Visualization Analysis of Intelligent Vehicles Research Field Based on Mapping Knowledge Domain

Yi He, Shuo Yang, Ching-Yao Chan, Long Chen, and Chaozhong Wu

***Abstract*— This study combines applied mathematics, visual analysis technology, information science with an approach of Scientometrics to systematically analyze the development status, research distribution and future trend of intelligent vehicles research. A total number of 3933 published paper index by SCIE and SSCI from 2000 to 2019 are researched based on Mapping Knowledge Domain (MKD) and Scientometrics approaches. Firstly, this paper analyzes the literature content in the field of intelligent vehicles by including the literature number, literature productive countries, research organization, co-authorship of main research groups and the journals from which the articles are mainly sourced. Then, co-citation analysis is used to obtain five major research directions in the field of intelligent vehicles, which include "system framework", "internet of vehicles", "intersection control algorithms", "influence on traffic flow", and "policies and barriers", respectively. The keyword co-occurrence analysis is applied to identify four dominant clusters: "planning and control system", "autonomous vehicle questionnaire", "sensor and vision", and "connected vehicles". Finally, we divide burst keywords into three phases according to the publication date to show more clearly the change of research focus and direction over time.**

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I. Introduction

VEHICLE crashes led to 34,080 fatalities in U.S and over 63,093 fatalities in China in 2012 [1] and remained a major issue, where about 90% of the accidents are attributed driver factor. World Health Organization indicates that road accident injuries will become the fifth leading cause of death by 2030 [2]. Intelligent vehicles have unparalleled advantages in improving traffic safety, and its social benefits and market potential have been supported and recognized.

It is meaningful to comprehensively understand the status quo of research on intelligent vehicles and identify the coverage and gaps among the abundant research papers. However, previous studies are mostly based on the summary of limited research literatures and discuss the literature review results according to subjective description which cannot fully reflect the whole picture of related research. In this case, how to quantify and comprehensive analysis the literature review of intelligent vehicle is a challenging research. Mapping Knowledge Domain (MKD) is a scientific and intuitive approach which combines applied mathematics, visual analysis technology, information science and other disciplines with Scientometrics and literature analysis. With high-performance computers, vast research databases and data visualization technologies, MKD can enable a novel approach to visualize the knowledge network structure, development status, research hotspots, and future trends of the discipline L. Zhu used the MKD method to study China's oil and gas industry [3]. Danmin Qian explored the frontiers of medical information education based on the MKD [4]. MKD can also be used to study the current state of international research and hot frontiers of knowledge communication [5]. Bibliometric analysis and MKD are widely used in the field of literature review and analysis for their advantages of intuitive quantitative statistics, clear visual graphic display, objective description and evaluation [6]. In this paper, MKD and bibliometric approaches are used for quantitative analysis to explore the state-of-the-art of intelligent vehicles, produce an objective summary of the current research status, and provide ideas for future research directions.

II. Methodology

Bibliometric analysis takes literature system and literature metrological characteristics as the research object, and adopts mathematical, statistical and other metrological research approaches to study the distribution structure, quantitative relationship and change law of literature information. This approach can be used to obtain the literature distribution, quantitative relationship and clustering.

MKD is a Scientometrics approach with a knowledge navigation function [7]. In addition, it can also display the complex knowledge domain through data mining, the information processing, the knowledge measurement and the graph drawing, reveals the dynamic development rule of the knowledge domain, and provides the practical and valuable reference for the discipline research.

A. Data Source and Retrieved Content

The SCIE and SSCI citation index databases in the Web of Science (WOS) Core Collection are retrieved as the source in this study. The retrieval keywords are "Autonomous Vehicles", "Autonomous Cars", "Self-driving Cars", "Driverless Cars", "Connected Vehicles", "Connected Cars", "Intelligent Cars", "Intelligent Vehicles", "Smart Cars", "Smart Vehicles". The autonomous level here refers to the SAE 6 levels standard. The time span is from 2000 to 2019, and the document type is "Article". A total number of 3933 pertinent published paper are collected, and the last update of the data is on December 31, 2019. The retrieved results are saved as a "Plain Text" with "Full Record and Cited References".

B. Analytical Tool and Approach

The Scientometrics is used for databases analysis based on VOSviewer and CiteSpace Tool software. VOSviewer is a literature knowledge unit visualization software based on similarity visualization technology developed by van Eck and Waltman. It is especially adept at mapping knowledge domains and clustering analysis of literature contents [8].

CiteSpace is a scientific literature analysis tool jointly developed by Chaomei Chen from school of computer and information science of Drexel University and WISE laboratory of Dalian University of technology. CiteSpace is embeded with a variety of database functions, which can load data sets of different formats and perform basic analysis of Scientometrics.

Mapping knowledge domain is an image reflecting the structural relationship and change process between knowledge. There are complex relationships among knowledge clusters, including structure, relation, network, mutual influence and so on. MKD can graph this complex relationship and present a serialized knowledge genealogy. By observing and summarizing these relationships, new relationships and conclusions can be drawn. This paper uses mapping knowledge domain to analyze from the following three aspects:

1) Document Co-Citation Analysis: In any research field, the importance of citations is self-evident, which reflects the current research direction and hot spots. Document co-citation analysis refers to that two documents used for statistical analysis being cited by one or more literatures at the same time, which can be described by network analysis and cluster analysis of cited documents, so as to extract the research topics of these documents.

2) Keywords Co-Occurrence Analysis: The key words of academic papers are important carriers to express the concept of literature subject. Keywords, as a means to quickly understand the content of the article, represent the research direction of the article. Keywords co-occurrence analysis first needs to count the quantity of same keywords cited in the same literature, and then conduct network relationship analysis and cluster analysis on these words, so as to obtain the knowledge framework and research scope of this discipline.

3) Burst Detection Analysis: This analysis is to identify keywords with burst growth characteristics in a specify research field in a certain period of time by analyzing the keyword frequency changes. By analyzing the changes of the occurrence frequency of these burst keywords with time, the research hotspots can be understood in the research field and predict the latest research trends.

C. Construction of Co-Word Similar Matrix

Clustering analysis is conducted by constructing the co-occurrence matrix of keywords. A $n \times n$ similarity matrix S can be constructed with n keywords:

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

where satisfying $s_{ij} \geq 0$, $s_{ii} = 0$, and $s_{ij} = s_{ji}$ for all $i, j \in \{1, \ldots, n\}$.

The principle for determining the similarity between two objects is to separate the objects with low similarity and cluster the objects with high similarity [9].

The similarity between object i and j can be expressed as:

$$S_{ij} = \frac{C_{ij}}{W_i W_j} \tag{2}$$

where C_{ij} is the co-occurrence frequency of object i and j, W_i and W_j are the occurrence frequency of object i and j respectively.

D. Construction of Knowledge Domain Maps

The weighted Euclidean distance sum of all objects in each cluster is minimized so that the clustering effect is improved. The distance of each cluster can be determined by the following formula:

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

where $\|\cdot\|$ denotes the Euclidean norm. Minimization of the objective function is subject to the following constraint [10]:

$$\sum_{i<j} \left\| x_i - x_j \right\| = 1 \tag{4}$$

In the VOSviewer, the color of each point in the density view reflects the density of that point, as will be illustrated in Figure 2 below.

The average distance between two points is denoted by distance d:

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

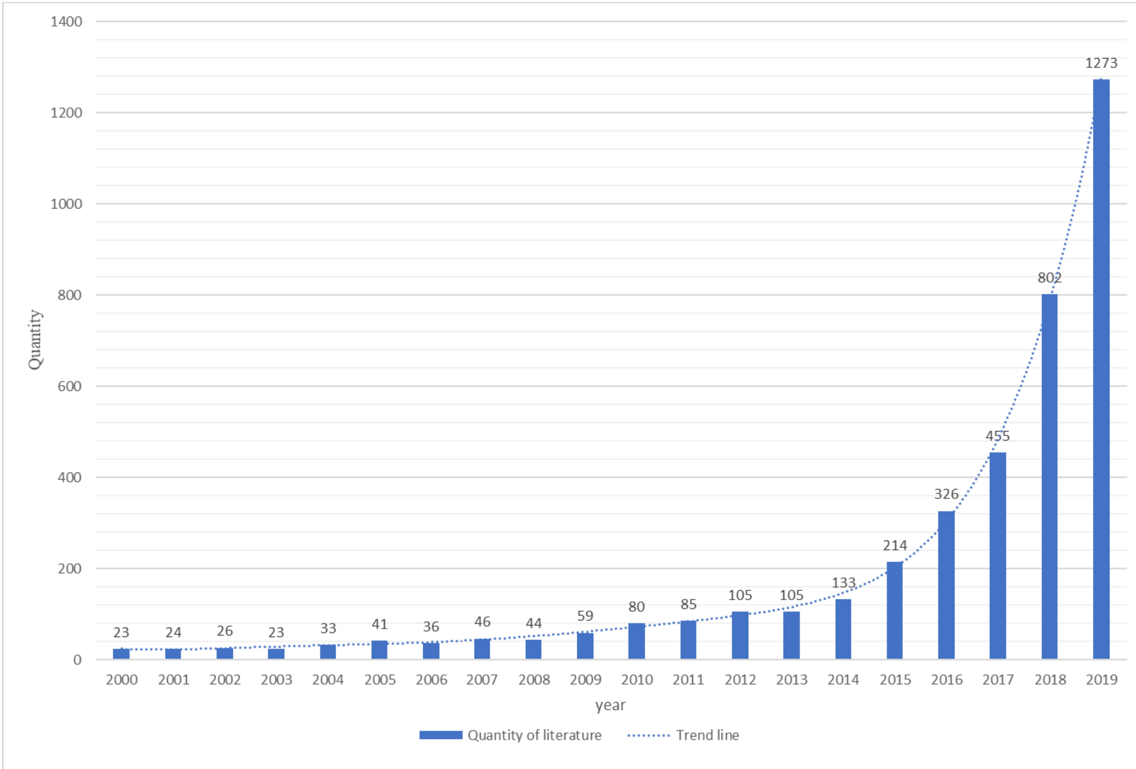

Fig. 1. Quantitative distribution of published articles in intelligent vehicles studies, 2000- 2019.

