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Review

Autonomous Vehicles in Mixed Traffic Conditions—A Bibliometric Analysis

Muhammad Azam [1,*], Sitti Asmah Hassan [1] and Othman Che Puan [2]

[1] Faculty of Engineering, School of Civil Engineering, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia
[2] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Gambang, Kuantan 26300, Pahang, Malaysia
* Correspondence: azam.muhammad@graduate.utm.my

Abstract: Autonomous Vehicles (AVs) with their immaculate sensing and navigating capabilities are expected to revolutionize urban mobility. Despite the expected benefits, this emerging technology has certain implications pertaining to their deployment in mixed traffic streams, owing to different driving logics than Human-driven Vehicles (HVs). Many researchers have been working to devise a sustainable urban transport system by considering the operational and safety aspects of mixed traffic during the transition phase. However, limited scholarly attention has been devoted to mapping an overview of this research area. This paper attempts to map the state of the art of scientific production about autonomous vehicles in mixed traffic conditions, using a bibliometric analysis of 374 documents extracted from the Scopus database from 1999 to 2021. The VOSviewer 1.1.18 and Biblioshiny 3.1 software were used to demonstrate the progress status of the publications concerned. The analysis revealed that the number of publications has continuously increased during the last five years. The text analysis showed that the author keywords "autonomous vehicles" and "mixed traffic" dominated the other author keywords because of their frequent occurrence. From thematic analysis, three research stages associated with AVs were identified; pre-development (1999–2017), development (2017–2020) and deployment (2021). The study highlighted the potential research areas, such as involvement of autonomous vehicles in transportation planning, interaction between autonomous vehicles and human driven vehicles, traffic and energy efficiencies associated with automated driving, penetration rates for autonomous vehicles in mixed traffic scenarios, and safe and efficient operation of autonomous vehicles in mixed traffic environment. Additionally, discussion on the three key aspects was conducted, including the impacts of AVs, their driving characteristics and strategies for their successful deployment in context of mixed traffic. This paper provides ample future directions to the people willing to work in this area of autonomous vehicles in mixed traffic conditions. The study also revealed current trends as well as potential future hotspots in the area of autonomous vehicles in mixed traffic.

Keywords: autonomous vehicles; mixed traffic; heterogeneous traffic; bibliometric; VOSviewer; biblioshiny; co-authorship; co-occurrences

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Citation: Azam, M.; Hassan, S.A.; Che Puan, O. Autonomous Vehicles in Mixed Traffic Conditions—A Bibliometric Analysis. *Sustainability* **2022**, *14*, 10743. https://doi.org/10.3390/su141710743

Academic Editors: Péter Gáspár and Tamás Bécsi

Received: 24 May 2022
Accepted: 19 August 2022
Published: 29 August 2022

1. Introduction

The Autonomous Vehicles (AVs), being one of the key developments of this era, are considered as a potential solution to future urban mobility, with several promised benefits regarding safety, operation and costs [1]. According to the National Highway Traffic Safety Administration (NHTSA), AVs are the vehicles which perform their operations without direct involvement of human drivers to control the steering, acceleration and braking. The concept of AVs started back in the 1920s and gained significant importance in the 1980s with the establishment of an automated highway [2], followed by the testing opportunity provided by the US Defense Advanced Research Projects Agency (DAPRA) challenge [3,4].

After the success of this challenge, many manufacturers started working on different aspects of AV technology. Many states in USA are currently working on AV concepts and trying to make this innovative technology available to general public in coming years [5]. Various sectors associated with industries and academics are conducting testing and simulation-based research on algorithms, sensors and in-vehicle technology [6,7].

The AVs with their sensing and navigating technologies are proving their potential in reducing the current externalities, especially the accidents and congestion. The findings from real-world testing and simulation studies have endorsed the potential of AVs in improving traffic conditions by reducing the overall road traffic [5,8], eliminating the need for parking spaces [9], improving throughput and stability [10], reducing the environmental impacts [11] and reducing delays [12]. In addition to the operational benefits, AVs are expected to improve the safety conditions as the introduction of AVs will limit the involvement of humans in the driving task [13,14]. The discrete nature of AVs will be able to eliminate human errors. The reported findings have shown great potential of AVs in solving mobility and safety-related issues, however, the actual impacts of this technology are still unknown and researchers, enterprises and policy makers are keen to know the future of these advanced vehicles [15,16]. Multiple studies involving every possible future scenario are working to provide a factual basis to the decision makers.

Various researchers have predicted the Market Penetration Rates (MPRs) for AVs [17,18]. The MPRs of AVs are estimated to be between 24% and 87% by 2045 [13]. Before the market penetration of AVs reaches 100%, AVs will share the road space with the Human-driven Vehicles (HVs). Most of the estimated benefits of Connected and Autonomous Vehicles (CAVs) are associated with the full market penetration, but there is a long way to reach 100% market penetration [19]. The anticipated benefits of AVs regarding reduced parking and traffic congestion, independent mobility, enhanced safety, energy efficiency and emissions' reductions will only be realized in 2040 to 2060 when AVs become common and affordable [20]. During the transition period, the AVs will interact with the HVs. The complicated environment created by these vehicles of different degrees of autonomy is expected to affect the driving behavior patterns in traffic streams and fleets [21]. Keeping in view the MPR predictions and the expected behavior of AVs when simulated with HVs, various researchers are working on the mixed traffic conditions and are publishing the useful literature on this key topic of this era. Despite sufficient available literature on this topic, a comprehensive analysis of the various published papers from a global perception remains deficient. On that note, this study conducts a bibliometric analysis and provides a landscape of the published literature in the area of autonomous vehicles and mixed traffic conditions. This study extracted 374 documents from the Scopus database published during the time period 1999–2021.

The paper is organized in five sections. Section 1 discusses the background and objectives of this study. Section 2 discusses three key aspects pertaining to the deployment of AVs in mixed traffic. Section 3 presents the method adopted to screen, extract and analyze the publications on the concerned topic. In Section 4, the basic bibliometric results and citation metrics pertaining to most productive and dominant articles, authors, sources, countries and organizations are presented. Section 5 provides the insights into the thematic areas and research hotspots associated with the autonomous vehicles in mixed traffic conditions. In Section 6, the conclusions are presented based on reviewed studies.

2. Key Aspects of AVs and Mixed Traffic

The discussion on the review was made by considering three key aspects of the topic. Firstly, the possible impacts of AVs on mixed traffic are highlighted. Secondly, the driving behavior characteristics of AVs are presented. Thirdly, the efforts that the researchers have made to address various aspects of AVs in mixed traffic are presented.

2.1. Impacts of AVs on Mixed Traffic

Autonomous Vehicles (AVs) are growing and are considered as one of the potential solutions to current transportation problems. Various studies have endorsed their potential in improving traffic conditions by reducing the overall road traffic [5,8], eliminating the need of parking spaces [9], improving throughput and stability [10], reducing the environmental impacts [11], increasing travel speed and reducing delays [12] and reducing the number of conflicts [13]. However, the actual impacts of this technology are still unknown and researchers, enterprises and policy makers are keen to know the future of these advanced vehicles [15,16]. Multiple studies involving every possible scenario of the future are working to provide a factual basis for decision makers.

Almobayedh [22] employed a VISSIM model and showed that Connected and Autonomous Vehicles (CAVs) can significantly improve the performance of a signalized intersection by reducing queue delays by 12%, vehicle travel time by 17% and queue length by 22%. The study considered three scenarios involving conventional vehicles only, CAVs only and a mix of both. Tibljaš [12] considered four roundabouts in Croatia and employed a microsimulation model, VISSIM, with modified driving behavior parameters for conventional vehicles and AVs. The study explored the benefits in terms of traffic performance by introducing AVs and Connected Vehicles (CVs) in different proportion with the conventional vehicles. An increase in travel speed and decrease in average stop delay was observed with the increase in AVs. Zhang [23] proposed a control optimization technique for signalized intersection by considering a simple four-leg intersection setting. VISSIM was employed and the results for the control optimization technique and proposed technique were compared based on delays for each approach to the intersection. The findings showed that the delays were minimized with the proposed control technique. Working with control problems for Connected and Autonomous Vehicles (CAVs) at intersections, Sun [24] proposed a new intersection operation scheme to replace the conventional signal scheme. The proposed scheme utilizes tall of the lanes simultaneously along with dynamically optimizing the lane assignment and green durations. The numerical examples showed that the capacity of an intersection nearly doubles when proposed control scheme is implemented as compared to conventional schemes. However, the system assumed to reach these findings is a simple intersection setting. One short coming of this scheme is that it is only practical in the real world when a sufficient amount of CAVs are already in the traffic stream. It needs connectivity of vehicles and is not effective when only AVs are employed.

Extending the scope from an individual facility towards a network level, Talebpour and Mahmassani [10] investigated the effect of AVs on traffic stability and throughput. The study considered a simulation environment to evaluate different scenarios and employed available driver models at varying percentages of regular, connected and autonomous vehicles. The findings showed an increase in throughput with the increased penetration of connected and autonomous vehicles. To assess the network level impacts of AVs, a study conducted by Patella [11] reported the impacts on the environmental aspects as well as the traffic performance of the entire network of Rome, Italy through a simulation environment. The findings showed that a 100% AVs' penetration rate reduces the environmental impacts at a mobility level by 60%. The network performances improved by 100%, AV penetration in terms of reduction in travel time by 33% and improved average network speed network by 51%, whereas the total distance travelled for highways increased by 8% and decreased for intra-urban roads by 5%. The study compared only two scenarios, having a current scenario or incorporating 100% AV penetration. However, the lower penetration rates of AVs were not considered and the interaction of AVs with human-driven vehicles was not considered in this study. To incorporate the lower level of penetration, Alfaseeh [25] conducted a study by considering the network in Toronto, Canada. The study found that incorporating higher percentages of CAVs improves the throughput, travel time, density and speed even with the highly congested conditions.

A lot of work has been conducted to investigate the impacts of AVs on highway sections. Rios-Torres and Malikopoulos [26] studied the operational impacts by considering the merging on-ramp section for the simulation settings. The results showed that the maximum benefits of CAVs' introduction in terms of fuel consumption and travel time were obtained at a 100% penetration rate when a reduction of 16–60% and 40–67% were observed, respectively. The study considered only one on-ramp section and the interaction between the different vehicle types was explored for the merging case only. To study the interaction of AVs with conventional vehicles thoroughly, Papadoulis [14] employed VISSIM by using Application Programming Interface (API) to a motorway section of 44.27 km in England. The results showed that the proposed algorithm improved the traffic flow and reduced the estimated traffic conflicts by 90–94% at 100% MPR of CAVs. Maarafi [27] considered a real-world segment in USA along with a hypothetical section having entrances and exits. The study simulated AVs by employing a VISSIM model. The study found an increase in throughput by above 17% for the freeways with an MPR of 60% and higher. Another study by Aria [28] considered a segment of highway including a network of secondary urban roads in Germany and simulated CAVs by employing VISSIM. The study found that the average density improved by 8.09%, average travel speed enhanced relatively by 8.48% and average travel time improved by 9.00% in the 100% AV scenario. Motamedidehkordi [29] simulated a stretch of freeway and showed that with an increase in MPR of CAVs, congestion length and congestion area became smaller. In addition, the speed of the shockwave reduced.

In parallel to the operational benefits, AVs are equally beneficial in improving safety situations. Morando [13] studied the safety impacts of AVs and employed VISSIM to simulate a signalized intersection and roundabout. The findings showed that for a signalized intersection, the number of conflicts reduced from 20% to 65% with MPR between 50–100%. For the roundabout conditions, the number of conflicts reduced by 29% to 64% with the 100% AV. Khashayarfard and Nassiri [30] investigated the impacts of AVs on unsignalized intersections in Iran. The study showed a significant decrease in potential for accidents by up to 93% with the presence of 100% AVs. El-Hansali [31] showed a 12% reduction in the annual crash rate with the introduction of AVs. They also showed a reduction in conflict points and rear-end collisions. Considering hypothetical conditions, Mousavi [32] investigated the operational and safety impacts of AVs on an urban arterial with unsignalized driveway. The findings of this study showed that an increase in MPR of AVs affected an increase in density and speed, whereas lane changing and rear-end conflicts reduced. Postigo [33] simulated a motorway stretch in Germany and showed higher vehicle throughput and lower travel delays as the AVs evolved from cautious to more advanced (all-knowing) driving logics. A summary of the studies covering the impacts of AVs on traffic operation, safety and environment are shown in Table 1.

Table 1. Impacts of AVs.

