

## Research Article

# Development Status and Hotspot Visualized Analysis of Autonomous Vehicles Based on CiteSpace

Lixin Yan , Tao Zeng, Guangyang Deng, and Qiujie Xu

School of Transportation Engineering, East China JiaoTong University, Nanchang, Jiangxi Province 330013, China

Correspondence should be addressed to Lixin Yan; yanlixinits@163.com

Received 16 November 2021; Revised 23 February 2022; Accepted 2 March 2022; Published 31 March 2022

Academic Editor: Alessandro Severino

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The safety of autonomous driving has been a constant concern, with autonomous driving becoming a research focus in the world today. This study collects the literature in the field of autonomous driving in the Web of Science core data collection from 2005 to 2020. The research status, hot research topics, and the development trend of autonomous driving are reviewed based on CiteSpace from the aspects of number of articles, national collaboration, institutions, scholars, research areas, literature co-citation, keywords, and trends. The results show that the quantitative development of autonomous driving literature has experienced three stages. The research of the United States, China, and Germany is leading in this field. The development of autonomous driving will be in the stage of man-machine driving for a long time. In this study, the progress and trend of visualization in the field of autonomous driving are given, and the future research direction is forecasted, which provides a theoretical basis for the development of autonomous driving. Furthermore, it has reference significance for relevant researchers to understand the research hotspots and future trends in this field.

## 1. Introduction

In recent years, due to the increasing number of car users, road traffic congestion, safety accidents, and other problems are becoming more serious. With the development of Internet of vehicles technology and artificial intelligence, autonomous driving vehicle is equipped with Intelligent Traffic System (ITS), which is connected to the V2X cloud platform. ITS must be upgraded with infrastructure on the road and V2X cloud platform to realize vehicle-to-vehicle communication, which can coordinate travel routes and planning time, thus greatly improving travel efficiency and reducing energy consumption [1]. At present, the major developed countries regard autonomous driving as an important strategic direction for future development, and this field is also widely concerned by academia and industry. Although unmanned driving is the “ultimate goal” of technology development, “highly automated driving” vehicles (HAVs), which can achieve automated driving function under some specific conditions, may come in the next few years [2]. Autonomous driving is beneficial to society, drivers, and

pedestrians. It is not affected by human factors so that the incidence of traffic accidents can almost drop to zero [3]. Even with the interference of the rate of traffic accidents of some autonomous driving, the rapid growth of the market share will reduce the overall traffic accident rate [4]. At the same time, the automated driving mode is more energy-efficient, green, and environmentally friendly, which is in line with the current international sustainable development needs. Society of Automotive Engineers (SAE) is divided into 6 levels: L0 (No Automation), L1 (Driving Assistant), L2 (Partial Automation), L3 (Conditional Automation), L4 (High Automation), and L5 (Full Automation) [5]. Autonomous driving is between L3–L5 grades, which is one of the research priorities of current enterprises and institutes.

Autonomous driving has been a hot topic. In terms of traffic safety, Juozas et al. [6] proposed a strict modular statistical method to demonstrate the safety or deficiency of autonomous driving. Li and Ban [7] proposed an automated driving algorithm in a 5G network environment. Compared with the traditional algorithm based on BP neural network and Bayes, the processing time of this algorithm is shortened

by 2.1s and 2.98s, and the driving safety reaches 100%. Due to the decision-making errors of autonomous driving leading to traffic accidents, Xuan and Rongye [8] investigated how autonomous driving affects road safety and, based on the game model, designed the social optimal liability provisions for the comparative negligence of the vehicle and the driver. Zheng [9] introduced the “rational car” standard from the perspective of the civil code to enrich the judgment of the fault of the “motor vehicle side” and overcame the liability dilemma caused by the replacement of manual driving by autonomous driving. In terms of driving performance, autonomous vehicles represent an important change for public transport efficiency due to the elevated performance so the relevant reduction of human mistakes because the high precision of headways would provide a high-quality service [10]. Comparing the safety of autonomous driving with nonautonomous, Selander et al. [11] showed that autonomous driving improved the older participants’ driving behavior as demonstrated by safer speed adjustment in urban areas, greater maneuvering skills, safer lane position, and driving in accordance with the speed regulations. Kim et al. [12] proposed a cooperative autonomous driving algorithm by using V2V communication to allow a safe and comfortable convoy driving with the preceding vehicles, which improved the performance of the existing autonomous driving functions relying solely on environmental sensors via V2V communication. Severino et al. [13] emphasized how road markings, intersections, and pavement design upgrades have a key role for autonomous vehicles operation. Tran and Bae [14] proposed an automated driving behavior model based on traffic safety, delay time, and stable driving. This model can reduce the braking time by 31.60% and increase smooth speed control by 51.20% compared with the classical adaptive model predictive control. The development of autonomous driving will be in a long-term and man-machine driving stage. In the L2 and L3 modes, people and vehicles share the control of intelligent vehicles. Yoon et al. [15] studied the influence of nondriving-related tasks (NDRT) on the control over crossing in highly automated driving (HAD). Wu et al. [16] used the driving simulator to do three different traffic scene experiments. The results show that when the driver is engaged in the visual secondary task, the steering response time increased significantly after take-over. To study how to safely and effectively transfer the take-over request of the autonomous driving to the driver, Yun and Yang [17] compared various warning combinations in the context of the take-over request classified by the system in conditional autonomous driving. The results show that the visual-auditory-haptic warning combination is the best way to take-over request. Merlhiot and Bueno [2] found that distraction and drowsiness increased the take-over request reaction time (TOR-RT), which leads to a reduction of the quality of take-overs.

Constantly discussing and summarizing the current research status of the world’s autonomous driving are very important for promoting the field. In this study, the bibliometric analysis method is used to analyze the current situation of the research on autonomous driving. The data are collected by the Web of Science core dataset, and the econometric analysis CiteSpace is used to refine, comb, and

summarize the literature and explore the research status, development, hot topics, evolution path, and development trend in this field, thereby showing the development in this field.

By combining the relevant literature in the field of autonomous driving, this study analyzes the research status of the autonomous driving from the aspects of quantity, national cooperation, research institutions, scholars, research areas, literature co-citation, keywords, and trends, summarizing the four hotspots of autonomous driving, automated guided vehicle, adaptive cruise control, eco-driving, and man-machine co-driving, to provide references for further research.

## 2. Methodologies

*2.1. Data Collection.* To clarify the hot topics and trends in the field of autonomous driving research in the international academic field, the data of this study are the scientific citation index of the Web of Science core dataset. The specific method of the literature search is shown in Table 1.