Representing the density of point $X(x_i, x_j)$ with $D(X)$:

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

where $k \in [0, \infty)$ denotes a kernel function ; $h > 0$ denotes kernel width parameter; W_i denotes the weight of object i, namely the total frequency that i appears, and VOS uses the Gaussian kernel function $k(t) = e^{-t^2}$.

In order to determine the color of each point on the map, first obtaining the color of the cluster with calculating the weighted average of the colors of the cluster midpoints. The object density of the corresponding cluster represents the weight of one color. Finally blending the obtained color with the background color of the cluster density view.

III. Document Statistical Analysis

A. Yearly Quantitative Distribution of Literature

The number of academic papers of a subject represents the development status of the subject field. The quantity variations of papers reflect the change of the subject field scope, and represents the research attention of the subject and number of researchers. The development level and future development trend of this discipline can be understood by drawing the quantitative map of literature changes over time and conducting multivariate statistical analysis.

From 2000 to 2019, a total of 3933 related articles have been collected. As can be seen from Fig. 1, the development of literature on intelligent vehicles has experienced three stages: "First stage", "Second stage" and "Third stage".

1) First Stage (2000-2007): From 2000 to 2007, there are few articles which averaging only 20 ∼ 50 per year published in this field. Research attention in this field is generally low.

2) Second Stage (2008-2014): The number of articles related to this stage starts to rise steadily, which indicates that relevant research on intelligent vehicles is under way in an orderly manner.

3) Third Stage (2015-2019): The number of articles related to this stage starts to increase rapidly, which indicates that this field starts to receive attention and relevant research becomes hot. This change is related to the development of technologies about intelligent vehicles and the promotion of certain countries and organizations.

B. Quantitative Analysis of Productive Countries

According to the retrieved data, literatures related to intelligent vehicles come from 88 countries (or regions). Table I lists the top 10 high-yielding countries, with a total of 3933 articles. It should be noted here that an article may involve more than one country, so the total number of articles counted by the country is bigger than the actual number of articles published. As the country with the most active scientific research in the world, the United States also leads the world in the field of intelligent vehicles research, with 1301 articles published, accounting for 33.079% of the total. China, which has a strong drive for scientific research and development, ranked second with 834 articles, accounting for 21.205 percent of the total. South Korea ranked third with 258, or 6.560% of the total. Germany and Britain, ranked fourth and fifth, had

TABLE I
TOP–10 PRODUCTIVE COUNTRIES, 2000-2019

Rank	Countries/ Territories	Region	Quantity	Percentage	Citation
1	USA	North America	1301	33.079%	28427
2	China	East Asia	834	21.205%	7171
3	South Korea	East Asia	258	6.560%	2028
4	Germany	Central Europe	252	6.407%	3517
5	England UK	Western Europe	250	6.356%	4729
6	Spain	South Europe	241	6.128%	3725
7	Canada	North America	219	5.568%	3293
8	Australia	Oceania	201	5.111%	3188
9	France	Western Europe	196	4.983%	2816
10	Italy	South Europe	181	4.602%	3685

6.407 percent and 6.356 percent, respectively. Countries in the sixth to tenth place account for an average of about 5.3 percent. These countries are either economically developed or in a stage of rapid development and these countries are more interested in the new technology of intelligent vehicles. They are clearly aware of the development prospect of intelligent vehicles and pay attention to it accordingly.

The citation analysis is used to generate a map of the scientific knowledge of the countries studied in the field of intelligent vehicles. Fig. 2 shows the density heat map of the countries involved in the intelligent vehicles research. The data labels represent the countries involved in the study, and the tag-centric colors represent the corresponding heat regions. The more articles the label (country) publishes, the warmer the color (red). The smaller the number of articles is, the colder the color (blue). Concentric color blocks are closely related to each other, while non-concentric circles are also related to each other if they are connected with different color blocks. Countries with larger nodes are located at the center of the blocks.

The United States, China and South Korea are at the center of the map. According to the statistics in Table I, the United States accounts for almost one-third of the total number of published papers, and has the highest density (the warmest color) on the map, indicating that the United States is the academic center of intelligent vehicles research, related research is very active. With the continuous development of China's comprehensive strength, China is dedicated to the development of the new technology of intelligent vehicles, ranking second in the number of articles. China is active in international academic journals in related fields. On January 5, 2020, South Korea released the safety standard of L3 autonomous driving, becoming the first country in the world to set safety standard and commercial standard for L3 autonomous driving. Some European countries, such as England, Germany and Spain also perform well in the field of intelligent vehicle research, as shown in Fig. 2.

TABLE II
TOP–10 PRODUCTIVE ORGANIZATIONS, 2000–2019

Rank	Organization	Country	Quantity	Percentage
1	Tsinghua University	China	87	2.212%
2	Massachusetts Institute of Technology	USA	66	1.678%
3	University of Michigan	USA	59	1.500%
4	University of Texas at Austin	USA	55	1.398%
5	University of Waterloo	Canada	54	1.373%
6	University of California, Berkeley	USA	46	1.170%
7	Georgia Institute of Technology	USA	43	1.093%
8	Tongji University	China	42	1.068%
9	Beijing Institute of Technology	China	41	1.042%
10	Delft University of Technology	Netherlands	41	1.042%

C. Quantitative Analysis of Main Research Organizations

By analyzing major research organizations, it is possible to determine which organizations or groups within the discipline that specialize in a particular topic are most productive. According to the quantitative analysis results, the research literature on intelligent vehicles comes from 2738 organizations, and the top 10 organizations with the largest number of published papers are shown in Table II.

Universities tend to produce many scientific research talents for a country. The scientific research strength of universities also represents the scientific research level of a country. Table II shows the top 10 universities which published 534 papers with the 13.6 percent of the total active in the field of intelligent vehicles. Furthermore, results show that some universities and research institutes in the United States and China are major contributors in the field of intelligent vehicles, which is also consistent with the previous statistics on countries. Of the 2738 related organizations, 2600 organizations have published less than 10 papers, accounting for 94.9% of the total. This result indicates that the published literatures are highly concentrated in a few organizations.

The distribution of research intensity can be found through the approach of co-author relationship analysis, and the collaborative network among various research institutions in the research of intelligent vehicles can be understood. In Fig. 3, each node represents an organization, and the node size represents the number of articles published. Links between nodes indicate collaboration, where the greater the width of the link (link strength) means the closer the collaboration is. 136 projects, 15 clusters and 549 links are selected

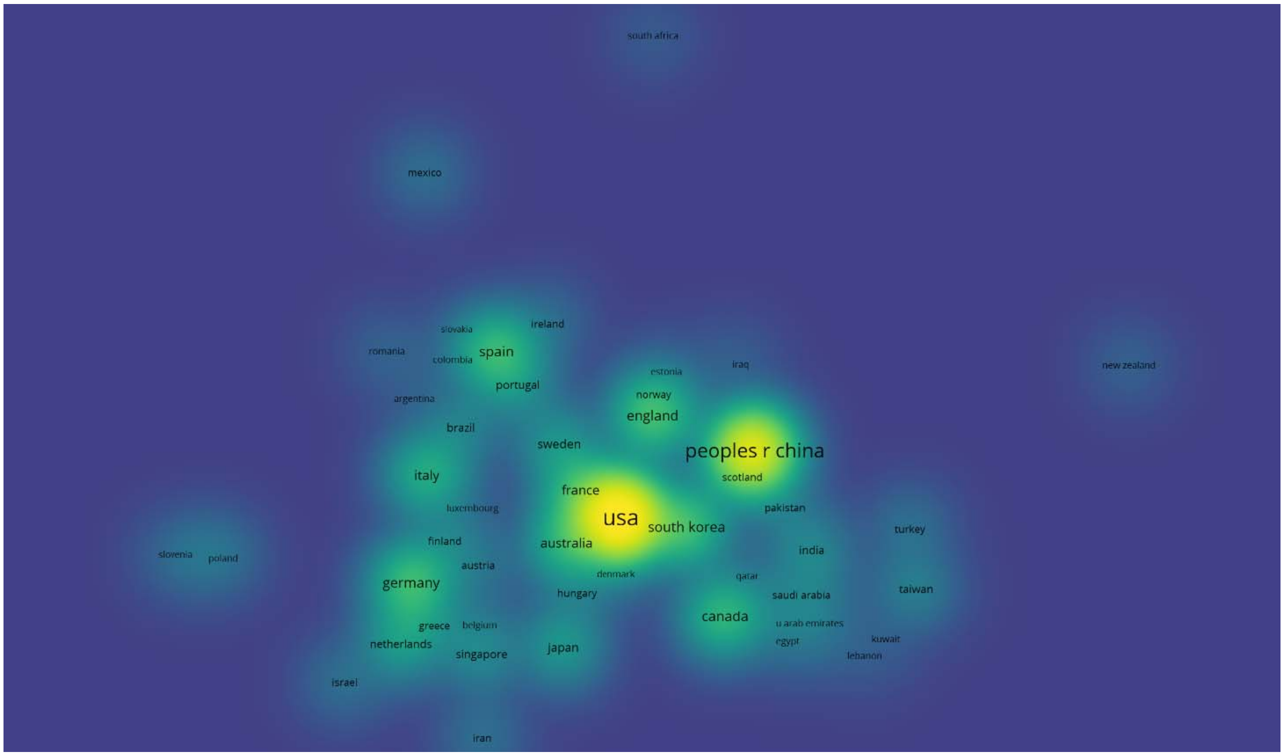

Fig. 2. Density of main research countries in intelligent vehicles studies.