Study	Study Site	Simulation Tool	Aspect	Impact/Findings
[27]	Freeway section Hypothetical section	VISSIM	Operation	Increase in throughput was observed by above 17% for freeways with MPR of 60% and higher.
[28]	Segment of highway including network of secondary urban roads	VISSIM	Operation	For AV scenario, average density improved by 8.09%, average travel speed enhanced relatively by 8.48% and average travel time improved by 9.00%.
[29]	Stretch of freeway	VISSIM	Operation	With increase in MPR of CAVs, congestion length and congestion area become smaller. In addition, the speed of shockwave reduces

Table 1. *Cont.*

Study	Study Site	Simulation Tool	Aspect	Impact/Findings
[34]	Freeway and arterial network Freeway corridor	VISSIM	Operation	For network level evaluation, the study finds an improvement of 30% in network total delay and 6% in average network speed at 100% CAV penetration rate. For freeway corridor, the results show 33% improvement in network total delay and 23% in average network speed.
[12]	Roundabout	VISSIM	Operation	In all cases there was an increase in travel speed and decrease in average stop delay with the increase in percentage of AVs.
[35]	-	VISSIM	Operation	The study found incorporation of CAVs advantageous for operational performance as it reduced the travel time by 11% and delays by more than 40%.
[36]	4-km long single lane road	VISSIM	Operation	The average capacity per lane for AV in single-lane road segment was 1.13% higher than HV.
[37]	Diverging Diamond Interchange Restricted Crossing U-Turn (RCUT) Intersection	VISSIM	Operation	The results show a 7% improvement in throughput when both Alternative Intersection Design and full penetration of level-3 autonomous vehicles are employed simultaneously.
[25]	Highway network	-	Operation	Incorporating higher percentages of CAVs improves the throughput, travel time, density and speed even with the highly congested conditions.
[33]	Motorway section	VISSIM	Operation	Results show higher vehicle throughput and lower travel delays as AVs evolve from cautious to more advanced logics.
[13]	Signalized intersection Roundabout	VISSIM	Safety	For signalized intersection, number of conflicts reduced from 20% to 65% with MPR between 50–100%. For the roundabout, the number of conflicts reduced by 29% to 64% with the 100% AV.
[30]	Unsignalized intersection	VISSIM	Safety	It was concluded that the presence of 100% of AVs could reduce the potential for accidents by up to 93%.
[31]	Motorway section	VISSIM	Safety	Reductions in total conflict points and rear-end collision points were 8.6% and 13%, respectively. Reduction in the annual crash rate was 12%
[38]	10.2 km three-lane roadway with 400 m as merging and diverging section	AIMSUN	Operation and Safety	The study found that at higher penetration rates of AVs, throughput can improve up to 84% while safety conditions are different at different penetration rates.
[16]	Freeway network CBD roads Streets in university campus/	Scalable Microscopic Adaptive Road Traffic Simulator (SMARTS)	Operation and Safety	The findings showed that higher proportion of low-level vehicles reduces the efficiency. A reduction of 11% in safety impact is reported for CBD at 3k volume when proportion of level 4 vehicles increases by 20%.
[32]	Urban arterial with unsignalized driveway	VISSIM	Operation and Safety	Increasing MPR of AVs improves the density and speed and reduces the number of lane changes and rear end collisions.

Table 1. *Cont.*

Study	Study Site	Simulation Tool	Aspect	Impact/Findings
[26]	Merging on-ramp area	-	Operation and Environment	At 100% penetration rate of CAVs, a reduction of 16–60% for fuel consumption and 40–67% for travel time was observed. Highest benefits in travel time and fuel consumption are achieved with medium traffic conditions.
[39]	Signalized urban corridor Freeway section	VISSIM	Operation and Environment	Aggressive AVs can reduce the subsequent emission factors by up to 26% on the expressway, while cautiously programmed AVs could deteriorate traffic performance and lead to a 35% increase in emissions.
[11]	Road Network	-	Operation and Environment	100% AVs penetration rate reduces the environmental impacts at mobility level by 60%. Network performances improves by 100% AV penetration in terms of travel time (–33%) and average network speed (+51%) whereas the total distance travelled increases for highways (8%).
[40]	Freeway corridor	VISSIM	Operation and Environment	Corridor-level analysis showed decreases of 5% in emissions can be expected with AV technology, but it penalizes travel time up to 13% for both AVs and CVs, when compared to the existing situation
[41]	Hypothetical 8-km single-lane road	VISSIM	Operation, Safety and Environment	The proposed algorithm involving connected vehicles can reduce travel time by 20%, safety improvement of 6–11% and overall fuel consumption reduction of 5–16% with 100% CV penetration
[42]	3 km stretch on Auckland Motorway	SUMO	Operation, Safety and Environment	For current scenarios, having 0.5% to 0.95% of the capacity, deploying more than 70% of AVs can improve travel time, TTC, emission and fuel consumption.

2.2. *Driving Characteristics of AVs*

The AVs are capable of sensing their environment and navigating by employing different sensors and technology without human input [43]. These advanced vehicles are expected to revolutionize the traffic environment by reducing the current externalities, especially accidents and congestion. Although AVs have the potential to improve the traffic conditions their full deployment will still take decades. Before the market penetration of AVs reaches 100%, these advanced vehicles will co-exist with the HVs. This transition phase of introducing a smaller proportion of AVs into the traffic stream of HVs will create a mixed traffic stream. Due to different driving logic for HVs and AVs, the driving behavior is expected to change with the introduction of AVs [10]. AVs obey certain programmed rules to monitor the traffic rules and roadway environment, based on sensing, planning and action phases, whereas the performance of HVs is highly dependent on the driver's characteristics, specifically the perception and reaction time. Based on some simulation studies, certain aspects of AVs driving which can affect the performance of system are as follows:

- During free-flow conditions, AVs keep their desired speed constant since they have a small speed range as compared to CVs. From a standstill position, AVs accelerate more smoothly than CVs [30];

- AVs show shorter values and lower deviation in time headway, distance headway and reaction time as compared to CVs. In addition, AVs show lesser deviation in speed, a greater look-ahead distance and smaller path deviation [44];
- Smaller standstill distance, smaller headway, strict desired speed and lesser variation in acceleration and deceleration are associated with the driving characteristics of AVs [45];
- AVs follow the speed limits strictly which can result in less fuel consumption as compared to CVs [40];
- AVs minimize the headway and required gap during lane changing maneuvers due to a smaller reaction time but it encourages fewer dangerous lane changes along with failure in recognizing the other vehicle's intention to change a lane [46];
- AVs follow a leading vehicle with a shorter headway than conventional vehicles. This shorter headway leads to increased vehicle throughput per lane [47];
- AVs are expected to behave deterministically and will show smaller oscillations during following conditions [48];
- AVs can dampen the shockwave propagation caused by the intensive behavior of leading vehicles, however, this will result in longer gaps between vehicles and consequently, decreases the capacity [49];
- AVs can be fuel efficient as compared to CVs due to various driving mechanisms, such as reduced distance between two vehicles, acceleration and deceleration characteristics, longitudinal and lateral behavior and gap acceptance thresholds [50];
- In a conservative environment, AVs do not effectively utilize the amber time which in turn results in lower traffic flow than conventional vehicles. AVs prefer to maintain acceleration/deceleration and speed limits, remain away from the dilemma zone and keep a clear distance from other vehicles [36];
- AVs show less speed deviances than conventional vehicles, which results in stability and better system performance [10];
- Cautious AVs improve the safety aspect by keeping longer time headways and distances, however, it affects the capacity and traffic performance [51];
- AVs affect the drivers of conventional vehicles to keep shorter headways when following platoons of equipped vehicles maintaining shorter headways [28];
- AVs equipped with higher automation levels tend to perform less lane changes to overtake slow moving vehicles which may increase the travel time [52].

Due to smaller values of time headways and standstill distances coupled with the smooth acceleration and deceleration characteristics of AVs, the simulation studies have proved the operational benefits. Although AVs have the potential to improve traffic safety and efficiency, there are still some challenges regarding uncertain human driving behavior which may significantly affect the stated benefits. The behavior of AVs in mixed traffic is still uncertain and people are working to provide data on the driving characteristics of AVs.

2.3. Efforts to Incorporate AVs in Mixed Traffic

The transition period will take decades to reach 100% penetration of AVs. The researchers have been working on various aspects related to the penetration of AVs into a mixed traffic environment. Mahmassani [53] proposed a microsimulation framework to study the mixed traffic environment. The proposed framework highlighted that autonomous vehicles are more advantageous than the same share of connected vehicles in improving throughput and stability. The involvement of the human factor in the transition of the control process was incorporated in the extended simulation framework [54]. Various other studies employed simulation platforms to study different aspects of mixed traffic [32,55,56]. The simulation frameworks provided the basis to test various real-world scenarios in a virtual environment.

Several studies developed certain strategies and analytical models to cover different aspects of AVs in mixed traffic. A study proposed an analytical capacity model for mixed traffic, while considering the platooning features of CAVs [57]. Seraj [56] also incorporated the platooning features of CAVs while developing a car-following strategy for a mixed traffic environment. Qin and Wang [58] showed that the proposed optimal control method for CAVs can improve the rear-end collision risk. Another strategy minimized the energy consumption of mixed traffic at a junction while maximizing the throughput [55]. Lee [59] focused on a traffic management strategy for mixed traffic while considering different aggressiveness levels for AVs. In another study, the impacts of CAVs on traffic flow were examined by developing a two-state safe-speed model, and the numerical investigations and simulations showed an increase in capacity with increase in CAV penetration rate [60]. By considering the information flow from surrounding vehicles and the subsequent driver reaction, Jin [61] proposed a mixed traffic model from the perspective of cyber physical fusion. The study found that the stability of mixed traffic system depends on driver's reaction delay, the penetration rate of CAVs and the information from multiple vehicles ahead that the CAVs can obtain. Mohajerpoor and Ramezani [62] developed an analytical model based on headway variability and studied the impacts of AVs on saturation flow rates. In car-following conditions, Fu [63] developed a human-like car-following model and studied the effect of cut-in vehicles on mixed traffic conditions along a real freeway. The study found that the developed model has a shorter response time and lower deceleration in cut-in situations. Another study incorporated trials from a real highway and developed a lane-change decision model for AVs. The proposed model improved the safety of AVs and the rear vehicle.

There have been several attempts to predict the trajectory of AVs in mixed traffic conditions. Ma [64] proposed a real time traffic prediction algorithm to predict the movement pattern and future trajectories of AVs in mixed traffic. Ghiasi [65] proposed a CAV-based trajectory-smoothing strategy. The proposed algorithm improved the fuel efficiency and reduced the environmental impacts. Another study used high resolution trajectory data to study the impacts of CAV-clustering strategy on mixed traffic flow [66]. Wang [67] used mobile sensing data acquired from CAVs to collect the trajectories of mixed traffic flow. In the same year, Sharath and Velaga [68] extended the classical Intelligent Driver Model (IDM) to enhance the longitudinal and lateral motion planning for a mixed-traffic environment. The study introduced eight new parameters to reflect the human-like responses. Using a roundabout as a case study, Debada [69] used the concepts of surrounding space and exploitation for the motion planning of CAVs in mixed traffic.

In addition to the mixed vehicle concept, some studies focused on providing exclusive lanes for AVs. Chen [70] developed a mathematical approach for the optimal deployment of AV lanes in a mixed traffic environment. The study employed a multi-class network equilibrium model and diffusion model to describe the flow distribution and to forecast the evolution of AVs market penetration, respectively. Both of these models helped to develop a time-dependent deployment model. The concept of dedicated CAV lanes was employed by [71]. The study employed simulations and investigated the impacts of dedicated CAV lanes on throughput by varying the demand levels and the CAV penetration rates. Another study used an improved cellular automata model to assess the influence of exclusive CAV lanes on freeway traffic flow [72]. The study found that setting up exclusive lanes improved the freeway traffic operations.

3. Data and Methods

This paper employed bibliometric analysis to fulfil the intended objective. Bibliometric analysis is a rigorous method which is conducted to visualize the current state of the art for a particular field. This statistical method collects, analyzes and extracts various metrics related to research productivity, institutional and individual authorship, publication journals, publications, keywords and more from published literature [73]. This method is not new, as the first use of this concept started in the 1950s [74]. In recent years, many researchers have employed this method to visualize the landscape of their research area [75–77]. The methodology adopted in this study consists of two major steps: (i) data collection, which involved selection of topic, formulation of search strategy, data screening and extraction and (ii) data analysis by using various tools. The key steps and associated sub-steps are shown in Figure 1.

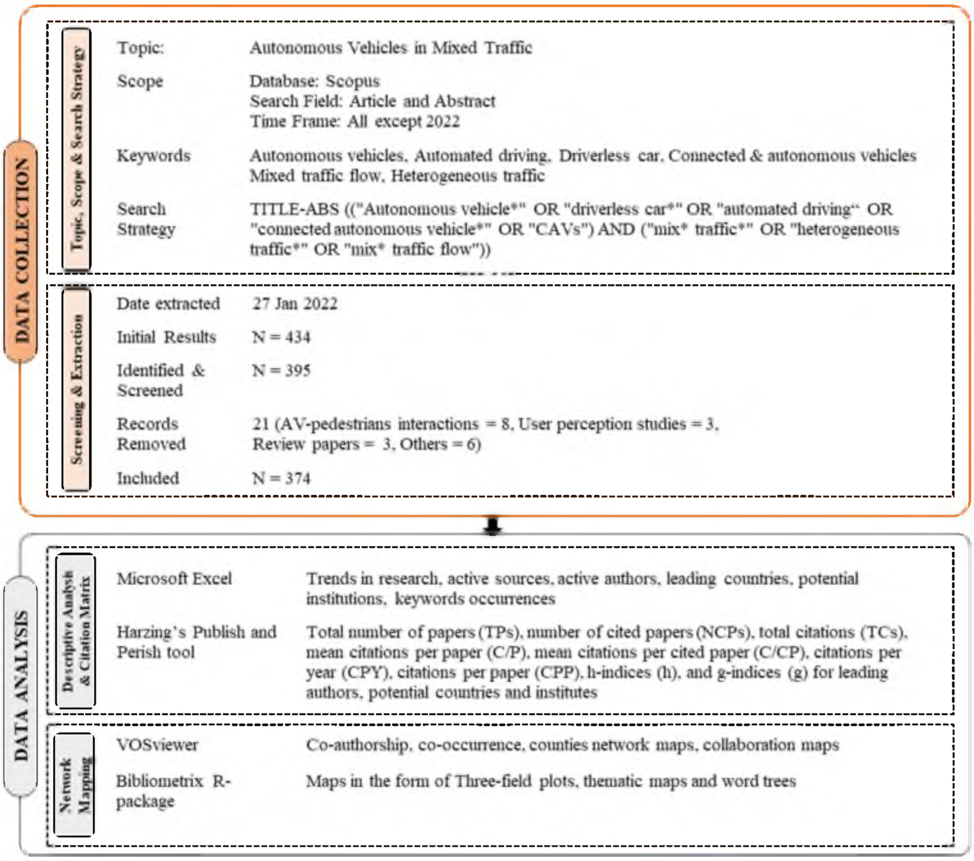

Figure 1. Proposed framework (adopted from Kushairi and Ahmi [78]), the asterisk (*) wildcard was used in search string to find word endings.