*2.2. Construction of Co-Word Similarity Matrix.* Clustering analysis is carried out by constructing a keyword co-occurrence matrix. A  $n \times n$  similarity matrix  $S$  can be constructed with  $n$  keywords [19]:

$$S = (s_{ij}), \quad (1)$$

where  $S_{ij} \geq 0$ ,  $S_{ii} = 0$ , and  $S_{ij} = S_{ji}$  for  $i, j \in \{1, \dots, n\}$ .

The principle for determining the similarity between two objects is to separate the objects with low similarity and cluster the objects with high similarity [19].

The similarity between objects and can be expressed as

$$S_{ij} = \frac{C_{ij}}{W_i W_j}, \quad (2)$$

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

*2.3. Construction of Knowledge Domain Maps.* The weighted Euclidean distance sum of all objects in each cluster is minimized to improve the clustering effect. The distance between clusters can be determined by the following formula [19]:

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

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

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

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

TABLE 1: Data source and processing results.

	Detail	Description
Search date	May 3, 2021	
Database	Web of science core dataset (WOS)	The web of science core dataset contains the characteristics of long time span, a large number of entries, and high quality, which provides a powerful guarantee for the reliability of raw data in the visual analysis [18]
Subject	TS = (automated/automatic/unmanned/ autonomous driving or vehicle)	The published article containing the above search keywords in the title, abstract, or keywords will be retrieved
Document type	Article	This type of article is reviewed by peers, which can represent the original scientific development
Language	English	
Time span	2005–2020	
Number of documents research	1213	
Number of valid documents	1072	Remove 141 papers irrelevant to this field by manual screening

In the CiteSpace, the color of each point in the density view reflects the density of that point. The average distance between two points is denoted by distance [19]

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

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

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

where  $k \in [0, +\infty)$  is a kernel function,  $h > 0$  is kernel width parameter, and  $W_i$  is the weight of object  $i$ , namely, the total frequency that  $i$  appears.

To determine the color of each point on the map, first obtain the color of the cluster by 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, blend the obtained color with the background color of the cluster density view.

**2.4. Knowledge Map.** Knowledge map is a series of graphics showing the relationship between the development process and structure of knowledge, which can express the information of the internet in a form closer to the human cognitive world and then provide a better way to organize, manage, and use massive information [20].

CiteSpace is one of those scientific knowledge mapping software, which realizes the mapping of scientific knowledge mapping through the relationship construction and visual analysis of “network data” (mainly literature knowledge unit) and shows the structure, evolution, cooperation, and other relationships of knowledge field. With the continuous maturity of the software, it is widely used in education, medical, and engineering fields, especially in the bibliometric analysis plate [18]. The screen of the CiteSpace is shown in Figure 1.

In this study, 1072 articles retrieved are imported into CiteSpace. Based on the software platform, the research status, hot research topics, and development trend of

autonomous driving are analyzed from the aspects of number of articles, national collaboration, institutions, scholars, research areas, literature co-citation, keywords, and trends. The framework is shown in Figure 2.

### 3. Results

#### 3.1. Research Status Analysis

**3.1.1. Number of Articles’ Analysis.** To explore the research status of autonomous driving, the number of articles published during 2005 and 2020 is analyzed. From Figure 3, the research area of autonomous driving has gone through three stages: the initial stage, the steady growth stage, and the fast growth stage.

**Initial stage (2005–2010):** at this stage, there are few related research achievements in the field of autonomous driving, and the maximum number of papers published each year is only 20, which means that a complete literature system has not yet been formed in this field.

**Stable growth stage (2011–2015):** at this stage, the number of articles on autonomous driving began to rise steadily by a small margin, with an annual increase of about 9 articles.

**Rapid development stage (2016–2020):** in 2016, for the first time, there was a substantial increase in the number of articles, which is 4.9 times higher than the trend before 2015. The largest increase was from 2018 to 2019. The reason is that, in September 2016, the United States government issued the world’s first driverless vehicle policy document “Federal Automated Vehicles Policy,” which provides a system guarantee for autonomous driving technology. In May of the same year, the Japanese police agency issued the “autonomous driving road test guide,” which allowed the autonomous driving road test. On March 1, 2018, the first batch of intelligent vehicle network open road test license plates was issued in Shanghai. In October of the same year, the United States Department of Transport issued the new version of the federal autopilot steering document “Preparing for the Future of Transportation: Automated Vehicle 3.0,” which promoted the fusion of various modes of

