. 4. Co-authorship network among productive authors.

Table 3
Top–10 main source journals in road safety studies, 2000–2018.

Rank	Journal Title	Citation Index	Impact Factor	Quantity	Percentage
1	Accident Analysis & Prevention	SSCI	2.685	1,263	12.842 %
2	Transportation Research Record	SCIE	0.592	740	7.524 %
3	Traffic Injury Prevention	SCIE SSCI	1.290	308	3.132 %
4	Transportation Research Part F: Traffic Psychology and Behaviour	SSCI	1.830	306	3.111 %
5	Journal of Safety Research	SSCI	1.841	222	2.257 %
6	Safety Science	SCIE	2.246	205	2.084 %
7	Injury Prevention	SCIE SSCI	1.482	185	1.881 %
8	IEEE Transactions on Intelligent Transportation Systems	SCIE	3.724	163	1.657 %
9	International Journal of Injury Control and Safety Promotion	SSCI	0.875	98	0996 %
10	IET Intelligent Transport Systems	SCIE	1.194	95	0.966 %

opportunities, and for publishers to assemble editorial teams (to publish books or special issues in journals). In VOSviewer, Co-Authorship Analysis was used to generate the knowledge domain maps of main research groups, as shown in Fig. 4.

In Fig. 4, each node represents an author, and the node sizes indicate the number of published articles. The link connecting two nodes stands for the cooperative relation between two authors, and the thickness of the link stands for the intensity of cooperation. Overall, the cooperation among productive authors is not close, however, there are several co-authorship groups, such as the yellow group taking Professor Mohamed Abdel-Aty (University of Central Florida) as the core, the purple group taking Professor Tarek Sayed (University of British Columbia) as the core, and the blue group taking Professor Michael G. Lenné (Monash University) as the core.

Co-authoring publications have critical significance for promoting research innovation and knowledge sharing, as well as improving the research quality. However, according to the analysis results on main research groups, most productive authors are in fact independent authors (grey nodes in Fig. 4) or work in pairs within the same organization, and the scale of such cooperation is nevertheless small and unstable, lacking effective international exchange and cooperation.

3.5. Quantitative analysis of main source journals

Academic journals are important information carriers for the communication, dissemination and inheritance of scientific achievements.

The journal analysis of an academic domain would identify the distribution of core journals in the field. Based on the retrieved results, 9835 articles were published by a total of 1950 journals, covering Engineering, Psychology, Transportation, Telecommunications, Business & Economics and other research domains. Journals with high degrees of aggregation of road safety articles are listed in Table 3.

The index databases (as shown in Table 3) to which the listed journals belong were retrieved through the Journal Citation Reports in the Web of Science including 4 journals in SSCI, 4 journals in SCIE, and 2 journals in both SSCI & SCIE. The number of SSCI collected articles (1889) is more than that of SCIE (1203), indicating that the majority of road safety studies are social sciences. In terms of the number of articles published by a journal, *Accident Analysis & Prevention (AA&P)* has the most articles published for road safety. In the second place is the *Transportation Research Record (TRR)*. *TRR* collects excellent papers in the Transportation Research Board (TRB) Annual Meeting which is the largest international conference in Transportation. *Traffic Injury Prevention (TIP)* ranks the third in terms of the number of articles published. Overall, the core journals in road safety studies are either multidisciplinary or interdisciplinary, indicating that road safety is a multidisciplinary or interdisciplinary science with characteristics from medicine, engineering, public health, social sciences and many other disciplines.

3.6. Document co-citation analysis: knowledge bases of road safety studies

The knowledge bases of road safety studies can be categorized into two types: 1) early fundamental documents on road safety; and 2) documents with high co-citation frequencies. Through document co-citation analysis, the important knowledge bases of the research field can be found efficiently and conveniently from the mass of cited references. Furthermore, the relevance and development process of documents can also be analyzed and excavated. In VOSviewer, Co-Citation Analysis was used to generate the cluster density map of document co-citation of road safety studies (Fig. 5).

As shown in Fig. 5, the cluster density view divides the entire knowledge network map into 5 clusters with different colors in accordance with the number and weight of nodes, and the relevance among the nodes using the default clustering method in VOSviewer (van Eck et al., 2010).

3.6.1. Cluster 1 (red): crash frequency data analysis

In this cluster, the classical document that has the largest density is “The statistical analysis of crash-frequency data: A review of assessment of methodological alternatives” by Lord and Mannering (2010) published in *Transportation Research Part A: Policy and Practice*. The number of co-citations is 148 with the largest total link strength of 750 which suggests that this article has a crucial position in the co-citation network structure.

In this paper, Lord and Mannering (2010) assessed the characteristics of crash-frequency data, discussed the methodological alternatives and limitations for examining such data. The traditional multiple linear regression, Poisson regression and negative binomial regression are well developed prediction modeling techniques of road crashes. Moreover, new models such as neural network, Bayesian neural network, and support vector machine have enriched the studies in this area. After conducting a specific comparative analysis of these models and approaches, Lord and Mannering (2010) believe that although the modeling approaches and techniques for analyzing crash frequency data have become increasingly complicated and more accurate, the traditional Poisson regression and negative binomial regression are still valuable because of their conciseness and practicability.