In the first step, the keywords were identified based on the objective of this paper. For autonomous vehicles, various possible alternative keywords, such as "Autonomous vehicle*" OR "driverless car*" OR "automated driving" OR "connected autonomous vehicle*" OR "CAVs" were used. For mixed traffic conditions, the terms used were "mix* traffic*" OR "heterogeneous traffic*" OR "mix* traffic flow". These keywords in the form of an appropriate search string were used in the Scopus database to extract data on the topic for the period of 1999 to 2021. The search was conducted on 27 January 2022 by using a validated search string. The Scopus database was chosen because of its comprehensive coverage of articles, publishing materials in more diverse research areas than the Web of Science could achieve [79]. The search was conducted by considering the title and abstract to provide extensive coverage on the topic.

In the second step, the validated string was used in the selected database and records were produced. The employed search string from the first stage to the final data extraction is shown in Table 2. The produced records in the first stage were refined, based on the identified document type and time frame. In the last step, the records were screened by reading the title and abstract of each document and some of the records were removed to produce the most relevant data. A total of 21 documents were excluded because of their focus on AV–pedestrian interaction (eight documents), user-perception studies (three documents), review studies (three documents) and others (six documents). The details of the excluded documents are given in Table 3. A careful scrutiny of all of these articles enabled the present researchers to focus on the autonomous vehicles in mixed traffic conditions, thus 374 papers were selected.

Table 2. Search strings for extraction of the relevant documents.

No.	Stage	Search String	Document Results
1	Initial search string	TITLE-ABS ((“Autonomous vehicle*” OR “driverless car*” OR “automated driving” OR “connected autonomous vehicle*” OR “CAVs”) AND (“mix* traffic*” OR “heterogeneous traffic*” OR “mix* traffic flow”))	434
2	Specifying the document type	TITLE-ABS ((“Autonomous vehicle*” OR “driverless car*” OR “automated driving” OR “connected autonomous vehicle*” OR “CAVs”) AND (“mix* traffic*” OR “heterogeneous traffic*” OR “mix* traffic flow”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”))	404
3	Limiting the time frame	TITLE-ABS ((“Autonomous vehicle*” OR “driverless car*” OR “automated driving” OR “connected autonomous vehicle*” OR “CAVs”) AND (“mix* traffic*” OR “heterogeneous traffic*” OR “mix* traffic flow”)) AND (LIMIT-TO (DOCTYPE,”ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (EXCLUDE (PUBYEAR, 2022))	395
4	Screening and excluding the irrelevant documents	TITLE-ABS ((“Autonomous vehicle*” OR “driverless car*” OR “automated driving” OR “connected autonomous vehicle*” OR “CAVs”) AND (“mix* traffic*” OR “heterogeneous traffic*” OR “mix* traffic flow”)) AND NOT EID (2-s2.0-85113502346 OR 2-s2.0-85110113635 OR 2-s2.0-85111559787 OR 2-s2.0-85105690111 OR 2-s2.0-85105304706 OR 2-s2.0-85102260094 OR 2-s2.0-8510292210 OR 2-s2.0-85120523634 OR 2-s2.0-85112662827 OR 2-s2.0-85101020669 OR 2-s2.0-85099345593 OR 2-s2.0-85092091552 OR 2-s2.0-85106318730 OR 2-s2.0-85097173824 OR 2-s2.0-85093119962 OR 2-s2.0-85086721434 OR 2-s2.0-85076820374 OR 2-s2.0-85074453871 OR 2-s2.0-85069684311 OR 2-s2.0-85031293900 OR 2-s2.0-85106204730) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (EXCLUDE (PUBYEAR, 2022))	374

Notes: The asterisk (*) wildcard was used in search string to find word endings.

Table 3. Details of excluded documents with reasons of exclusion.

Sr. No.	Reference	EID	Reason of Exclusion
1	[80]	2-s2.0-85113502346	Pedestrians’ trajectories at midblock—jaywalkers
2	[81]	2-s2.0-85110113635	Interaction between wheelchairs, pedestrians and AVs
3	[82]	2-s2.0-85111559787	Design to deploy AVs to carry a first aid robot
4	[83]	2-s2.0-85105690111	Policy study providing a framework to differentiate between installation and usage of AVs
5	[84]	2-s2.0-85105304706	AV-pedestrian interactions
6	[85]	2-s2.0-85102260094	Survey paper
7	[86]	2-s2.0-85102922104	Primarily not focused on AVs
8	[87]	2-s2.0-85120523634	Calibration method for existing traffic
9	[88]	2-s2.0-85112662827	AVs interactions with cyclists explored
10	[89]	2-s2.0-85101020669	Modeling pedestrians road crossing
11	[90]	2-s2.0-85099345593	Review paper
12	[91]	2-s2.0-85092091552	Pedestrian path prediction at signalized crosswalk
13	[92]	2-s2.0-85106318730	Key focus was connected buses and energy consumption
14	[93]	2-s2.0-85097173824	Survey-based study about user perceptions
15	[94]	2-s2.0-85093119962	User perception based on autonomous shuttle rides—user survey
16	[95]	2-s2.0-85086721434	User perception based on autonomous shuttle rides—user survey
17	[96]	2-s2.0-85076820374	Estimating pedestrian’s waiting time at unsignalized mid-block crosswalks
18	[97]	2-s2.0-85074453871	Pedestrians’ perspective
19	[98]	2-s2.0-85069684311	Vehicle–pedestrian encountering
20	[99]	2-s2.0-85031293900	Review paper discussing future perspectives of AVs
21	[100]	2-s2.0-85106204730	Prior focus was communication from in-vehicle and from infrastructure signage.

The third step involved application of analyzing and visualizing tools to produce citation metric records and network maps of bibliographic data exported from database. Various tools were deployed to obtain the desired outputs:

- Microsoft Excel was used to create appropriate graphs showing the frequency and percentage of each publication;
- Harzing's Publish and Perish tool was used to compute the citations metrics;
- VOSviewer was used to create and visualize the bibliometric networks;
- The Bibliometrix R-package was used to create three field plots, thematic maps and word trees.

Furthermore, the information on total publications (TPs), number of cited papers (NCPs), total citations (TCs), mean citations per paper (C/P), mean citations per cited paper (C/CP), citations per year (CPY), h-indices (h) and g-indices (g) were extracted to extend the proposed bibliometric analyses

4. Current Publication Status on Autonomous Vehicles in Mixed Traffic Conditions

4.1. Annual Publications Trends

The publication trends assessed on the annual basis are helpful for researchers to understand the growth evolution on the cited topic [101,102]. Figure 2 shows the three different sections during the evolution of the research on the autonomous vehicles in mixed traffic. Until 2014, the pace of research was not significant even after the introduction of the automated highway system [103] and the DAPRA challenge [3,104]. Later, there was an increase in research on autonomous vehicles due to the start of real-world testing by using test beds [51]. The projects, UK Autodrive and CoEXist, started in 2014 and 2017, respectively, and initiated a new topic of research in this field of autonomous vehicles. The research in the area of mixed traffic started with a considerable pace after the availability of empirical data and evidence from field testing. However, the annual growth was not exponential. The evolution trajectory of the chart clearly revealed the rapid increase in the publications from 2018 until 2021. Such exponential rise can be attributed to the renewed research interests that were generated in this area of mixed traffic streams having both AVs and HVs. In addition, the publications' development during 1999 to 2021 were clubbed into three domains, such as slow growth with only two average number of annual publications (1999–2014), steady growth with 10 average number of annual publications (2015–2017) and rapid growth with 84 average number of annual publications (2018–2021). The value of the regression coefficient is 0.9945 which indicates a best fit of the exponent function and predicts a positive growth trend in the proposed research area.

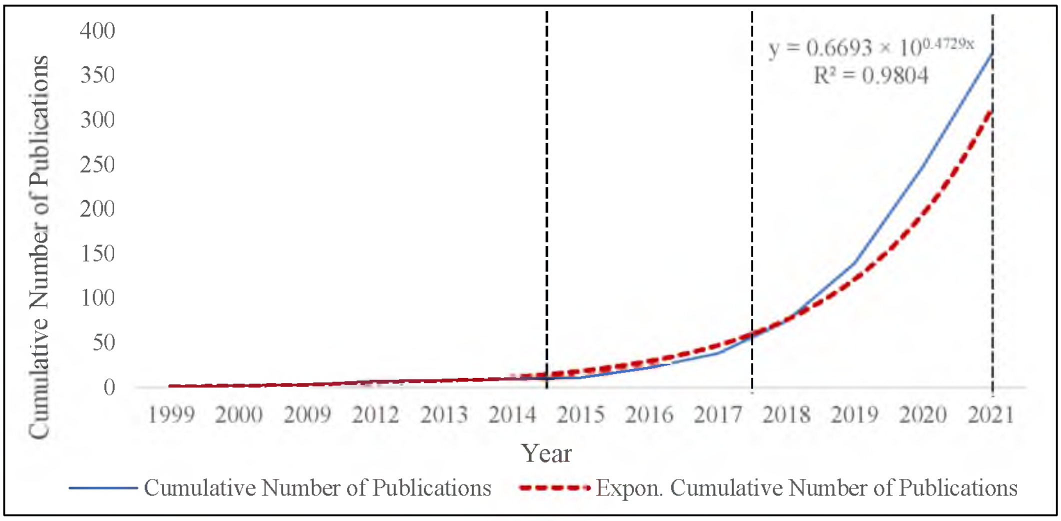

Figure 2. Evolution of publications during 1999–2021.

The distribution of annual published documents and the total citations received against the annual publications are illustrated in Figure 3 below. The tendency shown below is based on the 374 records extracted from the Scopus database during 1999–2021.

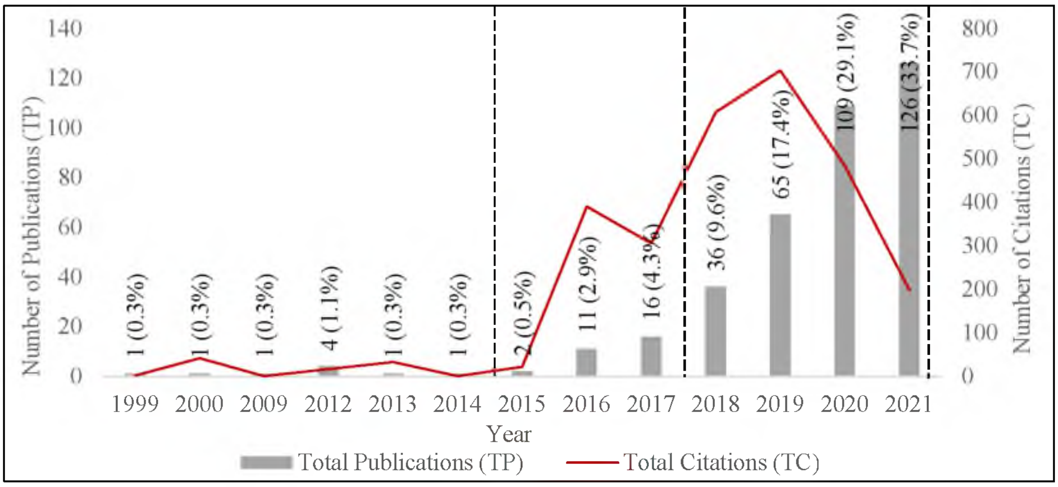

Figure 3. Annual publications and total citations during 1999–2021.

The discussion on autonomous vehicles is not new, the idea started back in the 1920s and gained significant importance in the 1980s with the establishment of the automated highway [2]. Although a lot of research has been conducted on autonomous vehicles in the last decade, a significant pace was only observed after 2017. Around 90% of the documents discussing autonomous vehicles in mixed traffic were published during the period 2018–2021. The first paper on this topic was published in 1999 which discussed the speed control techniques of automated heavy vehicles in a mixed traffic environment [105]. The highest number of articles were published in 2021, with a total of 126 which was around 16% higher than the total published documents in 2020.

A noticeable increase in the number of publications was observed after 2017. However, the total citations graph line showed a decline after 2019. It is certain that this decline is not due to lack of interest as endorsed by the significant increase in total publications, rather the decline is associated with the documents that are in a queue for publication. It is expected that the total citations for the documents published in 2020 and 2021 will also witness an increase in the coming year.

Table 4 enlists the citation matrix per year based on the retrieved documents. The highest citations to date were observed for the documents published in 2019, with 704 total citations. However, the total citations for recent years are expected to increase in the coming years since most of the documents citing them are not yet published.

Table 4. Yearly publications and citation matrix for the selected documents during 1999 to 2021.