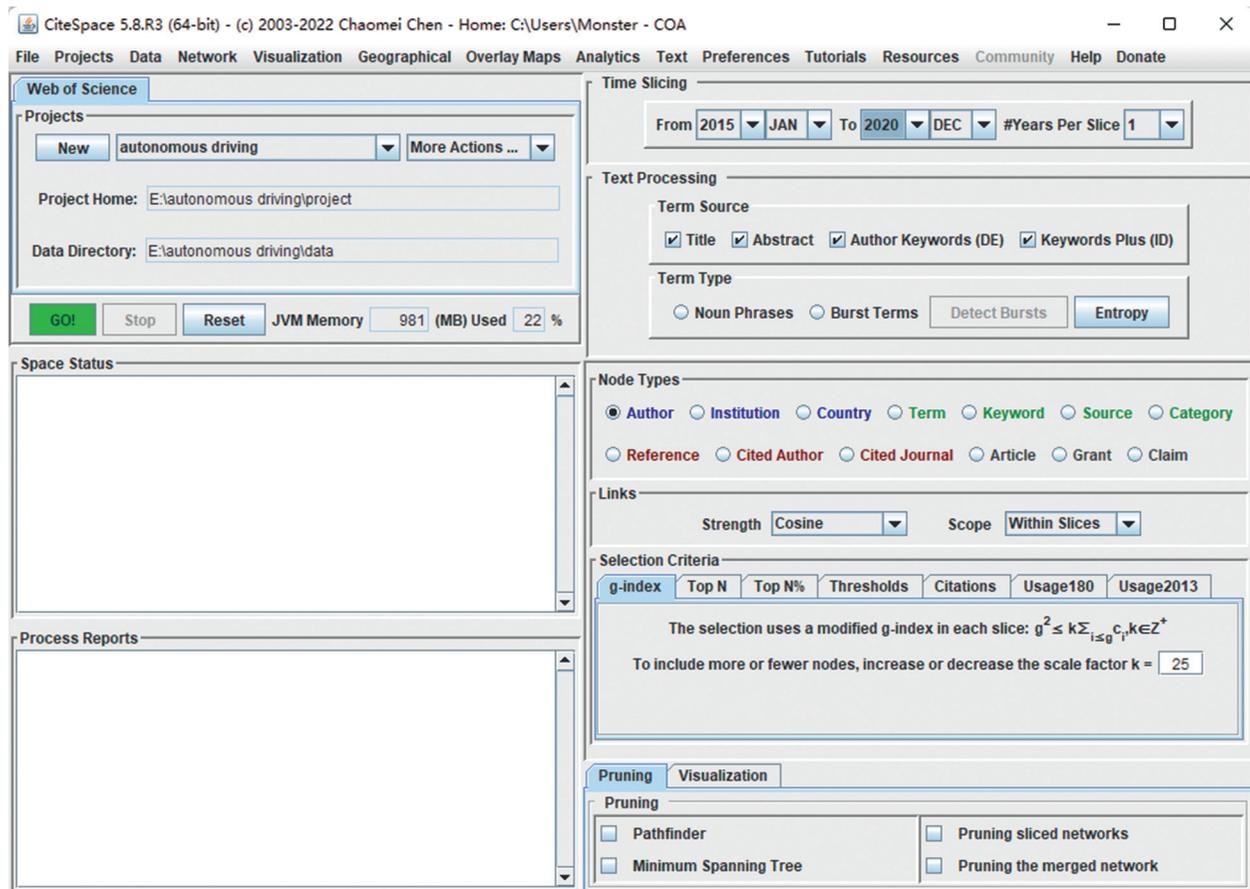


FIGURE 1: An example screen of software.

transportation between automated driving technology and ground transportation system. These related policies provide strong support for autonomous driving.

In addition, 72.3% of the literature (778 articles) were published in recent five years (2016–2020) and 59.3% of them (638 articles) were published in recent three years (2018–2020), which constantly reached the peak of the number of articles. This phenomenon reflects the novelty of autonomous driving research. It can be seen that the number of articles may reach an unprecedented increase in 2021, which once again confirms the research concern in this field and the importance of international scholars.

**3.1.2. National Collaboration Analysis.** To further understand the collaboration mode between countries, the node type of CiteSpace is changed to country for analysis. As shown in Figure 4, the network has 66 nodes, 248 related links, and a network density of 0.1156. This shows that the cooperation among countries in the field of autonomous driving research is close. However, the close ties among countries are focus on the United States, China, and Germany and have close cooperation with the United Kingdom, Canada, South Korea, the Netherlands, and Spain.

As shown in Table 2, the United States is the country with the highest number of articles published in this field, with 333 articles published, accounting for 23.85% of the

total number of papers published in this field, followed by China (232 papers), Germany (128 papers), and the United Kingdom (71 papers), accounting for 16.62%, 9.17%, and 5.09%, respectively. It can be seen that the number of articles published by the United States and China in this field is much higher than that of other countries in the world, which proves that the research of the United States and China in this field is at the forefront of the world. In January 2020, the U.S. Department of Transportation issued the “Autonomous Vehicle 4.0,” which proposes technical principles to protect the safety, promote innovation, and unify regulatory policies and summarizes 38 Efforts by federal departments, independent agencies, commissions, and the Executive Office of the President to advance the development of autonomous driving to ensure U.S. leadership in autonomous driving technology. As a giant in the field of autonomous driving, Waymo launched a L4-level autonomous driving system in 2020, and together with GM Cruise, Lyft, and other companies urged the National Highway Traffic Safety Administration (NHTSA) to formulate new autonomous driving regulations. Unnecessary regulatory hurdles are removed and vehicles without steering wheels and brake pedals are allowed to operate without compromising safety. In February of the same year, China issued the “Strategy for the Innovative Development of Intelligent Vehicles.” The strategy specifies the vision of realizing the large-scale production of