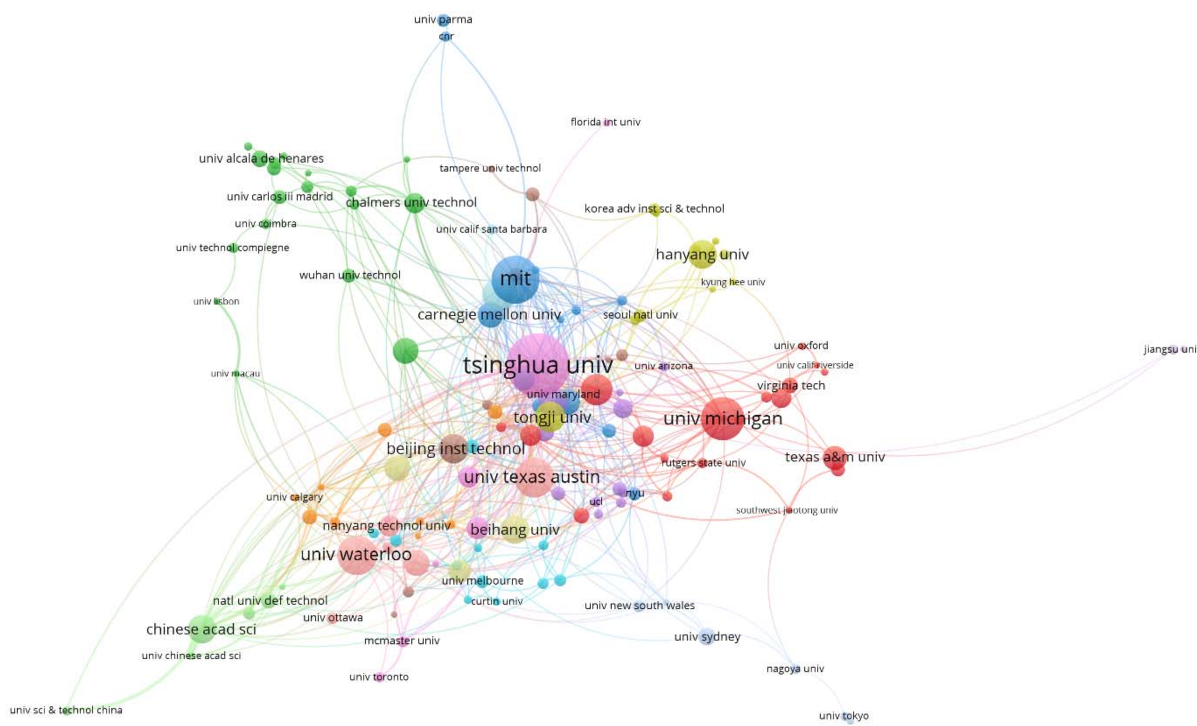

Fig. 3. Collaboration network among main research organizations.

and displayed through automatic clustering in the process of generating knowledge domain diagrams for collaboration among major research institutions. The collaborative knowledge domain diagram shows an obviously locally centralized but globally discrete type, which indicates that the collaboration between these organizations is not very close. The map also shows that Tsinghua University has the most articles, followed by the Massachusetts Institute of Technology and the University of Michigan. Tsinghua University also has the highest number of links (link = 44), followed by MIT

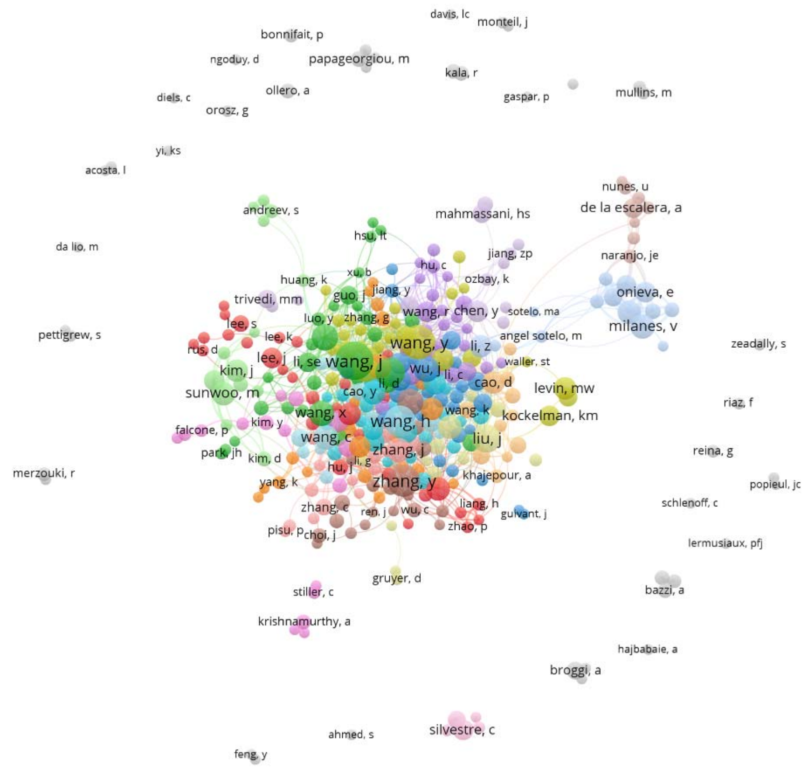

Fig. 4. Co-authorship network among productive authors.

(link = 25) and the University of Michigan (link = 24), indicating that these organizations are key nodes in the collaborative network. The node with the highest link strength with Chinese Academy of Sciences is University of Science and Technology of China (link strength = 9), both of which are located in China. The node with the highest link strength with the University of Wisconsin is Rensselaer Polytechnic University (link strength = 6), both located in the United States.

D. Co-Authorship Analysis of Main Research Groups

The research on intelligent vehicles has a highly interdisciplinary nature with the advantage on cooperation and drawing on each other's strength. Researchers come from different fields, such as vehicle engineering, intelligent transportation engineering, computer science, human factors, automobile control and so on. The establishment and analysis of the knowledge map of the collaborative network of prolific authors can provide valuable cooperative information for the development of cooperative groups and individual researchers in research institutions.

Co-author analysis is used to generate the knowledge domain graph of the main research group. As shown in Fig. 4, the text on the node is the author's name, and the size of the node reflects the number of articles published by the author. The connection between two nodes indicates that the authors have direct cooperation, and the width of the link indicates the strength of cooperation. The cooperation between authors can make research data sharing, improve research efficiency and promote the birth of innovation points. Results show that international exchanges and cooperation among high-yielding authors are quite active in general.

E. Quantitative Analysis of Main Source Journals

Academic journals are important carriers of academic papers and platforms for the dissemination of research results. By analyzing the source journals of the literature related to intelligent vehicles, it is easy to understand which journal plays an important role in this field. Table III lists the journals with high concentration of intelligent vehicles articles. These journals are all included in SCIE. In general, SCIE has included more articles than SSCI has included, indicating that the research on intelligent vehicles is basically in the field of engineering technology.

As can be seen from Table III, ≪IEEE Transactions on Intelligent Transportation Systems≫ has published the most articles on intelligent vehicles. ≪Transportation Research Part C: Emerging Technologies≫ following closely. The ≪IEEE Access≫ has ranked third in the number of published articles. In general, the core journals of the research on intelligent vehicles are either multidisciplinary or interdisciplinary, indicating that intelligent vehicles are a multidisciplinary or interdisciplinary science with the characteristics of communication, engineering, computer, automation and other disciplines.

