Mechatronics and Intelligent Transportation Systems
https://www.acadlore.com/journals/MITS

A Bibliometric Analysis of Trends and Collaborations in Autonomous Driving Research (2002-2024)

Edi Purwanto*

Department of Management, Universitas Pembangunan Jaya, 15413 South Tangerang, Indonesia

* Correspondence: Edi Purwanto (edi.purwanto@upj.ac.id)

Received: 03-25-2024 **Revised:** 04-30-2024 **Accepted:** 05-15-2024

Citation: E. Purwanto, "A bibliometric analysis of trends and collaborations in autonomous driving research (2002-2024)," *Mechatron. Intell Transp. Syst.*, vol. 3, no. 2, pp. 85–112, 2024. https://doi.org/10.56578/mits030202.

Abstract: Through the deployment of bibliometric techniques and network visualizations, this analysis synthesizes the evolution and trajectories of autonomous driving research from 2002 to May 2024, as captured in the Scopus database encompassing 342 scholarly documents. This study was conducted to delineate the developmental contours, thematic emphases, and the expansive growth trajectory within this field, particularly noting a surge in scholarly outputs since 2017. Such growth has been primarily facilitated by breakthroughs in artificial intelligence and sensor technologies, along with burgeoning interdisciplinary collaborations and escalating academic and industrial investments. A meticulous examination of publication trends, document types, subject areas, and geographic distributions elucidates the multidisciplinary and international nature of this burgeoning field. Key thematic clusters identified—comprising foundational technologies, environmental sustainability, safety measures, regulatory frameworks, user experience, connectivity, and technological innovations—underscore the prevailing research directions and emerging focal areas poised to shape future autonomous mobility solutions. Notably, increased emphasis on environmental sustainability and regulatory frameworks has been observed, highlighting their critical roles in advancing and integrating autonomous driving systems. This study provides pivotal insights for researchers, policymakers, and industry stakeholders, fostering a nuanced understanding of the field's dynamics and facilitating strategic alignments and innovations in autonomous mobility. The emergent research domains and collaborative networks revealed herein not only map the current landscape but also guide future scholarly endeavors in autonomous driving systems globally.

Keywords: Autonomous driving systems; Bibliometric analysis; Scholarly publications; Technological advancements; Urban studies

1 Introduction

Autonomous driving systems are at the forefront of transportation technology evolution, promising improved safety, efficiency, and mobility [1, 2]. The advancements in AI, machine learning, and sensor technologies are reshaping the field, leading to a critical need to understand the research trajectory [3]. Integrating sensor data from cameras, radar, and LiDAR sensors is crucial for enhancing autonomous vehicle perception, with proposed flexible selective sensor fusion frameworks showing promise in overcoming challenges related to sensor fusion [4, 5]. Additionally, the development of autonomous electric vehicles (A-EVs) is gaining traction, with life cycle assessments revealing higher impacts during the manufacturing phase but better environmental performance during the use phase, especially in regions with hydropower-based electric grids [6]. Furthermore, the safety evaluation of autonomous driving systems necessitates the artificial generation of safety-critical scenarios, highlighting the importance of scenario-generation algorithms for risk assessment and cost reduction [7].

The scholarly interest in autonomous driving systems has surged in recent years, prompting a need for a comprehensive analysis of the research landscape, trends, and emerging trajectories. Studies have highlighted the development of safety-critical scenario generation algorithms [8], life cycle assessments comparing autonomous electric vehicles (A-EVs) with conventional vehicles [2], advancements in electric vehicle technologies and autonomous features [6], critical scenario identification methods in automated driving systems [9], and a Survey of Surveys (SoS) outlining the history and future directions of autonomous driving and intelligent vehicle research [10]. This collective body of research provides insights into the technological innovations, environmental impacts, safety evaluations, and future research directions in autonomous driving systems, offering a holistic view of the evolving landscape and paving the way for further exploration and advancements. This study, driven by this pressing need, aims to fill this gap by systematically examining the scholarly output and identifying key trends, thematic concentrations, and global perspectives in autonomous driving systems through a bibliometric analysis.

The emergence of autonomous driving systems heralds a paradigm shift in transportation, aiming to redefine mobility by delegating driving tasks to automated vehicles. This transition holds immense potential to revolutionize various sectors, from urban mobility and logistics to public transportation. The pursuit of autonomous driving encompasses many technologies, including sensor fusion, AI-driven decision-making, connectivity, and infrastructure optimization [4]. As research and development in this domain intensify, it becomes crucial to assess the evolution of scholarly discourse, identify emerging challenges, and chart future research directions.

While the proliferation of research in autonomous driving systems underscores its growing significance, several critical challenges and knowledge gaps persist. The rapid pace of technological innovation necessitates the continuous evaluation and synthesis of scholarly outputs to inform strategic decision-making and policy formulation. Moreover, as autonomous vehicles transition from experimental prototypes to real-world deployment, addressing regulatory, ethical, and societal implications becomes imperative. Understanding the prevailing research dynamics and thematic concentrations is essential for fostering interdisciplinary collaborations, driving innovation, and ensuring the responsible development and adoption of autonomous driving technologies.

Despite the burgeoning literature on autonomous driving systems, specific research gaps and areas of ambiguity warrant attention. These include, but are not limited to: (1) While the field of autonomous driving systems inherently encompasses multidisciplinary expertise, fostering seamless integration across disciplines remains a challenge. Bridging the gap between engineering, computer science, social sciences, and policy domains is essential for developing holistic solutions. (2) The deployment of autonomous vehicles raises complex regulatory and ethical dilemmas, ranging from liability frameworks and data privacy to algorithmic biases and societal acceptance. Addressing these considerations requires nuanced, interdisciplinary research and policy interventions. (3) Ensuring the safety and reliability of autonomous driving systems is paramount for widespread adoption. Research efforts must focus on robust validation methodologies, real-world testing frameworks, and fail-safe mechanisms to mitigate risks and enhance public trust. (4) Understanding human perceptions, behaviors, and preferences concerning autonomous vehicles is critical for designing user-centric interfaces and fostering trust. Research should delve into human-machine interaction dynamics to optimize the user experience and facilitate seamless integration into existing transportation ecosystems.

Against this backdrop, this study aims to conduct a comprehensive bibliometric analysis of publications related to autonomous driving systems. By examining publication trends, thematic concentrations, global perspectives, and key contributors, the study seeks to elucidate the evolving research landscape and identify emerging research trajectories. Through insights from this analysis, stakeholders can inform evidence-based decision-making, prioritize research investments, and foster collaborative initiatives to accelerate the responsible development and deployment of autonomous driving technologies.

2 Methodology

This paper employs a comprehensive bibliometric approach to analyze the trends and characteristics of publications related to autonomous driving systems. The methodology consists of several key steps: data collection, analysis, and visualization.

2.1 Data Collection

The primary data source for this study is the Scopus database, which provides a vast collection of scholarly publications across various disciplines. A search query using the term "autonomous driving systems" within article titles was executed to retrieve relevant documents. The search encompassed publications from 2002 to May 2024, capturing a substantial portion of the scholarly output in this research domain.

The search query utilized specific keywords, such as "autonomous driving systems" to ensure comprehensive coverage of relevant literature. Furthermore, filtering conditions were applied to include only peer-reviewed journal articles, conference papers, and book chapters, ensuring the selection of high-quality scholarly works relevant to the research objectives.

2.2 Analysis

The analysis begins with exploring publication trends over the specified period, aiming to identify patterns and dynamics in scholarly output related to autonomous driving systems. The number of publications per year is examined to discern growth trajectories and significant milestones in the field's development. Additionally, the distribution of publication types (e.g., conference papers, peer-reviewed articles, book chapters) and subject areas is analyzed to understand the dissemination practices and interdisciplinary nature of autonomous driving systems research.

2.3 Visualization

To enhance understanding and engagement, we employ visual representations, including figures and network visualizations, to effectively present the findings of the bibliometric analysis [11]. Figures such as publication trends, distribution by publication type, country contributions, organizational affiliations, and top researchers offer insights into various aspects of autonomous driving systems research [12]. Network visualizations, generated using VOSviewer 1.6.19, facilitate the exploration of thematic clusters and co-occurrence patterns within scholarly publications, providing a nuanced understanding of research themes and their interrelationships [13].

2.4 Interpretation

The bibliometric analysis results are presented and interpreted to provide a deeper understanding of the key trends, emerging research themes, and significant contributors within the autonomous driving systems research landscape [14]. This interpretation encompasses discussions on technological advancements, interdisciplinary collaboration, global perspectives, thematic areas, and temporal dynamics, offering valuable insights for researchers, policymakers, and industry stakeholders [15].

2.5 Stages of Bibliometric Analysis

The stages of the bibliometric analysis of this study are shown in Figure 1.

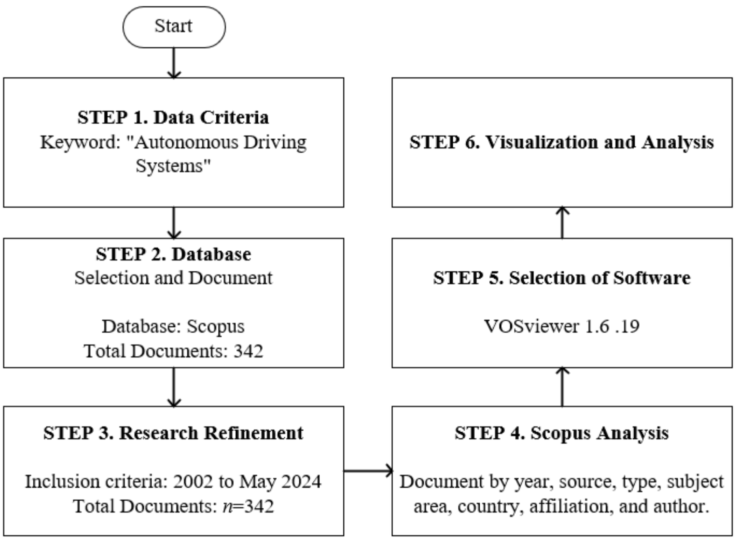

Figure 1. Stages of bibliometric analysis

3 Results

The Results section may be divided into subsections. It should describe the results concisely and precisely, provide their interpretation, and draw possible conclusions from the results.

3.1 Exploring Trends and Characteristics of Publications on Autonomous Driving Systems

This analysis provides a comprehensive bibliometric overview of research trends in the "autonomous driving systems" field based on data from the Scopus database. From 2002 to May 2024, 342 documents were identified using the search term "autonomous driving systems" within article titles.

Figure 2 illustrates the publication trends over the specified period. The first document indexed on this topic appeared in 2002. From 2002 to 2016, the number of publications fluctuated modestly between 1 and 3 papers annually, reflecting a period of developing interest and foundational research in the field. A marked increase in the number of publications began in 2017. This surge signifies a growing academic and industrial interest in autonomous driving technologies, likely driven by advancements in artificial intelligence, machine learning, and sensor technologies, and increased funding for research and development in this area. The publication count continued to rise significantly in the subsequent years, peaking in 2023 with 78 documents. This peak represents

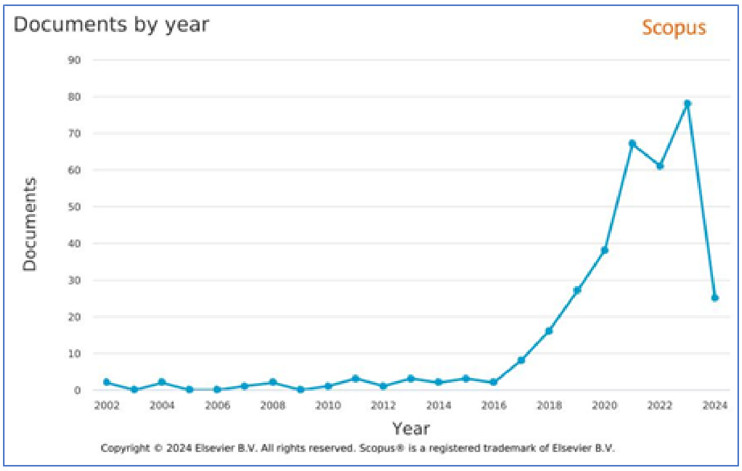

Figure 2. Publication trends about autonomous driving systems
Source: Scopus.com (2024)

the highest annual output within the study period, indicating a robust and expanding research community focused on autonomous driving systems.

The initial phase (2002-2016), characterized by low publication counts, suggests exploratory and foundational research activities. The fluctuations in publication numbers during these years could be attributed to the developmental and experimental nature of the researched technologies. The period from 2017 onward marks a transition into more extensive research and development efforts. The significant rise in publications corresponds with technological advancements and a broader acceptance of autonomous driving systems in both academic and commercial spheres. Factors contributing to this growth include advances in AI and machine learning, which are critical for developing robust autonomous driving algorithms. Then, improvements in sensor technologies, such as LIDAR, radar, and camera systems, enhance the perception capabilities of autonomous vehicles. They then increased investment from the automotive industry and governmental bodies, aiming to push the adoption of autonomous vehicles. Then, many interdisciplinary research efforts combine expertise from fields such as computer science, engineering, robotics, and transportation systems.

The bibliometric analysis of "autonomous driving systems" publications from 2002 to May 2024 highlights a significant growth trajectory in this research domain. The substantial increase in publications since 2017 underscores this field's dynamic and rapidly advancing nature, driven by technological innovations and growing interdisciplinary collaborations. As the research community continues to address critical challenges, the impact and adoption of autonomous driving systems are poised to expand further, shaping the future of transportation. This analysis provides valuable insights into the historical and emerging trends in autonomous driving systems research, serving as a foundational reference for future studies and strategic planning in this transformative field.