3.6.2. Cluster 2 (green): driver behavior questionnaire

In this cluster, the classical document that has the largest density is “Errors and violations on the roads: a real distinction?” by Reason et al. (1990) published in *Ergonomics*. The number of co-citations is 127, and the total link strength is 291.

For studying the relation between illegal driving behaviors and road accidents, a driver behavior questionnaire (DBQ) which exhibits a high reliability and validity is extremely crucial. Reason et al. (1990) established the original version of DBQ, which includes two factors, namely error and violation. The biggest difference between error and violation lies in the diverse psychological roots and interference mode demands. In particular, error is caused by the problems during the process of cognition, while violation includes motivational components and situational demands. Studies on the factor structure of DBQ (Blockey and Hartley, 1995; Lawton et al., 1997; Aberg and Rimmo, 1998; Mesken et al., 2002) come into basically the same finding: whether three-factor structure or four-factor structure, they are all the subdivisions of the two-factor (errors and violations) structure. The research significance of DBQ structure does not lie in the simple division of its structure, but the discussion of causes behind different risk-taking behaviors and various consequences. The division of DBQ structure is significant for understanding the mechanisms of risk-taking driving behaviors and for proposing effective intervening measures.

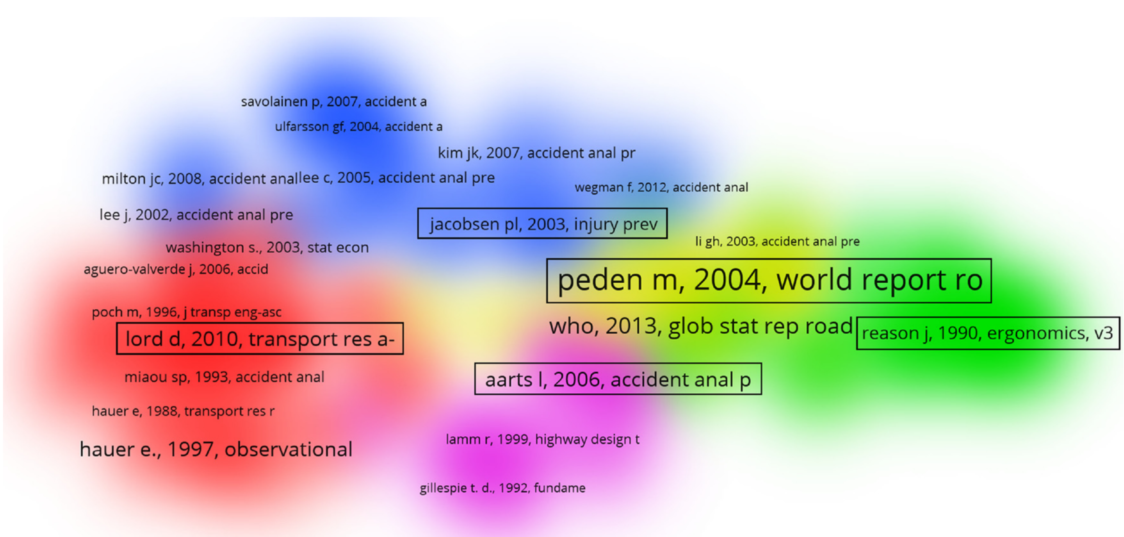

Fig. 5. Cluster density view of document co-citation network.