F. Document Co-Citation Analysis: Knowledge Bases of Intelligent Vehicles Studies

In a research field, the literature with the highest number of co-citations can often reflect the general situation of

TABLE III
TOP–10 MAIN SOURCE JOURNALS IN INTELLIGENT VEHICLES STUDIES, 2000-2019

Rank	Journal Title	Citation Index	Impact Factor	Quantity	Percentage
1	IEEE Transactions on Intelligent Transportation Systems	SCIE	5.744	271	6.890%
2	Transportation Research Part C: Emerging Technologies	SCIE	5.775	159	4.043%
3	IEEE Access	SCIE	4.098	147	3.738%
4	Sensors	SCIE	3.031	138	3.509%
5	IEEE Transactions on Vehicular Technology	SCIE	5.339	136	3.458%
6	Transportation Research Record	SCIE	0.748	118	3.000%
7	Robotics and Autonomous Systems	SCIE	2.928	46	1.170%
8	IET Intelligent Transport Systems	SCIE	2.050	40	1.017%
9	Transportation Research Part B: Methodological	SCIE/SSCI	4.574	36	0.915%
10	Journal of Advanced Transportation	SCIE	1.983	36	0.915%

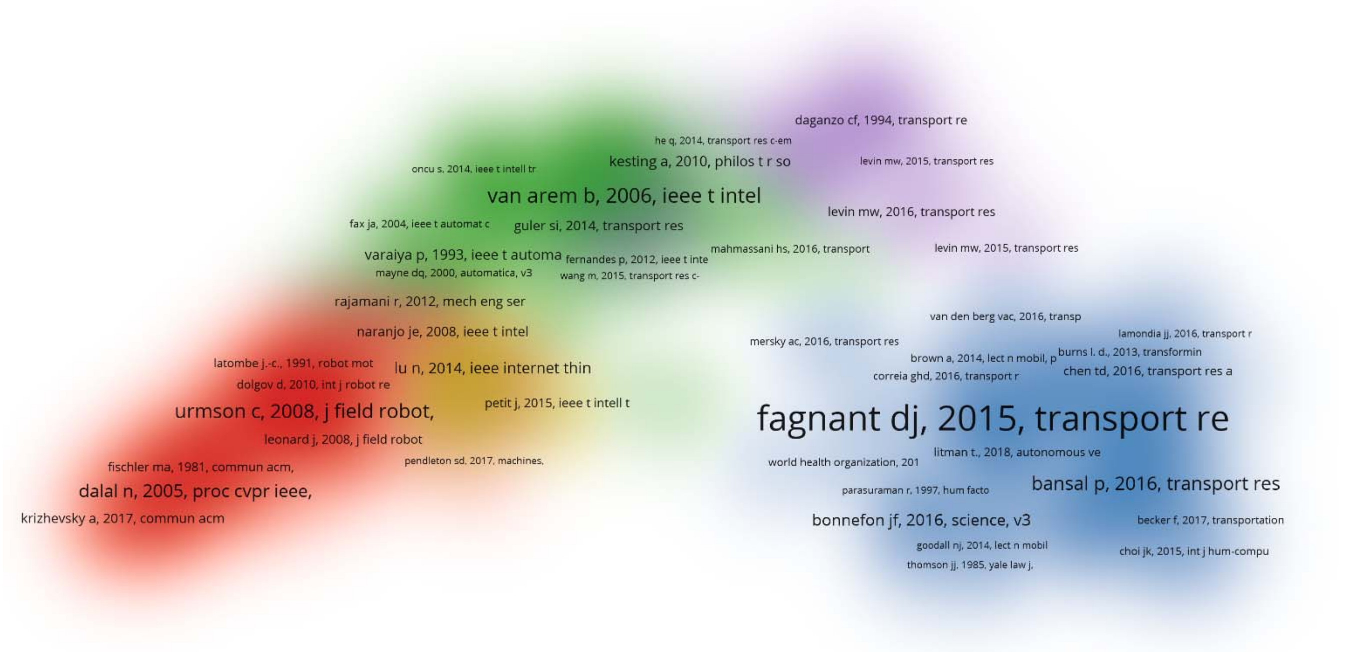

Fig. 5. Cluster density view of document co-citation network.

the research field. Through the analysis and mining of the correlation and development process of literatures, one can quickly and accurately find the main content of this research field from a large number of cited literatures. The Document Co-citation Analysis function is used to obtain the cluster density map of document co-citation for intelligent vehicles research. As shown in Fig. 5, the entire knowledge network map is divided into five color-coded clusters using the default clustering approach.

1) Cluster 1 (Red): System Framework: In this cluster, the classic literature with the largest density is "Autonomous driving in urban environments: Boss and the urban Challenge" by Chris Urmson (2008) published in *Journal of Field Robotics*. The number of co-citations is 88 and the total link strength is 463, indicating that this paper plays an important role in the structure of co-citations network.

In this article, Chris Urmson introduces a self-driving car named Boss that uses on-board sensors to perceive its surroundings. It can use the road model to locate itself and the information collected by the sensors to track other vehicles and detect static obstacles. The vehicle is equipped with a planning system that combines mission, behavior and motion planning to drive the vehicle in the urban environment. The role of the mission planning layer is to select the route to the destination. The behavior layer determines the vehicle's processing behavior, such as the timing of lane changes and the priority of vehicles passing at intersections. The motion planning layer ensures the collision avoidance action of the vehicle when driving [11].

In this field, we also recommend "Junior: The Stanford entry in the Urban Challenge" and "Stanley: The robot that won the DARPA Grand Challenge" as two important articles according to the ranking.

"Junior: The Stanford entry in The Urban Challenge" is written by Michael Montemerlo (2008) and published in *Journal of Field Robotics*. This paper introduces the structure and functions of a robotic vehicle named Junior, which won the second place in the DARPA Urban Challenge [12].

"Stanley: The robot that won the DARPA Grand Challenge" is written by Sebastian Thrun (2006) and published in *Journal of Field Robotics*. This paper describes the architecture of Stanley, a robot equipped with artificial intelligence techniques such as machine learning and probabilistic reasoning. The robot also won the 2005 DARPA Grand Challenge [13].

2) Cluster 2 (Yellow): Internet of Vehicles: The classic literature with the largest density in this cluster is "Connected Vehicles: Solutions and Challenges" published by Ning Lu (2014), with a total of 59 co-citations and a total link strength of 185.

Connected vehicles are equipped with advanced on-board sensing systems and control systems, and integrates modern communication and network technology to realize the information exchange between people, vehicles, roads and the environment. Connected vehicles combine the technology of Internet of vehicles and intelligent vehicles and are also a development direction of intelligent transportation systems in the future.

This paper focuses on connection, systematically introduces wireless communication and challenges between vehicles and different devices or environments. At the end of the paper, the author puts forward some suggestions and solutions to the challenges in this field, and gives some prospects for the future research problems and development [14].

In this field, we also recommend "Potential Cyberattacks on Automated Vehicles" and "Dedicated Short-Range Communications (DSRC) Standards in the United States" as two important articles according to the ranking.

"Potential Cyberattacks on Automated Vehicles" is written by Jonathan Petit and Steven E. Shladover (2014), published in *IEEE Transactions on Intelligent Transportation Systems*. This paper expresses concern about safety issues in the development of automated vehicles. The authors investigate the potential cyberattacks specific to automated vehicles, with their special needs and vulnerabilities. Aiming at the cybersecurity challenges faced by automated vehicles, they carry out risk assessment and proposes relevant countermeasures [15].

"Dedicated Short-Range Communications (DSRC) Standards in the United States" is written by John B. Kenney (2011), published in *Proceedings of the IEEE*. This paper introduces Dedicated Short-Range Communications (DSRC) standards in the United States, including the content of the technical solution, the reasons for its adoption, and the challenges faced [16].

3) Cluster 3 (Purple): Intersection Control Algorithms: In this cluster, the largest density classical document is "A Multiagent Approach to Autonomous Intersection Management" which Kurt Dresner (2008) published in the *Journal of Artificial Intelligence Research*. The number of co-citations is 67 and the total link strength is 378.

One of the applications of intelligent vehicles is to improve traffic efficiency and reduce collisions. The problem of intersection control of traditional vehicles is still very complex, and the future of connected vehicles and self-driving cars at the intersection of the rules and control methods are more different from traditional vehicles. Therefore, it is necessary to study the intersection traffic of intelligent vehicles in order to meet the challenges. In this paper, a new multiagent framework is proposed to control the intersection traffic of self-driving vehicles, and the effectiveness of this method is proved by simulation. In their system, intersection uses a new reservation-based approach built around communication protocols to ensure safe and efficient vehicle traffic [17].

In this field, we also recommend "Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm Under the Connected Vehicles Environment" and "Using connected vehicle technology to improve the efficiency of intersections" as two important articles according to the ranking.

"Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm Under the Connected Vehicles Environment" is written by Joyoung Lee and Byungkyu Park (2012) and published in *IEEE Transactions on Intelligent Transportation Systems*. In this paper, a Cooperative Vehicle Intersection Control (CVIC) algorithm without traffic signal is proposed. An additional algorithm is designed to solve the system failure problem caused by trajectory overlaps and infeasible solutions. Simulation results show that CVIC algorithm has advantages over traditional methods [18].

"Using connected vehicle technology to improve the efficiency of intersections" is written by S. Ilgin Guler (2014) and published in *Transportation Research Part C : Emerging Technologies*. In this paper, an intersection traffic control algorithm is proposed based on the information collected by the equipment on the connected vehicles. Simulation results show that the algorithm can improve the crossing efficiency. This algorithm enumerates the vehicle discharge sequences of different vehicles in a certain range at the intersection, minimizes the objective function and obtains the optimal strategy [19].