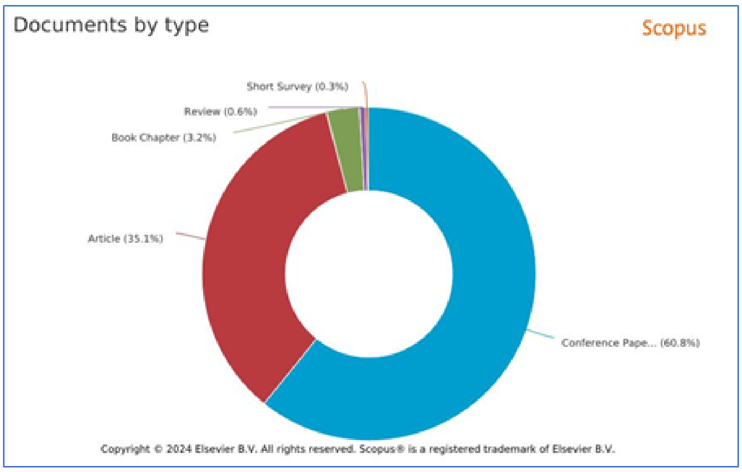

Figure 3. Publication by type
Source: Scopus.com (2024)

Figure 3 reveals the predominance of various publication types within the dataset. The analysis categorizes the publications into five types: conference papers, peer-reviewed articles, book chapters, reviews, and short surveys. Conference papers constitute the largest portion of the publications, representing 60.8% (208 documents) of the total. This high percentage highlights the importance of conferences as a primary venue for disseminating research findings in autonomous driving systems. Conferences provide a platform for rapidly sharing cutting-edge developments, fostering immediate feedback, and encouraging research collaborations. Peer-reviewed articles are the second most common type, comprising 35.1% (120 documents) of the total publications. These articles typically undergo rigorous review processes, ensuring the quality and reliability of the research. The substantial proportion of peer-reviewed articles indicates a strong emphasis on validated, high-quality research contributions within the academic community. Only 3.2% (11 documents) of book chapters provide in-depth discussions on specific aspects of autonomous driving systems. These chapters often provide a broader context and integrate various research findings, making them valuable resources for understanding complex topics.

The predominance of conference papers underscores the research's dynamic and fast-paced nature in autonomous driving systems. Conferences are critical venues for presenting preliminary results, innovative ideas, and technological advancements. This trend reflects the research community's preference for rapid dissemination and engagement with the latest developments. The substantial share of peer-reviewed articles highlights the maturity and academic rigor within the field. These articles contribute to building a robust and credible knowledge base essential for advancing autonomous driving technologies. The rigorous review process ensures that only high-quality and impactful research is published. Although limited, the presence of book chapters indicates an interest in providing comprehensive coverage and educational resources. These chapters often explore theoretical foundations, practical implementations, and interdisciplinary connections, making them valuable for researchers and practitioners.

Understanding the distribution of publication types provides valuable insights into the field's research dynamics and dissemination practices. It highlights the importance of conferences for real-time knowledge exchange and the role of peer-reviewed articles in maintaining research quality. As the field continues to evolve, increasing the proportion of review articles and short surveys could enhance knowledge synthesis and the exploration of new research avenues.

As illustrated in Figure 3, the dominance of conference papers in the publication landscape of autonomous driving systems research is influenced by several technological, policy, and market factors that drive research trends. Autonomous driving systems research's dynamic and fast-paced nature necessitates rapidly disseminating new findings and technological advancements. Conferences provide researchers with a real-time platform to share preliminary results, innovative ideas, and experimental findings, facilitating immediate feedback and collaboration within the research community. As technological innovations continue to drive the field forward, conferences are critical venues for showcasing cutting-edge developments and fostering interdisciplinary exchanges. Autonomous driving systems research is inherently interdisciplinary, drawing expertise from computer science, engineering, robotics, and transportation systems. Conferences offer a unique opportunity for researchers from diverse backgrounds to exchange ideas and collaborate on complex research problems. The interdisciplinary nature of conferences aligns with the multifaceted challenges of autonomous driving systems, allowing researchers to address technical, social, and policy issues collaboratively.

Governmental agencies and research institutions often provide funding and grants to support research projects in autonomous driving systems. Conferences serve as venues for researchers to present their work and showcase the outcomes of funded projects, fulfilling reporting requirements and demonstrating the impact of public investments in research. The emphasis on conference presentations may be driven by the need to promptly disseminate research findings to funding agencies and stakeholders, thereby influencing publication practices within the field.

As policymakers and regulatory bodies play an increasingly important role in shaping the development and deployment of autonomous driving technologies, conferences provide researchers with opportunities to engage with policymakers, industry stakeholders, and regulatory experts. Presenting research findings at conferences allows researchers to contribute to policy discussions, share insights on regulatory challenges, and advocate for evidence-based policy decisions. The prominence of conference papers may reflect researchers' efforts to actively participate in policy dialogues and influence regulatory frameworks governing autonomous driving systems.

Collaboration with industry partners is integral to advancing autonomous driving systems research and accelerating technology transfer from academia to industry. Conferences serve as platforms for researchers to showcase their work to industry stakeholders, establish collaborative relationships, and explore commercialization and technology transfer opportunities. The prevalence of conference papers may reflect researchers' motivations to disseminate their findings to potential industry partners and attract industry funding or support for future research endeavors. The competitive landscape of the autonomous driving industry drives researchers to rapidly disseminate their findings and maintain visibility within the research community. Conferences offer researchers a platform to present their work to a broad audience of peers, competitors, and industry observers, thereby enhancing their visibility and reputation within the field. The emphasis on conference presentations may be driven by researchers' desire to stay competitive and position themselves as leaders in the rapidly evolving field of autonomous driving systems.

Figure 4 showcases the distribution of publications across various fields, highlighting the multidisciplinary scope of autonomous driving systems research. The primary disciplines include computer science, engineering, mathematics, physics and astronomy, social sciences, decision sciences, and others.

Computer science has the largest share of publications, 38.3% (274 documents). This prominence underscores the critical role of computational technologies, algorithms, artificial intelligence, and machine learning in developing and enhancing autonomous driving systems. Research in this field focuses on software development, data processing, system integration, and real-time decision-making processes. Accounting is the second largest contributor, or 29.9% (214 documents). Engineering covers various topics, including system design, robotics, control systems, and sensor technologies. Engineering research addresses the practical and technical challenges of deploying autonomous vehicles, such as ensuring reliability, safety, and efficiency. Mathematics represents 10.1% (72 documents) of the theoretical underpinnings of autonomous driving systems. Research in this area includes algorithm development, optimization techniques, statistical analysis, and modeling of complex systems. Mathematical approaches are essential for improving the accuracy and performance of autonomous systems. 4.9% (35 documents) of physics and astronomy contribute to understanding environmental interactions and sensor technologies. Research in this field can involve the study of physical principles that underpin sensor operations, including LIDAR, radar, and optical systems.

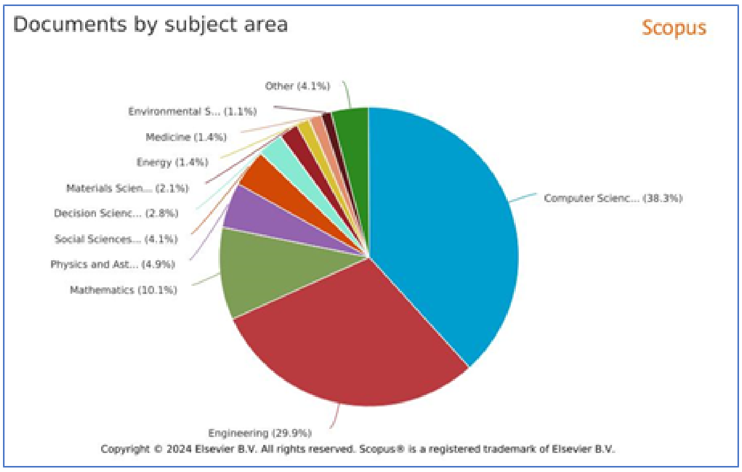

Figure 4. Publication by subject area
Source: Scopus.com (2024)

Comprising 4.1% (29 documents), the social sciences explore the human and societal impacts of autonomous driving systems. This research includes studies on user acceptance, ethical considerations, regulatory frameworks, and the societal implications of widespread autonomous vehicle adoption. Making up 2.8% (20 documents), decision sciences focus on decision-making processes, risk assessment, and operational strategies for autonomous driving systems. This field helps optimize route planning, traffic management, and the integration of autonomous vehicles into existing transportation networks. With 2.1% (15 documents), materials science research involves the development of materials for sensors, vehicle components, and energy storage systems. Advancements in this field can lead to more durable, efficient, and cost-effective autonomous vehicles. Energy and medicine, each constituting 1.4% (10 documents), explore the energy efficiency of autonomous vehicles and their potential applications in medical transportation and healthcare logistics. 1.1% (8 documents) of environmental science research examines the ecological impacts of autonomous vehicles, including their potential to reduce emissions and improve urban air quality. The remaining 4.1% of publications are spread across business, management and accounting, biochemistry, genetics and molecular biology, chemistry, chemical engineering, psychology, neuroscience, agricultural and biological sciences, economics, econometrics and finance, pharmacology, toxicology, and pharmaceutics. These fields contribute unique perspectives, such as the economic implications of autonomous vehicles, human factors in system design, and the integration of autonomous systems in various biological and chemical processes.

The wide distribution of publications across various disciplines highlights the inherently interdisciplinary nature of autonomous driving systems research. Collaboration between fields such as computer science, engineering, and social sciences is essential for addressing autonomous vehicles' multifaceted challenges and opportunities. The significant contributions from fields like social sciences and decision sciences are not just indicators of growing recognition but also emphasize the profound societal impact of autonomous driving systems. Understanding user behavior, ethical considerations, and regulatory environments is crucial—it's a responsibility we all share for the successful integration of these technologies. The presence of publications in less dominant fields such as energy, medicine, and environmental science is more than just a sign of emerging research areas. Still, it's also a beacon of hope for new insights and applications for autonomous driving systems. For example, exploring energy-efficient technologies and the role of autonomous vehicles in healthcare logistics can lead to not just innovative solutions but a whole new world of possibilities.

The bibliometric analysis of disciplinary distribution in "autonomous driving systems" publications reveals a diverse and multidisciplinary research landscape. The dominance of computer science and engineering reflects the field's technological foundations, while significant contributions from mathematics, social sciences, and other disciplines underscore the comprehensive approach required to advance autonomous driving systems. This interdisciplinary collaboration is essential for addressing the complex challenges of autonomous driving, from technical development to societal integration. As the field continues to evolve, fostering cross-disciplinary research will be crucial for driving innovation and ensuring the successful adoption of autonomous driving systems across various sectors.

The distribution of publications across diverse disciplines in autonomous driving systems research reflects the multifaceted nature of this technology and its broader societal implications. Technological advancements, policy considerations, and market dynamics intersect to shape research trends, drive innovation, inform policy decisions, and guide business strategies in the rapidly evolving field of autonomous driving. Collaboration across disciplines is essential for addressing complex challenges and unlocking the full potential of autonomous vehicle technology to transform transportation and improve quality of life.

Figure 5 highlights the five most trusted platforms for publishing research on autonomous driving systems. These platforms include journals and conference proceedings, indicating the importance of both outlets in this research domain. *IEEE Transactions on Intelligent Transportation Systems* is a leading publication venue in the field, known for its high-quality, peer-reviewed articles. It covers various topics related to intelligent transportation, including autonomous driving systems. The journal's rigorous review process and high impact factor make it a preferred choice for researchers aiming to publish significant advancements and comprehensive studies.

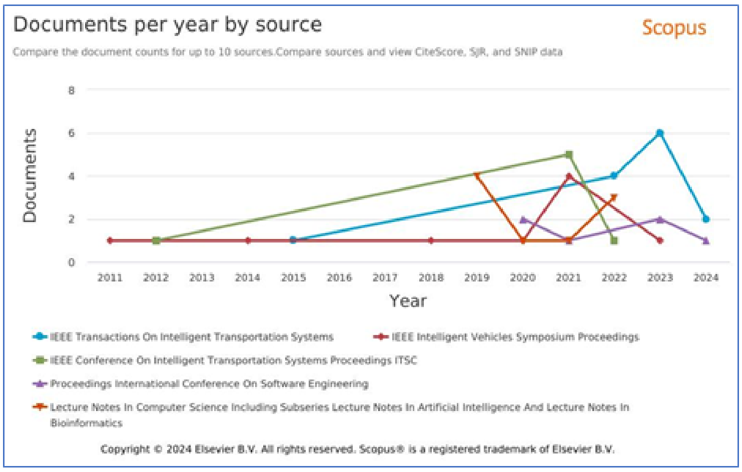

Figure 5. Top platforms

Source: Scopus.com (2024)

As a premier conference in the field, the *IEEE Intelligent Vehicles Symposium Proceedings* provides a dynamic platform for presenting the latest research findings. The conference proceedings from this symposium are highly regarded for their cutting-edge contributions and timely dissemination of innovative research. The seminar fosters interaction among researchers, industry professionals, and policymakers, promoting collaboration and exchanging ideas. *Lecture Notes in Computer Science Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes In Bioinformatics* is renowned for its comprehensive coverage of computer science topics, including autonomous driving systems. It publishes proceedings from various conferences, offering diverse research papers that address both theoretical and practical aspects of autonomous driving technologies. Including subseries on artificial intelligence and bioinformatics highlights the interdisciplinary nature of the research.