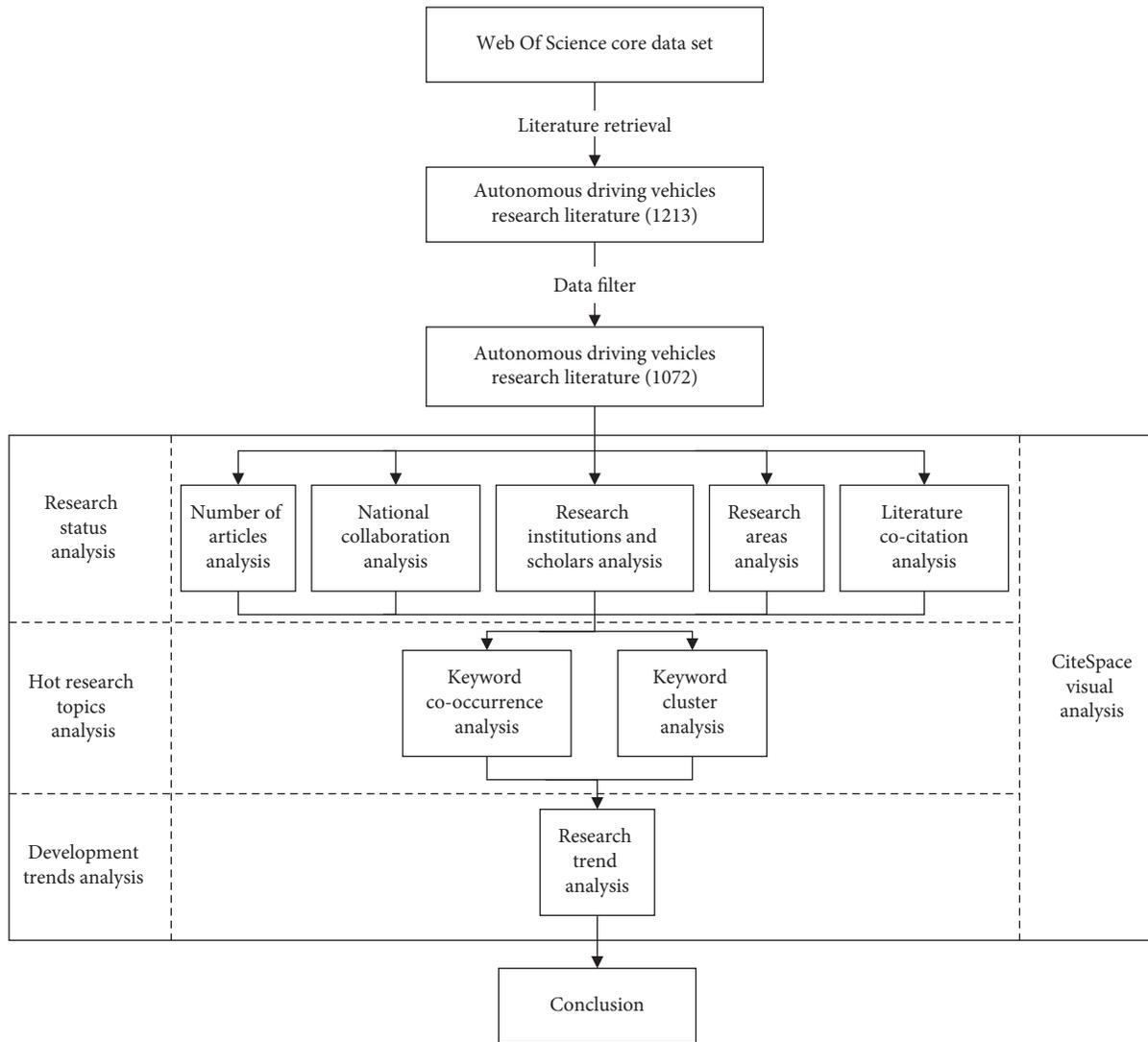


FIGURE 2: Framework of this study.

conditional smart cars by 2025 and the full completion of China’s standard autonomous driving system by 2035, points out the main tasks of autonomous driving development such as developing core technologies, improving infrastructure construction and perfecting the relevant legal and regulatory system, and announces safeguard initiatives such as strengthening organization and implementation and improving support policies. Changan Automobile, GAC, SAIC, etc., have launched L3-level models that can be mass-produced.

**3.1.3. Research Institutions and Scholars’ Analysis.** To further understand the cooperation mode of various organizations, the node type of CiteSpace is changed to institution for analysis. As shown in Figure 5, the network has 415 nodes, 390 related links, and the network density is 0.0045, which indicates that there is less cooperation between research institutions in the field of autonomous driving. The Delft University of Technology, Tongji University, and the

Technical University of Munich are the top three centers, which indicate that these three organizations have close cooperation with other organizations. The Delft University of Technology is closely related to Tongji University, Technical University of Munich, and Delft University of Technology. Tsinghua University has close ties with institutions such as the University of Michigan and Tongji University. Delft University of Technology worked on high-performance vehicles’ stream for FHWA in collaboration with UC Berkeley, on congestion reduction at sags by intelligent vehicles with Toyota, with Nissan on simulation of testing scenarios for autonomous vehicles and on driver support and automation with the ITS Research Centre of the Chinese Ministry of Transport. The “Tu Ling TIEV” of Tongji University unmanned vehicle lab develops L4 level fully autonomous driving systems. In 2018, the lab cooperated with UCloud to put the training of the core “driving brain” into the cloud, promoting the development of autonomous vehicles into a new stage. Munich Technical University has developed a new early warning system for

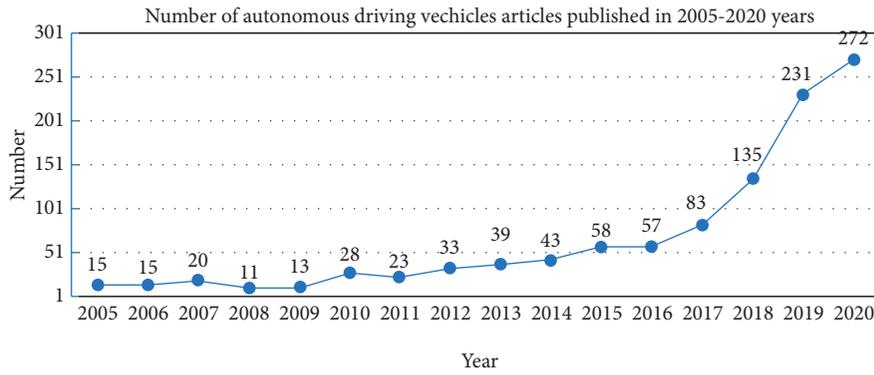


FIGURE 3: Number of autonomous driving articles published in 2005–2020 years.



FIGURE 4: National collaboration network.

autonomous driving vehicles. The system uses artificial intelligence to learn from thousands of real traffic situations and can provide 7 seconds in a critical situation, with an accurate rate of more than 85%.

On the contrary, Table 3 shows the number of articles published by the top 10 autonomous driving research institutions. The University of Michigan, Delft University of

Technology, and Tsinghua University are the institutions with the largest number of articles published, with 30 articles published. Among the top 10 institutions with the largest number of articles published, three are from the United States and three are from China, which proves once again that the research of the United States and China in this field is located at the forefront of the world.

TABLE 2: The number of articles published by countries.

Rank	Country	Number
1	USA	333
2	China	232
3	Germany	128
4	England	71
5	Canada	61
6	South Korea	56
7	Netherlands	56
8	Sweden	44
9	Spain	36



FIGURE 5: Organization collaboration network.

TABLE 3: Number of articles published by institutions.

Rank	Institution	Number	Percent (%)
1	University of Michigan	30	2.87
2	Delft University of Technology	30	2.87
3	Tsinghua University	30	2.87
4	Technical University of Munich	25	2.39
5	Tongji University	24	2.30
6	Chalmers University of Technology	21	2.01
7	University of Wisconsin	16	1.53
8	Southeast University	14	1.34
9	University California, Berkeley	13	1.25
10	University of Toronto	12	1.15

As shown in Table 4, the author with the largest number of articles is Bin Ran, who has close cooperation with Xu Qu and Linheng Li. Ran et al. [21], studied the autonomous

transportation system in combination with expressway and made the autonomous vehicles more safe and reliable through hardware, software, and communication

TABLE 4: The number of articles published by authors.