4) Cluster 4 (Green): Influence on Traffic Flow: In this cluster, the classic literature with the largest density is B. van Arem (2006) "The Impact of Cooperative Adaptive Cruise Control on traffic-flow Characteristics" published in *IEEE Transactions on Intelligent Transportation Systems*, with a total of 95 co-citations and a total link strength of 879.

Cooperative adaptive cruise control (CACC) is an extension of ACC. In addition to measuring the distance to the vehicle in front, the vehicle can also exchange information with the vehicle in front through wireless communication. This allows the vehicle to follow its predecessor more closely under tighter control. This paper focuses on the influence of CACC on traffic flow characteristics. It uses specially designed traffic flow simulation model MIXIC to study the impact of intelligent vehicles on traffic flow. The influence of CACC on the combination scheme of four-lane to three-lane expressway is studied. The results show that the proposed scheme improves the stability and efficiency of traffic flow compared with the unequipped vehicle scheme [20].

In this field, we also recommend "Influence of connected and autonomous vehicles on traffic flow stability and throughput" and "Congested traffic states in empirical observations and microscopic simulations" as two important articles according to the ranking.

"Influence of connected and autonomous vehicles on traffic flow stability and throughput" is written by Alireza Talebpour (2016) and published in *Transportation Research Part C: Emerging Technologies*. This paper studies the influence of autonomous vehicles and connected vehicles on traffic flow and proposes a framework. This framework can simulate the traffic flow stability performance of autonomous vehicles and connected vehicles by setting different conditions such as different communication environments and different vehicle types [21].

"Congested traffic states in empirical observations and microscopic simulations" is written by Martin Treiber (2000) and published in *Physical Review E*. This paper studies the congested traffic states on German freeways and uses a continuous microscopic single-lane model to simulate and interpret it [22].

5) Cluster 5 (Blue): Policies and Barriers: "Preparing a nation for autonomous vehicles" which Daniel J. Fagnant (2015) published in *Transportation Research Part A : Policy and Practice*, is the most concentrated of the classic literature in this cluster. The number of co-citations is 207 and the total link strength is 1585, including opportunities, barriers and policy recommendations.

It is generally believed that autonomous vehicles can bring many beneficial social effects, such as reducing exhaust emissions, shortening travel time, easing traffic congestion, reducing the number of vehicle collisions, and improving energy efficiency. However, the application of autonomous vehicles may also have adverse effects on the existing traffic system, such as interfering with road traffic, affecting the safety of other vehicles and other potential threats.

Barriers to the implementation of autonomous vehicles and mass market penetration remain. One reason is that the initial cost may not be affordable to the public. Another reason is that the relevant laws and regulations are not perfect, the ethical issues of responsibility are not clear, and safety problems still exist. Without new privacy standards, privacy breaches when using autonomous vehicles could become the norm. At present, autonomous vehicles have not been put into market use, so the impact of their use on the components of the traffic system is not clear. In addition, the implementation details and laws and regulations related to autonomous vehicles are still unclear. In order to solve these problems, the author suggests to expand the research in these areas. Relevant countries should establish a reasonable legal framework for autonomous vehicles to guarantee the safety and privacy of users [23].

In this field, we also recommend "Autonomous Vehicle Technology: A Guide for Policymakers" and "Public opinion on automated driving: Results of an international questionnaire among 5000 respondents" as two important articles according to the ranking.

"Autonomous Vehicle Technology: A Guide for Policymakers" is written by Daniel James M. Anderson (2014) and published in *RAND Corporation*. This paper points out some of the problems caused by autonomous vehicle technology and gives some advice to policy makers [23].

"Public opinion on automated driving: Results of an international questionnaire among 5000 respondents" is written by Daniel James M. Kyriakidis (2015) and published in *Transportation Research Part F : Traffic Psychology and Behavior*. This paper surveyed 5,000 respondents from 109 countries about their opinions on the acceptance, concerns, and willingness to buy partially, highly, and fully automated vehicles through online surveys. A short version of the Big Five Inventory was used to evaluate some variables [24].

G. Keywords Co-Occurrence Analysis: Main Research Topics and Fronts of Intelligent Vehicles

Keyword co-occurrence analysis refers to the analysis of the co-occurrence relationship of keywords in a large number of literatures to obtain the relationship between keywords, so as to obtain the knowledge structure relationship of this research field. This is a kind of commonly used research approaches of Scientometrics. The Keywords Co-occurrence Analysis function is used to generate keywords co-occurrence of intelligent vehicle research network. As can be seen from Fig. 6, four clusters are formed in the research frontier of intelligent vehicle. Keywords classified into the same cluster are highly correlated and represent a research topic. Combining with the contents of each cluster, the characteristics of each cluster can be summarized and analyzed.

1) Cluster 1 (Green): Planning and Control System: The co-occurrence keywords include: autonomous vehicle, stability, vehicle dynamic, steering control, path planning, lateral control, fuzzy control, motion planning, guidance, etc. In order to realize its functions as an intelligent vehicle, it is necessary to configure appropriate motion control systems and algorithms. It also borrows from related technologies in the field of robotics.

Autonomous vehicles have a variety of sensors, which can achieve navigation and positioning, intelligent decision-making and control functions, in fact, is a different form of mobile robot [25]. There are many sample-based path planning algorithms, such as probability road map (PRM) and fast exploring random tree (RRT). These algorithms are theoretically guaranteed by probabilistic completeness and have achieved good results in practice [26]. Path tracking control of autonomous vehicles is one of the most difficult challenges in the field of automation. There are many ways to achieve path tracking through horizontal control. PID control has such advantages as a simple structure, good control effect and robust and easy implementation [27]. However, this approach cannot optimize the parameters, and cannot

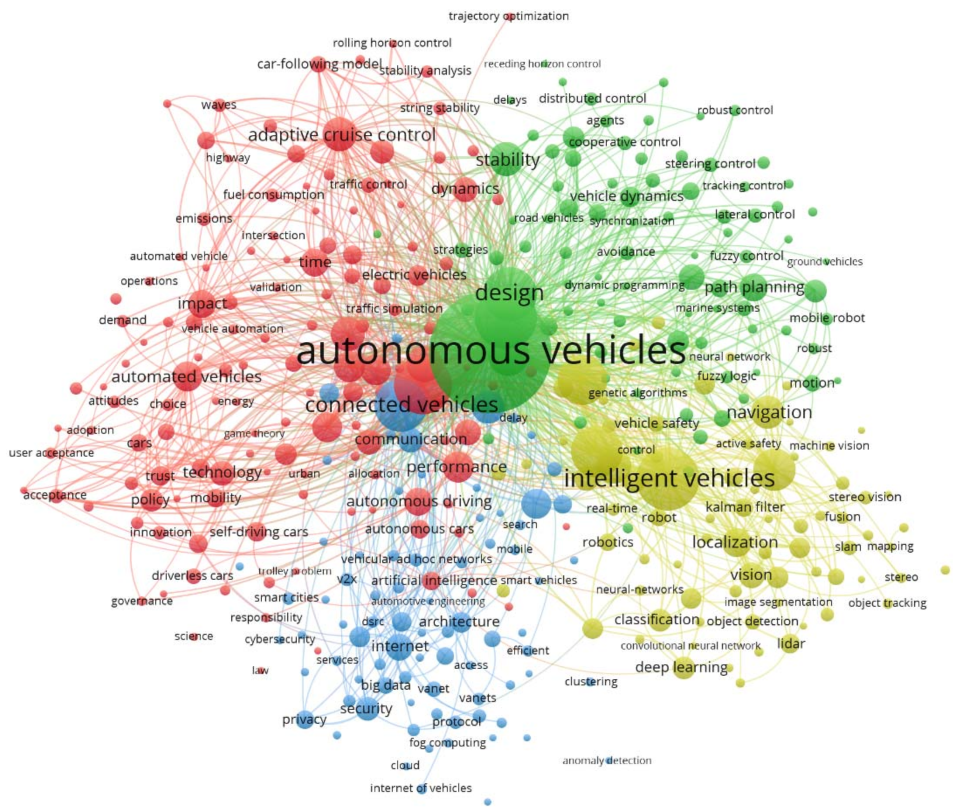

Fig. 6. Keywords co-occurrence network of intelligent vehicles studies.

automatically adapt to the complex external environment and vehicle problems [28]. Adding vehicle-vehicle wireless communication on the basis of ACC can provide additional information to augment range sensor data, leading to cooperative ACC (CACC) [29]. ACC usually adopts distance setting strategy or other safety following strategy to determine the following distance. This is because the main goal of ACC is to maintain a safe distance, reduce the pressure on the driver and make the driving more comfortable, and increase road capacity is the secondary goal [30]. Fuzzy logic control is tolerant to imprecise measurements and to component variability [31].

2) Cluster 2 (Red): Autonomous Vehicle Questionnaire: The co-occurrence keywords include: technology, policy, trust, time, impact, choice, adaptive cruise control, electric vehicles, behavior, safety, traffic flow, etc. Autonomous vehicle in its design process should consider many factors, such as operational modes, level of automation, desired functionality, cybersecurity and so on. Before the autonomous vehicles on the road still need a lot of simulation experiments and real vehicle experiment, to ensure its safe driving on the road.