Year	TP	%	NCP	TC	C/P	C/CP	h	g
2021	126	33.69%	52	198	1.57	3.81	6	11
2020	109	29.14%	75	484	4.44	6.45	12	15
2019	65	17.38%	58	704	10.83	12.14	13	24
2018	36	9.63%	34	608	16.89	17.88	12	24
2017	16	4.28%	14	306	19.13	21.86	8	14
2016	11	2.94%	11	391	35.55	35.55	7	11
2015	2	0.53%	2	22	11.00	11.00	2	2
2014	1	0.27%	1	1	1.00	1.00	1	1
2013	1	0.27%	1	33	33.00	33.00	1	1
2012	4	1.07%	3	17	4.25	5.67	2	3
2009	1	0.27%	1	1	1.00	1.00	1	1
2000	1	0.27%	1	42	42.00	42.00	1	1
1999	1	0.27%	1	2	2.00	2.00	1	1

Notes: total publications (TPs); number of cited papers (NCPs); total citations (TC); mean citations per paper (C/P); mean citations per cited paper (C/CP); h-indices (h); g-indices (g).

4.2. Citation Analysis of Most Dominant Articles

This section explains the most cited documents in the research area of autonomous vehicles in mixed traffic conditions. A total of 374 documents were retrieved from the Scopus database having both journal articles (59.1%) and conference papers (40.9%). The network visualization map based on the highest number of total citations is illustrated in Figure 4 below. The size of the node denotes the impact of a document based on the total citations. The co-occurrence between the documents is presented by the line between two nodes. The strength of co-occurrence between documents is specified by the thickness of the lines.

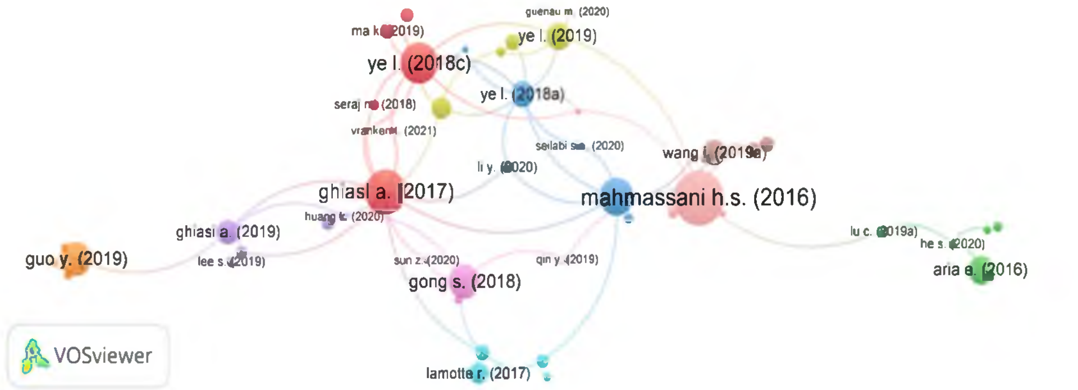

Figure 4. Document network visualization based on citations.

Out of 374 documents, the 10 most cited documents are presented in Table 5. All of these highly cited documents were published during 2016–2019. This shows that the most productive work on this research area has been executed in the recent years. The impact of a published paper is assessed based on the Total Citations (TC) and Citations per Year (CPY). In terms of total citations, the highest total citations of 162 were received by Mahmassani [10], with 27 citations per year. Another document by Y. Ma et al. [64] received the highest citations per year of 32.33 among these most cited documents, with 97 total citations.

Table 5. Top 10 most cited documents.

No.	TC	Author	Title	Type	Source	CPY
1	162	[53]	Autonomous vehicles and connected vehicle systems: Flow and operations considerations	Article	*Transportation Science*	27
2	115	[57]	A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method	Article	*Transportation Research Part B: Methodological*	23
3	99	[60]	Modeling connected and autonomous vehicles in heterogeneous traffic flow	Article	*Physica A: Statistical Mechanics and its Applications*	24.75
4	97	[64]	TrafficPredict: Trajectory prediction for heterogeneous traffic-agents	Conference Paper	Proceedings of the AAAI Conference on Artificial Intelligence	32.33
5	85	[70]	Optimal deployment of autonomous vehicle lanes with endogenous market penetration	Article	*Transportation Research Part C: Emerging Technologies*	14.17

Table 5. *Cont.*

No.	TC	Author	Title	Type	Source	CPY
6	76	[106]	What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space?	Article	*Accident Analysis and Prevention*	19
7	75	[107]	Cooperative platoon control for a mixed traffic flow including human drive vehicles and connected and autonomous vehicles	Article	*Transportation Research Part B: Methodological*	18.75
8	73	[108]	Joint optimization of vehicle trajectories and intersection controllers with connected automated vehicles: Combined dynamic programming and shooting heuristic approach	Article	*Transportation Research Part C: Emerging Technologies*	24.33
9	55	[109]	Mixed-integer linear programming for optimal scheduling of autonomous vehicle intersection crossing	Article	*IEEE Transactions on Intelligent Vehicles*	13.75
10	53	[28]	Investigation of Automated Vehicle Effects on Driver's Behavior and Traffic Performance	Conference Paper	Transportation Research Procedia	8.83

Notes: total citations (TC); citations per year (CPY).

4.3. Citation Analysis of Most Productive Sources

This section highlights the potential journals which are publishing considerable documents on autonomous vehicles in mixed traffic conditions. Table 6 provides the names of the leading sources with a minimum of eight publications in the research area of concern along with other useful information including total publications (TP), total citations (TC) and the name of the publisher. In the context of TC, *Transportation Research Part C Emerging Technologies* was the most productive source with 31 publications followed by IEEE Conference on Intelligent Transportation Systems Proceedings (ITSC) with 25 published documents. The other notable aspect is total citations received by each of the sources based on their published documents. Although the aforementioned sources produced higher number of documents, the sources *Transportation Research Part B: Methodological* and *Physica A: Statistical Mechanics and its Applications* are also notable with total citations of 331 and 306, respectively.

The citation analysis of the potential sources was conducted by using VOSviewer. For visualization, minimum number of documents was set at one and the total citations were set at two. Only 80 sources out of 150 met the criteria. Out of 80 sources, 40 showed a citation relationship with other sources in terms of the link strength as specified by the thickness of connecting lines. The clustering technique in VOSviewer gathers the potential sources having a citation relationship with other sources into one cluster [110]. Only 40 sources having some citation relationship with other sources were included in the network, which were further grouped into 11 clusters as shown in Figure 5 below. All of the sources within one cluster have a citation relationship with other sources within that cluster. Cluster-1 and 2 consist of six sources, cluster-3, 4 and 5 consist of five sources, cluster-6 consists of four sources, cluster-7 and 8 consists of three and two sources, respectively, and cluster-9, 10 and 11 consist of one source each. It is shown that the potential source *Transportation Research Part C: Emerging Technologies* contributed the highest share, followed by IEEE Conference on Intelligent Transportation Systems Proceedings (ITSC) during the recent years.

Table 6. Most active source title with minimum TP of 8.

Rank	Source Title	TP	%	Publisher	NCP	TC	C/P
1	*Transportation Research Part C Emerging Technologies*	31	8.29%	Elsevier Ltd.	27	412	13.29
2	IEEE Conference on Intelligent Transportation Systems Proceedings (ITSC)	25	6.68%	IEEE Inc.	13	104	4.16
3	*IEEE Transactions on Intelligent Transportation Systems*	20	5.35%	IEEE Inc.	14	108	5.40
4	*Journal Of Advanced Transportation*	16	4.28%	Hindawi Limited	11	75	4.69
5	*Physica A: Statistical Mechanics and Its Applications*	14	3.74%	Elsevier B.V.	10	306	21.86
6	*IET Intelligent Transport Systems*	11	2.94%	Institution of Engineering and Technology	8	48	4.36
7	*SAE Technical Papers*	11	2.94%	SAE International	5	14	1.27
8	*Transportation Research Record*	10	2.67%	SAGE Publications Ltd.	9	79	7.90
9	*IEEE Access*	9	2.41%	IEEE Inc.	8	55	6.11
10	*Transportation Research Part B: Methodological*	8	2.14%	Elsevier Ltd.	7	331	41.38
11	*Transportation Research Procedia*	8	2.14%	Elsevier B.V.	7	83	10.38

Notes: total publications (TPs); number of cited papers (NCPs); total citations (TC); mean citations per paper (C/P).

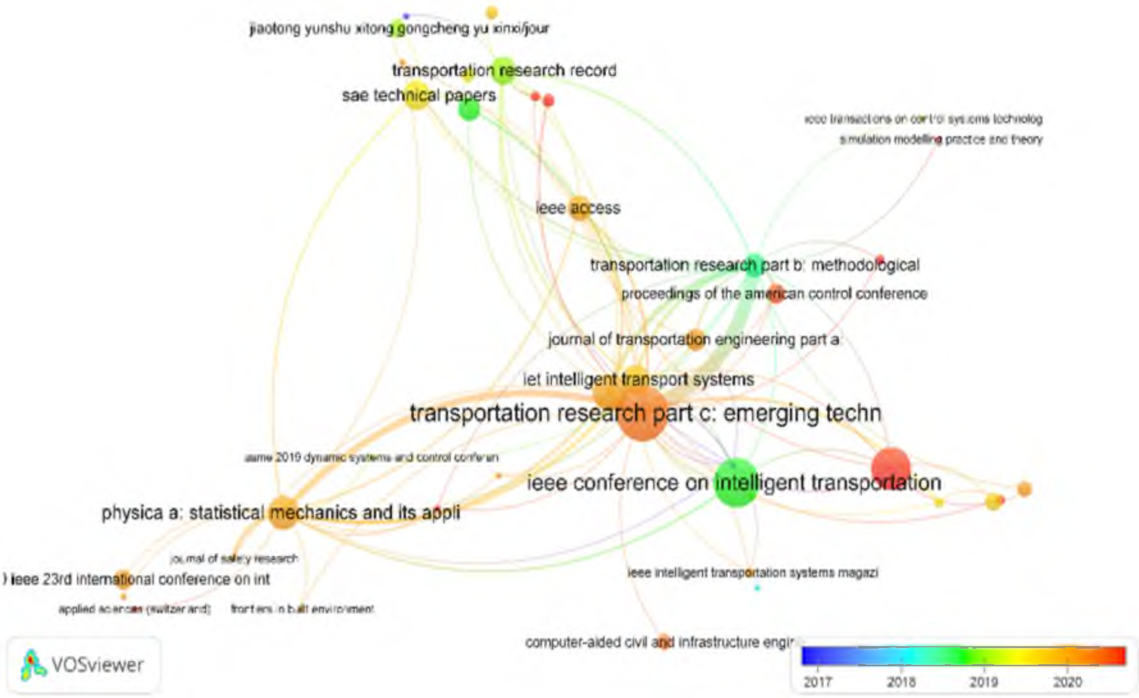

Figure 5. Citation analysis of the sources based on single document and two citations.

4.4. *Citation Analysis of Most Prolific Authors*

The productivity of authors in terms of their total publications over time and their impact on the research area of concern was analyzed by using the visual network maps constructed in VOSviewer. In VOSviewer, the network map was produced by defining criteria. The authors with two publications and 20 citations were analyzed through visual network maps. The criteria were chosen to obtain the most productive authors working on the concerned research area. Out of a total of 966 total authors, only 69 met the threshold. The most extensive set of related authors consisted of 63 items which were further grouped into nine clusters. The authors having a citation relationship between them were placed in one cluster. The network visualization of nine clusters with different colors is shown in Figure 6.

The names, affiliations, citation matrix and the most cited paper of the potential authors in the research area of autonomous vehicles in mixed traffic are shown in Table 7 below. Based on the minimum of five publications' criteria, the 12 most productive authors were selected. Out of the 12 authors, seven have their affiliations with institutions in China. Three authors were affiliated to the United States, and Ireland and Netherlands were affiliated with one author each. Ran, B. and Wang, H. were the most productive authors each, with a total of nine publications and both are affiliated to the Southeast University, China. Li, X. received the highest total citations of 252 for 5 published documents with a highest value of 50.40 for citations per cited document among the selected authors. The author is affiliated to the University of South Florida and received a maximum of 115 citations for a single document.

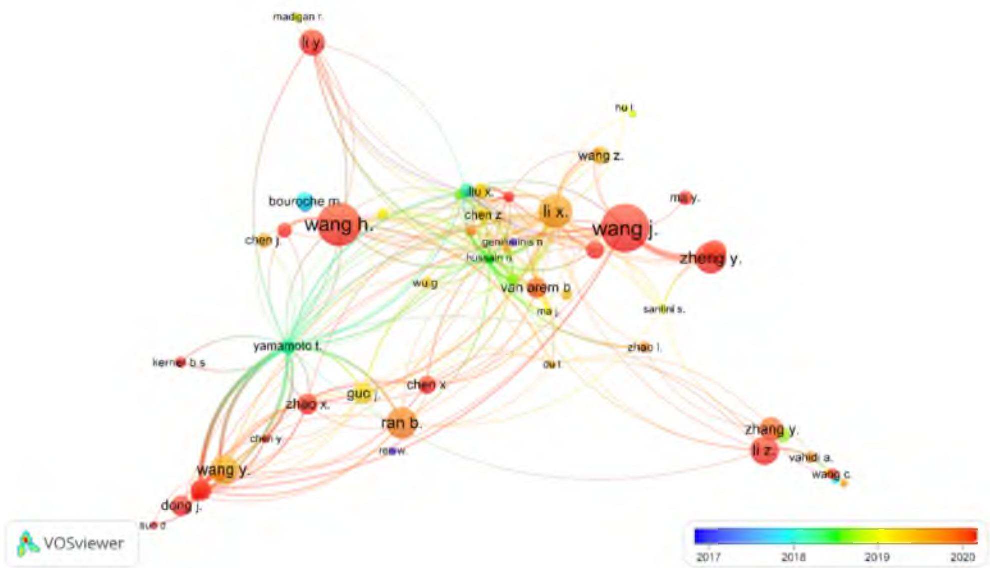

Figure 6. Author network visualization based on 20 citations and two documents per author.