The IEEE Conference on Intelligent Transportation Systems Proceedings (ITSC) is another critical venue for publishing research on intelligent transportation systems, including autonomous vehicles. The conference attracts high-quality submissions and provides a forum for presenting state-of-the-art research, discussing emerging trends, and exploring future directions in the field.

Proceedings of the International Conference on Software Engineering focus on software engineering, which is critical for developing and implementing autonomous driving systems. The proceedings include papers on software design, development, testing, and maintenance, all essential for creating reliable and efficient autonomous driving technologies. The conference's interdisciplinary nature promotes the integration of software engineering principles with autonomous driving research.

The prominence of IEEE journals and conferences indicates the high standards of quality and impact associated with these platforms. Researchers prefer these venues due to their rigorous peer-review processes, high citation rates, and broad visibility within the academic and professional communities. Platforms like *Lecture Notes in Computer Science and the International Conference on Software Engineering* underscore the interdisciplinary nature of autonomous driving systems research. These platforms facilitate collaboration among computer scientists, engineers, software developers, and other specialists, promoting comprehensive and integrative approaches to solving complex challenges in autonomous driving. Conference proceedings are particularly valued for their ability to disseminate innovative research findings quickly. The rapid publication cycle of conferences allows researchers to share their latest discoveries and receive timely feedback, which is crucial in a fast-evolving field like autonomous driving. The top platforms cover a broad spectrum of topics related to autonomous driving systems, from theoretical foundations and algorithm development to practical implementations and real-world applications. This comprehensive coverage ensures that researchers have access to a wide range of knowledge and perspectives, fostering a holistic understanding of the field.

The bibliometric analysis of top publishing platforms for "autonomous driving systems" research reveals a strong preference for high-quality, impactful journals and conferences. *IEEE Transactions on Intelligent Transportation Systems*, *IEEE Intelligent Vehicles Symposium Proceedings*, *Lecture Notes in Computer Science*, *IEEE Conference on Intelligent Transportation Systems Proceedings*, and *Proceedings of the International Conference on Software Engineering* are the most trusted venues for publishing research in this domain. These platforms are crucial in advancing the field by ensuring rigorous peer review, fostering interdisciplinary collaboration, and facilitating the rapid dissemination of innovative research. As autonomous driving systems evolve, these top publishing platforms will remain instrumental in shaping the future of intelligent transportation and autonomous vehicle technologies.

3.2 Global Perspectives on Researching Autonomous Driving Systems

Figure 6 presents the ranking of countries based on the number of publications related to autonomous driving systems. The leading countries include China, the United States, Japan, South Korea, France, India, Germany, Italy, Canada, and Singapore.

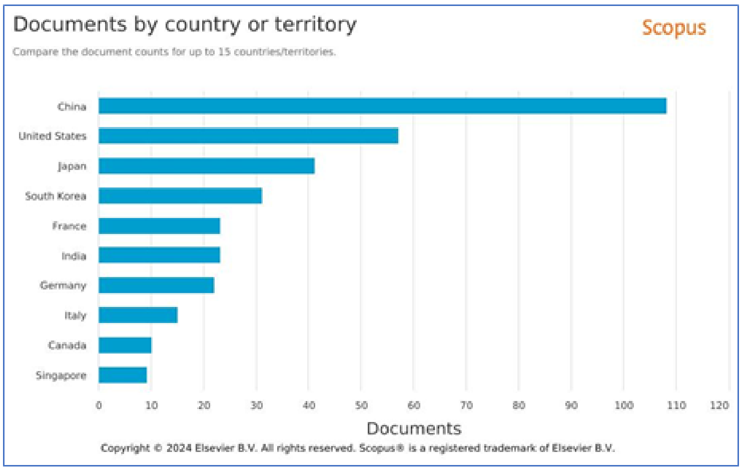

Figure 6. Publication by country
Source: Scopus.com (2024)

China leads the list as the top contributor to research on autonomous driving systems. This dominance reflects significant investment in research and development by both the government and private sector. China's focus on advancing autonomous driving technology aligns with its broader goals of becoming a global leader in artificial intelligence and smart transportation. The country's large volume of publications underscores its commitment to innovation and technological advancement in this field. The United States ranks second, indicating a robust research environment supported by leading universities, research institutions, and technology companies. The U.S. has been at the forefront of developing foundational technologies for autonomous driving, including AI, machine learning, and sensor technologies. The strong collaboration between academia and industry in the U.S. contributes to a high volume of impactful research outputs. Positioned third, Japan has a long history of excellence in automotive engineering and robotics, translating into significant contributions to autonomous driving research. Japanese research emphasizes precision engineering, safety, and the integration of autonomous systems with existing transportation infrastructure. South Korea ranks fourth, reflecting its strong emphasis on information technology and electronics innovation. The country's major technology firms and research institutions are actively developing autonomous driving technologies, supported by government initiatives to foster innovation in smart mobility.

France and India, in fifth place, have shown considerable interest in autonomous driving systems. France's contributions are driven by its robust automotive industry and research in artificial intelligence. At the same time, India's growing focus on technology and innovative city initiatives has led to increased research output in this area. Its world-renowned automotive industry underpins Germany's contributions to the sixth ranking. German research in autonomous driving focuses on engineering excellence, reliability, and integration with advanced manufacturing technologies. Collaborative efforts between automotive giants and research institutions are vital to Germany's research landscape. Italy's contributions, ranked seventh, emphasize advanced engineering and design. Italian researchers are involved in various aspects of autonomous driving, including system design, human-machine interaction, and regulatory frameworks. Canada ranks eighth in terms of its robust research community focused on AI and machine learning, which are critical for autonomous driving systems. Canadian institutions are known for their innovative research and collaboration with industry partners, contributing to the global advancement of autonomous vehicle technologies. Positioned ninth, Singapore's contributions are driven by its strategic focus on becoming a smart nation. The city-state invests heavily in the research and development of autonomous driving technologies, aiming to enhance urban mobility and reduce congestion in densely populated areas.

The diverse geographical distribution of research output indicates a global effort to advance autonomous driving technologies. Leading countries are not only competing but also collaborating through international partnerships and research networks, accelerating the pace of innovation. The high volume of research from China, the United States, and other leading countries reflects significant policy support and investment in R&D. Government initiatives, funding programs, and strategic industry partnerships are crucial drivers of research output in these countries. Countries like China and the United States, with their vast resources and technological capabilities, are poised to lead in developing and deploying autonomous driving systems. Their research outputs set the pace for global advancements and standards in this field. Countries such as India and Singapore, while newer to the field, are emerging as significant contributors. Their increasing research output indicates a growing interest and capability in developing autonomous driving technologies, supported by favorable policy environments and investments in smart infrastructure.

The bibliometric analysis of country contributions to "autonomous driving systems" research highlights a dynamic and competitive global landscape. China and the United States lead research output, reflecting their strong focus on innovation and technological advancement. Other countries, including Japan, South Korea, and Europe, also play crucial roles, contributing unique strengths and perspectives to the field. This geographical diversity fosters a rich, collaborative environment essential for addressing the complex challenges of autonomous driving. As the field continues to evolve, the contributions from these leading countries will be instrumental in shaping the future of autonomous transportation and innovative mobility solutions worldwide.

The ranking of countries based on publications related to autonomous driving systems reflects the complex interplay of technological, policy, and market factors driving research trends worldwide. Countries with solid R&D ecosystems, supportive regulatory environments, and competitive automotive industries are well-positioned to lead in autonomous vehicle innovation and commercialization. International collaboration, standards development, and market dynamics shape the trajectory of autonomous driving systems research, paving the way for the future of transportation and mobility.

Figure 7 presents the top organizations based on the number of publications related to autonomous driving systems. These organizations include universities, research institutes, and governmental bodies, indicating this field's diverse range of contributors. Leading the list, Tsinghua University in China and the Research Organization of Information and Systems National Institute of Informatics in Japan are at the forefront of autonomous driving systems research. Tsinghua University's contributions are driven by its strong engineering programs and extensive research facilities, which focus on various aspects of autonomous driving technologies. Similarly, the National Institute of Informatics leverages its information systems and AI expertise to contribute significant research outputs. Technische Universität München (TUM) and the University of Chinese Academy of Sciences share the second position. TUM in Germany is renowned for its engineering excellence and interdisciplinary research in autonomous systems, robotics, and AI.

The University of Chinese Academy of Sciences supports a wide range of scientific research, contributing to advancements in autonomous driving through its strong emphasis on innovation and collaboration across disciplines. Ranking third, Nanyang Technological University in Singapore has established itself as a critical player in the field. The university's robust research initiatives in AI, robotics, and intelligent transportation systems drive its contributions to autonomous driving research. NTU's strategic location in a city-state aiming to become a global leader in intelligent mobility further enhances its research impact.

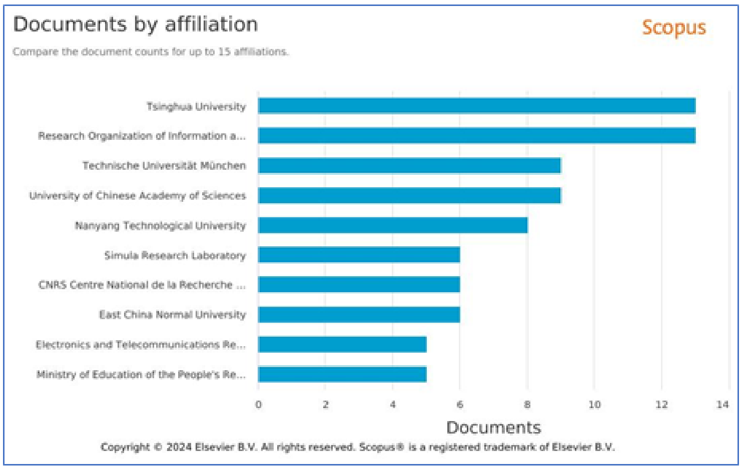

Figure 7. Publication by affiliation

Source: Scopus.com (2024)

Fourth, Simula Research Laboratory, CNRS Centre National de la Recherche Scientifique, and East China Normal University are positioned. Simula Research Laboratory in Norway focuses on computational science and engineering, contributing valuable insights into the software and algorithmic aspects of autonomous driving. CNRS in France is a major research organization that supports diverse studies in autonomous systems through its national network of laboratories. East China Normal University in China emphasizes interdisciplinary research, combining strengths in computer science, engineering, and applied mathematics. Electronics and Telecommunications Research Institute (ETRI) and Ministry of Education of the People's Republic of China organizations rank fifth. ETRI in South Korea is a leading research institute focusing on electronics, telecommunications, and IT, playing a crucial role in developing core technologies for autonomous driving. The Ministry of Education of the People's Republic of China oversees numerous research initiatives across Chinese universities and institutes, supporting the national agenda of advancing autonomous driving technologies through policy and funding.

The leading organizations, such as Tsinghua University, TUM, and NTU, are known for their research excellence and innovative approaches. Their contributions underscore the importance of institutional support, advanced research facilities, and interdisciplinary collaboration in driving breakthroughs in autonomous driving systems. The geographical diversity of these institutions highlights the global nature of autonomous driving research. Institutions from Asia, Europe, and North America are pivotal in fostering international collaboration and knowledge exchange. This global network is essential for addressing the complex, multifaceted challenges associated with autonomous driving technologies. Prominent organizations often align their research focus with national and regional priorities. For instance, Chinese institutions benefit from strong governmental support for AI and intelligent transportation, while European institutions emphasize engineering excellence and sustainable mobility. This strategic alignment enhances the impact and relevance of their research outputs. Many leading organizations adopt interdisciplinary approaches, integrating computer science, engineering, AI, and other fields to develop comprehensive solutions for autonomous driving. This holistic perspective is crucial for addressing the technical, regulatory, and societal aspects of deploying autonomous vehicles.

The bibliometric analysis of organizational contributions to "autonomous driving systems" research highlights the critical role of leading universities and research institutes in advancing this field. Tsinghua University, the National Institute of Informatics, TUM, and NTU, among others, are key players driving innovation and research excellence. These organizations' contributions reflect the importance of institutional support, interdisciplinary collaboration, and strategic alignment with national and regional priorities. As autonomous driving technologies continue to evolve, the ongoing efforts of these leading institutions will be instrumental in shaping the future of intelligent transportation systems and autonomous vehicles on a global scale.

A combination of technological excellence, policy support, and market opportunities drives the prominence of organizations in autonomous driving systems research. Academic institutions like Tsinghua University, TUM, and the University of Chinese Academy of Sciences contribute to advancing autonomous vehicle technologies through their research capabilities, interdisciplinary collaboration, and industry partnerships. Government initiatives, regulatory frameworks, and industry alliances shape the research landscape and drive innovation in autonomous driving systems, positioning organizations at the forefront of this transformative field.

Figure 8 and Table 1 list the top researchers based on the number of publications related to autonomous driving systems. These researchers come from diverse geographical locations and institutions, indicating a global interest and collaboration in this field. Leading the list, Paolo Arcaini from the Research Organization of Information and Systems, National Institute of Informatics, Tokyo, Japan, has made significant contributions to autonomous driving systems. His research focuses on formal methods, verification, and validation of autonomous systems, ensuring their reliability and safety. Fuyuki Ishikawa, also from the Research Organization of Information and Systems, National Institute of Informatics, Tokyo, Japan, ranks second. His work complements Arcaini's, focusing on model-driven development and automated testing of autonomous systems, which contribute to the robustness and efficiency of these technologies. Sharing the third position, Florian Hauer from Technische Universität München (TUM), Munich, Germany, and Yuan Zhou from the School of Computer Science and Engineering, Singapore City, Singapore, are notable for their contributions. Hauer's research includes system architecture and real-time data processing for autonomous vehicles, while Zhou focuses on machine learning algorithms and sensor integration.