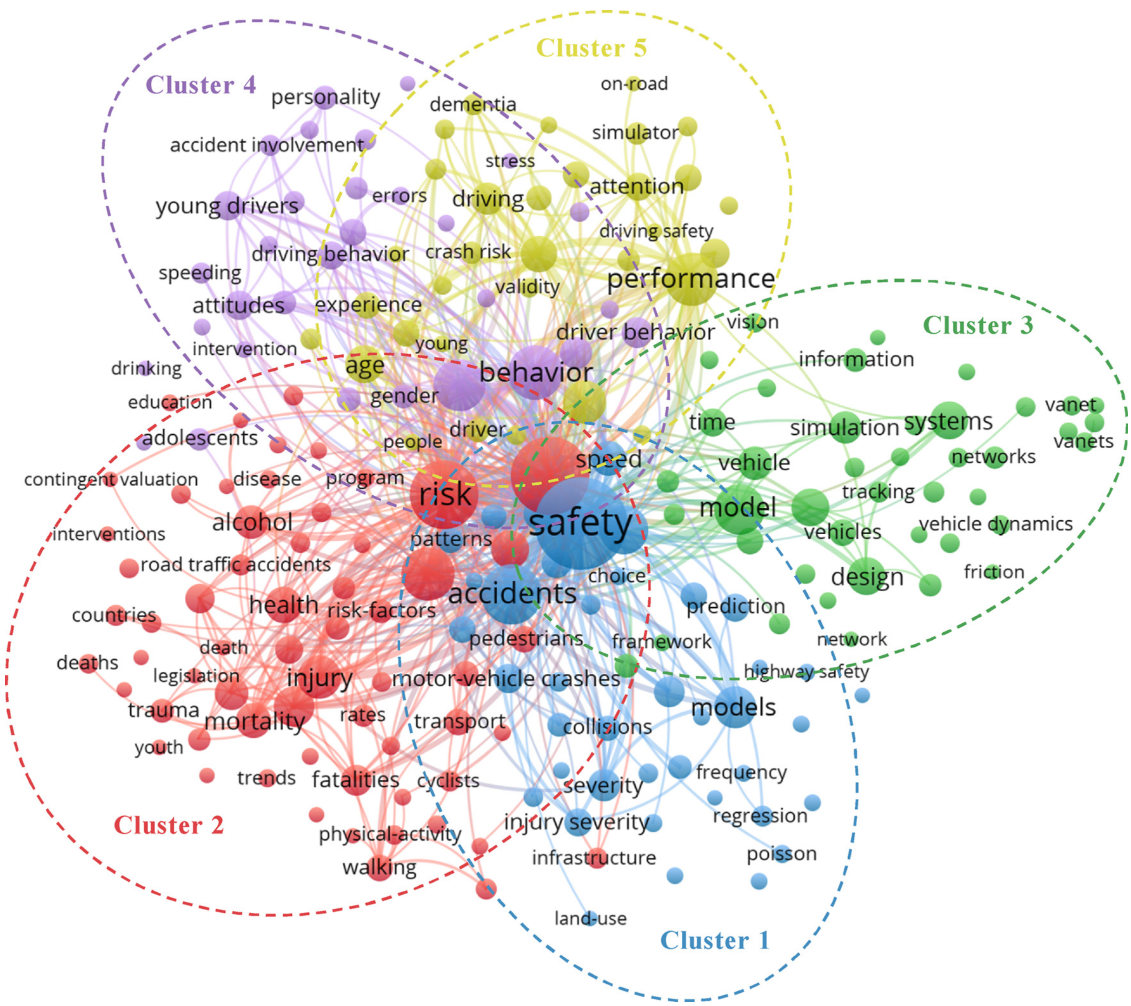

Fig. 6. Keywords co-occurrence network of road safety studies.

3.6.3. *Cluster 3 (blue): safety in numbers for walkers and bicyclists*

In this cluster, the classical document that has the largest density is "Safety in numbers: more walkers and bicyclists, safer walking and bicycling" by Jacobsen (2003) published in *Injury Prevention*. The number of co-citations is 108, and the total link strength is 307.

According to Jacobsen (2003), the increased levels of walking or cycling contribute to safer walking or cycling, and accordingly the effect of "Safety in Numbers" was first proposed, which has been verified in different cities and countries at different time periods. There is an obvious inverse correlation between the rate of walking or cycling with the mortality rate of walkers or bicyclists per trip and per kilometer. Moreover, in all the studied cities or countries, the mortality rate of walkers or bicyclists decreases with the rising level of walking or cycling. Despite the possible reason of smaller motor vehicle volume, this outcome could indicate a non-linear safety-in-numbers effect (Woodcock et al., 2009). Many scholars (Geyer et al., 2006; Tin et al., 2011; Johnson et al., 2014; Yao and Loo, 2016; Elvik and Bjørnskau, 2017; Fyhri et al., 2017) have adopted the data of various countries (or regions) to explore the causes and mechanisms of the effect of safety in numbers proposed by Jacobsen (2003).

3.6.4. *Cluster 4 (yellow): road traffic injury and prevention*

In this cluster, the classical document that has the largest density is "World Report on Road Traffic Injury Prevention" edited by Peden et al. (2004) and published by the World Health Organization (WHO). The number of co-citations is 283 which is the biggest in the entire co-citation network, and the total link strength is 409.

The WHO named the World Health Day (WHD) on April 7, 2004 as "WHD 2004: Road Safety" with the slogan "Road Safety Is No Accident", and road safety was discussed as an issue in the subsequent United Nations General Assembly (UNGA) together with the issuance of the "World Report on Road Traffic Injury Prevention". The compilation of this authoritative report convened a considerable number of senior experts and scholars who analyzed the global impact brought by road traffic injuries from multiple dimensions, and specifically analyzed the risk factors influencing exposure, crash involvement, injury severity and post-crash injury outcome in combination with data. On this basis, corresponding intervening measures have been proposed from several dimensions. After the release of this report in 2004, it has attracted extensive attention from the academic circles and been cited for as many as 3903 times in Google Scholar (recorded on May 12, 2018), making it an important knowledge basis.

3.6.5. *Cluster 5 (pink): driving speed and road crashes*

In this cluster, the classical document that has the largest density is "Driving speed and the risk of road crashes: A review" by Aarts and van Schagen (2006) published in *Accident Analysis & Prevention*. The number of co-citations is 151, and the total link strength is 349.

Driving speed has a direct influence on the occurrence and severity of road accidents. In this paper, Aarts and van Schagen (2006) reviewed the different models developed to reflect the relationship between collision rates and driving speed (in terms of absolute speed and/or speed dispersion), suggesting that roads with higher speed limits have the higher crash potential. Based on their research results, many scholars have conducted a series of studies on the relation between road safety and speed-related factors, such as variable speed limits (Yang et al., 2013; Yu and Abdel-Aty, 2014), speed variation (Quddus, 2013; Wang et al., 2016) and speed dispersion (Qu et al., 2014; Xu et al., 2016).