Although level 4 and level 5 autonomous vehicles have not been put into the market at present, many related surveys have been conducted on future consumers and users. Most respondents are highly concerned about safety issues in autonomous vehicles, such as equipment or system failures, and how safe will autonomous vehicles be in comparison to human drivers [32]. Among the factors, the convenience, safety, morality, permission and monetary cost of autonomous vehicles are found to have a direct impact on attitude, while the convenience, safety and monetary cost are found to have a direct impact on intention. In addition, the public's attitude towards autonomous vehicles has a significant impact on the purchase intention of autonomous vehicles [33]. Sharing autonomous vehicles is a good idea. According to the survey, some potential consumers indicate that travel time, travel expenses and service waiting time will be decisive factors influencing consumers' acceptance of this services [34]. Using an internet-based survey of 63 questions and 5,000 questionnaires from 109 countries, the majority of respondents said manual driving is the most pleasant way to drive. 22 percent people said they would not pay for a fully autonomous system, while 5 percent said they would pay more than $30,000 for the technology. 33 percent questionnaires said they would enjoy fully autonomous driving. 69 percent of respondents expect the market share of fully autonomous vehicles to reach 50 percent between now and 2050. In addition, the survey found that respondents are most concerned about hacking or software errors, as well as legal and security issues [35]. People who don't own a car or who own a highly automated car have a more positive attitude toward autonomous vehicles than people who own a less automated vehicle [36]. Consumers have great differences in their preferences for intelligent vehicle functional technologies. They have small differences in their preferences for intelligent vehicle applications that provide real-time traffic information such as parking and traffic conditions, but great differences in their preferences for smart technologies such as wireless Internet, vehicle connectivity and voice commands [37]. Because there are still a lot of imperfections in autonomous vehicles, many people believe that people should retain control of them [38].

3) Cluster 3 (Yellow): Sensor and Vision: The co-occurrence keywords include: intelligent vehicle, deep learning, sensor fusion, recognition, tracking, localization, sensors, vision, classification, pedestrian detection, etc.

In 2000, the importance of machine vision and computer vision for intelligent vehicles is proposed [39]. With the progress of camera sensing and computing technology, vehicle detection technology using monocular vision, stereo vision and sensor vision fusion has become a research hot spot in the field of intelligent vehicles. There are three main reasons for the application of vision-based vehicle assisted driving detection in intelligent vehicles: the high incidence of traffic accidents, the continuous development and progress of computer vision technology, and the exponential increase in processor speed [40]. Sensors can collect information about the surrounding environment so that the car can make correct processing. Radar technology is required for adaptive cruise control (ACC) and side warning assistance [41]. Due to the use and development of sensors, the ACC system has become a widely accepted upper level vehicle, with enhanced functions that can achieve seamless transition from highway cruising to stop-and-go [42].

Lane marking (or boundary) detection technology shall have the following requirements: the quality of detection shall not be affected by the shadow; Technology is suitable for different roads; Improving the ability to detect lane marking (or boundaries) on both sides; The reliability of the results can be clearly judged [43]. The purpose of vehicle tracking is to identify and recognize vehicles from a given captured frame, measure the dynamic and kinematic characteristics of the vehicle, and predict the road vehicle trajectory. Unfortunately, vehicle tracking has imperfect problems, including uncertainty of measurement and sensor, data correlation and tracking management [44].

4) Cluster 4 (Blue): Connected Vehicles: The co-occurrence keywords include: networks, intelligent transportation system, connected car, management, internet, sensor networks, security, vehicular networks, architecture, big data etc.

In recent years, the concept of Internet of Vehicles, intelligent network connected vehicles and cloud computing have attracted more and more researchers' attention, and relevant research and development are also carried out in a large number.

The growth of cloud computing and the Internet of things (IoT) presents a great opportunity to address the challenges posed by the increasing number of transportation problems. Intelligent automobile data cloud platform based on cloud computing and Internet of things technology is born [45]. There are two immediate reasons for applying wireless connectivity to vehicles. One is the urgent need to improve the efficiency and safety of road traffic systems. The other is the increasing demand for mobile data by road users [46]. Compared with traditional intelligent transportation system (ITS), Internet of Vehicles (IoV) pays more attention to the interactive connection between people and vehicles, aiming to accommodate for fifth generation (5G)-enabled vehicular networks [47]. And in IoV, the trajectory of vehicles is subject to the road distributions in the city [48].

The focus of automotive interconnection application is to develop applications to solve traffic problems. The main research areas are vehicle-to-vehicle communication (V2V) and vehicle-to-infrastructure communication (V2I) for security, real-time data acquisition and management, and road weather management applications [49].

Vehicular Cloud Computing (VCC) has become increasingly successful in application, but this technology also faces many challenges. High mobility of vehicles affects cloud computing performance of vehicles. There is a correlation between wireless transmission efficiency and running speed. In the behavior mode of high-speed movement, efficiency is also affected by high dynamics. Due to the characteristics of VCC, it will become more important as a target of various attacks, which will bring about severe security and privacy challenges.

H. Burst Detection Analysis: Research Trends of Intelligent Vehicles

Burst Detection Algorithm (BDA) identifies keywords with high frequency and density characteristics in documents by detecting the density of keyword frequency changes. This algorithm is first proposed by Kleinberg in 2003 [50]. BDA can be used to detect the sudden increase in the frequency of words used in topics and keywords, and to obtain the starting time, ending time and weight of emergencies. Through this information, the burst hot spots and research trends in the research field of intelligent vehicles can be analyzed.

The BDA is used to get the burst keywords for a certain period of time in the research field and the duration of these keywords. CiteSpace sees this mutation information as a way to measure deeper changes [51]. Burst detection in CiteSpace can be used for two types of variables: one is the frequency of words or phrases used in cited literatures, and the other is the frequency of citations obtained from cited literatures. The data is imported into the CiteSpace tool and run for burst detection. The parameters are set as follows: Gamma $= 1.0$, the number of states $= 2.0$, minimum duration $= 1$. The first 30 meaningful keywords with the largest burst weight are selected for the visualization analysis. Then the burst keywords are analyzed in three stages according to time, so as to have a certain understanding of the burst research hotspots in each stage and provide ideas for the subsequent research direction.

1) The First Stage (2000-2007): As shown in Table IV, the "Begin year" and "End year" indicate the duration year of the burst keywords from the beginning to the end. Strength indicates the frequency of the keyword. In this stage, the research on intelligent vehicles is in the initial stage. The burst keywords began from 2000 to 2007 are: Mobile robot, Control system, Tracking, Computer vison, etc. As can be seen from the keywords in the figure, the focus of this stage is on the control system and motion drive of the intelligent vehicles, and some technologies of robot control are used for reference. Among the burst keywords, mobile robot is an

TABLE IV
TOP-10 BURST KEYWORDS IN 2000-2007

Keywords	Strength	Begin year	End year	Year from 2000 to 2019
Mobile robot	21.028	2000	2009	
Control system	12.9382	2000	2010	
Navigation	11.2155	2000	2015	
Neural network	6.3446	2001	2007	
Vehicle dynamics	8.1307	2002	2010	
Urban environment	8.4699	2005	2012	
Stereo vision	7.4075	2005	2012	
Tracking	23.3582	2006	2015	
Path planning	14.0548	2007	2015	
Computer vision	6.5275	2007	2012	

TABLE V
TOP-10 BURST KEYWORDS IN 2008-2014

Keywords	Strength	Begin year	End year	Year from 2000 to 2019
Stability	9.806	2008	2014	
Predictive control	5.4362	2009	2014	
Intelligent vehicle	18.1688	2010	2014	
Autonomous underwater vehicle	4.7142	2011	2011	
Traffic flow	12.0432	2012	2014	
Human driver	3.306	2012	2012	
Simulation	4.0035	2013	2013	
Dynamics	4.0035	2013	2013	
Intelligent transportation system	9.9086	2014	2016	
Motion planning	4.6199	2014	2014	

important factor. A new approach to steering control around a pre-plan path is proposed in 2001 [52]. By deducing the control parameters of vehicle speed function, the system can maneuver accurately at low speed. This approach can be applied to the steering control of autonomous vehicles. Computer vision is widely used in intelligent vehicles. It takes into account the environment, vehicles and drivers to detect and track the road, avoid hitting obstacles or pedestrians, and make the vehicle safer [53]. Multi-target tracking is the key problem of autonomous vehicle. Many advanced approaches have been proposed, such as the modification of the detect-by-trace strategy to make it capable of reidentification (ReID) when the tracked object is lost [54]. In this stage, many researches on the necessary technologies of intelligent vehicles were carried out, which provided the foundation for the development behind.