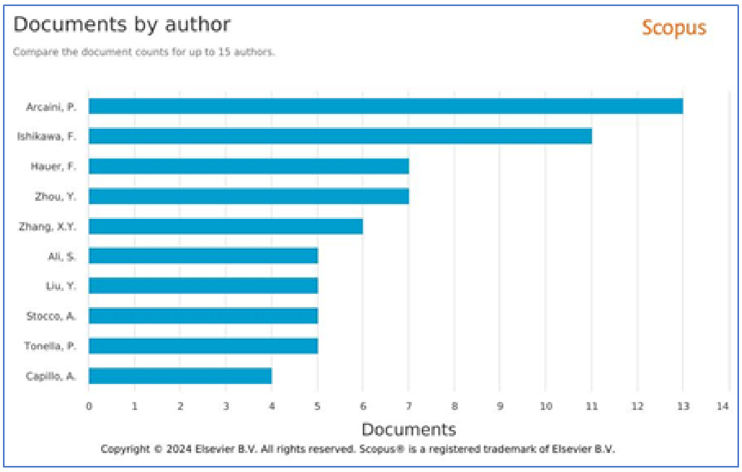

Figure 8. Publication by author
Source: Scopus.com (2024)

Table 1. Top 10 Researchers in autonomous driving systems

No.	Researcher	Affiliation	Publications
1	Paolo Arcaini	Research Organization of Information and Systems National Institute of Informatics, Tokyo, Japan	[16–27]
2	Fuyuki Ishikawa	Research Organization of Information and Systems National Institute of Informatics, Tokyo, Japan	[16–21, 24–27]
3	Florian Hauer	Technische Universität München (TUM), Munich, Germany	[24, 28–31]
4	Yuan Zhou	School of Computer Science and Engineering, Singapore City, Singapore	[32–38]
5	Xiaoyi Zhang	University of Science and Technology Beijing, China	[17–19, 21, 24]
6	Shaukat Ali	OsloMet—StorbyUniversitetet, Oslo, Norway	[24, 26, 27, 39, 40]
7	Yang Liu	Nanyang Technological University, Singapore	[33, 35–38]
8	Andrea Stocco	Technische Universität München, Munich, Germany	[41–45]
9	Paolo Tonella	Università della Svizzera italiana, Lugano, Switzerland	[41–45]
10	Antonino Capillo	Sapienza Università di Roma, Rome, Italy	[46–48]

Ranking fourth, Xiaoyi Zhang from the University of Science and Technology Beijing, China, has contributed extensively to developing intelligent control systems and advanced driver assistance systems (ADAS), enhancing the functionality and safety of autonomous vehicles. Shaukat Ali, Yang Liu, Andrea Stocco, and Paolo Tonella are researchers who share the fifth position, each bringing unique expertise. Shaukat Ali, from OsloMet—StorbyUniversitetet, Oslo, Norway, focuses on software engineering and testing methodologies for autonomous systems. Yang Liu, from Nanyang Technological University, Singapore, is known for his work on cybersecurity and the reliability of autonomous driving systems. Andrea Stocco from Technische Universität München, Munich, Germany, and Paolo Tonella from Università della Svizzera Italiana, Lugano, Switzerland, contribute to software engineering and testing, ensuring the robustness and security of autonomous systems. Ranked sixth, Antonino Capillo from Sapienza Università di Roma, Rome, Italy, along with researchers like E. De Santis, E. Ferrandino, T. Laurent, C. Liu, A. Pretschner, A. Rizzi, J. Sifakis, A. Ventresque, and T. Zhang, represent a diverse group of contributors. Their research spans various aspects of autonomous driving, including control systems, software verification, and algorithm development.

The leading researchers come from diverse fields, such as computer science, engineering, and software development. This interdisciplinary expertise is crucial for addressing the multifaceted challenges of autonomous driving systems, from algorithm development and system integration to safety verification and cybersecurity. The geographical diversity of these researchers underscores the global collaboration in autonomous driving systems. Researchers from Asia, Europe, and North America actively contribute, facilitating the exchange of knowledge and innovations across borders. A significant portion of the leading researchers' work focuses on the safety and reliability of autonomous driving systems. This includes the development of formal methods, verification and validation techniques, and advanced testing methodologies to ensure that autonomous vehicles can operate safely in diverse and complex environments. The research outputs of these leading researchers drive technological innovation in autonomous driving systems. Their work on machine learning, sensor technologies, and real-time data processing contributes to the continuous improvement and sophistication of autonomous vehicle capabilities.

The bibliometric analysis of leading researchers in "autonomous driving systems" research highlights the contributions of key individuals and their institutions. Researchers like Paolo Arcaini, Fuyuki Ishikawa, Florian Hauer, and Yuan Zhou are at the forefront of advancing this field, supported by a global network of experts. Their interdisciplinary expertise, focus on safety and reliability, and commitment to technological innovation are critical for developing and deploying autonomous driving systems. As the field evolves, the contributions of these leading researchers will continue to shape the future of autonomous transportation and intelligent mobility solutions worldwide.

Top researchers in autonomous driving systems drive technological innovation, shape policy agendas, and address market demands through their specialized expertise, collaborative research efforts, and contributions to safety, reliability, and performance standards. Their work advances the state-of-the-art in autonomous driving technologies. It fosters interdisciplinary collaboration, knowledge exchange, and technology transfer across academia, industry, and government sectors, positioning them as key influencers in the global autonomous vehicle ecosystem.

3.3 Thematic Areas

Bibliometric analysis, a methodological approach employed to evaluate scholarly publications quantitatively, has been pivotal in elucidating the thematic landscape surrounding "autonomous driving systems". Utilizing VOSviewer 1.6.19, this analysis has delineated seven distinct clusters encapsulating various research themes within the domain. The bibliometric analysis delineated seven discernible clusters, each representing a unique thematic concentration within autonomous driving systems research (see Figure 9). These clusters, demarcated by distinct colors in the visual representations, offer insights into the field's prevalent research trajectories and focal points.

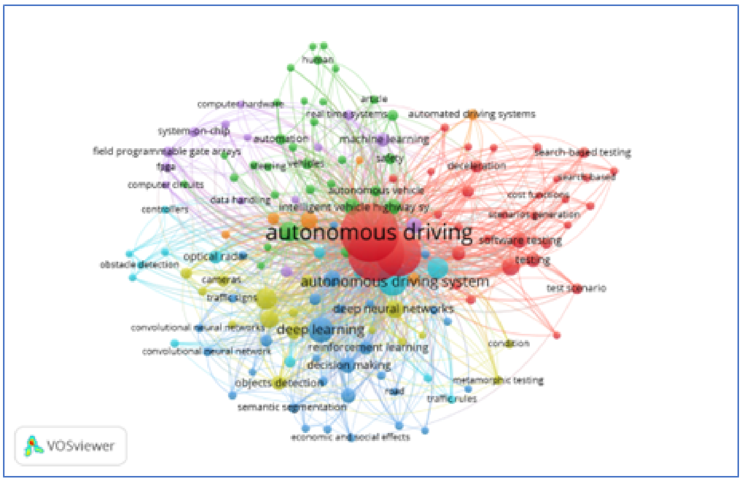

Figure 9. Network visualization

Source: VOSviewer 1.6.17 (2024)

Cluster 1 exhibits a thematic concentration characterized by pink/peach hues in the visualization. Research within this cluster likely revolves around specific aspects or subdomains of autonomous driving systems, potentially focusing on foundational technologies, such as sensor fusion or perception algorithms. Cluster 2, which is green-themed, likely encompasses research endeavors related to environmental sustainability, energy efficiency, or ecofriendly approaches within autonomous driving systems. This cluster may explore energy optimization, emission reduction, or green infrastructure integration. With a predominantly blue color scheme, Cluster 3 signifies a thematic area that possibly delves into safety and risk mitigation strategies within autonomous driving systems. Research topics within this cluster may include collision avoidance systems, risk assessment methodologies, or human-machine interaction for enhanced safety. The olive green Cluster 4 indicates research endeavors related to regulatory frameworks, legal implications, and policy considerations surrounding autonomous driving systems. This cluster may encompass studies on legislative frameworks, liability issues, or ethical dimensions pertinent to autonomous vehicle deployment. Cluster 5, which is purple/magenta-themed, likely encompasses research focusing on user experience, human factors, and the socio-cultural implications of autonomous driving systems. Topics within this cluster may span user acceptance, trust-building mechanisms, or the societal impacts of autonomous vehicle integration. Cluster 6, represented by cyan blue tones, may encapsulate research endeavors about vehicle-to-everything (V2X) communication, connectivity, and infrastructure requirements for autonomous driving systems. Topics within this cluster could include communication protocols, network optimization, or infrastructure deployment strategies. With an orange color scheme, Cluster 7 may represent a thematic concentration on technological innovation, R&D advancements, and emerging trends within autonomous driving systems. Research topics within this cluster may include breakthroughs in AI algorithms, novel sensor technologies, or next-generation autonomous vehicle architectures.

The following figures provide comprehensive network visualizations that offer deeper insights into the interconnectivity and co-occurrence patterns of research themes within each cluster. These visual representations elucidate the network dynamics, highlighting vital focal points, central themes, and interdisciplinary linkages within the autonomous driving systems research landscape.

The bibliometric analysis utilizing VOSviewer 1.6.19 has not just provided an understanding, but a unique and nuanced understanding of the thematic trajectories within autonomous driving systems research. By delineating seven distinct clusters and elucidating their respective thematic nuances through network visualizations, this analysis offers you, as researchers, policymakers, and industry stakeholders, valuable and exclusive insights to navigate and contribute to the evolving landscape of autonomous mobility.

Figure 10 presents an overlay visualization, offering crucial insights into the temporal dynamics of research themes within autonomous driving systems. Through the juxtaposition of bright/yellow-colored themes, indicative of recent research endeavors, and dark/purple-colored themes, representative of comparatively well-established research domains, this visualization facilitates a nuanced understanding of the evolving landscape of scholarly inquiry in this field.

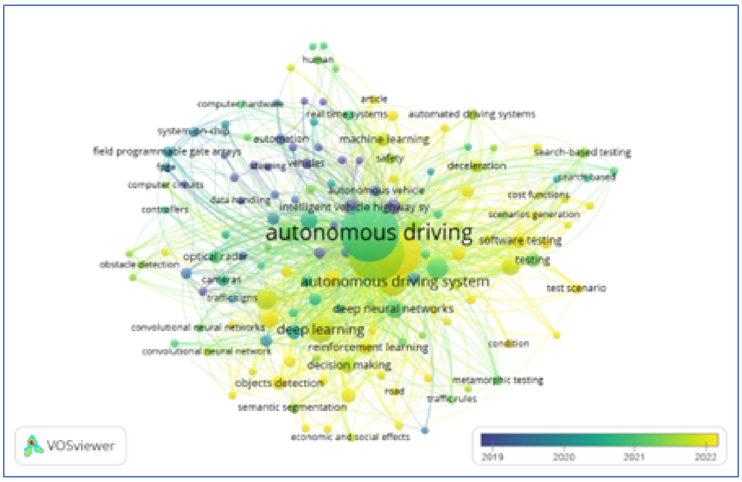

Figure 10. Overlay visualization
Source: VOSviewer 1.6.17 (2024)

Bright or yellow-colored themes within the overlay visualization serve as beacons, illuminating emerging areas of research interest within autonomous driving systems. These vibrant hues signify themes that have garnered increased scholarly attention in recent times, potentially reflecting the evolving technological landscape, emerging challenges, or paradigm shifts within the field. Researchers and stakeholders can leverage insights from these emergent themes to identify novel research opportunities, anticipate future trends, and align their research agendas with the evolving needs and demands of the autonomous driving systems domain. Conversely, dark or purple-colored themes denote research domains subject to relatively prolonged scholarly inquiry within the autonomous driving systems paradigm. These established themes likely represent foundational concepts, seminal research areas, or persistent, enduring challenges. While these established domains may continue to serve as cornerstones of autonomous driving systems research, their juxtaposition with emerging themes offers a holistic perspective on the temporal evolution of research priorities and trajectories within the field.

The overlay visualization highlights the dichotomy between established and emerging research themes and underscores the dynamic nature of scholarly inquiry within the autonomous driving systems domain. Temporal shifts, as evidenced by the transition from dark to bright hues, signify the evolutionary trajectory of research focus areas over time. By discerning these temporal trends, researchers can gain valuable insights into the trajectory of scholarly discourse, anticipate future research directions, and adapt their research agendas to align with the evolving needs and challenges of the autonomous driving systems landscape.

The insights from the overlay visualization carry profound implications for research, innovation, and strategic decision-making within the autonomous driving systems domain. By identifying emerging themes and delineating established research domains, stakeholders can foster interdisciplinary collaborations, prioritize research investments, and drive innovation to address the evolving complexities of autonomous mobility. Overlay visualization offers a compelling narrative of temporal trends and research trajectories within autonomous driving systems research, empowering stakeholders to navigate the ever-evolving landscape of autonomous mobility with foresight and precision.

Figure 11, a density visualization, is a pivotal tool for understanding the distribution and density of research themes within autonomous driving systems. By visualizing themes in varying shades of blue, ranging from faded to bold and even yellow, this visualization elucidates the extent of scholarly attention and research activity surrounding different thematic areas.