Rank	Authors	Number
1	Bin Ran	11
2	Hong Chen	6
3	Bart Van Arem	6
4	Klaus Bengler	6
5	Jiaqi Ma	6
6	Natasha Merat	6
7	Shengbo Eben Li	5
8	Xu Qu	5
9	Dongpu Cao	5

technology. The second authors of the number of articles are Hong Chen, Bart Van Arem, Klaus Bengler, Jiaqi Ma, and Natasha Merat, all of whom have published 6 articles. Chen et al. [22] through the type of collision, the severity of the collision, the movement of the vehicle before the collision, and the damage to the vehicle explored the contributing factors of the automatic driving vehicle collision. Van et al. [23] studied the impact of autonomous vehicles on traffic flow efficiency and road user behavior. Bengler et al. [24] proposed a guidance and control framework for driver-vehicle interaction during autonomous driving. The results show good system performance and robustness. Ma et al. [25] proposed a cooperative adaptive cruise control (CACC) and a cooperative line and speed coordinated autopilot system. The test results show the stability of the system. Merat et al. [26] explored the effects of the driver's workload on the performance of the autonomous driving take-over through a simulation experiment. The results show that when the driver is doing nondriving-related task (NDRT), the performance is the worst. When the driver's attention is not dispersed by NDRT, the performance after the take-over is not affected. The third author has published five papers, including Shengbo Eben Li, Xu Qu, and Dongpu Cao. Li et al. [27] proposed a linear predictive lateral control method, which makes the highly autonomous vehicle more stable when the road adhesion coefficient is very small. The robustness of the controller is verified by experiments. Yi et al. [28] put forward an intelligent back range driving model (IBDM). The results show that IBDM is more stable than the intelligent driving model (IDM) in the process of controlling the autonomous driving following. Guo et al. [29] proposed an implicit linear model predictive control (MPC) method to design a mobile horizontal line path tracking controller to solve the situation where the vehicle collides and runs in the traditional path tracking method.

Change the node type of CiteSpace to author for analysis, and the generated author network diagram is shown in Figure 6. The co-occurrence network has 499 nodes and 383 related links, and the network density is 0.0031, which indicates that there is less and cooperation between the research authors in the field of autonomous driving. However, there are several author cooperation groups, such as Natasha Merat and Manuel Schmidt as the core group to study the human-computer take-over and human-machine interaction of autonomous vehicles, and Hong Chen and Dongpu Cao as the

core group to study the path problem of autonomous vehicles. The larger research group is important for promoting research innovation and knowledge sharing and improving research quality [30]. However, according to the analysis results, most of the authors who have academic achievements are independent authors or cooperate in the same organization. The scale of such cooperation is small and unstable, which leads to the lack of effective international cooperation in the field of autonomous vehicles.

*3.1.4. Research Area Analysis.* Co-occurrence category analysis is often used to study interdisciplinary connections. Through the construction of a disciplinary correlation network, it can reveal the internal connections among different disciplinary categories [31]. Due to the certain intersections of various disciplines, the research fields including engineering and transportation are classified into one category in this study. As shown in Table 5, the top 5 disciplines in the field of autonomous driving research were obtained, including 1440 articles in engineering (37.5%), 743 articles in transportation (19.35%), 436 articles in computer science (11.35%), 1440 articles in engineering (37.5%), 113 in automation and control systems (2.94%), and 71 in telecommunications (1.85%). The top three disciplines are engineering, computer science, and biochemistry and molecular biology, and the three major disciplines appear as a medium, which connects many different disciplines, including computer science, science and technology, electrical, and other disciplines. The intersecting nature of the disciplines indicates that the topic is global research that requires the joint efforts of different disciplines.

*3.1.5. Literature Co-Citation Analysis.* Through co-citation analysis, the important knowledge base in this research field can be found efficiently and conveniently from a large number of cited literature [32]. The node type of CiteSpace was changed to reference for analysis. As shown in Figure 7, the top 3 cited articles were Fagnant D.J., 2015 (59 times), Talebpour A., 2016 (35 times), and Kyriakidis M., 2015 (33 times). According to the literature co-citation cluster analysis, it is divided into six clusters: autonomous driving vehicle, policy, human-computer interaction, automated driving behavior, expressway-intelligent vehicle integrated system, and acceptance survey.



FIGURE 6: Author collaboration network.

TABLE 5: Number of articles published by areas.

Rank	Area	Number	Percent (%)
1	Engineering	1440	37.50
2	Transportation	743	19.35
3	Computer science	436	11.35
4	Automation and control systems	113	2.94
5	Telecommunications	71	1.85



FIGURE 7: Literature co-citation network.

Fagnant and Kockelman [33] analyzed the impact of autonomous driving on society from 12 factors including safety, traffic congestion, and cost. It concluded that there are six major problems: vehicle cost, vehicle permit, insurance and liability, safety, privacy, and lack of research. Fagnant pointed out that current policies and objectives have a positive impact on the future development of autonomous driving, and three suggestions have been made to address the above issues: expanding federal funding for autonomous driving research, developing federal guidelines for the certification of autonomous driving, and determining appropriate standards for accountability, security, and data privacy.

Talebpur and Mahmassani [34] proposed a micro-simulation framework, which can identify different vehicle types and use different existing models to capture the

interaction between conventional, connected (at different communication levels), and autonomous driving. Through the analysis and simulation of the stability of mixed traffic flow with different proportions, the analysis showed that the autonomous driving can improve the stability of traffic flow better than the other two types of vehicles.

Kyriakidis et al. [35] investigated user acceptance, concern, and purchase intention of partially automated, highly automated, and fully autonomous vehicles. Through a 63-question internet survey, 5,000 samples were collected from 109 countries (with at least 25 respondents in 40 countries) and were analyzed in terms of both transnational differences and individual differences. The results showed that the majority of respondents thought manual driving was the most enjoyable way to drive. Twenty two percent of respondents said they would not want to pay more than \$0

for a fully automated system, while five percent said they would pay more than \$30,000, and thirty three percent said fully automated driving was fun. Sixty nine percent of respondents believe fully automated driving will have a fifty percent market share by 2050. According to the survey, people are most concerned about the immaturity of smart cars, legal issues and, safety issues.

### 3.2. Research Topics and Hotspot Analysis

**3.2.1. Keyword Co-Occurrence Analysis.** Keywords usually describe the core content of the article. Usually, keywords also involve the frontier development of related fields. If a word appears frequently in a certain period, it can be concluded that the word reflects the most important content of the research field in that period [36]. Change the node type of CiteSpace to keyword for analysis, and the generated keyword co-occurrence network is shown in Figure 8. Since the keywords of autonomous driving and vehicle are included in the search formula, it is not meaningful to consider them separately. In addition, according to Table 6, the top 10 nodes with the highest frequency are model (134 times), design (124 times), system (123 times), adaptive cruise control (73 times), optimization (64 times), automated guided vehicle (53 times), algorithm (51 times), safety (49 times), time (46 times), and performance (44 times). This shows that over the past 2005–2020 years, the above keywords have become the research focus of scholars in the field of autonomous driving. While paying attention to autonomous driving vehicles, the diversification of vehicles also starts to pay more attention to intelligence, which will promote the development of autonomous driving in the direction of diversification.