2) The Second Stage (2008-2014): Research on intelligent vehicles in this phase continues to develop in Table V. As can be seen from the burst keywords began at this stage, the research depth of algorithms and motion behavior control of intelligent vehicles is constantly increasing. The burst keywords in this stage are: Intelligent vehicle, Traffic flow, Stability, Motion planning, etc. The sudden increase in the occurrence frequency of the term intelligent vehicles indicates that research on intelligent vehicles has become hot. With the development of vehicle technologies, highly autonomous vehicles are emerging, and researchers are beginning to pay attention to the impact of these new vehicles on traffic flow. Many new intelligent vehicle stability control algorithms or frameworks have been proposed to improve the vehicle's lateral or longitudinal stability. Intelligent vehicles need to plan their motion behavior, so the research on motion planning

TABLE VI
TOP-10 BURST KEYWORDS IN 2015-2019

Keywords	Strength	Begin year	End year	Year from 2000 to 2019
Optimal control	5.7857	2015	2015	
Adaptive cruise control	19.6037	2016	2017	
Smart vehicle	10.28	2016	2016	
Connected vehicle	3.6497	2016	2016	
Collision avoidance	12.8639	2017	2017	
Algorithm	8.8329	2017	2017	
Automated vehicle	29.548	2018	2019	
Network	25.7577	2018	2019	
Autonomous driving	16.436	2018	2019	
Self-driving car	7.7849	2018	2019	

algorithm is also very hot. For example, a real-time motion planning algorithm based on the rapidly exploring random tree (RRT) approach for autonomous vehicles in urban environments was proposed in 2009 [55].

3) The Third Stage (2015-2019): In recent years, the concept of intelligent vehicles has become increasingly popular, with more and more branches of related research and more and more extensive depth. Many companies and countries are involved in the research of intelligent vehicles and intelligent vehicles testing on the road. This stage of the main burst keywords in Table VI are: Connected vehicle, Collision avoidance, Automated vehicle, Adaptive cruise control, Network, etc. The development of sensors and infrastructure has enabled the collection of diverse vehicle and environmental information. This information can be transmitted through advanced communication technologies to provide data support for graphics and computer algorithms [56]. The intensification of connected vehicle researches is consistent with the current popularity of vehicle network and connected vehicles. Vehicle network technologies can help the vehicle with other vehicles or the whole traffic system to exchange information, so as to better coordinate. Continuous improvement and innovation of various collision avoidance control strategies will also improve the safety of intelligent vehicles. At present, many vehicles are equipped with Adaptive Cruise Control (ACC) function to ensure a safe distance during driving. Cooperative Adaptive Cruise Control (CACC) is an extension of ACC. In addition to measuring the distance to the vehicle in front, the vehicle can also exchange information with the vehicle in front through wireless communication. This allows the vehicle to follow its predecessor more closely under tighter control.

IV. CONCLUSION AND FUTURE WORK

The development process and structural relationship of the research field of intelligent vehicles, including complementary analyses from the aspects of co-citation analysis, quantitative analysis, keywords co-occurrence analysis as well as burst detection analysis, have been comprehensively illustrated in this paper based on MKD approach with VOSviewer and CiteSpace tools. The main highlights are summarized below.

(1) The increasing number of papers in the research field of intelligent vehicles indicates that the international academic community is paying more and more attention to intelligent vehicles, and relevant researches are also being carried out.

The United States, China and South Korea rank the top, according to the article's distribution among countries, indicating that these countries are active regions for intelligent vehicles research. In terms of research institutions, Tsinghua University, Massachusetts Institute of Technology and the University of Michigan have the highest research output, but it will be encouraging to see the cooperation among major research institutions further strengthened. From the analysis results of the main research groups, international exchanges and cooperation among high-yielding authors are quite active. In terms of source journals, the ≪IEEE Transactions on Intelligent Transportation Systems≫, ≪Transportation Research Part C: Emerging Technologies≫ and ≪IEEE Access≫ are the authoritative journals in the field of intelligent vehicles research and an important platform for publishing research results.

(2) By establishing the clustering density map of document co-citation in literature, it is found that there are five research directions with the highest co-citation: System Framework, Internet of Vehicles, Intersection Control Algorithms, Influence on Traffic Flow, Policies and Barriers. This result reflects that most of the major research fields in the field of intelligent vehicles need the literature support in the above aspects. At present, many researches require knowledge of system architecture, and the field of intelligent vehicles is no exception. A variety of Internet and communication technologies are widely used in the field of intelligent vehicles, enabling vehicles to achieve path selection, automatic control and

other functions. The relevant technologies of Internet of Vehicles provide support for vehicle intelligence. Efficient and safe intelligent vehicle intersection traffic control is an important part of the development of Intelligent Traffic System. In the future, the performance of intelligent vehicles in traffic flow and their impact on traffic flow are still very concerned by researchers. Now, in the face of the rapid development of intelligent vehicles related technology, scholars have begun to explore the development of intelligent vehicle related policies and barriers. It is also necessary to establish reasonable industry norms and policy guidance.

(3) Through the analysis of intelligent vehicle keywords co-occurrence network graph, the research directions represented by these keywords can be divided into four categories: Planning and Control System, Autonomous Vehicle Questionnaire, Sensor and Vision, Connected Vehicles. These four representative keywords also reflect the research trends in this field in recent years. Researches on planning and control systems, sensors and vision are of great importance to the development of autonomous vehicles, which have attracted more and more attention in recent years. Questionnaires about the legal, ethics and public attitudes of autonomous vehicles are also emerging one after another. The laws and regulations of autonomous vehicles as well as the draft and discussion of industry norms are also emerging. In addition, with the continuous development of big data, cloud system, intelligent network and other technologies, there are also many researches to explore the improvement of people's living standard and traffic environment brought by Internet of vehicles technology.

(4) We explore the research trend of intelligent vehicles by using burst detection in CiteSpace. Burst keywords in related research can be divided into three stages: the first stage (2000-2007) is the initial stage of the research. In this stage, the focus is on the control system and motion drive of intelligent vehicles. In the second stage (2008-2014), relevant researches on intelligent vehicles are developing continuously. As can be seen from the burst keywords at this stage, the research depth of algorithms and motion behavior control of intelligent vehicles is constantly increasing. The sudden emergence of the term intelligent vehicle indicates that research on intelligent vehicles has become hot topic. In the third stage (2015-2019), the development of related technologies and facilities has provided the conditions for the in-depth study of intelligent vehicles. With the support of advanced Internet and communication technologies, intelligent vehicles are also developing towards more automation and interconnectivity.

There are also some deficiencies in this study. The retrieval keywords used in this study are representatives of the research in this field, and cannot fully contain all the keywords in the research field. In addition, the retrieval scope of this study is only for the SCIE and SSCI citation index databases in the Web of Science (WOS) Core Collection. The proportion and cooperative relationship of each subject are not be discussed in this research. However, this study aims to provide a visualization analysis method using MKD method, which is also applicable to other keywords and databases. In terms of the visual method, different analysis objectives based on different visual methods can be further considered in future work.

In this paper, the MKD-based systematic analysis approach is used to understand the past and up to date research distribution in the field of intelligent vehicles and the development trend. As a future extension of this work, the topics in the field of intelligent vehicle will be researched to further exploration on the development of a certain research branch or topic, such as connected vehicles, automated and autonomous vehicles.

References

[1] *Early Estimate of Motor Vehicle Traffic Fatalities in 2012*, Traffic Saf. Facts-Crash Stats, Washington, DC, USA, 2013.

[2] *Global Status Report on Road Safety 2013: Supporting a Decade of Action: Summary*, World Health Org., Geneva, Switzerland, 2013.

[3] L. Zhu, X. Liu, S. He, J. Shi, and M. Pang, "Keywords co-occurrence mapping knowledge domain research base on the theory of big data in oil and gas industry," *Scientometrics*, vol. 105, no. 1, pp. 249–260, Oct. 2015.

[4] D. Qian, Y. Zhang, J. Dong, and L. Wang, "Mapping knowledge domain analysis of medical informatics education," in *Frontier and Future Development of Information Technology in Medicine and Education*. Amsterdam, The Netherlands: Springer, 2014.

[5] J. Qiu, S. Yang, and Y. Song, "International research status, hotspots and frontier about knowledge communication based on mapping knowledge domain," *J. Library Sci. China*, vol 38, no 2, pp. 78–89, 2012.

[6] X. Zou, W. L. Yue, and H. L. Vu, "Visualization and analysis of mapping knowledge domain of road safety studies," *Accident Anal. Prevention*, vol. 118, pp. 131–145, Sep. 2018.

[7] R. M. Shiffrin and K. Börner, "Mapping knowledge domains," *Proc. Nat. Acad. Sci. USA*, vol. 101, no. 1, pp. 5183–5185, 2004.

[8] N. J. van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," *Scientometrics*, vol. 84, no. 2, pp. 523–538, Aug. 2010.

[9] N. J. Van Eck and L. Waltman, "VOS: A new method for visualizing similarities between objects," in *Advances in Data Analysis*. Berlin, Germany: Springer, 2007, pp. 299–306.

[10] N. J. van Eck, L. Waltman, J. van den Berg, and U. Kaymak, "Visualizing the WCCI 2006 knowledge domain," in *Proc. IEEE Int. Conf. Fuzzy Syst.*, 2006, p. 1671.

[11] C. Urmson *et al.*, "Autonomous driving in urban environments: Boss and the urban challenge," *J. Field Robot.*, vol. 25, no. 8, pp. 425–466, 2008.