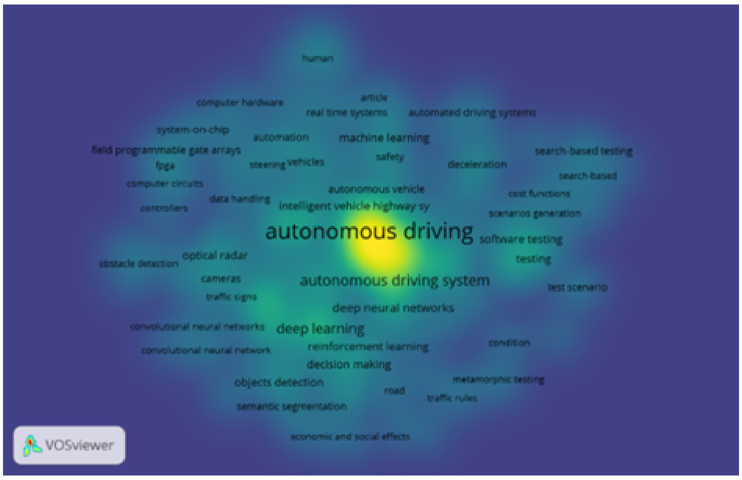

Figure 11. Density visualization
Source: VOSviewer 1.6.17 (2024)

The varying shades of blue within the density visualization offer valuable insights into the research density dynamics within autonomous driving systems. Themes depicted in faded or light blue hues signify areas with relatively sparse research activity, indicating limited scholarly attention or nascent research trajectories. Conversely, themes rendered in bold or even yellow hues represent areas of high research density, indicative of substantial scholarly interest and extensive research endeavors.

Faded or light blue-colored themes highlight potential research gaps or underexplored areas within the autonomous driving systems domain. These themes present opportunities for researchers to pioneer novel investigations, address overlooked challenges, and contribute to the expansion of knowledge boundaries within the field. Conversely, bold or yellow-colored themes denote research hotspots or focal points characterized by robust scholarly activity and a wealth of existing literature. Researchers can leverage insights from these densely researched areas to identify collaborative opportunities, build upon existing knowledge frameworks, and delve deeper into nuanced research questions.

Density visualization has profound implications for scholarly inquiry, innovation, and strategic decision-making within the autonomous driving systems domain. By identifying areas of sparse research activity, stakeholders can channel resources and expertise toward addressing critical research gaps, fostering interdisciplinary collaborations, and driving innovation in emerging domains. Conversely, recognizing densely researched areas enables researchers to navigate the existing literature landscape, identify niche research niches, and strategically position their research contributions within the broader scholarly discourse.

Figure 11's density visualization provides a nuanced depiction of research density dynamics within autonomous driving systems research. By elucidating areas of sparse research activity and highlighting research hotspots, this visualization empowers stakeholders to make informed decisions regarding research prioritization, resource allocation, and strategic research direction. Ultimately, it catalyzes the advancement of knowledge, innovation, and transformative impact within autonomous mobility's dynamic and multifaceted field.

Figure 12, a network visualization, provides a comprehensive overview of Cluster 1 within the thematic landscape of autonomous driving systems research. Marked by shades of pink/peach, this cluster encapsulates a constellation of research themes, each contributing uniquely to the overarching discourse within the field. Key themes identified within Cluster 1 encompass diverse topics, each bearing significance in shaping the trajectory of autonomous mobility research and development.

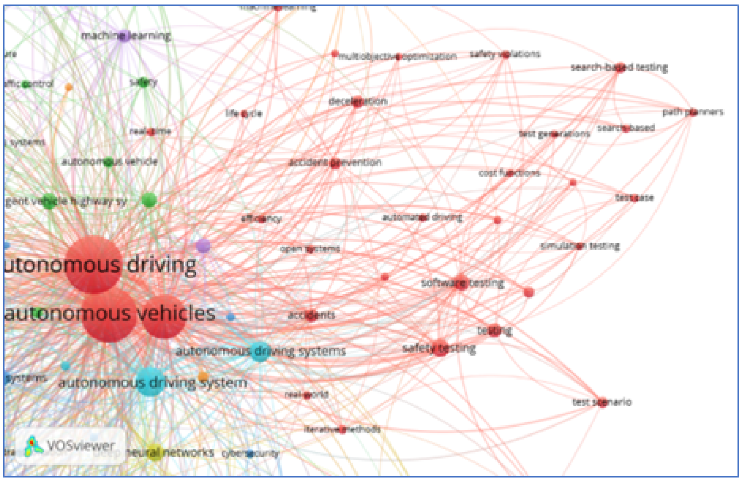

Figure 12. Cluster 1 – network visualization

Source: VOSviewer 1.6.17 (2024)

The significant themes are: Firstly, accident prevention. Research endeavors within this theme likely focus on developing robust strategies and technologies to mitigate the risk of accidents and enhance the safety of autonomous driving systems. This theme underscores the importance of safety considerations in designing and deploying autonomous vehicles, reflecting broader societal concerns regarding road safety and risk management. The results emphasize the imperative for continued efforts to enhance the safety features of autonomous vehicles, thereby instilling greater confidence in their widespread adoption and deployment.

Secondly, automated driving. Central to the ethos of autonomous mobility, automated driving represents a core theme within Cluster 1. Research within this domain likely explores advancements in automation technologies, algorithmic innovations, and sensor fusion methodologies aimed at enabling seamless autonomous driving experiences. This theme underscores the transformative potential of automation in revolutionizing transportation paradigms and reshaping urban mobility landscapes. By enabling seamless autonomous driving experiences, advancements in automated driving have the potential to redefine the future of transportation and contribute to sustainable urban development.

Thirdly, autonomous vehicles. As the focal point of research and innovation in autonomous mobility, autonomous vehicles constitute a pivotal theme within Cluster 1. Research endeavors within this domain likely span various topics, including vehicle dynamics, perception systems, navigation algorithms, and vehicle-to-infrastructure communication protocols. This theme reflects the interdisciplinary nature of autonomous vehicle research, encompassing contributions from engineering, computer science, and applied mathematics disciplines. Research within this theme lays the foundation for continued innovation and progress in the field by addressing the multifaceted challenges associated with autonomous vehicle development.

Fourth, combinatorial testing. With the complexity of autonomous driving systems, combinatorial testing emerges as a critical theme within Cluster 1. Research in this domain likely revolves around developing rigorous testing methodologies, simulation frameworks, and validation protocols to ensure the reliability and robustness of autonomous vehicle technologies. This theme underscores the importance of comprehensive testing regimes for verifying the functionality and safety of autonomous driving systems. The results emphasize the need for holistic approaches to address economic factors and ensure the long-term viability of autonomous mobility solutions.

Fifth, cost functions. It reflects economic considerations in autonomous mobility, and cost functions emerge as a significant theme within Cluster 1. Research endeavors within this domain likely delve into cost-benefit analyses, optimization algorithms, and economic modeling techniques to optimize resource allocation, enhance cost-effectiveness, and foster sustainable deployment strategies for autonomous driving systems. The results emphasize the need for holistic approaches to address economic factors and ensure the long-term viability of autonomous mobility solutions.

Sixth, efficiency. Efficiency emerges as a cross-cutting theme within Cluster 1, encompassing research efforts to improve autonomous vehicles' energy efficiency, resource utilization, and operational performance. This theme underscores the imperative of optimizing efficiency metrics, such as fuel consumption, route planning, and vehicle utilization rates, to maximize autonomous mobility solutions' economic and environmental sustainability. The results highlight the imperative of optimizing efficiency metrics to maximize the benefits of autonomous mobility solutions while minimizing their environmental footprint.

Seventh, safety testing. Complementing the overarching theme of accident prevention, safety testing represents a critical aspect of autonomous vehicle development within Cluster 1. Research endeavors within this theme likely focus on devising robust testing methodologies, simulation frameworks, and validation protocols to assess autonomous driving systems' safety performance and reliability under diverse operating conditions. The results underscore the proactive approach toward ensuring the safety and reliability of autonomous vehicle technologies through rigorous testing and validation practices.

Eighth, real-time. Real-time responsiveness emerges as a pivotal theme within Cluster 1, reflecting the difficulties of real-world deployment scenarios in autonomous driving systems. Research within this domain likely revolves around developing real-time control algorithms, sensor fusion techniques, and data processing frameworks to enable autonomous vehicles' swift and adaptive decision-making capabilities. This theme underscores the importance of real-time responsiveness in ensuring autonomous driving systems' safety, reliability, and efficiency in dynamic and unpredictable environments. The results emphasize the importance of real-time responsiveness in ensuring the safety, reliability, and efficiency of autonomous driving systems in real-world settings.

Nineth, multi-objective optimization. Given the multifaceted nature of autonomous mobility challenges, multi-objective optimization emerges as a salient theme within Cluster 1. Research endeavors within this domain likely focus on devising optimization algorithms, decision-making frameworks, and Pareto-efficient solutions to reconcile competing objectives, such as safety, efficiency, and comfort, in autonomous vehicle design and operation. This theme reflects the inherent trade-offs and complexities of optimizing autonomous driving systems for diverse performance metrics and stakeholder preferences. The results highlight the inherent trade-offs and complexities in optimizing autonomous driving systems for diverse performance metrics, underscoring the need for integrated approaches that account for stakeholders' diverse needs and priorities.

Figure 12's Network Visualization offers a rich tapestry of research themes within Cluster 1 of the autonomous driving systems landscape. Each theme, from accident prevention and automated driving to cost functions and multi-objective optimization, underscores the multifaceted nature of scholarly inquiry and technological innovation within the field. By elucidating key themes and their significance, this analysis provides valuable insights for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and shape the future of transportation.

Figure 13 presents a network visualization delineating Cluster 2 within the thematic framework of autonomous driving systems research. Marked by shades of green, this cluster encapsulates diverse research themes, each contributing uniquely to the multidimensional discourse surrounding autonomous mobility. Key themes identified within Cluster 2 underscore pivotal aspects of technological innovation, interdisciplinary collaboration, and societal implications within the field.

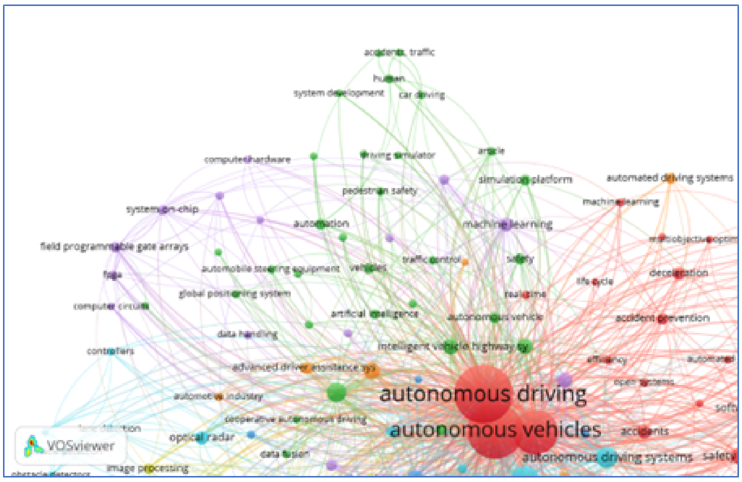

Figure 13. Cluster 2 – network visualization
Source: VOSviewer 1.6.17 (2024)

The key themes of Cluster 2 are: Firstly, traffic accidents. As a foundational theme within Cluster 2, the focus on traffic accidents underscores the imperative of enhancing road safety and mitigating collision risks within the context of autonomous driving systems. Research endeavors within this theme likely span accident analysis, risk assessment methodologies, and intervention strategies aimed at reducing the incidence and severity of traffic accidents in autonomous mobility scenarios. These insights inform the development of intervention strategies to reduce the incidence and severity of traffic accidents, thus advancing existing safety theories and practices in autonomous mobility.

The second, artificial intelligence. Central to the advancement of autonomous driving systems, artificial intelligence emerges as a pivotal theme within Cluster 2. Research within this domain likely encompasses machine learning algorithms, deep neural networks, and cognitive computing frameworks to enable autonomous vehicle perception, decision-making, and adaptive behavior. This theme reflects the transformative potential of AI technologies in revolutionizing transportation paradigms and reshaping urban mobility landscapes. The integration of AI technologies enhances vehicle autonomy and impacts existing theories of human-machine interaction and adaptive behavior in dynamic environments.

The third, automation. Building upon the ethos of autonomy, the automation theme underscores the integration of advanced technologies to enable seamless operation and control of autonomous vehicles. Research endeavors within this domain will likely focus on automation technologies, control systems, and human-machine interaction paradigms to optimize vehicle performance, enhance operational efficiency, and ensure user acceptance in autonomous mobility scenarios. By optimizing vehicle performance and ensuring user acceptance, these efforts reshape existing practices in autonomous mobility, paving the way for more efficient and reliable transportation systems.

The fourth, automobile steering equipment. With a focus on vehicle dynamics and control, automobile steering equipment emerges as a significant theme within Cluster 2. Research within this theme advances existing theories of steering control algorithms and adaptive steering technologies, thereby enhancing vehicle maneuverability and safety in autonomous driving environments. These advancements inform practical applications in vehicle design and integration, influencing existing autonomous mobility research and development practices.

The fifth, autonomous systems. It reflects the overarching theme of autonomy; autonomous systems constitute a core research area within Cluster 2. Research endeavors within this theme likely span various topics, including perception systems, navigation algorithms, sensor fusion methodologies, and decision-making frameworks to enable autonomous operation across diverse environmental conditions and operational scenarios. By enabling autonomous vehicles to navigate complex environments, these advancements impact existing urban mobility and transportation infrastructure design practices, fostering safer and more efficient transportation systems.