3.7. Keywords co-occurrence analysis: main topic distribution and research fronts of road safety

Keywords co-occurrence analysis is a common research method in Scientometrics. It is used to analyze the link strength between co-occurrence keywords by studying their co-occurrence relation in a large number of documents. Its purpose is to describe the internal composition relationship and structure in a certain academic domain as well as to reveal the research fronts of that discipline. Research front refers to the conceptual combination of a provisional research subject and its basic research problems, as well as the rising or unexpectedly emerging theoretical trends and new topics. In VOSviewer, Co-Occurrence Analysis was used to generate the keywords co-occurrence network of road safety studies, as shown in Fig. 6.

In Fig. 6, it can be seen that the frontier topics of road safety studies form five clusters, and the keywords in the same cluster show greater similarity in respect of research topic. With reference to the characteristics and status of road safety studies, these five clusters were analyzed respectively as follows:

3.7.1. Cluster 1 (blue): causation and injury severity analysis of road accidents

(The co-occurrence keywords include: accident frequencies, weather, exposure, geometric design, injury severity, models, speed, prediction, regression)

Due to the unavoidability of road accidents (not all accidents can be avoided), it is of great importance to reduce the frequency and severity of road accidents as much as possible. Using statistical and machine-learning models to analyze accident data and explore the complex relationship between contributing factors and frequency and severity of road accidents has become an important research branch.

Of all models used for causation and injury severity analysis of road accidents, Models For Count Data are often used for analysis of the contributory factors to crash frequency (Martin, 2002; Lord et al., 2005; Wong et al., 2007); Discrete Outcome Models are often used for analysis of the injury severities in crashes (Kim et al., 2007; Savolainen and Mannering, 2007; Tay et al., 2011;), causation analysis of road accidents (Sullman et al., 2002; Young and Liesman, 2007) and violation analysis of traffic laws (Kim et al., 2008b); Structural Equation Models were used to analyze the causal relationship between psychological factors and driving behavior (Ulleberg and Rundmo, 2003; Machin and Sankey, 2008); Classification and Regression Trees were used to identify the critical factors affecting road accidents (Chang and Chen, 2005; Kashani and Mohaymany, 2011); non-regression models, such as Support Vector Machine Models (Li et al., 2012; Chen et al., 2016a, b), Decision Tree Models (de Oña et al., 2013a, b; Abellán et al., 2013), Naïve Bayes Models (Chen et al., 2016a, b) and Bayesian Network Models (de Oña et al., 2013a, b; Prati et al., 2017; Zou and Yue, 2017), were also used for the causation and injury severity analysis of road accidents.

In recent years, the great improvement in computing power and development of more sophisticated statistical techniques have contributed to the rapid progress in developing road safety prediction models. The multivariate multi-level complex modeling techniques are gradually replacing the traditional univariate single-level modeling methods that are based on linear model and Poisson model, and have been validated and applied in practice (Deublein et al., 2013; Dong et al., 2015; Fawcett et al., 2017; Iranitalab and Khattak, 2017; Basso et al., 2018). The multivariate multi-level complex models integrate multivariate response variables like frequency, severity and type of road accidents, and also simultaneously consider socio-economic factors at the regional level, road environmental factors at traffic facility level, vehicle and driver-related factors at accident level and other multi-level influencing variables. In addition, the application of Bayesian estimation method and artificial intelligence (AI) modeling techniques are two major development directions in this domain.

3.7.2. Cluster 2 (red): epidemiologic studies and prevention of road traffic injury

(The co-occurrence keywords include: epidemiology, helmet use, crashes, trauma, injury, mortality, prevention, impact, risk)

Road traffic injury (RTI) is not only a road safety concern but also an important public health issue. RTI claims more than 1.2 million lives each year, thus deeply impacts health and society (World Health Organization, 2015). Injury epidemiology is mainly used to analyze the causes and types of personal injuries in road accidents, to study the human factors, environment and engineering technology, and to evaluate the effectiveness of various measures taken in the process of RTI protection.

The existing epidemiologic studies of RTI are mainly based on the distribution, risk factors and prevention of RTI. The distribution research of RTI include temporal distribution (Connor et al., 2002; Nakahara et al., 2005; Akaateba et al., 2014), spatial distribution (Odero et al., 2003; Oluwadiya et al., 2009), age distribution (Kim et al., 2008a; Chini et al., 2009; Wong et al., 2009), road user type (Naci et al., 2009; Constant and Lagarde, 2010; Hatamabadi et al., 2012), and type of injury (Oluwadiya et al., 2009). The risk factor research of RTI include fatigue driving (Connor et al., 2001; Bunn et al., 2005; Robb et al., 2008), driving under the influence of alcohol (Connor et al., 2004; Di Bartolomeo et al., 2009; Ditsuwan et al., 2013), driving under the influence of drugs (Smink et al., 2005; Michael Walsh et al., 2005; Elvik, 2013), seatbelt non-use (Bendak, 2005; Movahedi et al., 2010; Abbas et al., 2011), helmet non-use (Valent et al., 2002; Liu et al., 2008; Kim et al., 2017), and speeding (Bener and Alwash, 2002; Abegaz et al., 2014). Accordingly, many scholars have studied the prevention of RTI, such as speed zone setting (Noland et al., 2008; Grundy et al., 2009; Steinbach et al., 2011), utilization of speed cameras (Pilkington and Kinra, 2005; Pérez et al., 2007; Wilson et al., 2010), alcohol-impaired driving law enforcement (Nagata et al., 2008), and seat belt law enforcement (Houston and Richardson, 2002; Cohen and Einav, 2003; Farmer and Williams, 2005).