Table 7. Authors with a minimum of 5 publications.

Author Name (Scopus ID)	TP	%	Affiliation	Country	NCP	TC	C/P	C/CP	h	g
Ran, B. (7003397581)	9	2.41%	Southeast University	China	6	56	6.22	9.33	3	6
Wang, H. (55883671300)	9	2.41%	Southeast University	China	6	59	6.56	9.83	4	6
Li, K. (26643211100)	7	1.87%	Tsinghua University	China	6	39	5.57	6.50	3	6
Wang, J. (57211026358)	7	1.87%	Tsinghua University	China	6	39	5.57	6.50	3	6
Ahn, S. (7401989918)	5	1.34%	University of Wisconsin–Madison	United States	5	15	3.00	3.00	2	3
Bouroche, M. (15134891000)	5	1.34%	Trinity College Dublin	Ireland	4	39	7.80	9.75	4	4
Jiang, Y. (34876737100)	5	1.34%	Southwest Jiaotong University	China	3	65	13.00	21.67	3	3
Li, X. (57192545155)	5	1.34%	University of South Florida	United States	5	252	50.40	50.40	4	5
Shao, Y. (57188803628)	5	1.34%	Oak Ridge National Laboratory	United States	5	11	2.20	2.20	2	3
Xu, Q. (57199199887)	5	1.34%	Tsinghua University	China	4	14	2.80	3.50	2	3
Yao, Z. (57190090062)	5	1.34%	Southwest Jiaotong University	China	3	65	13.00	21.67	3	3
van Arem, B. (6602784888)	5	1.34%	Delft University of Technology	The Netherlands	3	29	5.80	9.67	2	3

Notes: total publications (TPs); number of cited papers (NCPs); total citations (TC); mean citations per paper (C/P); mean citations per cited paper (C/CP); h-indices (h); g-indices (g).

4.5. Citation Analysis of the Leading Organizations

Table 8 below shows the top 10 most prominent organizations in the world organized based on the total publications. Out of the ranked organizations, 70% belong to China and the remaining three are affiliated with the United States. The top three organizations which are working actively on autonomous vehicles are from China and hold a total of 64 publications in the area of autonomous vehicles in mixed traffic. The University of Wisconsin–Madison from the United States is ranked fourth with a total of 17 publications. Another aspect to be considered was total citations. Although the organizations at the top positions hold higher numbers of total publications, the organizations ranked at 9 and 10 hold the most notable total citations of 149 and 137, respectively. The most cited papers (MCP) and the total citations of the most cited papers from each of the leading organizations are also shown in the Table 8. The most cited paper received 85 citations and the authors of this paper are affiliated with Tsinghua University, China [70]. Another document with the same number of total citations was written by authors from Zhejiang University, China

Table 8. Top 10 productive organizations ranked based on total publications.

Rank	Institution	TP	Country	TC	C/P	C/CP	Authors of MCP	TC of MCP
1	Southeast University	27	China	94	3.48	6.27	[72]	22
2	Tsinghua University	21	China	187	8.90	11.00	[70]	85
3	Ministry of Education China	18	China	71	3.94	5.92	[61]	17
4	University of Wisconsin–Madison	17	United States	81	4.76	6.75	[111]	34
5	Tongji University	17	China	63	3.71	5.73	[112]	25
6	Southwest Jiaotong University	14	China	136	9.71	12.36	[111]	34
7	Chang'an University	13	China	76	5.85	7.60	[113]	18
8	Clemson University	10	United States	110	11.00	18.33	[109]	55
9	University of South Florida, Tampa	9	United States	149	16.56	21.29	[108]	73
10	Zhejiang University	8	China	137	17.13	22.83	[70]	85

Notes: total publications (TPs); total citations (TC); mean citations per paper (C/P); mean citations per cited paper (C/CP); most cited paper (MCP)s.

4.6. Citation Analysis of the Potential Countries

The geographical distribution of the publications is shown in Figure 7 below. The number of publications are presented, based on the countries around the globe. This analysis is helpful in understanding which part of the world is leading in terms of research on autonomous vehicles in mixed traffic conditions. The countries with publications were grouped according to the seven continents, which were Europe, Asia, North America, South America, Africa and Oceania. It was found that Asia holds the highest position, having 189 total publications from 11 different countries. China, Japan and Singapore were the leading countries from Asia with total publications of 146, 15 and 6, respectively. The second most productive continent was North America, with the United States and Canada as the leading countries with total publications of 148 and 6, respectively.

Figure 7 above shows the collective number of publications by all of the countries within a continent. Asia was the leading continent, having total publications of 189 from 11 different countries. Figure 8 shows the most productive countries with minimum total publications of five. In terms of total publications and total citations from a single country, the United States is the leading country, holding around 40% of the total publications in the area of autonomous vehicles in mixed traffic. In terms of total publications and total citations, the United States published 148 documents with total citations of 1470. The second leading country is China with total publications of 146 (39.0% of TPs) and total citations of 866. Table 9 shows further information about the most productive countries with minimum total publications of five.

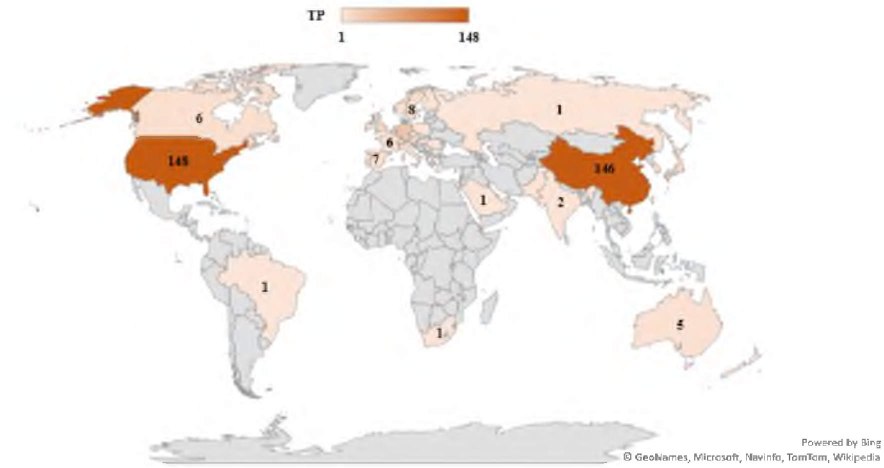

Figure 7. Geographical distribution of the publications.

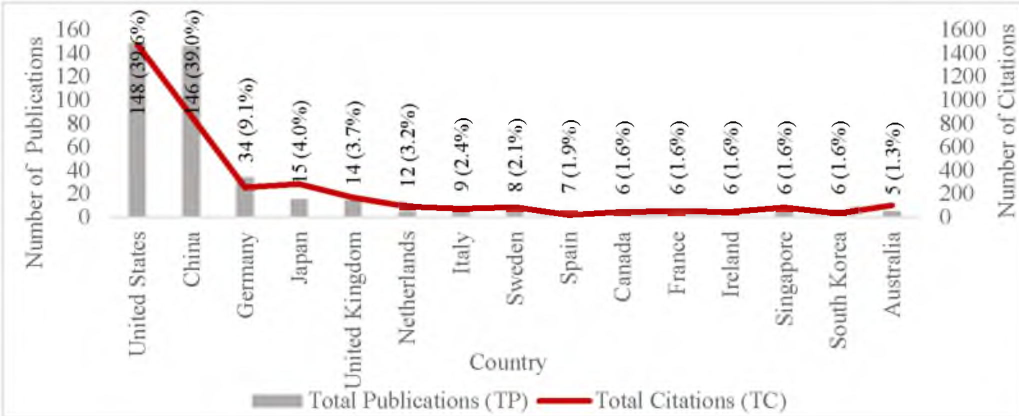

Figure 8. Countries with the minimum of 5 publications.

Table 9. Most leading countries with minimum of 5 publications.

Country	TP	%	NCP	TC	C/P	C/CP	h	g
United States	148	39.6%	113	1470	9.93	13.01	17	34
China	146	39.0%	86	866	5.93	10.07	16	24
Germany	34	9.1%	23	252	7.41	10.96	6	15
Japan	15	4.0%	12	283	18.87	23.58	7	12
United Kingdom	14	3.7%	11	167	11.93	15.18	6	11
Netherlands	12	3.2%	11	91	7.58	8.27	6	9
Italy	9	2.4%	8	71	7.89	8.88	5	8
Sweden	8	2.1%	6	84	10.50	14.00	4	6
Spain	7	1.9%	4	18	2.57	4.50	3	4
Canada	6	1.6%	5	45	7.50	9.00	4	5
France	6	1.6%	5	49	8.17	9.80	3	5
Ireland	6	1.6%	5	44	7.33	8.80	4	5
Singapore	6	1.6%	5	83	13.83	16.60	3	5
South Korea	6	1.6%	5	32	5.33	6.40	3	5
Australia	5	1.3%	4	101	20.20	25.25	4	4

Notes: total publications (TPs); number of cited papers (NCPs); total citations (TC); mean citations per paper (C/P); mean citations per cited paper (C/CP); h-indices (h); g-indices (g).

Figure 9 below shows the network visualization of the co-authorship and collaboration between countries. A strong correlation is represented by the countries that are close together and have thicker connecting lines between them [102]. In terms of co-authorship between countries, the United States and China holds the strongest correlations as these two are located near to each other and are connected with a thicker line. The United States exhibited the highest international collaborations of 12 between the USA and other nations with a total link strength of 67, followed by China (10 associations with other countries and 67 total link strength), Germany (9 associations with other countries and 12 total link strength) and the United Kingdom (5 associations with other countries and 12 total link strength). From the cluster colors, it can be observed that South Korea, China, Germany and Canada are recently active countries in the research on autonomous vehicles.

Figure 9. Co-authorship network visualization between countries.

Figure 10 illustrates a density visualization map reflecting the density for a country's total citations received, which was built with VOSviewer. It can be seen that the maximum concentration of citations is around the United States and China followed by Germany, Japan and the United Kingdom. The two counties, the United States and China, produced comparable citations on the topic of autonomous vehicles in mixed traffic conditions.

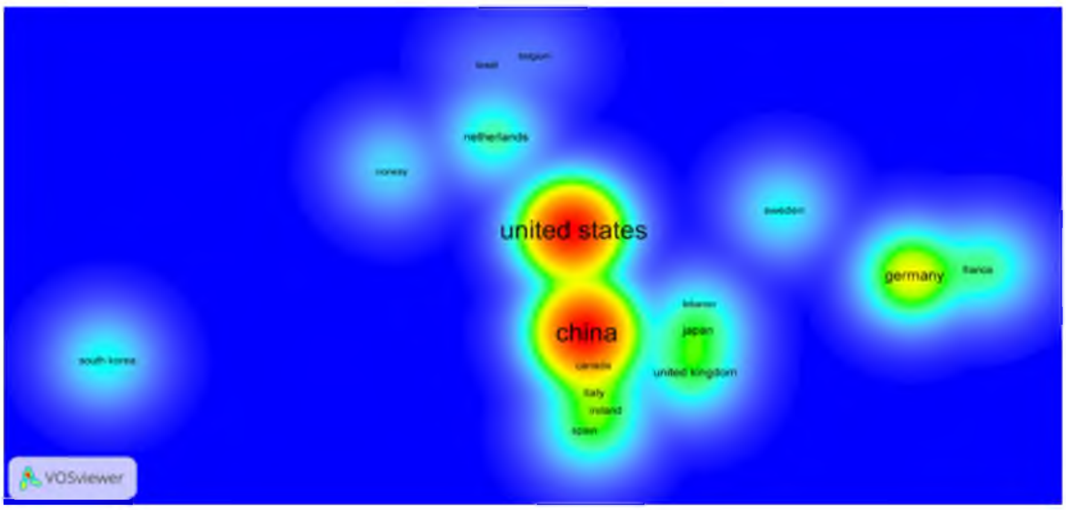

Figure 10. Density map of country-based citations.

4.7. Co-Authorship Analysis

A total of 966 authors are involved in the research area of autonomous vehicles in mixed traffic. The network map was created by setting the minimum documents to two and citations to 10 (Figure 11). Out of 966 authors, 119 authors met the threshold. There were 93 authors with higher link strengths, and these were further grouped into 13 clusters. The authors having co-authorship relationships were grouped into one cluster. Cluster-1 represented a network of 12 authors, cluster-2, 3 consisted of 11 authors, cluster-4 of 10 authors, cluster-5 and 6 of nine authors, cluster-7 and 8 represented a network of six authors, cluster-9 and 10 of five authors and cluster11, 12 and 13 consisted of three authors each.