The sixth, an autonomous vehicle. As the focal point of research and innovation in autonomous mobility, autonomous vehicles represent a pivotal theme within Cluster 2. Research within this domain likely encompasses vehicle design, sensor integration, software development, and validation methodologies aimed at realizing the vision of fully autonomous transportation systems. By addressing vehicle validation and deployment challenges, these efforts shape existing practices in autonomous mobility, paving the way for widespread adoption of autonomous transportation systems.

The seventh, computer software. In the era of intelligent mobility, computer software emerges as a critical enabler of autonomous driving systems within Cluster 2. Research endeavors within this domain likely revolve around software architecture, programming paradigms, and software engineering methodologies tailored to the unique requirements and challenges of autonomous vehicle development and deployment. By developing software solutions optimized for autonomous mobility, researchers impact existing practices in software development and integration, ensuring the reliability and scalability of autonomous driving systems.

The eighth, control system synthesis. With an emphasis on robust control and optimization, control system synthesis emerges as a significant theme within Cluster 2. Research within this domain likely focuses on synthesizing control algorithms, feedback mechanisms, and adaptive control strategies to ensure autonomous driving systems' stability, performance, and reliability in dynamic and uncertain environments. By synthesizing adaptive control strategies, researchers influence existing practices in autonomous mobility, enhancing the safety and reliability of autonomous driving systems.

The ninth, a driving simulator. Complementing real-world experimentation, driving simulators represent a valuable tool for research and development within Cluster 2. Research endeavors within this theme likely explore the design, validation, and utilization of driving simulators for human factors studies, system testing, and training purposes in the context of autonomous driving systems. By facilitating safe and cost-effective experimentation, driving simulators contribute to advancing autonomous mobility research and practice.

The tenth, intelligent systems. They reflect the integration of advanced technologies and cognitive capabilities and constitute a salient theme within Cluster 2. Research within this domain likely encompasses AI-driven algorithms, decision support systems, and cognitive architectures to enable intelligent behavior and adaptive learning in autonomous vehicles. By enabling intelligent behavior in autonomous vehicles, researchers influence existing practices in human-machine interaction and autonomous vehicle operation, fostering safer and more efficient transportation systems.

The eleventh, Intelligent Vehicle Highway Systems (IVHS), which focuses on infrastructure integration and vehicle-to-infrastructure communication. IVHS emerges as a significant theme within Cluster 2. Research endeavors within this domain likely explore intelligent transportation systems' design, deployment, and optimization, including traffic management, congestion mitigation, and cooperative driving scenarios. IVHS contributes to safer and more efficient transportation systems by enabling seamless communication between vehicles and infrastructure, reshaping urban mobility landscapes.

The twelfth, safety. The theme of safety permeates Cluster 2, underscoring its paramount importance in autonomous mobility. Research within this domain likely focuses on safety-critical systems, fail-safe mechanisms, and risk assessment methodologies aimed at ensuring the safe operation and deployment of autonomous driving systems in real-world environments. By implementing fail-safe mechanisms and rigorous testing protocols, researchers ensure the safe operation and deployment of autonomous driving systems, fostering public trust and confidence in autonomous mobility technologies.

The thirteenth, a simulation platform. As a cornerstone of research and development, simulation platforms are crucial in validating and testing autonomous driving systems within Cluster 2. Research within this theme likely encompasses developing, validating, and utilizing simulation frameworks for scenario testing, algorithm verification, and system validation in autonomous vehicle development. By providing a virtual environment for experimentation, simulation platforms accelerate innovation in autonomous mobility, enabling researchers to test and refine autonomous driving systems more efficiently.

The fourteenth, traffic control. With a focus on optimizing traffic flow and congestion mitigation, traffic control emerges as a significant theme within Cluster 2. Research endeavors within this domain likely explore dynamic traffic management strategies, intelligent signal control systems, and cooperative driving scenarios to enhance traffic efficiency and safety in autonomous mobility environments. By implementing cooperative driving scenarios and dynamic traffic management strategies, researchers contribute to safer and more efficient transportation systems, enhancing urban mobility, and reducing environmental impact.

The fifteenth, vehicle-to-vehicle communications (V2V). It facilitates cooperative driving and situational awareness, and V2V communications represent a pivotal theme within Cluster 2. Research within this domain likely focuses on communication protocols, network architectures, and collision avoidance strategies enabled by vehicle-to-vehicle communication technologies. By allowing seamless communication between vehicles, V2V technologies contribute to safer and more efficient transportation systems, reshaping existing practices in vehicle-to-vehicle communication and collision avoidance.

Figure 13's Network Visualization offers a rich tapestry of research themes within Cluster 2's autonomous driving systems landscape. Each theme, from artificial intelligence and automation to safety and simulation platforms, underscores critical facets of technological innovation, interdisciplinary collaboration, and societal implications within the field. By elucidating key themes and their significance, this analysis provides valuable insights for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and shape the future of transportation.

Figure 14. Cluster 3 – network visualization
Source: VOSviewer 1.6.17 (2024)

Figure 14 presents a network visualization depicting Cluster 3 within the thematic landscape of autonomous driving systems research. Characterized by shades of blue, this cluster encompasses diverse research themes, each offering valuable insights into the multifaceted dimensions of autonomous mobility. Key themes identified within Cluster 3 shed light on critical aspects of technological innovation, societal implications, and interdisciplinary collaboration within the field.

The key themes of the cluster are: first, anomaly detection. As an essential aspect of ensuring the safety and reliability of autonomous driving systems, anomaly detection emerges as a pivotal theme within Cluster 3. Research within this domain likely focuses on developing advanced algorithms, sensor fusion methodologies, and anomaly detection frameworks to identify abnormal behaviors, environmental conditions, or system malfunctions in autonomous vehicle operations. By developing robust anomaly detection frameworks, researchers contribute to enhancing existing safety practices in autonomous mobility, fostering greater trust and confidence in autonomous vehicle technologies.

Second, there is the autonomous car. This theme reflects the overarching goal of autonomy in transportation and represents a central focus within Cluster 3. Research endeavors within this domain likely encompass vehicle design, perception systems, decision-making algorithms, and human-machine interaction paradigms aimed at realizing the vision of fully autonomous vehicles capable of navigating diverse environments with minimal human intervention. By advancing technologies aimed at minimizing human intervention in vehicle operation, researchers impact existing practices in autonomous mobility, paving the way for safer and more efficient transportation systems.

Third, behavioral research. Complementing technological advancements, behavioral research constitutes a significant theme within Cluster 3. Research endeavors within this domain likely explore human factors, user acceptance, trust dynamics, and behavioral adaptation patterns in the context of autonomous driving systems. This theme underscores the importance of understanding human behavior and preferences in designing user-centric autonomous mobility solutions. By understanding user acceptance and trust dynamics, researchers influence existing practices in autonomous vehicle design and deployment, fostering greater user adoption and satisfaction with autonomous driving technologies.

Fourth, Convolutional Neural Network (CNN). With the proliferation of deep learning techniques, CNNs have emerged as a cornerstone of perception and recognition systems within Cluster 3. Research within this domain likely focuses on developing CNN-based algorithms for object detection, scene understanding, and semantic segmentation in autonomous vehicle perception frameworks. By developing robust CNN architectures, researchers impact existing practices in autonomous mobility, enabling vehicles to perceive and interact with their surroundings more effectively.

Fifth, cybersecurity. Amidst the growing interconnectedness of autonomous vehicles, cybersecurity emerges as a critical theme within Cluster 3. Research endeavors within this domain likely revolve around threat modeling, vulnerability analysis, and intrusion detection techniques to safeguard autonomous driving systems against cyber threats, malicious attacks, and data breaches. By addressing cybersecurity concerns, researchers influence existing practices in autonomous vehicle development and deployment, ensuring the integrity and security of autonomous mobility technologies.

Sixth, decision-making. Decision-making is central to the autonomy paradigm, which represents a core theme within Cluster 3. Research within this domain likely explores decision-making algorithms, reinforcement learning frameworks, and uncertainty quantification methodologies aimed at enabling autonomous vehicles to make context-aware, adaptive decisions in dynamic and uncertain environments. By developing robust decision-making strategies, researchers impact existing practices in autonomous mobility, enabling vehicles to navigate complex scenarios more effectively.

Seventh, deep learning. With the advent of deep learning methodologies, deep learning emerges as a pervasive theme within Cluster 3. Research endeavors within this domain likely span neural network architectures, training algorithms, and optimization techniques tailored to autonomous driving systems' unique requirements and challenges. By leveraging deep learning techniques, researchers impact existing practices in autonomous mobility, enabling vehicles to perceive, reason, and act in real-world environments more intelligently.

Eighth, economic and social effects. Beyond technological advancements, the economic and social effects theme underscores the broader implications of autonomous mobility within Cluster 3. Research within this domain likely explores the economic impact, societal implications, and policy considerations associated with the widespread adoption of autonomous vehicles. By examining economic and social factors, researchers influence existing practices in autonomous mobility, ensuring that technological advancements align with societal needs and preferences.

Ninth, feature extraction. In perception and sensor fusion, feature extraction emerges as a critical theme within Cluster 3. Research endeavors within this domain likely focus on extracting salient features, patterns, and descriptors from sensor data streams for robust perception and scene understanding in autonomous driving systems.

Tenth, the Internet of Things (IoT). Facilitating vehicle connectivity and data exchange, IoT emerges as a significant theme within Cluster 3. Research within this domain likely explores IoT architectures, communication protocols, and edge computing paradigms to enable seamless integration of autonomous vehicles into the broader IoT ecosystem. By extracting salient features from sensor data streams, researchers impact existing practices in autonomous mobility, enabling vehicles to perceive and interpret their surroundings more accurately.

Eleventh, motor transportation. Reflecting the domain-specific focus on transportation systems, motor transportation constitutes a salient theme within Cluster 3. Research endeavors within this domain likely span transportation planning, logistics optimization, and mobility-as-a-service (MaaS) frameworks tailored to autonomous mobility's unique requirements and challenges. By addressing the unique requirements and challenges of motor transportation in autonomous mobility, researchers impact existing practices in transportation planning and infrastructure development, facilitating the integration of autonomous vehicles into existing transportation networks.

Twelfth, risk assessment. With a focus on safety and risk management, risk assessment emerges as a critical theme within Cluster 3. Research within this domain likely revolves around probabilistic modeling, risk quantification methodologies, and scenario analysis techniques to assess and mitigate risks associated with autonomous vehicle operations. By developing robust risk assessment frameworks, researchers impact existing practices in autonomous vehicle design and deployment, ensuring the safety and reliability of autonomous mobility technologies.

Thirteenth, self-driving cars. It reflects the everyday vocabulary of autonomous vehicles; self-driving cars represent a central theme within Cluster 3. Research endeavors within this domain likely encompass vehicle autonomy levels, regulatory frameworks, and user acceptance dynamics shaping the adoption and deployment of self-driving cars. By addressing regulatory challenges and user acceptance dynamics, researchers impact existing practices in autonomous vehicle deployment and public perception, fostering greater trust and confidence in self-driving car technologies.

Fourteenth, uncertainty. Acknowledging the inherent uncertainties in real-world environments, uncertainty constitutes a pervasive theme within Cluster 3. Research endeavors within this domain likely focus on uncertainty modeling, probabilistic reasoning, and decision-theoretic frameworks to enable autonomous vehicles to navigate uncertain terrain and make informed decisions under uncertainty. By addressing uncertainty in autonomous vehicle operations, researchers impact existing practices in autonomous mobility, ensuring the robustness and adaptability of autonomous driving systems in dynamic and unpredictable environments.

Figure 14's Network Visualization comprehensively depicts research themes within Cluster 3 of the autonomous driving systems landscape. Each theme, from anomaly detection and deep learning to cybersecurity and risk assessment, underscores critical facets of technological innovation, societal implications, and interdisciplinary collaboration within the field. By elucidating key themes and their significance, this analysis provides valuable insights for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and navigate the complex intersections of technology, society, and policy in the era of autonomous driving.

Figure 15 presents a network visualization illustrating Cluster 4 within the thematic landscape of autonomous driving systems research. Distinguished by shades of olive green, this cluster encompasses diverse research themes, each contributing uniquely to the advancement of autonomous mobility. Key themes identified within Cluster 4 shed light on critical aspects of technological innovation, methodological advancements, and interdisciplinary collaboration.

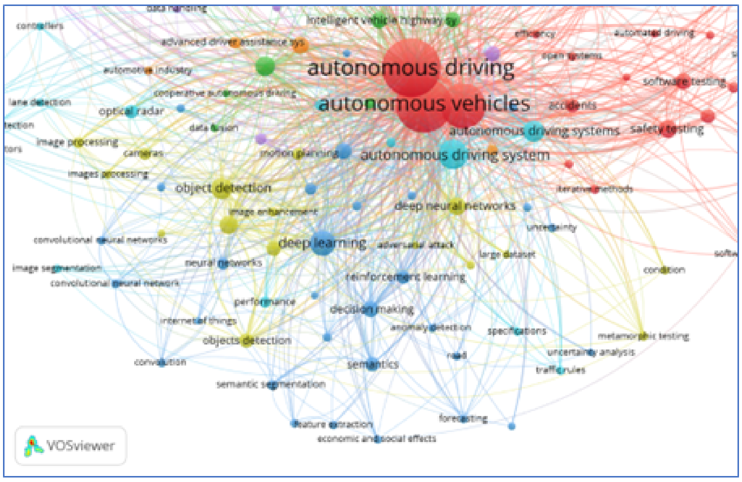

Figure 15. Cluster 4 – network visualization

Source: VOSviewer 1.6.17 (2024)

The cluster's significant themes are: First, adversarial attacks. A focal point within Cluster 4, adversarial attacks underscore the vulnerability of autonomous driving systems to malicious manipulation and adversarial perturbations. Research endeavors within this domain likely focus on adversarial robustness, defense mechanisms, and countermeasures aimed at fortifying autonomous vehicles against adversarial attacks and ensuring their resilience in real-world deployment scenarios. By addressing these vulnerabilities, researchers contribute to the resilience and safety of autonomous systems, impacting existing theories of cybersecurity and system robustness.