**3.2.2. Keyword Cluster Analysis.** Figure 9 shows a cluster map of keywords. After excluding the search keyword autonomous driving, according to the cluster analysis results, the high-frequency keywords in the field of autonomous driving are integrated, and the hot topics for research are finally summarized for the following four aspects:

(1) *Automated Guided Vehicle (AGV)*. Keywords mainly include genetic algorithm, routing problem, and infrared rays. In the early research, in order to rapidly develop intelligent logistics, a large number of scholars studied automated guided vehicles. Correa et al. [37] proposed a hybrid method to solve the scheduling and collision-free path problems of automated guided vehicles in flexible manufacturing systems (FMS). This method can solve up to six instances of automated guided vehicles. Lu et al. [38] proposed a positioning system that supports radio frequency identification (RFID) in AGVs for smart factories and quantitatively extracts the key influences on AGV accuracy. Through simulation research and test platform, the feasibility and practicability of this method are evaluated. Fazlollahtabar et al. [39] proposed an optimization method to solve the scheduling problem of multiple AGVs

in two stages of solving space and finding the optimal solution.

(2) *Adaptive Cruise Control (ACC)*. Keywords mainly include four-lane traffic model, road network environment, and intersection coordination. Li et al. [40] designed a road queuing system through the dynamics of nodes in the road, information flow network, distributed controller, and road geometry, which improved road safety and efficiency and reduced energy consumption. Ghiasi et al. [41] proposed a highway mixed traffic analysis capability model based on Markov chain representation of heterogeneous and random headspace distribution. The experiment verified that the model accurately quantified the road mixed traffic capability under various conditions. This model can be used as a decision-making tool for lane management of autonomous driving in a short time. Letter and Elefteriadou [42] proposed a longitudinal highway merging control algorithm to maximize the average driving speed of intelligent networked vehicles. Experiments showed that this algorithm can reduce vehicle travel time, increase average travel speed, and change traffic without congestion. When the road is crowded, queuing will be formed in the ramp and the mainline segment in the merging area. This algorithm can provide safe merging operations in congested traffic conditions.

(3) *Eco-Driving*. Keywords mainly include eco-approach, biological system modeling, and speed harmonization. Transportation is one of the main sources of energy consumption and greenhouse gas emissions. Eco-driving technology minimizes fuel consumption and emissions during driving. Zhao et al. [43] proposed a model predictive control (MPC) method, which reasonably queues up to reduce fuel consumption when passing green light intersections. A large number of simulation tests have proved that the model can reduce energy consumption under different road conditions and, at the same time, realizes the ecological driving strategy without compromising traffic efficiency and driving comfort. Wang et al. [44] gave a cooperative environmental driving (CED) target signal channel system. The simulation results show that, with the increase in the popularity of autonomous vehicles, the energy consumption and pollutant emissions of the transportation system have declined. Specifically, when the system is full of autonomous driving, energy consumption can be reduced by more than 7% and pollutant emissions can be reduced by up to 59%. Huang et al. [45] developed an eco-driving system in an autonomous vehicle environment. The system includes three functions: traffic state prediction, eco-driving speed control, and power control. Based on real-time traffic information, the embedded traffic state prediction model will estimate and predict the average speed and density of vehicles on highway sections.

(4) *Cooperative Perception*. Keywords mainly include human-vehicle interaction, take-over, and preferences. The development of autonomous driving will be in the stage of man-machine co-driving for a long time. In the partially automated driving assistance (L2 level) and combined automated driving assistance (L3 level) modes of driving,

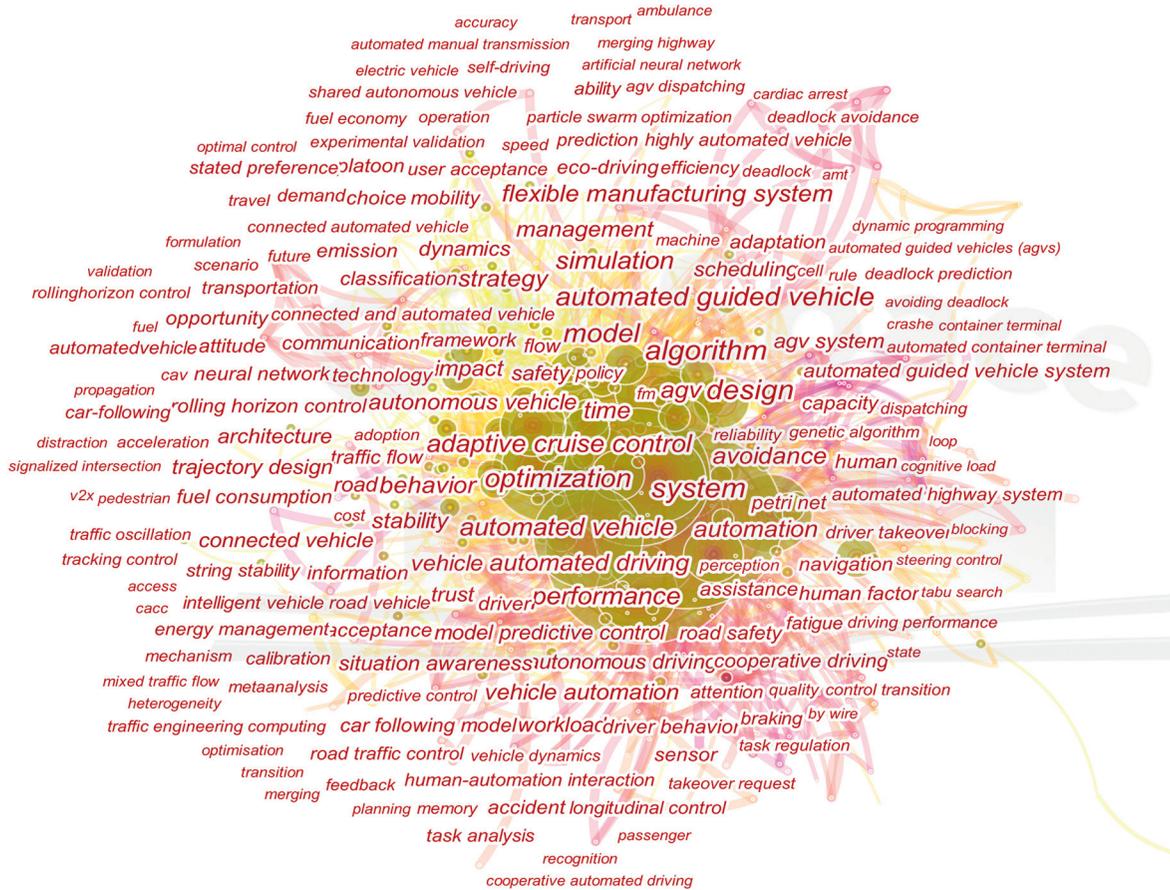


FIGURE 8: Keyword co-occurrence network.