However, the current epidemiologic studies of RTI mostly position at the descriptive research level, with less analytic research, not to mention the experimental research. In future, the study of RTI should be further expanded to other fields, such as the study of behavior and environment related to RTI. More measures need to be taken, such as strengthening the analytic and experimental researches, establishing the monitoring systems of road accidents, and carrying out the evaluation research of road accident prevention. They will allow the epidemiologic studies of RTI to play a more active and effective role in improving road safety.

3.7.3. Cluster 3 (green): intelligent transportation system and active safety

(The co-occurrence keywords include: ad-hoc networks, intelligent transportation systems, vanets, simulation, active safety, vehicular networks, and identification)

In the development of modern transportation systems, Intelligent Transportation System (ITS) is an important research area, and also one of the most important technological means to realize road safety in the contemporary world. At present, there are a great variety of ITS technologies, and based on the idea of "Haddon Matrix" (Haddon, 1999) which considers road accidents from the perspective of development process (pre-crash phase → crash phase → post-crash phase), the ITS technologies can improve road safety from the following three levels:

- Reduce the number of traffic conflicts to eliminate the occurrence possibility of a road accident, such as Intelligent Speed Adaptation (Carsten and Tate, 2005; Vlassenroot et al., 2007; Lai et al., 2012), Electronic Stability Control (Erke, 2008; Høye, 2011; Strandroth et al., 2012), and Anti-Lock Braking Systems (Broughton and Baughan, 2002; Mirzaei and Mirzaeinejad, 2012)

- Reduce the severity of a road accident when it occurs, such as Brake Asist System (Oh et al., 2009; Badea-Romero et al., 2013) and Collision Avoidance Systems (McLaughlin et al., 2008; Brännström et al., 2013).
- Shorten the time for rescue to reduce the possibilities of serious injury and death after a road accident, such as eCALL (Jarašūniene and Jakubauskas, 2007) and Automatic Collision Notification (Ponte et al., 2016).

In recent years, the driving assistance systems used to improve driving safety have been greatly improved. Furthermore, new emerging technologies such as vehicle-vehicle communication, vehicle-road communication, event detection and autonomous vehicles will be widely used in the road traffic system in the foreseeable future. Thus, researchers must consider whether driving behavior and its safety will be affected and what changes will take place during the mix-driving period of traditional and new-technology vehicles. It is necessary to study the reciprocal and mutual effects between driving behaviors and ITS technologies and systems.

3.7.4. Cluster 4 (purple): young drivers' driving behavior and psychology

(The co-occurrence keywords include: adolescents, attitudes, drinking, novice drivers, personality, speeding, violations, driver behavior, and sensation seeking)

Young drivers are universally recognized as a major problem in public health and injury prevention due to their persistent over-representation in road crashes (Scott-Parker et al., 2015). Young drivers are more prone to road accidents due to lack of experience and sensation seeking (Jonah et al., 2001; Clarke et al., 2006; Mayhew, 2007; Braitman et al., 2008; Scott-Parker et al., 2009; Cestac et al., 2011). A large number of studies indicate that, compared to senior drivers, young drivers are more prone to speeding (Clarke et al., 2005), violations and crashes (Hirsch et al., 2006), dangerous driving behaviors (Palk et al., 2011), texting while driving (Nemme and White, 2010), aggressive driving behaviors (Shinar and Compton, 2004; Constantinou et al., 2011; Lambert-Bélanger et al., 2012), and overestimate their driving skills, thereby underestimating the potential dangers in the driving environment (White et al., 2011; De Craen et al., 2011).

Driving behavior and psychology of young drivers, especially young novice drivers, have been an important research topic in the field of road safety. This topic focuses on studying the fields related to road users, including the relationship between drivers and vehicles, drivers and road environment, drivers and pedestrians and other road users. In the domain of road safety psychology, young drivers' personality, behavior, perception and attitude are all the key research directions. This kind of research is mostly realized by questionnaire survey, and the simulation experiments using vehicle driving simulators are more and more applied to such research.