Second, computer vision. Central to perception and scene understanding, computer vision emerges as a pivotal theme within Cluster 4. Research within this domain likely spans image processing algorithms, feature extraction techniques, and deep learning methodologies to enable autonomous vehicles to interpret visual data streams and extract meaningful insights from their surroundings. By improving computer vision algorithms, researchers impact existing practices in autonomous mobility, enhancing the safety and efficiency of autonomous vehicles on the road.

Third, Deep Neural Networks (DNNs). With the proliferation of deep learning techniques, DNNs constitute a cornerstone of perception and decision-making systems within Cluster 4. Research endeavors within this domain likely focus on developing DNN architectures, training methodologies, and optimization techniques tailored to autonomous driving systems' unique requirements and challenges. By optimizing DNNs for autonomous mobility, researchers advance existing deep-learning theories and reinforce the foundation of autonomous vehicle intelligence.

Fourth, image enhancement. It complements computer vision algorithms, and image enhancement represents a critical theme within Cluster 4. Research within this domain likely explores techniques for denoising, deblurring, and enhancing visual imagery to improve the performance and robustness of perception systems in autonomous vehicles. By refining image enhancement techniques, researchers contribute to the reliability and safety of autonomous driving systems in real-world scenarios.

Fifth, image processing. It builds upon the foundation of computer vision, and image processing emerges as a significant theme within Cluster 4. Research endeavors within this domain likely focus on image segmentation, feature extraction, and pattern recognition techniques to enable autonomous vehicles to interpret and analyze visual information from their surroundings. By developing robust image processing algorithms, researchers refine existing theories of visual perception, improving autonomous vehicles' ability to interpret complex environments.

Sixth, the large dataset. It reflects the data-driven nature of deep learning methodologies; large datasets constitute a pivotal theme within Cluster 4. Research endeavors within this domain likely revolve around data collection, annotation, and curation efforts to create comprehensive datasets for training and validating autonomous driving systems. By creating large datasets tailored to autonomous driving, researchers advance existing machine learning practices, enhancing autonomous vehicles' performance and reliability.

Seventh, metamorphic testing. It focuses on robustness and reliability, and metamorphic testing emerges as a critical theme within Cluster 4. Research within this domain likely explores techniques for generating metamorphic relations, designing test cases, and evaluating the resilience of autonomous driving systems to unforeseen inputs and perturbations. By implementing metamorphic testing strategies, researchers strengthen existing system verification and validation practices, ensuring the safety and reliability of autonomous driving systems.

Eight, motion planning. Integral to decision-making and control, motion planning represents a central theme within Cluster 4. Research endeavors within this domain likely focus on path-planning algorithms, trajectory optimization techniques, and collision avoidance strategies to enable autonomous vehicles to navigate complex environments safely and efficiently. By refining motion planning techniques, researchers contribute to existing theories of decision-making and control, enhancing the autonomy and safety of autonomous vehicles.

Ninth, object detection. Essential for situational awareness, object detection emerges as a pivotal theme within Cluster 4. Research within this domain likely explores detection algorithms, feature extraction techniques, and sensor fusion methodologies aimed at identifying and localizing objects of interest in the vicinity of autonomous vehicles. By enhancing object detection capabilities, researchers reinforce existing practices in perception and navigation, ensuring the safety and efficiency of autonomous driving systems.

Figure 15's Network Visualization provides valuable insights into the thematic landscape of autonomous driving systems research within Cluster 4. Each theme, from adversarial attacks and deep neural networks to image processing and object detection, underscores critical facets of technological innovation, methodological advancements, and interdisciplinary collaboration within the field. By elucidating key themes and their significance, this analysis offers valuable guidance for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and navigate the complexities of perception, decision-making, and control in autonomous driving systems.

Figure 16 offers a network visualization that delineates Cluster 5 within the thematic landscape of autonomous driving systems research. Identified by shades of purple/magenta, this cluster encapsulates a spectrum of research themes, each contributing to the multifaceted discourse surrounding autonomous mobility. Key themes within Cluster 5 shed light on pivotal aspects of technological innovation, system design, and safety engineering within the field.

The cluster's key themes are, first, Computer-Aided Design (CAD). A cornerstone of engineering practice, CAD emerges as a significant theme within Cluster 5. Research endeavors within this domain will likely focus on developing CAD tools, modeling techniques, and simulation frameworks tailored to the unique requirements and challenges of autonomous driving systems design and development. By enhancing CAD tools for autonomous systems, researchers

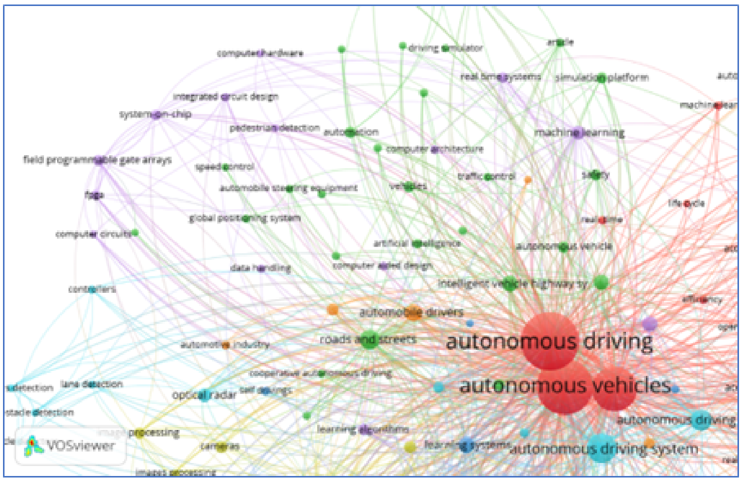

Figure 16. Cluster 5 – network visualization

Source: VOSviewer 1.6.17 (2024)

streamline the design process, leading to more efficient and reliable autonomous driving solutions.

Second, computer architecture. Central to system design and optimization, computer architecture constitutes a pivotal theme within Cluster 5. Research within this domain likely explores hardware-software co-design, processor architectures, and memory hierarchies optimized for the computational demands of autonomous driving systems. By exploring novel computer architecture designs, researchers push the boundaries of existing theories, leading to more powerful and energy-efficient autonomous vehicles.

Third, computer circuits. It complements computer architecture, and computer circuits represent a critical theme within Cluster 5. Research endeavors within this domain likely focus on circuit design methodologies, signal processing techniques, and power management strategies to optimize electronic components' performance and efficiency within autonomous vehicles. By refining circuit design strategies, researchers contribute to existing theories of electronics optimization, leading to more robust and power-efficient autonomous systems.

Fourth, Field-Programmable Gate Arrays (FPGAs). Focusing on reconfigurable hardware platforms, FPGAs emerge as a significant theme within Cluster 5. Research within this domain likely explores FPGA-based accelerators, hardware-in-the-loop simulation frameworks, and rapid prototyping methodologies for accelerating the development and testing of autonomous driving systems. By leveraging FPGAs, researchers impact existing theories of hardware acceleration, facilitating faster and more cost-effective autonomous vehicle development.

Fifth, integrated circuit design. It reflects the pervasive role of electronics in autonomous mobility, and integrated circuit design constitutes a salient theme within Cluster 5. Research endeavors within this domain likely span analog and digital IC design, mixed-signal integration, and system-on-chip (SoC) architectures tailored to the stringent requirements of autonomous vehicle electronics. By developing innovative IC design techniques, researchers shape existing theories of electronics integration, leading to more compact and efficient autonomous vehicle electronics.

Sixth, pedestrian detection. It focuses on safety and collision avoidance; pedestrian detection is a critical theme within Cluster 5. Research within this domain likely explores sensor fusion techniques, machine learning algorithms, and real-time processing methodologies for detecting and tracking pedestrians near-autonomous vehicles. By improving pedestrian detection capabilities, researchers contribute to existing sensor fusion and object recognition theories, enhancing autonomous vehicles' safety and reliability.

Seventh, real-time systems. Integral to system responsiveness and safety, real-time systems represent a central theme within Cluster 5. Research endeavors within this domain likely focus on real-time operating systems, scheduling algorithms, and temporal analysis techniques to ensure timely and predictable behavior in autonomous driving systems. By optimizing real-time system performance, researchers refine existing theories of temporal analysis, enabling autonomous vehicles to operate reliably in dynamic environments.

Eighth, safety engineering. It underscores the importance of safety, and safety engineering emerges as a pervasive theme within Cluster 5. Research within this domain likely revolves around hazard analysis, fault tolerance mechanisms, and safety-critical system design methodologies aimed at ensuring the safe operation and deployment of autonomous vehicles. By advancing safety engineering principles, researchers are not just strengthening existing theories of system safety, but also playing a crucial role in mitigating risks and enhancing public trust in autonomous driving technology.

Figure 16's Network Visualization provides valuable insights into the thematic landscape of autonomous driving systems research within Cluster 5. Each theme, from computer-aided design and computer architecture to pedestrian detection and safety engineering, underscores critical facets of technological innovation, system design, and safety engineering within the field. By elucidating key themes and their significance, this analysis offers valuable guidance for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and navigate the complexities of system design, safety assurance, and real-time responsiveness in autonomous driving systems.

Figure 17 presents a network visualization showcasing Cluster 6 within the thematic landscape of autonomous driving systems research. Distinguished by shades of cyan blue, this cluster encompasses a variety of research themes, each contributing uniquely to the advancement of autonomous mobility. Key themes within Cluster 6 highlight crucial aspects of system functionality, safety assurance, and performance optimization within the field.

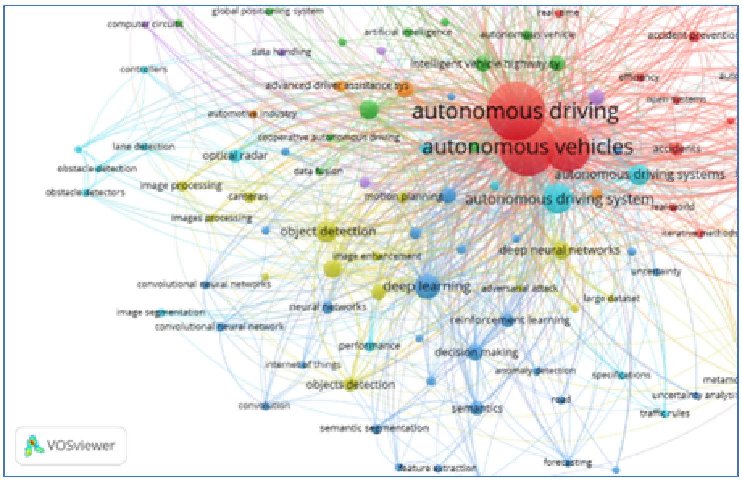

Figure 17. Cluster 6 – network visualization
Source: VOSviewer 1.6.17 (2024)

The key themes of the cluster are, first, autonomous driving systems. At the core of research efforts in Cluster 6 lies the theme of autonomous driving systems. This theme encompasses the overarching goal of developing sophisticated systems capable of autonomously navigating and operating vehicles. Research within this domain likely explores system architectures, sensor fusion methodologies, and decision-making algorithms aimed at achieving high levels of autonomy in driving tasks. By focusing on achieving greater independence, researchers contribute to theories of artificial intelligence, robotics, and cyber-physical systems, shaping the future of autonomous mobility.

Second, collision avoidance. Ensuring the safety of both occupants and pedestrians is paramount in autonomous driving. The theme of collision avoidance underscores research efforts focused on developing advanced sensor systems, real-time processing algorithms, and decision-making strategies for detecting and avoiding potential collisions in dynamic traffic environments. By enhancing collision avoidance capabilities, researchers contribute to theories of computer vision, machine learning, and control systems, improving the safety and reliability of autonomous vehicles.

Third, controllers. Control systems are pivotal in regulating vehicle behavior and ensuring stability and performance in autonomous driving scenarios. The theme of controllers likely encompasses research into various control strategies, such as PID control, model predictive control, and adaptive control, tailored to the unique requirements of autonomous vehicles. By optimizing control strategies, researchers contribute to theories of control theory and cyber-physical systems, enhancing the autonomy and maneuverability of autonomous vehicles.

Fourth, image segmentation. Visual perception is essential for autonomous vehicles to interpret and understand their surroundings. Image segmentation techniques, a key theme in Cluster 6, involve partitioning images into meaningful regions, enabling the vehicle's perception system to identify objects, road markings, and obstacles with precision and accuracy. Research in image segmentation advances computer vision and pattern recognition theories, improving the accuracy and reliability of visual perception systems in autonomous vehicles.

Fifth, lane detection. Lane detection is critical for autonomous vehicles to maintain proper lane positioning and trajectory planning. Research within this theme likely focuses on developing robust lane detection algorithms that accurately identify lane boundaries under diverse environmental conditions, including varying lighting, weather, and road surface conditions. By improving lane detection capabilities, researchers contribute to computer vision and sensor fusion theories, enhancing autonomous vehicles' navigation and safety.

Sixth, obstacle detection. Detecting and avoiding obstacles is essential for safe autonomous driving. The theme of obstacle detection encompasses research efforts aimed at developing sensor fusion techniques, machine learning algorithms, and real-time processing strategies to identify and classify obstacles, such as vehicles, pedestrians, and cyclists, in the vehicle's path. By enhancing obstacle detection capabilities, researchers contribute to theories of sensor fusion, machine learning, and real-time processing, improving the safety and reliability of autonomous vehicles.