TABLE 6: Frequency of keywords for autonomous driving vehicles.

Rank	Keywords	Number	Centrality
1	Model	134	0.19
2	Design	124	0.21
3	System	123	0.17
4	Automated vehicle	111	0.13
5	Autonomous vehicle	103	0.05
6	Adaptive cruise control	73	0.06
7	Automated driving	69	0.08
8	Optimization	64	0.13
9	Automated guided vehicle	53	0.09
10	Algorithm	51	0.14
11	Safety	49	0.02
12	Time	46	0.08
13	Performance	44	0.06
14	Simulation	42	0.11
15	Impact	42	0.1

humans and vehicles share the control of smart vehicles. Therefore, man-machine co-driving has led to a large number of scholars' research. Greenlee et al. [46] designed an automated driving simulation experiment, in which the driver simulated the autonomous driving for 40 minutes, and the task was to monitor the danger on the road. The results showed that the danger detection rate would drop sharply after a long time of detection, and the reaction time

would slow down with the progress of driving. Wandtner et al. [47] found that, in the highly automated driving process, when the driver is engaged in nondriving-related tasks, the take-over performance is significantly reduced. Du et al. [48] studied the evaluation of the driver's emotions on the take-over performance conditional autonomous driving. Experiments show that positive emotions can shorten the take-over time.

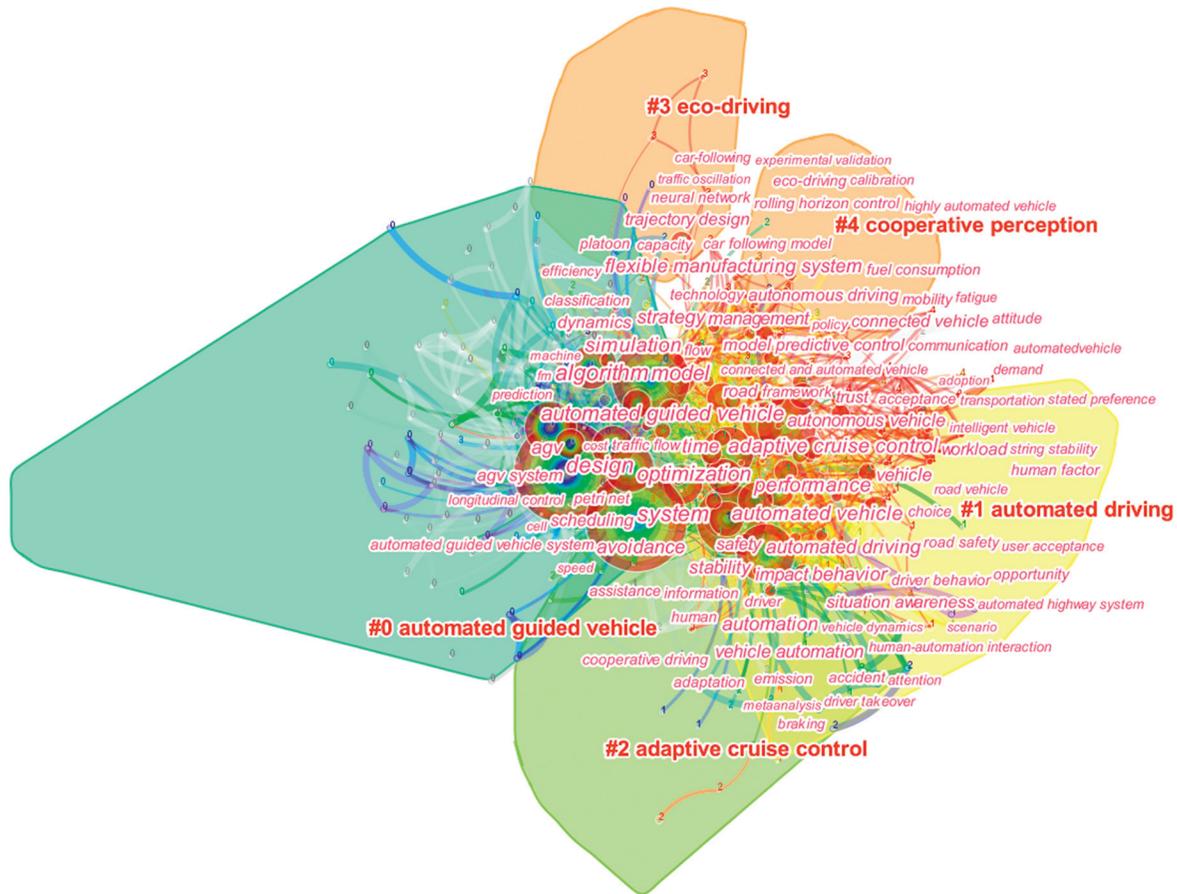


FIGURE 9: Keyword clustering map.

3.2.3. *Research Trends' Analysis.* The burst of articles and research fields can be used as indicators for judging research frontiers and trends. Keyword burst detection means the focus of research in a certain period, and it can be found that the research in a certain field presents an evolution trend from micro to macro and from single to diversified [49]. Therefore, using CiteSpace based on keyword co-occurrence, select burstness in the control panel and then standalone refresh and view. The generated keywords burst, as shown in Figure 10, where the red bar represents the time sequence of the keywords from the beginning to the end.

As shown in Figure 10, the earliest keywords are automated guided vehicle (AGV) and AGV system. In the early days for the development of smart factories, scholars began to research automated guided vehicles to promote the efficiency of logistics, but the research on AGV only lasted until 2015. In the steady growth stage of research, keywords such as avoidance, simulation, design, optimization, and algorithm appeared. Due to factors such as unsafeness in the on-road vehicle experiments, scholars began to research autonomous driving by designing simulation experiments. The keywords that have appeared in the past five years are strategy and framework. The behavioral decision-making and behavior mechanism of autonomous driving directly affect the safety and efficiency of driving. Decision-making is the core competitiveness of automated driving technology, and it is also an important scenario for artificial intelligence applications. Decision planning

is a direct manifestation of the intelligence of automated driving systems. The difference between an unmanned driving system and an ADAS system is whether it has automated decision-making capabilities. Therefore, research on automated driving mechanisms will continue until 2020.