[12] M. Montemerlo *et al.*, "Junior: The Stanford entry in the urban challenge," *J. Field Robot.*, vol. 25, no. 9, pp. 569–597, 2008.

[13] S. Thrun *et al.*, "Stanley: The robot that won the DARPA grand challenge," *J. Field Robot.*, vol. 23, pp. 661–692, Sep. 2006.

[14] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.

[15] J. Petit and S. E. Shladover, "Potential cyberattacks on automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 546–556, Sep. 2014.

[16] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the united states," *Proc. IEEE*, vol. 99, no. 7, pp. 1162–1182, Jul. 2011.

[17] K. Dresner and P. Stone, "A multiagent approach to autonomous intersection management," *J. Artif. Intell. Res.*, vol. 31, pp. 591–656, Mar. 2008.

[18] J. Lee and B. Park, "Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 81–90, Mar. 2012.

[19] S. Ilgin Guler, M. Menendez, and L. Meier, "Using connected vehicle technology to improve the efficiency of intersections," *Transp. Res. C, Emerg. Technol.*, vol. 46, pp. 121–131, Sep. 2014.

[20] B. van Arem, C. J. G. van Driel, and R. Visser, "The impact of cooperative adaptive cruise control on traffic-flow characteristics," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 429–436, Dec. 2006.

[21] A. Talebpour and H. S. Mahmassani, "Influence of connected and autonomous vehicles on traffic flow stability and throughput," *Transp. Res. C, Emerg. Technol.*, vol. 71, pp. 143–163, Oct. 2016.

[22] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 62, no. 2, pp. 1805–1824, Aug. 2000.

[23] D. J. Fagnant and K. Kockelman, “Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations,” *Transp. Res. A, Policy Pract.*, vol. 77, pp. 167–181, Jul. 2015.

[24] M. Kyriakidis, R. Happee, and J. C. F. de Winter, “Public opinion on automated driving: Results of an international questionnaire among 5000 respondents,” *Transp. Res. F, Traffic Psychol. Behav.*, vol. 32, pp. 127–140, Jul. 2015.

[25] P. Zhao, J. Chen, Y. Song, X. Tao, T. Xu, and T. Mei, “Design of a control system for an autonomous vehicle based on adaptive-PID,” *Int. J. Adv. Robotic Syst.*, vol. 9, no. 2, p. 44, Aug. 2012.

[26] S. Karaman and E. Frazzoli, “Sampling-based algorithms for optimal motion planning,” *Int. J. Robot. Res.*, vol. 30, no. 7, pp. 846–894, Jun. 2011.

[27] A. Visioli, *Practical PID Control*. London, U.K.: Springer, 2006.

[28] M. Barton, “Controller development and implementation for path planning and following in an autonomous urban vehicle,” M.S. thesis, Dept. Australian Centre Field Robot., School Aerosp., Mech. Mechatron. Eng., Univ. Sydney, Sydney, NSW, Australia, 2001.

[29] V. Milanes, S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, “Cooperative adaptive cruise control in real traffic situations,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 296–305, Feb. 2014.

[30] A. Vahidi and A. Eskandarian, “Research advances in intelligent collision avoidance and adaptive cruise control,” *IEEE Trans. Intell. Transp. Syst.*, vol. 4, no. 3, pp. 143–153, Sep. 2003.

[31] N. J. Schouten, M. A. Salman, and N. A. Kheir, “Fuzzy logic control for parallel hybrid vehicles,” *IEEE Trans. Control Syst. Technol.*, vol. 10, no. 3, pp. 460–468, May 2002.

[32] B. Schoettle and M. Sivak, “Public opinion about self-driving vehicles in China, India, Japan, the US, the UK, and Australia,” Univ. Michigan Ann Arbor Transp. Res. Inst., Ann Arbor, MI, USA, Tech. Rep. UMTRI-2014-30, 2014.

[33] Y. Ro and Y. Ha, “A factor analysis of consumer expectations for autonomous cars,” *J. Comput. Inf. Syst.*, vol. 59, no. 1, pp. 52–60, Jan. 2019.

[34] R. Krueger, T. H. Rashidi, and J. M. Rose, “Preferences for shared autonomous vehicles,” *Transp. Res. C, Emerg. Technol.*, vol. 69, pp. 343–355, Aug. 2016.

[35] M. Kyriakidis, R. Happee, and J. C. F. de Winter, “Public opinion on automated driving: Results of an international questionnaire among 5000 respondents,” *Transp. Res. F, Traffic Psychol. Behav.*, vol. 32, pp. 127–140, Jul. 2015.

[36] M. König and L. Neumayr, “Users’ resistance towards radical innovations: The case of the self-driving car,” *Transp. Res. F, Traffic Psychol. Behav.*, vol. 44, pp. 42–52, Jan. 2017.

[37] J. Shin, C. R. Bhat, D. You, V. M. Garikapati, and R. M. Pendyala, “Consumer preferences and willingness to pay for advanced vehicle technology options and fuel types,” *Transp. Res. C, Emerg. Technol.*, vol. 60, pp. 511–524, Nov. 2015.

[38] A. Nunes, B. Reimer, and J. F. Coughlin, “People must retain control of autonomous vehicles,” *Nature*, vol. 556, no. 7700, pp. 169–171, Apr. 2018.

[39] M. Bertozzi, A. Broggi, and A. Fascioli, “Vision-based intelligent vehicles: State of the art and perspectives,” *Robot. Auto. Syst.*, vol. 32, no. 1, pp. 1–16, Jul. 2000.

[40] Z. Sun, G. Bebis, and R. Miller, “On-road vehicle detection: A review,” *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 28, no. 5, pp. 694–711, May 2006.

[41] S. Tokoro, K. Kuroda, A. Kawakubo, K. Fujita, and H. Fujinami, “Electronically scanned millimeter-wave radar for pre-crash safety and adaptive cruise control system,” in *Proc. IEEE IV Intell. Vehicles Symp.*, Jun. 2003, pp. 304–309.

[42] U. Ozguner, C. Stiller, and K. Redmill, “Systems for safety and autonomous behavior in cars: The DARPA grand challenge experience,” *Proc. IEEE*, vol. 95, no. 2, pp. 397–412, Feb. 2007.

[43] Y. Wang, E. K. Teoh, and D. Shen, “Lane detection and tracking using B-Snake,” *Image Vis. Comput.*, vol. 22, no. 4, pp. 269–280, Apr. 2004.

[44] S. Sivaraman and M. M. Trivedi, “Looking at vehicles on the road: A survey of vision-based vehicle detection, tracking, and behavior analysis,” *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 4, pp. 1773–1795, Dec. 2013.

[45] L. Da Xu, W. He, and S. Li, “Internet of Things in industries: A survey,” *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[46] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, “Connected vehicles: Solutions and challenges,” *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.

[47] L. Zhang, W. Cao, X. Zhang, and H. Xu, “MAC2: Enabling multicasting and congestion control with multichannel transmission for intelligent vehicle terminal in Internet of vehicles,” *Int. J. Distrib. Sensor Netw.*, vol. 14, no. 8, Aug. 2018, Art. no. 155014771879358.

[48] F. Yang, S. Wang, J. Li, Z. Liu, and Q. Sun, “An overview of Internet of vehicles,” *China Commun.*, vol. 11, no. 10, pp. 1–15, Oct. 2014.

[49] J. A. Guerrero-Ibanez, S. Zeadally, and J. Contreras-Castillo, “Integration challenges of intelligent transportation systems with connected vehicle, cloud computing, and Internet of Things technologies,” *IEEE Wireless Commun.*, vol. 22, no. 6, pp. 122–128, Dec. 2015.

[50] J. Kleinberg, “Bursty and hierarchical structure in streams,” *Data Min. Knowl. Disc.*, vol. 7, pp. 373–397, Oct. 2003.

[51] C. Chen, “CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature,” *J. Amer. Soc. Inf. Sci. Technol.*, vol. 57, no. 3, pp. 359–377, 2006.

[52] N. E. Pears, “Mobile robot tracking of pre-planned paths,” *Adv. Robot.*, vol. 15, no. 1, pp. 97–107, 2001.

[53] T. Gandhi and M. M. Trivedi, “Vehicle surround capture: Survey of techniques and a novel Omni-video-based approach for dynamic panoramic surround maps,” *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 3, pp. 293–308, Sep. 2006.

[54] D. Zhao, H. Fu, L. Xiao, T. Wu, and B. Dai, “Multi-object tracking with correlation filter for autonomous vehicle,” *Sensors*, vol. 18, no. 7, p. 2004, 2018.

[55] Y. Kuwata, S. Karaman, J. Teo, E. Frazzoli, J. P. How, and G. Fiore, “Real-time motion planning with applications to autonomous urban driving,” *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 5, pp. 1105–1118, Sep. 2009.

[56] L. Chen, Q. Wang, X. Lu, D. Cao, and F.-Y. Wang, “Learning driving models from parallel end-to-end driving data set,” *Proc. IEEE*, vol. 108, no. 2, pp. 262–273, Feb. 2020.

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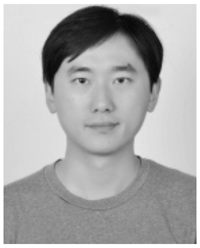

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