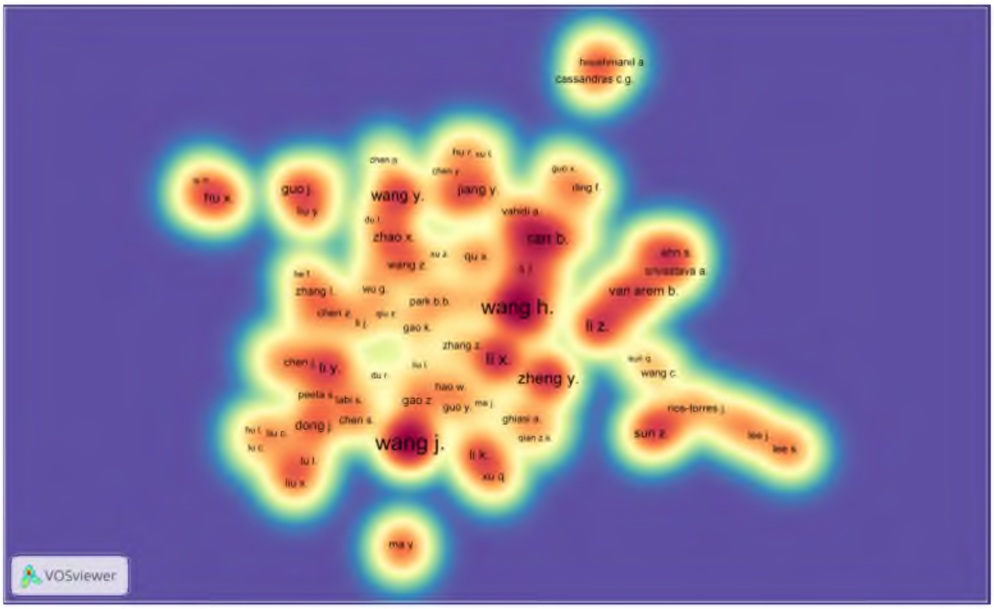

Figure 11. Density map of co-authorship.

4.8. Co-Occurrence Analysis of Authors Keywords

The co-occurrence of author keywords was determined by using the extracted Scopus data into VOSviewer. Initially, 781 words appeared on the concerned topic when analyzing the Scopus file into VOSviewer. The keyword clusters were obtained on the basis of three author keyword occurrences to obtain the most relevant information. A total of 70 author keywords met the threshold. The potential 70 author keywords grouped into 10 clusters are shown in Figure 12 below.

Autonomous vehicles, mixed traffic and mixed traffic flow are the most co-occurred author keywords as denoted by the large size circles. Each of the clusters contains various author keywords, as discussed below:

- The cluster-1 is denoted by a red color and contains 13 author keywords, including “automated vehicles”, “autonomous vehicles”, connected and autonomous vehicle”, “connected vehicle”, “cooperative driving”, “market penetration”, “microscopic simulation”, “mixed traffic”, mixed traffic stream”, “optimal control”, “string stability”, “traffic engineering” and “traffic safety”;
- The cluster-2 is denoted by a green color and consists of 10 author keywords, such as “adaptive cruise control”, “connected and automated vehicle (cav)”, “connected and automated vehicles”, “connected autonomous vehicles”, “cooperative adaptive cruise control”, “intelligent transportation”, “intersection control”, “motion planning”, “smart city” and “trajectory planning”;
- The cluster-3 is denoted by a blue color and contains eight author keywords, including “car-following model”, “connected and automated vehicle”, “energy efficiency”,

"machine learning", "model predictive control", "numerical simulation", "stability analysis" and "trajectory prediction";

- The cluster-4 is denoted by a yellow color and contains seven author keywords, including "connected vehicles", "deep reinforcement learning", "roads", "safety", "traffic control", "vehicle dynamics" and "vehicles";
- The cluster-5 is denoted by a purple color and contains seven author keywords, including "automated driving", "autonomous driving", "connected and automated vehicles (CAVs)", "platooning", "plex", "simulation" and "traffic flow";
- The cluster-6 is denoted by a sky blue color and contains six author keywords, such as "cellular automation", "connected and autonomous vehicles", "dedicated lanes", heterogeneity", heterogeneous flow" and "traffic throughput";
- The cluster-7 is denoted by an orange color and consists of six author keywords, such as "car-following", "cellular automata model", "connected automated vehicle", "connected automated vehicles", "mixed traffic flow" and "stability";
- The cluster-8 is denoted by a brown color and contains five author keywords, including "cellular automata", "connected and automated vehicles (CAVs)", "heterogeneous traffic flow", "linear stability" and "reaction time";
- The cluster-9 is denoted by a pink color and includes four author keywords, such as "automated vehicles", "capacity", "fundamental diagram" and "microscopic traffic simulation";
- The cluster-10 is denoted by a cyan color and consists of four author keywords, including "autonomous vehicles", "dynamic programming", "human factors" and "traffic simulation".

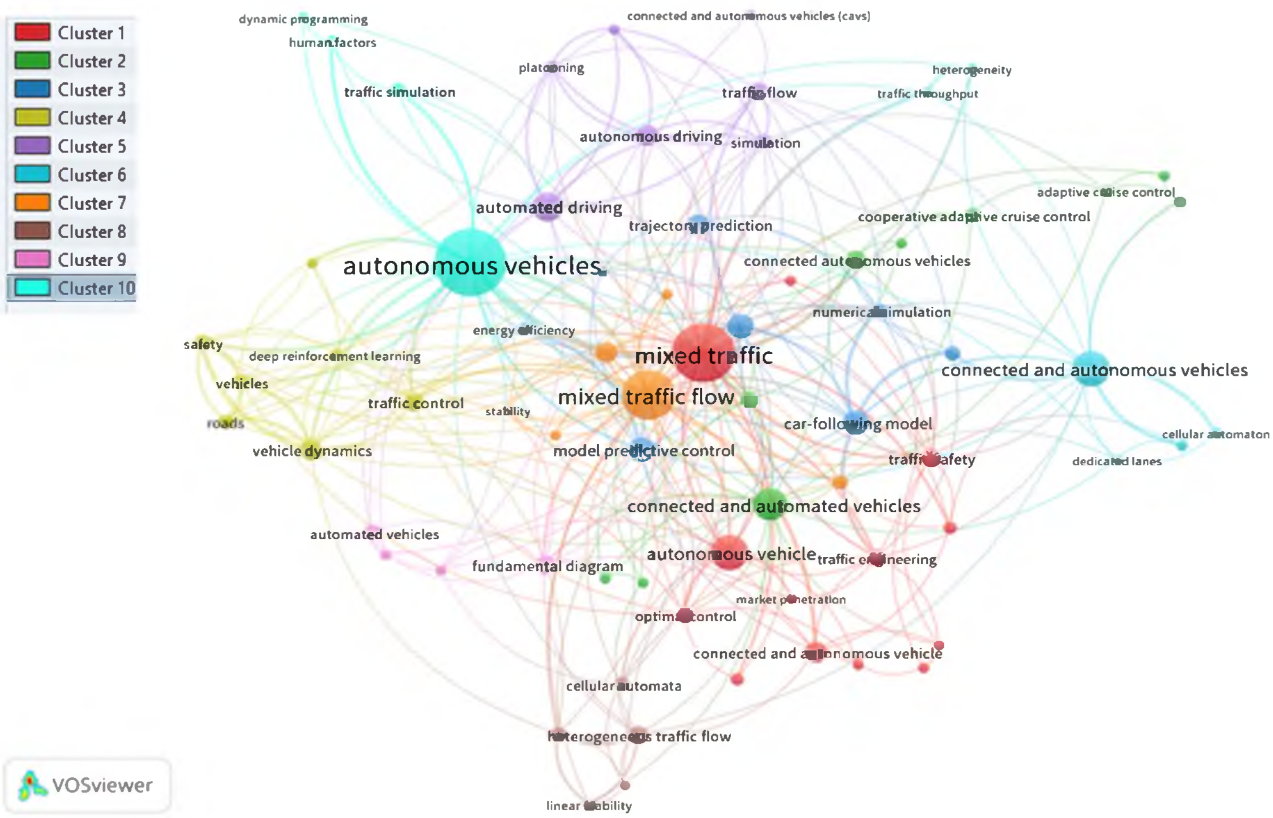

Figure 12. Visualization network of co-occurrence of author keywords.

Then, the top 20 author keywords used in the research area of autonomous vehicles in mixed traffic conditions were illustrated in a tree-map, as shown in Figure 13. The documents retrieved from Scopus database used the author keyword "autonomous vehicles" for 45 times contributing to 16% of the top 20 author keywords. The word "mixed traffic" was the second most frequently adopted author keyword among the top 20, with a total occurrence of 35 and contribution of 13%. The third leading author keyword was "mixed traffic flow" with an occurrence of 35 and contribution of 10%.

Figure 13. Tree-Map of top 20 author keywords.

4.9. Text-Data Analysis

The VOSviewer offers extraction and analysis of text data and computes the relevance score of each term used in the title or/and abstract of the documents. The terms with a higher relevance score refer to a specific theme of research area and the terms with a low relevance score refer to general areas and do not represent any specific theme. The VOSviewer extracts the terms from the Scopus file and offers an option to exclude 40% of the irrelevant terms while including the remaining 60% for analysis [114]. In the text analysis, the terms can be extracted from the title, abstract or from both. The extracted text is analyzed by binary coding and relevance score [115].

The Scopus file was used in VOSviewer which showed a total of 8035 terms extracted from the titles and abstracts of the documents. To have a clear image of the topics discussed in the titles and abstracts of the documents, the minimum occurrence for a term was set to 10. This reduced the total text terms to 207 which were further reduced to 124 after the software selected the 60% most relevant terms. A density map created based on the aforementioned criteria is shown in Figure 14 below. It is then followed by Table 10 which shows the top 10 terms used in titles and abstracts of the documents. The ranking of terms was completed based on the occurrence frequency and relevance score of each term.

As seen in Table 10 above, the terms "traffic flow", "mixed traffic flow" and "CAVs" appeared more than 80 times among the top 10 terms with relevance values of 0.53, 0.83 and 0.33, respectively. In terms of the highest relevance score, the terms "mixed traffic situation", "cooperative adaptive cruise control" and "cellular automata" showed the highest relevance values of 3.45, 2.17 and 2.07, respectively. The term "mixed traffic situation" showed the highest relevance score of 3.45 but it only occurred 12 times.

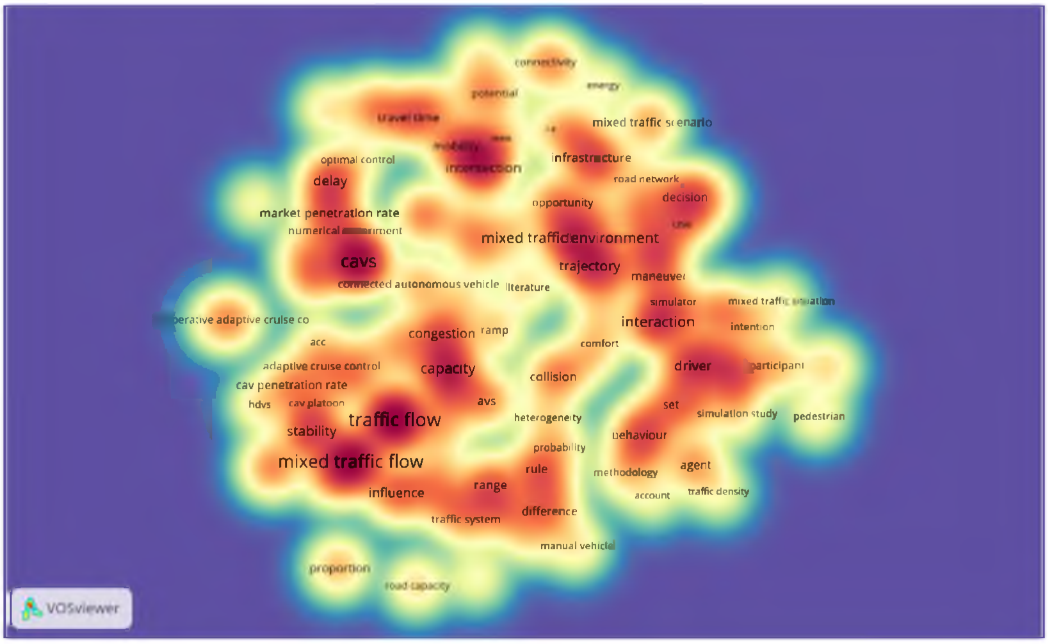

Figure 14. Density map showing the most occurring author keywords.

Table 10. Top 10 terms based on occurrence frequency and relevance score.

Rank	Based on Occurrence Frequency			Rank	Based on Relevance Score		
	Term	Occurrence	Relevance Score		Term	Occurrence	Relevance Score
1	Traffic flow	99	0.53	1	Mixed traffic situation	12	3.45
2	Mixed traffic flow	88	0.83	2	Cooperative adaptive cruise control	18	2.17
3	CAVs	86	0.33	3	Cellular automata	11	2.07
4	Capacity	52	0.54	4	Numerical simulation	31	1.9
5	Interaction	50	0.84	5	Situation	42	1.86
6	Mixed traffic environment	49	0.52	6	Mixed traffic scenario	26	1.83
7	Stability	48	1.13	7	Road capacity	17	1.79
8	Intersection	47	0.44	8	Automated driving	27	1.58
9	Driver	46	0.94	9	Simulation study	15	1.56
10	Delay	43	0.56	10	Adaptive cruise control	19	1.54

4.10. Three Field Plots on Autonomous Vehicles in Mixed Traffic Conditions

For this paper, three field plots were prepared in the Bibliometrix R-package to understand the relationship between the sources, countries, organizations, affiliations and keywords [116]. For each of the considered aspects, the rectangles of different colors appear in the plots and the height of the rectangle denotes the strength of the relationship with other components.