#### 4. Discussion

At present, research on autonomous driving is in a stage of rapid development. Combined with the development and changes of today's world, there are still many new directions that need to be studied by scholars. Based on the visual analysis of the literature in this field, we can continue to deepen it from the following four aspects.

From the perspective of the distribution of articles, the promotion of national policies has had a significant impact on research. Current laws and regulations restrict the use of autonomous driving on the road. Although the United States, China, Japan, and other countries are constantly researching autonomous driving, the scope of application was limited. In addition, there is a lack of coordination between the existing road infrastructure construction and the development of autonomous driving vehicles. There is a big gap between the installation of transportation facilities and the need for autonomous driving. The government should improve the laws on autonomous driving and upgrade ITS and road infrastructure.

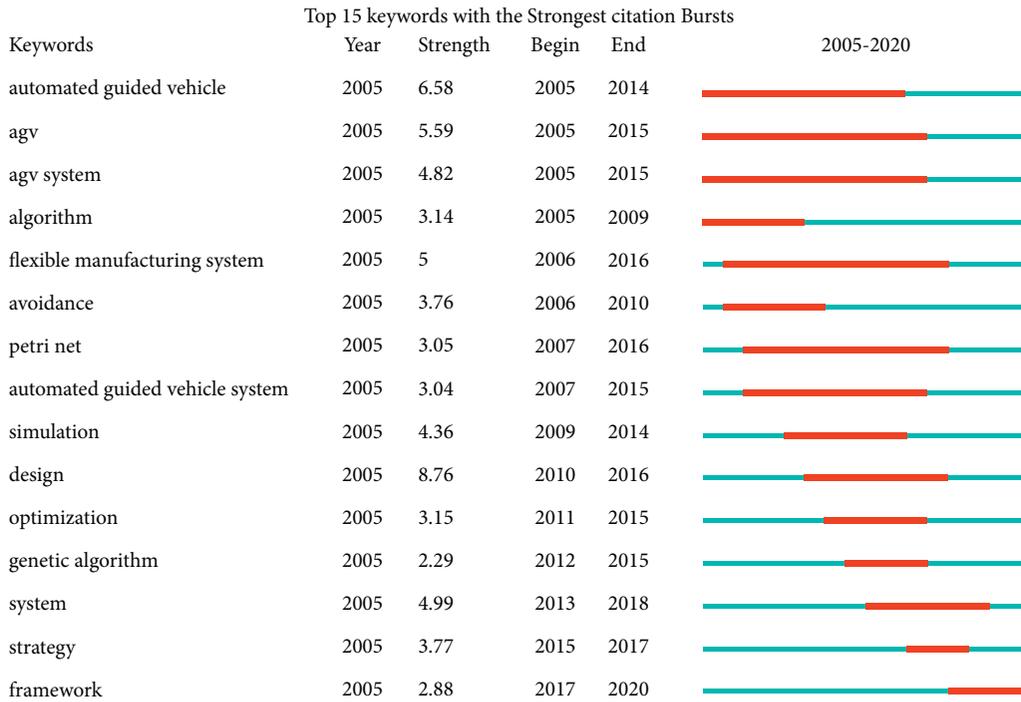


FIGURE 10: Keyword burst map.

From the perspective of research institutions and scholars, the cooperation between various institutions and the cooperation between authors is not close enough. Scholars with a high volume of publications only cooperate in groups, which greatly restricts the innovation and sharing of knowledge. On the contrary, the ties between countries are relatively close. Therefore, appropriate measures should be taken to promote exchanges among research institutions and scholars. At the same time, research should continue to absorb and learn from the successful experience gained from the development of autonomous driving in various countries, to form information resources sharing, which enhances the universality and comprehensiveness of the research in this field.

From the perspective of the period of keywords, the field of autonomous driving lacks normalized attention and research, and some research directions only lasted for a few years. The experience and research summarized in time are gradually forgotten after a long period of shelving. It is also the shortcomings of research in this field.

From the perspective of research trends, the development of autonomous driving will be in the stage of human-machine co-driving for a long time. Levels L2 and L3 have become research hotspots at this stage. It has become an urgent need to establish a technical evaluation system for man-machine co-driving at different levels of autonomous vehicles. So, future research can be conducted in this direction to lay a good foundation for highly automated driving and fully automated driving.

The progress and trend of visualization in the field of autonomous driving are given, and the future research direction is forecasted, which provides a theoretical basis for

the development of autonomous driving. Furthermore, it has reference significance for relevant researchers to understand the research hotspots and future trends in this field.

### 5. Conclusions

In this study, CiteSpace is used to visually analyze 1072 articles about autonomous driving in the Web of Science core dataset from 2005 to 2020. The number of articles, national collaboration, institutions, scholars, research areas, literature co-citation, keywords, and trends are summarized. The results show that the development of autonomous driving has gone through three stages. The first is the initial stage from 2005 to 2010. Second is the steady growth stage from 2011 to 2015. Third, the period from 2016 to 2020 will be a stage of rapid development. In terms of spatial distribution, the United States, China, and Germany are leading the research in the field of autonomous driving. Among them, Michigan University in the United States and Tsinghua University in China have higher research frequencies and are the backbone of this field. In addition, the United States has the most extensive cooperation with other countries, while China is slightly inferior in this regard. In terms of time, the research on autonomous driving has evolved from simple automated guided vehicles to assisted driving vehicles and finally to autonomous driving.

There are still some shortcomings. Firstly, to ensure the quality of the data, the data in this paper is only selected from the Web of Science database. Although it is the largest scientific literature database in the world, it may lead to the omission of some research results. Secondly, the number of documents in this study is huge. Although the development

of autonomous driving is depicted, it is impossible to conduct an in-depth analysis of every subtopic. Therefore, future research should expand the database, such as Scopus and CNKI, and explore more areas in depth.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

### Acknowledgments

This research was supported by the National Nature Science Foundation of China (52162049, 51805169, 52062014, and 52062015), Natural Science Foundation of Jiangxi Province (20202BABL212009), Jiangxi Provincial Major Science and Technology Project-5G Research Project (Grant no. 20212ABC03A07), and Jiangxi Province 2021 Graduate Innovation Special Fund Project (YC2021-S458).

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