3.7.5. Cluster 5 (yellow): older drivers' psychological and physiological characteristics

(The co-occurrence keywords include: older drivers, distraction, ability, disease, dementia, fatigue, driving performance, reliability, sleepiness)

With aging population, the increased number of elderly drivers not only changes the characteristic of the traffic flow, but also requires more specific attention to their driving ability and safety. In particular, the vision, perception, self-regulation, reaction ability and many other psychological and physiological aspects of older drivers will directly affect their driving behaviors and driving abilities (Mori and Mizohata, 1995; Anstey et al., 2005; Cantin et al., 2009). As the psychological factors of drivers are the important factors affecting drivers' behaviors, many scholars have studied the older drivers from the aspect of individual psychological factors, including personality and attitudes (Owsley et al., 2003; Schwebel et al., 2007; Classen et al., 2011; McPeek et al., 2011; Nichols et al., 2012; Lucidi et al., 2014), self-assessment (Marottoli and Richardson, 1998; McPeek et al., 2011; Siren and Meng, 2013), self-regulation (Benekohal et al., 1994; Molnar and Eby, 2008; Blanchard and Myers, 2010). With the increase of age, the changes of physiological characteristics of older drivers lead to the decline of driving ability, thus affecting safe driving. Such studies on physiological characteristics of older drivers including nervous system and cognitive function (Anstey et al., 2005; Devlin et al., 2012; Ferreira et al., 2013; Aksan et al., 2015), perception and reaction ability (Bieliauskas, 2005; Horswill et al., 2008; Anstey and Wood, 2011; Boot et al., 2014), visual sense (Wood, 2002; Mainster and Timberlake, 2003; Clay et al., 2005), and hearing sense (Green et al., 2013; Thorslund et al., 2014).

Another research direction in traffic management for the elderly is to study the travel characteristics of the elderly from the aspects of physiological characteristics and psychological cognition, in order to construct specific measurement models of the travel characteristics for elderly by synthesizing statistical and psychological analysis methods. Moreover, it is important to evaluate the driving ability of the elderly, to study the travel modes (or choices) suitable for the elderly, and to design the transportation facilities based on the driving characteristics of older drivers.

3.8. Burst detection analysis: research trends of road safety

Burst Detection Algorithm (BDA) was first proposed by Kleinberg (2003), which considers the density of the frequency changes of keywords to identify the keywords with characteristics of high concentration and high density in documents. BDA can be used to detect the sudden growth in the frequency of usage of subject terms in a certain research field, which can be applied to authors, citations, journals, countries, organizations, keywords and other subject terms in topics and keywords. When conducting burst detection to author original keywords, the burst weight, burst start and end years of each burst keyword can be obtained, so as to analyze the change of research trends in the field of road safety studies.

In Sci2 Tool, Temporal Bar Graph is used to show the temporal distribution of burst keywords, in particular, show the time span of burst keywords. As shown in Fig. 7, each horizontal bar represents a burst keyword on its left side, the length of a horizontal bar represents the burst duration, the two sides of the horizontal bar represent a specific start and end year, and the size of a horizontal bar represents the burst weight of a keyword.

Herein we import the data into Sci2 Tool and run Burst Detection. The parameter settings are as follows: Gamma = 1.0, Density Scaling = 2.0, Bursting States = 1, Burst Length = 1 (year). In consideration of the visualization effect, the Top-30 keywords with the largest burst weights were selected to conduct visualized analysis, as shown in Fig. 7 and Table 4:

During the period 2000–2005, road safety studies began to develop rapidly, in which a large number of burst keywords were produced, such as Speed, Sleepiness, Road Rage, and Aggressive Driving, indicating that road safety has become a hot research field and formed diversified studies in such period. Among the burst keywords, "Speed" is an important factor in road safety, as speed not only affects the severity of a crash, but is also related to the risk of being involved in a crash (Aarts and van Schagen, 2006); "Sleepiness" is closely related to drowsy driving: people who experience acute or chronic sleepiness can increase drowsiness and the risk of crash involvement (Beirness et al., 2005); As for "Road Rage" and "Aggressive Driving", the (anger) emotion of drivers can seriously affect driving safety, which is mainly reflected in the decline of driver's attention, perception, information processing, judgment and decision making, and usually lead to stronger