Figure 15 shows a Sankey diagram for autonomous vehicles in mixed traffic conditions created between author keywords (left), authors (middle) and sources (right). For better visualizations of potential components, the number of keywords was set to 15 and the values for authors and sources were set to 10.

It can be observed from Figure 15 that the “mixed traffic flow”, “autonomous vehicle” and “mixed traffic” are the most dominant keywords, and authors Wang, J., Wang, H., Li, X., and Zheng, Y., mainly worked and published in sources such as *Transportation Research Part C: Emerging Technologies*, *IEEE Transactions on Intelligent Transportation Systems*, *Journal of Advanced Transportation* and *Physica A: Statistical Mechanics and its Applications*.

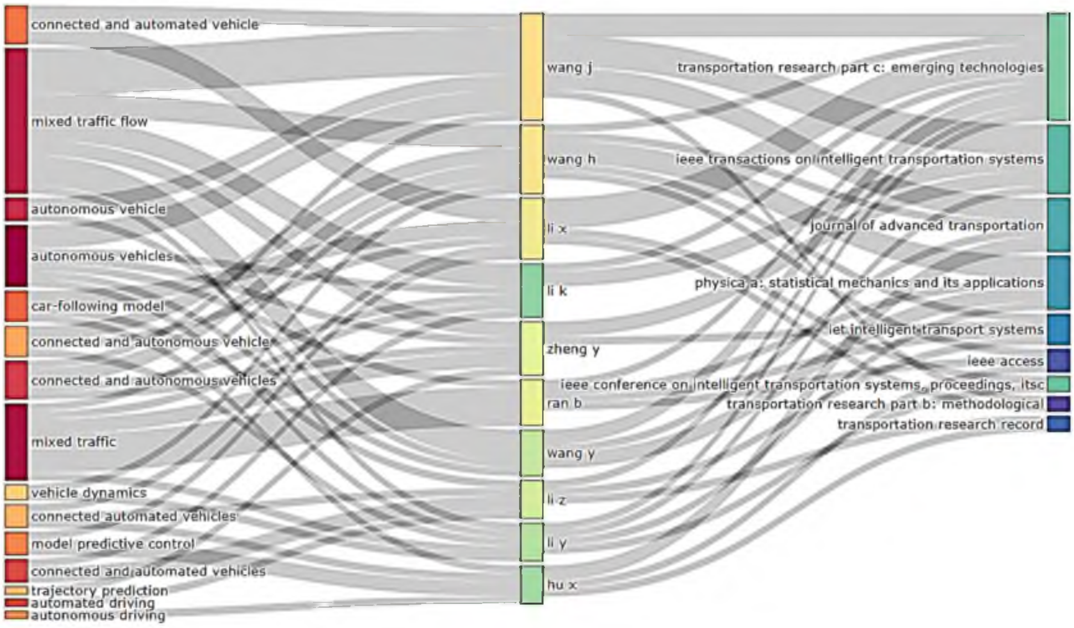

Figure 15. Three field plots between keywords (**left**), authors (**middle**) and sources (**right**).

Another plot explaining the relationship between authors (left), countries (middle) and keywords (right) is shown in Figure 16. The information of the most productive authors, their affiliated countries and their research areas can be seen with the help of rectangle sizes for each of the considered components. This graph was generated by considering the number of counties as 10 and the authors and keywords as 15. It can be seen that the most productive authors are from China, the United States and Germany and their potential areas are autonomous vehicles, mixed traffic flow and mixed traffic.

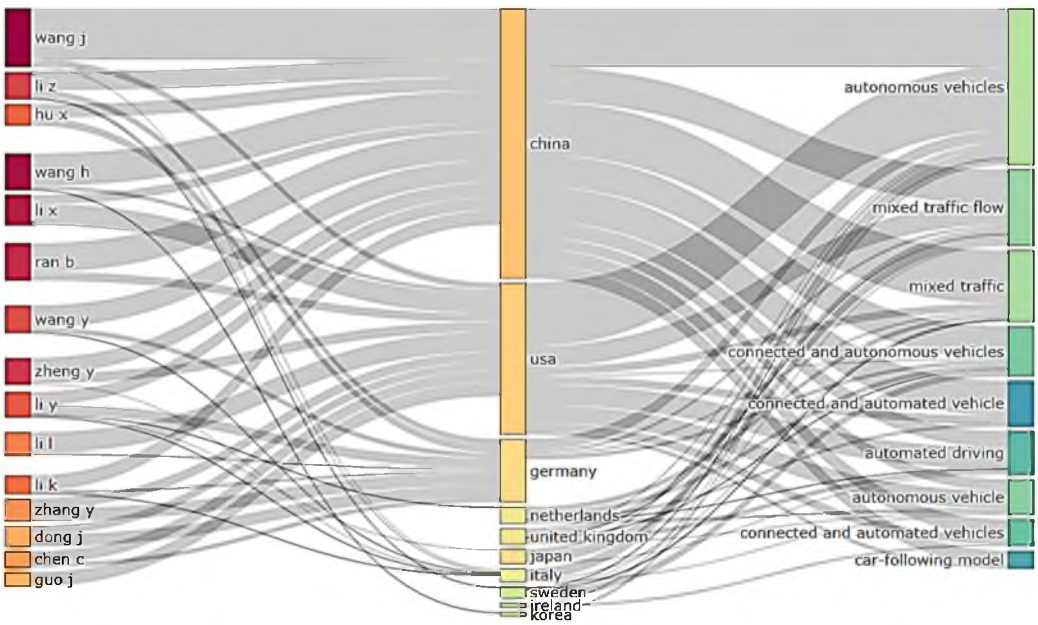

Figure 16. Three field plots between authors (**left**), countries (**middle**) and keywords (**right**).

Figure 17 below explains the relationship between the prominent institutions, their most productive authors and the journals where they are publishing their work. Three field plots were created by considering 15 institutions (left), 10 authors (middle) and 15 potential sources (right). The potential authors Zheng, Y., and Wang, H. have their affiliations with the Southeast University, China and Wang, J., is affiliated with Tsinghua

University, China. These institutions with their productive authors are publishing their research works in *Transportation Research Part C: Emerging Technologies*, *IEEE Transactions on Intelligent Transportation Systems*, *IEE conference on Intelligent Transportation Systems* and *Journal of Advanced Transportation.*

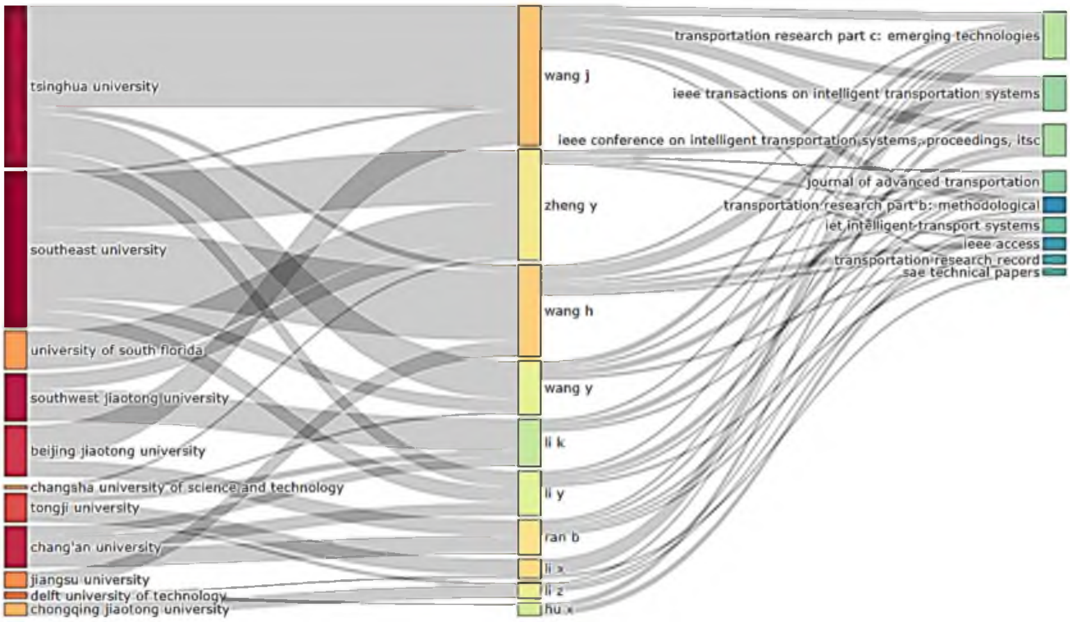

Figure 17. Three field plots between institutions (**left**), authors (**middle**) and sources (**right**).

5. Discussion on Thematic Areas and Research Hotspots

This section elaborates the evolution of the various research areas linked with the autonomous vehicles in previous years. The latest areas in the concerned research domain will be highlighted through the text analysis in the form of clusters and thematic maps.

5.1. Thematic Evolution of Autonomous Vehicles in Mixed Traffic from 1999 to 2021

The evolution of different research areas associated with autonomous vehicles is shown in Figure 18 below. The thematic map was created by considering three time slices, based on what has been published in the previous years (1999–2017), what were the hotspots research areas on this concerned topic in recent years (2018–2020) and what areas are current research themes (2021).

The potential areas from each of the considered time slices based on notable keywords are given in Table 11 below. The prominent keywords in each time slice denote the maturity of the research areas for that time frame. For the time slice 1999–2017, the keywords such as transportation system, algorithms and controller specify the active start of this research area and the major research concerns were the development of interfaces and algorithms as an input to in-vehicle controllers for the development of automation in vehicular technology. The time slice 2017–2020 denotes the maturity of the research concerning the development of autonomous vehicular technology having valid control algorithms and in-vehicle sensors. During the years 2017–2020, the most prominent research areas were related to enhancement of autonomous vehicles for different traffic situations and human–machine interactions. The key interests were to develop highly automated vehicles which would be capable of driving in any traffic situation and their errorless interaction with human drivers and pedestrians. These preparations were based on certain control algorithms, sensors, cameras and radars that provided information on the surrounding roadway conditions [117].

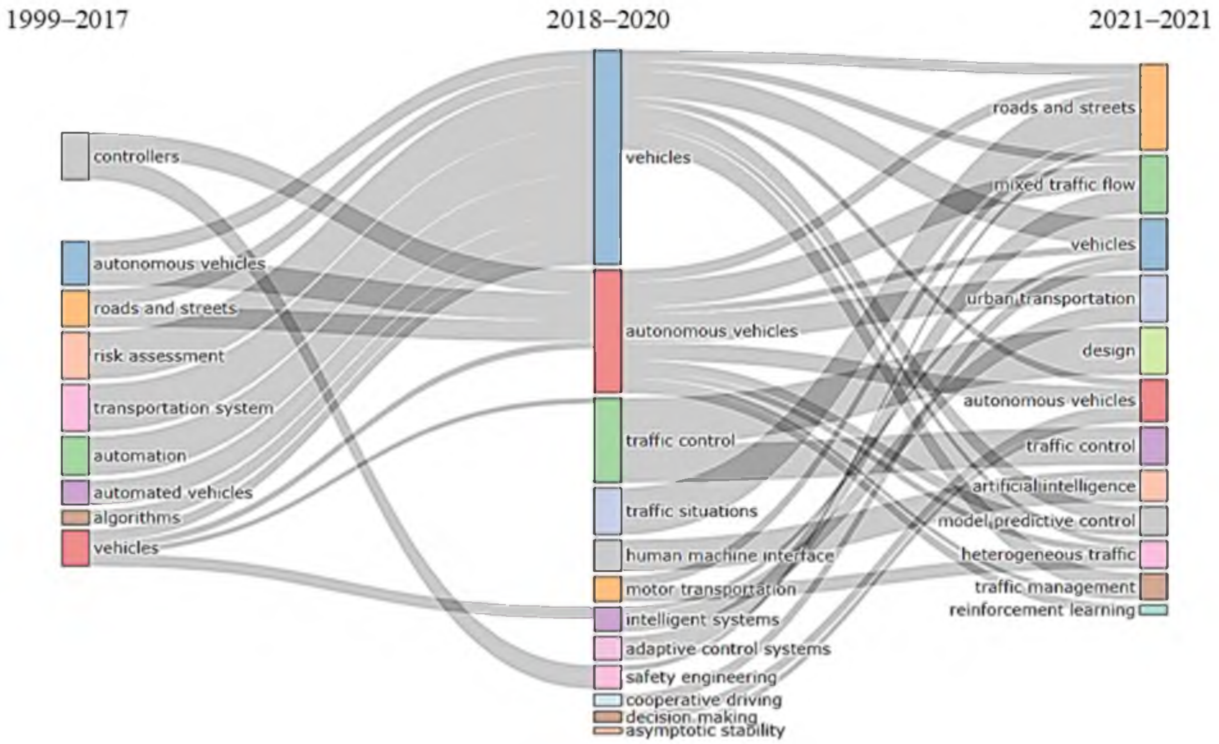

Figure 18. Thematic evolution of AVs in mixed traffic during different time slices.

Table 11. Notable Keywords and Research Themes.