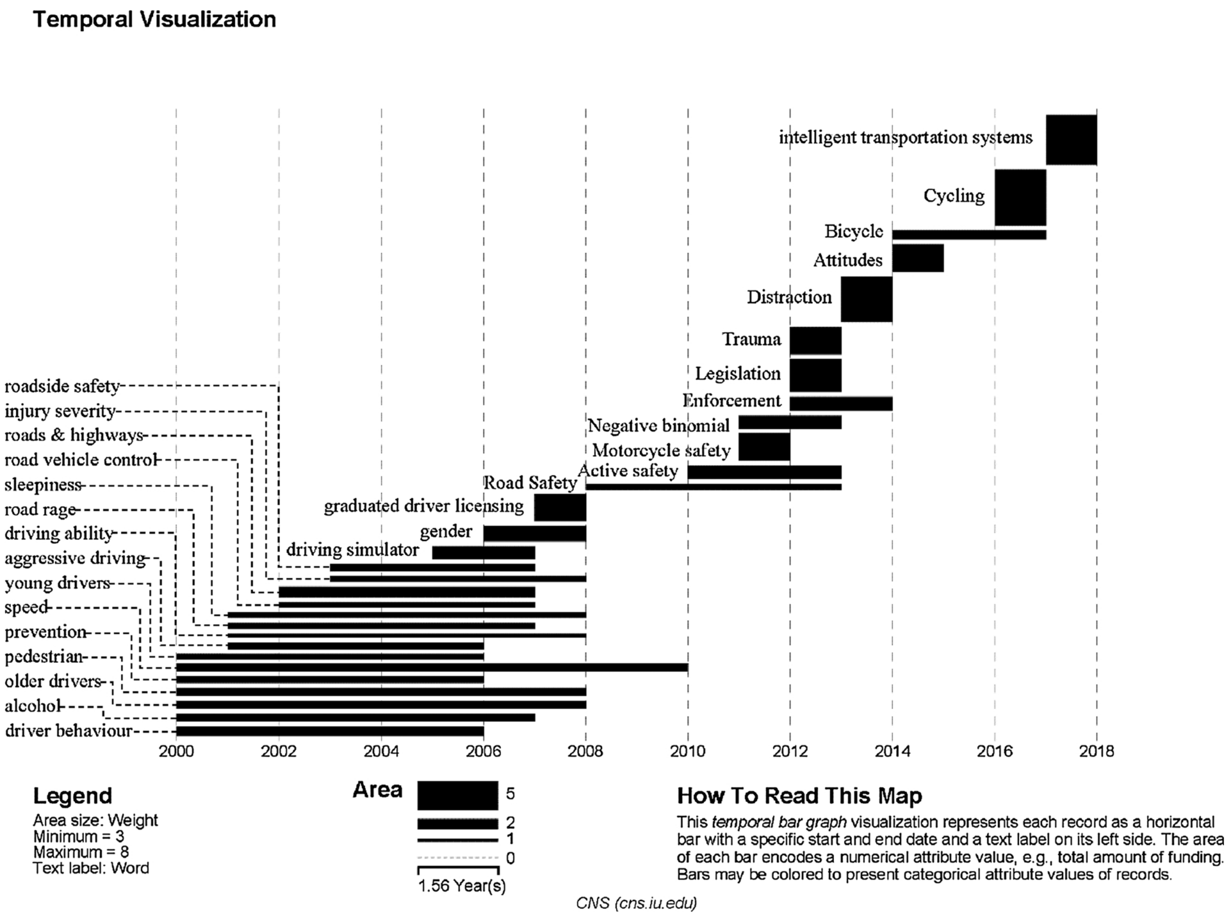

Fig. 7. Temporal bar graph of Top–30 original keywords burst in 2000–2018.

Table 4
Top–30 original keywords burst in 2000–2018.

Period	Keywords	Weight	Length	Start	End
2000–2005	Speed	8.4291	11	2000	2010
	Pedestrian	7.7083	9	2000	2008
	Older drivers	7.3124	9	2000	2008
	Alcohol	6.5612	7	2000	2006
	Roads & highways	6.1570	6	2002	2007
	Driver behaviour	6.0326	8	2000	2007
	Prevention	4.6877	7	2000	2006
	Road rage	4.2186	7	2001	2007
	Sleepiness	4.1411	8	2001	2008
	Aggressive driving	3.9521	6	2001	2006
	Roadside safety	3.3664	5	2003	2007
	Young drivers	3.3253	7	2000	2006
	Road vehicle control	3.2987	6	2002	2007
	Driving ability	3.1090	8	2001	2008
	Driving simulator	2.9768	3	2005	2007
	Injury severity	2.9750	6	2003	2008
2006–2011	Active safety	4.5209	4	2010	2013
	Gender	3.6567	3	2006	2008
	Road Safety	3.2540	6	2008	2013
	Motorcycle safety	3.2038	2	2011	2012
	Graduated driver licensing	3.0950	2	2007	2008
	Negative binomial	2.9521	3	2011	2013
2012–2018	Cycling	6.5321	2	2016	2017
	Intelligent transportation systems	5.7693	2	2017	2018
	Distraction	5.3305	2	2013	2014
	Legislation	3.8093	2	2012	2013
	Enforcement	3.2668	3	2012	2014
	Bicycle	3.2164	4	2014	2017
	Attitudes	3.1572	2	2014	2015
	Trauma	3.1417	1	2012	2012

driving movements and more frequent change of driving operations. Additionally, serious road rage can lead to speeding and aggressive driving behavior.

During the period between 2006 and 2011, the number of burst keywords decreased, and the distribution of burst weights was more even compared with that of the period from 2000 to 2005. The results indicated that the research network of road safety has been gradually expanded, and more research branches have been produced. It can be seen from Table 4 that the main research trends during this period focus on Gender, Motorcycle Safety, and Graduated Driver Licensing. Although there is no consensus on whether the risk of road accident varies by “Gender”, the driving behaviors of female drivers differ from that of male drivers due to the different physiological and psychological factors. It is worth studying the contributing factors to road accidents resulted by female and male drivers respectively, in order to propose more appropriate and effective countermeasures for the betterment of road safety; Due to the high speed and less physical protection of “Motorcycles”, both the drivers and passengers are at great risk by taking such trip mode in road traffic activities. During this period, risk factors, especially helmet non-use, have become the hot issues in the motorcycle safety studies (Passmore et al., 2010; Yu et al., 2011; Zamani-Alavijeh et al., 2011); “Graduated driver licensing (GDL)” systems, which was firstly introduced in 1960s in Australia, were designed to reduce the high crash risk of young novice drivers (Fell et al., 2011). The evaluation research of GDL has also become the hotspot in the field of road safety studies (Shope, 2007; Neyens et al., 2008).