Time Frame	Notable Keywords	Research Front
1999–2017	Autonomous vehicles, controllers, transportation system, algorithms	Pre-Development
2017–2020	Autonomous vehicles, traffic control, traffic situation, human–machine interface, intelligent systems	Development
2021	Mixed traffic flow, autonomous vehicles, heterogeneous traffic, traffic management, urban transportation	Deployment

The latest developments in the research pertaining to autonomous vehicles are illustrated in Figure 18 above for the time slice 2021 and the notable keywords for the same time slice are given in Table 11 below. The new and notable terms which appeared during this time frame are linked with the deployment of autonomous vehicles in real-world mixed traffic streams. Mixed traffic streams refer to the traffic streams having both autonomous vehicles and human-driven vehicles. The latest research areas working on various components include the impacts of autonomous vehicles on network performance [118,119], infrastructure planning and management for heterogeneous traffic streams [120,121] and interaction with different vehicular classes in urban transport networks [34,122,123].

5.2. Trending Topics and Research Hotspots

Based on the occurrence frequency of author keywords, the trending research areas allied with autonomous vehicles in mixed traffic conditions for each specific year are shown in Figure 19 below. For a better demonstration, the minimum words per year were chosen as five and the minimum occurrence was set to three. A total of 19 words met the defined criteria spanning from 2016 to 2021. The size of the circle refers to the occurrence frequency of the author keyword. In 2017, some work had been published on the motion planning of autonomous vehicles. The capacity, cellular automation and heterogeneous flow were the most trending topics in 2018 but the smaller size of the circles denotes the fewer publications on these topics. In 2020, the terms "autonomous vehicles" and "mixed traffic" were the most occurring author keywords as specified by the greater size of the circles. In recent years, the most trending topics are related to the mixed traffic flow having both AVs and HVs. In 2021, the author keyword "mixed traffic flow" denoted by the greater size of the circle shows that this research area is of utmost importance to many researchers now and sufficient work is being published to advance this field.

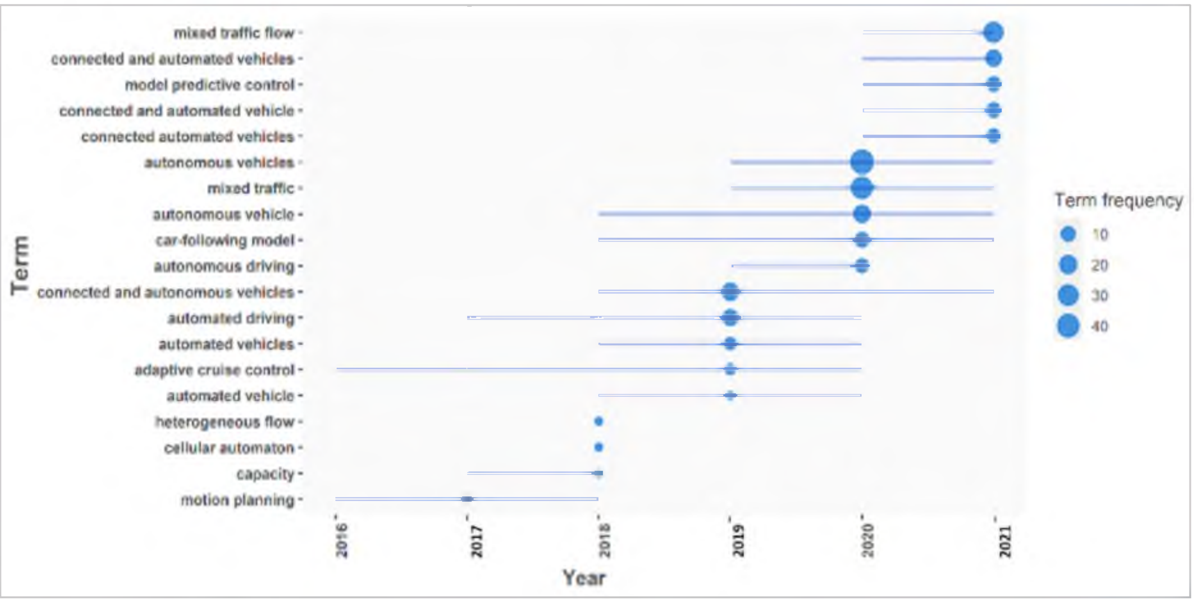

Figure 19. Trending topics in concerned research area.

In addition to the author keywords, the network map shown in Figure 20 below was created in VOSviewer by considering the index keywords with minimum occurrences of 15. The higher number for the minimum occurrences was used to reduce the keywords that appear on the map and to obtain the most closely linked research areas with the topic of concern. The concentration of any keyword is denoted by the size of the circle, and strength of its linkage with another area is specified by the thickness of the connecting line. The color scheme is used to identify the year-wise potential areas on which most the work is being published. Pertaining to the autonomous vehicles, the current research areas are transportation planning, traffic efficiency, reinforcement learning and trajectories of traffic flow. The smaller size of circle for these aforementioned areas show that the areas are under-saturated and more research is needed to signify these areas in the context of autonomous vehicles.

As seen in Figure 20, the other prominent areas which were a topic of interest to many researchers in recent years are mixed traffic flow, energy efficiency, heterogeneous traffic and automobile drivers. Among these index keywords, the mixed traffic flow has the larger size of circle showing significant research in this area and also the strongest link is observed between autonomous vehicles and mixed traffic flow. Although the research on mixed traffic flows is being carried out, the majority of it is still centered in developed economies having homogeneous traffic conditions. Only Europe and North America hold around 80% of the studies discussing the impacts of AVs [124,125]. The traffic conditions in developing economies are characterized by various factors which include: static and dynamic characteristics of the vehicles, non-lane-based movement, greater proportion of two-wheeler vehicles (motorcycles) and involvement of some unique three-wheeler vehicular classes, such as rickshaws and qingqis. Sufficient research on mixed traffic from the perspective of developing economies is needed to create a regional balance. The keywords "automobile drivers" and "energy efficiency" have smaller sizes of circles showing that these research areas are underexplored and need further research with a link with autonomous vehicles. Computer simulations, intelligent systems and intelligent vehicle highway systems were popular topics in previous years. Computer simulations have provided a competent means of exploring the various components and uncertainties associated with autonomous vehicles.

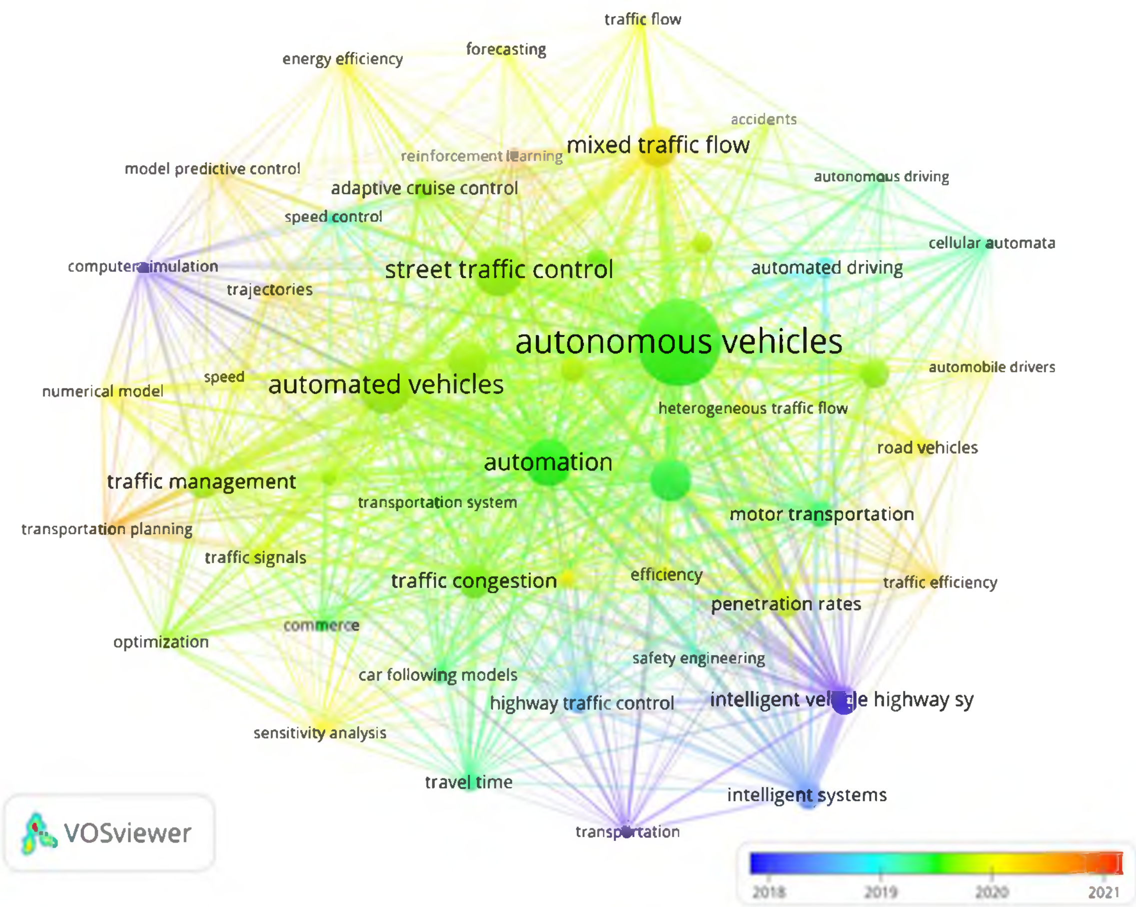

Figure 20. Research hotspots created based on occurrence of index keywords.

6. Concluding Remarks

The objective of this paper was to provide a landscape of the research in the area of autonomous vehicles in mixed traffic conditions. The specific data on the topic of concern were extracted from the Scopus database from 1999 to 2021. The use of a valid search string in the title and abstract field of Scopus produced 434 documents which were further screened and refined to 374 documents. The extracted data were used to conduct a systematic bibliometric analysis and visualization review to highlight the potential components and identify the hotspots in research. The research area pertaining to the autonomous vehicles in mixed traffic has gained immense scholarly attention as endorsed by the exponential increase in the number of publications since 2017. Based on the results of citation analysis, the most productive and highly cited article is by [53] with the title "Autonomous vehicles and connected vehicle systems: Flow and operations considerations" and published in *Transportation science*. The most productive and dominant source was the *Transportation Research Part C: Emerging Technologies* followed by the IEEE Conference on Intelligent Transportation Systems Proceedings (ITSC), and *IEEE Transactions on Intelligent Transportation Systems*. Among the potential authors, Ran, B. published the highest number of articles followed by Wang, H. The Southeast University, China emerged as the leading institution with the highest total publications of 27 and total citations of 94. Among the top ranking countries, the United States is the highest ranked country in terms of total publications and total citations, followed by China and Germany.

The "autonomous vehicle" was the leading author keyword contributing 16% followed by "mixed traffic" with a 13% contribution. On the relevance score, the terms "mixed traffic situation", "cooperative adaptive cruise control" and "cellular automata and numerical simulation" showed the highest relevance values. The value relationships among the authors, keywords, sources, countries and institutions were produced and visualized with the help of the three field plots. The thematic map showed different themes of research during three different phases based on notable keywords. The research progress was divided into three phases: pre-development (1999–2017), development (2018–2020) and deployment (2021). The research hotspots indicate that the transportation planning, traffic efficiency, reinforcement learning and trajectories of traffic flow need to be explored in the context of autonomous vehicles. Computer simulations have been a competent method of exploring the different aspects of autonomous vehicles. The study highlighted various potential areas, such as the involvement of autonomous vehicles in transportation planning, interaction between autonomous vehicles and human-driven vehicles, traffic and energy efficiencies associated with automated driving, penetration rates for autonomous vehicles in mixed traffic scenarios and the safe and efficient operation of autonomous vehicles in mixed traffic environments. This paper provides ample future directions to the people willing to work on this area of autonomous vehicles in mixed traffic conditions.

The review summarized the findings based on three areas: impacts of AVs on mixed traffic, driving characteristics of AVs and various strategies to address different aspects of AVs for the case of mixed traffic. The studies endorsed the positive operational, safety and environmental impacts of AVs when simulated in mixed traffic streams. The review showed that VISSIM was the most frequently adopted simulation tool for the assessment of various scenarios involving AVs. For the driving characteristics of AVs, the studies showed that AVs maintain a smaller time headway, smaller standstill distances, strict speed deviation and less deviation in acceleration and deceleration compared with conventional vehicles. Most of the reported advantages of AVs are associated with the driving characteristics of AVs. The review also highlighted the strategies to understand the behavior of AVs in mixed traffic. The researchers provided the basis for the simulation frameworks, motion and trajectory planning, development of human-like driving models and the role of exclusive CAV lanes for the enhancement of operational efficiency. There are further studies in progress to provide a competent environment for the successful deployment of AVs in mixed traffic during the transition period. Further research topics can be comprehended by extracting the relevant data from databases and creating more visualization networks with a prior focus on other aspects, such as smart and responsive infrastructure, public transport aspects after introduction of autonomous vehicles in urban areas and performance of autonomous vehicles in a heterogeneous traffic environment having a higher proportion of two-wheelers.

Author Contributions: Conceptualization, M.A., S.A.H. and O.C.P.; methodology, M.A. and S.A.H.; software, M.A. and S.A.H.; validation, S.A.H. and O.C.P.; formal analysis, M.A.; investigation, M.A. and S.A.H.; resources, S.A.H.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, M.A., S.A.H. and O.C.P.; supervision, S.A.H. and O.C.P.; funding acquisition, S.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Universiti Teknologi Malaysia, vote number Q.J130000.2551.21H41 (PY/2019/01306).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge financial support from the Universiti Teknologi Malaysia.

Conflicts of Interest: The authors declare no conflict of interest.

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