During the period from 2012 to 2018, three keywords with high burst weights appeared in road safety research, which became new research branches. Among them, the burst weight of “Cycling” was 6.5321, which reflected the sharp increase of correlational research on cycling safety, and then condensed into a research trend of this period. Cycling has the characteristics of low road occupancy, fitness and environmental protection, however, only by improving the safety level of cyclists can highlight the value of cycling; the burst weight of "Intelligent Transportation Systems" was 5.7693, which had formed a research hotspot in this period. As discussed in Section 3.7.3, the functions of ITS to road safety were embodied in the uses of advanced technologies to detect road traffic information, providing sufficient information for drivers, reducing accident factors in the road environment, and automatically avoiding risk in emergency situations as well as speeding up rescue activities and reducing after treatment delays; In addition, "Distraction" also presents a higher burst weight (5.3305). The effects of distraction on drivers are multi-level, including visual/operational behavior, driving stress, and risk perception ability. The two major types of distraction are visual distraction and cognitive distraction which can be defined as “eyes-off-road” and “mind-off-road” respectively (Almahasneh et al., 2014). Texting is the most alarming distraction, which has attracted a great deal of attention (McKeever et al., 2013; Stavrinos et al., 2013; Yannis et al., 2014; Gauld et al., 2014; Caird et al., 2014)

4. Conclusion and future work

The use of MKD aims to describe the development process and structural relationship of scientific knowledge, which has the advantages of visualization, quantitative analysis, and knowledge discovery. Based on the MKD analysis method in Scientometrics, the VOSviewer and Sci2 Tool were used to conduct multi-angle and complementary analyses on road safety studies from the aspects of document co-citation analysis, keywords co-occurrence analysis as well as burst detection analysis. The main research conclusions are as follows:

(1) The vigorous growth of the number of articles indicates that road safety studies are developing rapidly in the global academic community. According to the article distribution by countries, USA, China and Australia are on top of the list, which indicates that these countries are the development centers and active regions in road safety science. In terms of research organizations, the research outputs from Monash University, Queensland University of Technology, and University of British Columbia are the highest, however, the cooperation density among these main research organizations needs to be further strengthened. Within the co-authorship network, the research groups in the University of Central Florida (UCF), University of British Columbia (UBC), and Monash University (MU) are the major groups with great influence and contributions, nevertheless, the cooperation among productive authors is at a low level, which indicates the not-close academic relationship among scholars. In the aspect of source journals, *Accident Analysis & Prevention*, *Transportation Research Record*, and *Traffic Injury Prevention* are the authoritative journals in the field of road safety studies, which are the important platforms for the publication and exchange of research findings.

(2) The knowledge bases on road safety studies were extracted by creating the cluster density map of document co-citation which provides insight into the development of theories and methods, as well as highlights results for road safety studies in recent years. It found that the five classical documents with the highest co-citations focus on the issues of “Crash Frequency Data Analysis”, “Driver Behavior Questionnaire”, “Safety in Numbers for Walkers and Bicyclists”, “Road Traffic Injury and Prevention”, and “Driving Speed and Road Crashes”, which were the core research hotspots of road safety. The authors of these five articles (Lord and Mannering, 2010; Reason et al., 1990; Jacobsen, 2003; Peden et al., 2004; Aarts and van Schagen, 2006) are the research experts with prominent contributions in the field of road safety studies.

(3) By clustering network map for keywords co-occurrence and analyzing the research activities in road safety, it was found that the frontier topics in road safety studies consist of five representative areas: “Causation and Injury Severity Analysis of Road Accidents”, “Epidemiologic Study and Prevention of Road Traffic Injury”, “Intelligent Transportation System and Active Safety”, “Young Drivers’ Driving Behavior and Psychology”, and “Older Drivers’ Psychological and Physiological Characteristics”. There are some overlapping among the five clusters (Fig. 6), indicating that cross-over studies exist among the various research areas which is expected in this multidisciplinary research field.

(4) Using the Burst Detection in Sci2 Tool to explore the research trends of road safety, it was found that most of the burst keywords in road safety were appeared during the period from 2000 to 2005, such as speed, older drivers, driver behavior, and road rage. Started from 2006, the research hotspots have gradually turned to the keywords of gender, motorcycle safety, and graduated driver licensing; and since 2012, cycling, ITS, distraction, and legislation have gradually become the new research hotspots. In addition, it can also be found that the main keywords appeared in the research trends overlap with the frontier topics. These overlapping keywords, such as speed, driver behavior, and ITS, are all the important contents of road safety studies.

In this research, we focus on the research topics and fronts of road safety studies where we propose a MKD-based systematic analysis to identify the knowledge bases, topic distribution and research trends. For future work, the topics in the research field of road safety will be studied to further investigate the development of a certain research branch or topic. The weights of keywords, authors, organizations and journals will also be studied to make the analysis results more insightful.

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