Seventh, optical radar. Optical radar, or lidar, is a key sensing technology in autonomous driving systems. Research within this theme likely focuses on enhancing lidar performance, resolution, and reliability and exploring novel lidar architectures and signal processing algorithms to improve obstacle detection and environmental perception capabilities. By improving lidar capabilities, researchers contribute to remote sensing and environmental perception theories, enhancing the accuracy and range of perception systems in autonomous vehicles.

Eighth, performance. Ensuring high performance is crucial for the widespread adoption and acceptance of autonomous driving systems. The performance theme likely encompasses research into optimizing system response times, computational efficiency, energy consumption, and overall system reliability to meet the demanding requirements of real-world driving scenarios. By improving system performance, researchers contribute to optimization and system engineering theories, enhancing the efficiency and reliability of autonomous vehicles in real-world scenarios.

Ninth, specifications. Clearly defining system specifications and requirements is essential for guiding the design, development, and testing of autonomous driving systems. Research within this theme likely involves establishing performance metrics, safety standards, and regulatory frameworks to ensure compliance and interoperability across different autonomous vehicle platforms. By developing comprehensive specifications, researchers contribute to theories of system engineering and regulatory compliance, ensuring the safety and interoperability of autonomous vehicles.

Tenth, traffic rules. Adhering to traffic rules and regulations is fundamental for safe and lawful operation on public roads. The theme of traffic rules likely encompasses research into developing rule-based decision-making algorithms, traffic law compliance strategies, and communication protocols to enable autonomous vehicles to navigate complex traffic scenarios while adhering to legal and ethical guidelines. By ensuring compliance with traffic laws, researchers contribute to theories of ethics and legal studies, promoting safe and responsible behavior in autonomous driving systems.

Figure 17's network visualization offers valuable insights into the thematic landscape of autonomous driving systems research within Cluster 6. Each theme, from collision avoidance and lane detection to optical radar and traffic rules, underscores critical aspects of system functionality, safety assurance, and performance optimization within the field. By elucidating key themes and their significance, this analysis provides valuable guidance for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and address the complex challenges of developing safe, reliable, and efficient autonomous driving systems.

Figure 18 presents a network visualization showcasing Cluster 7 within the thematic landscape of autonomous driving systems research. Identified by shades of orange, this cluster encompasses a range of research themes, each offering unique insights into the intersection of technology, industry, and human factors within autonomous mobility. Key themes within Cluster 7 shed light on critical aspects of driver assistance, automation, automotive industry dynamics, and digital infrastructure.

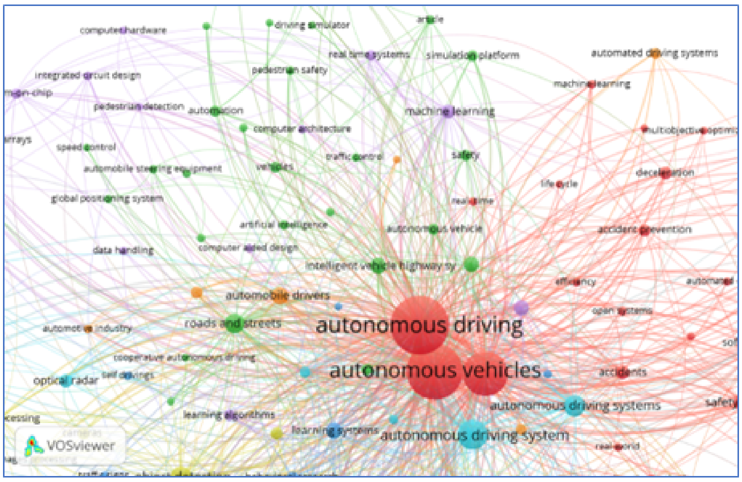

Figure 18. Cluster 7 – network visualization
Source: VOSviewer 1.6.17 (2024)

The cluster's significant themes are Advanced Driver Assistance Systems (ADAS). At the forefront of Cluster 7 lies the first theme of ADAS. ADAS technologies, such as adaptive cruise control, lane-keeping assistance, and collision avoidance systems, are pivotal in augmenting driver capabilities and enhancing vehicle safety. Research within this domain likely explores ADAS features' development, integration, and adoption to improve driving comfort, convenience, and safety. The advancement of ADAS contributes to theories of human factors and transportation engineering, reshaping the relationship between drivers and vehicles while promoting safer driving practices.

The second theme is automated driving systems. Building upon ADAS's foundation, this theme represents a natural progression toward full autonomy. Automated driving systems aim to delegate driving tasks to the vehicle, reducing the need for human intervention and enabling fully autonomous operation. Research within this theme likely focuses on sensor fusion, decision-making algorithms, and human-machine interaction paradigms to realize the vision of autonomous vehicles. By striving for fully autonomous operation, researchers push the boundaries of vehicle autonomy and mobility services.

The third theme is automobile drivers. Despite advancements in automation, human drivers remain integral to the transportation ecosystem. The theme of automobile drivers likely encompasses research into human factors, driver behavior, and driver-machine interaction dynamics in the context of autonomous driving systems. Understanding driver preferences, perceptions, and limitations is essential for designing user-centric autonomous mobility solutions.

The fourth theme is the automotive industry. The automotive industry plays a central role in shaping the development and deployment of autonomous driving systems. Research within this theme likely explores industry trends, market dynamics, and regulatory frameworks impacting the adoption and commercialization of autonomous vehicle technologies. Collaboration between academia, industry, and policymakers is crucial for navigating the complex landscape of automotive innovation.

The fifth theme is digital storage. With the proliferation of data-driven technologies, digital storage emerges as a critical theme within Cluster 7. Autonomous driving systems generate vast amounts of sensor data, requiring efficient storage, retrieval, and processing capabilities. Research within this domain likely focuses on data compression techniques, storage architectures, and cloud computing solutions tailored to the unique requirements of autonomous vehicle data management. Digital storage advances contribute to data management and cloud computing theories, enabling efficient and scalable solutions for autonomous vehicle data processing.

Figure 18's network visualization provides valuable insights into the thematic landscape of autonomous driving systems research within Cluster 7. Each theme, from advanced driver assistance systems and automated driving to automotive industry dynamics and digital storage, underscores critical aspects of technology adoption, human factors, and industry collaboration within the field. By elucidating key themes and their significance, this analysis offers valuable guidance for researchers, policymakers, and industry stakeholders seeking to advance the state-of-the-art in autonomous mobility and navigate the complex interplay of technological innovation, regulatory frameworks, and societal acceptance in the era of autonomous driving.

4 Conclusions

The bibliometric analysis presented in this study offers a comprehensive overview of research trends, global perspectives, thematic areas, and key contributors to autonomous driving systems. Through an extensive examination of publications from 2002 to May 2024, several significant conclusions can be drawn, shedding light on the past, present, and future of autonomous mobility research.

The analysis reveals a remarkable growth trajectory in autonomous driving systems research, marked by a surge in publications since 2017. This exponential increase underscores the dynamic nature of the field, driven by technological advancements, interdisciplinary collaborations, and increased investment from academia, industry, and governmental bodies. The transition from exploratory and foundational research activities in the early 2000s to extensive research and development efforts in recent years reflects autonomous driving technologies' maturation and broader acceptance.

The dominance of conference papers in the publication landscape highlights the importance of real-time knowledge exchange and collaboration within the academic community. Peer-reviewed articles, conversely, signify a commitment to validated, high-quality research contributions, ensuring the reliability and credibility of scholarly output.

The global perspective on research contributions underscores autonomous driving systems research's competitive and collaborative nature. Leading countries such as China, the United States, Japan, and Europe play pivotal roles, contributing unique strengths and perspectives to the field. Similarly, prominent organizations and researchers from diverse locations demonstrate a global interest and collaboration in advancing autonomous mobility.

Thematic analysis reveals seven distinct clusters encapsulating various research themes within autonomous driving systems. From foundational technologies and environmental sustainability to safety, regulation, user experience, connectivity, and technological innovation, these thematic areas offer a comprehensive understanding of the multidimensional challenges and opportunities in the field. Overlay visualization further illuminates temporal trends, highlighting emerging research areas and established domains of scholarly inquiry.

While this study provides valuable insights into the current state of autonomous driving systems research, it has limitations. The bibliometric analysis relies on data from the Scopus database, which may only encompass some relevant publications in the field. Moreover, the study primarily focuses on quantitative analyses, limiting the depth of qualitative insights into specific research topics or methodologies. Future research directions may involve more in-depth analyses of thematic clusters, exploring interdisciplinary linkages, and investigating emerging research trends through qualitative approaches.

This study contributes to a nuanced understanding of autonomous driving systems research, highlighting its significance, challenges, and opportunities for future exploration. As the field continues to evolve, interdisciplinary collaboration, strategic investments, and a commitment to addressing societal needs will be essential for realizing the transformative potential of autonomous mobility.

Data Availability

Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Z. Lv and W. Shang, "Impacts of intelligent transportation systems on energy conservation and emission reduction of transport systems: A comprehensive review," *Green Technol. Sustain.*, vol. 1, no. 1, p. 100002, 2023. https://doi.org/10.1016/j.grets.2022.100002

[2] S. Heiberg, E. Emond, C. Allen, D. Raya, V. Gadhamshetty, S. S. Dhiman, A. Ravilla, and I. Celik, "Environmental impact assessment of autonomous transportation systems," *Energies*, vol. 16, no. 13, p. 5009, 2023. https://doi.org/10.3390/en16135009

[3] S. E. Bibri, J. Krogstie, A. Kaboli, and A. Alahi, "Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review," *Environ. Sci. Ecotechnology*, vol. 19, p. 100330, 2024. https://doi.org/10.1016/j.ese.2023.100330

[4] A. Thakur and S. K. Mishra, "An in-depth evaluation of deep learning-enabled adaptive approaches for detecting obstacles using sensor-fused data in autonomous vehicles," *Eng. Appl. Artif. Intell.*, vol. 133, p. 108550, 2024. https://doi.org/10.1016/j.engappai.2024.108550

[5] H. A. Ignatious, H. El-Sayed, and P. Kulkarni, "Multilevel data and decision fusion using heterogeneous sensory data for autonomous vehicles," *Remote Sens.*, vol. 15, no. 9, p. 2256, 2023. https://doi.org/10.3390/rs15092256

[6] G. E. M. Abro, S. A. B. Zulkifli, K. Kumar, N. El Ouanjli, V. S. Asirvadam, and M. A. Mossa, "Comprehensive review of recent advancements in battery technology, propulsion, power interfaces, and vehicle network systems for intelligent autonomous and connected electric vehicles," *Energies*, vol. 16, no. 6, p. 2925, 2023. https://doi.org/10.3390/en16062925

[7] M. Hasanujjaman, M. Z. Chowdhury, and Y. M. Jang, "Sensor fusion in autonomous vehicle with traffic surveillance camera system: Detection, localization, and AI networking," *Sensors*, vol. 23, no. 6, p. 3335, 2023. https://doi.org/10.3390/s23063335

[8] W. Ding, C. Xu, M. Arief, H. Lin, B. Li, and D. Zhao, "A survey on safety-critical driving scenario generation - A methodological perspective," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 7, pp. 6971–6988, 2023. https://doi.org/10.1109/TITS.2023.3259322

[9] X. Zhang, J. Tao, K. Tan *et al.*, "Finding critical scenarios for automated driving systems: A systematic mapping study," *IEEE Trans. Softw. Eng.*, vol. 49, no. 3, pp. 991–1026, 2023. https://doi.org/10.1109/TSE.2022.3170122

[10] L. Chen, Y. Li, C. Huang *et al.*, "Milestones in autonomous driving and intelligent vehicles: Survey of surveys," *IEEE Trans. Intell. Veh.*, vol. 8, no. 2, pp. 1046–1056, 2023. https://doi.org/10.1109/TIV.2022.3223131

[11] E. Purwanto, Y. Iskandar, and P. Bhaktiar, "A bibliometric analysis on energy efficiency and conservation," in *E3S Web Conf.*, vol. 517, 2024, p. 03001. https://doi.org/10.1051/e3sconf/202451703001

[12] E. Purwanto, N. Uddin, and H. Nugraha, "Hybrid solar-electric cart efficiency enhancement: A bibliometric analysis," in *E3S Web Conf.*, vol. 506, 2024, p. 11001. https://doi.org/10.1051/e3sconf/202450611001

[13] E. Pitaloka, E. Purwanto, Y. Suyoto, A. Dwianika, and D. Anggreyani, "Bibliometrics analysis of green financing research," *Int. J. Sustain. Dev. Plann.*, vol. 19, no. 3, pp. 853–865, 2024. https://doi.org/10.18280/ijsdp.190305

[14] A. Dwianika, E. Purwanto, Y. T. Suyoto, and E. Pitaloka, "Bibliometrics analysis of green accounting research," *Int. J. Energy Econ. Policy.*, vol. 14, no. 1, p. 349, 2024. https://doi.org/10.32479/ijeep.15055

[15] E. Purwanto and A. P. Irawan, "Bibliometric analysis of electric vehicle adoption research: Trends, implications, and future directions," *Int. J. Saf. Secur. Eng.*, vol. 13, no. 5, pp. 789–800, 2023. https://doi.org/10.18280/ijsse.130503

[16] T. Laurent, S. Klikovits, P. Arcaini, F. Ishikawa, and A. Ventresque, "Parameter coverage for testing of autonomous driving systems under uncertainty," *ACM Trans. Softw. Eng. Methodol.*, vol. 32, no. 3, p. 58, 2023. https://doi.org/10.1145/3550270

[17] Y. Luo, X. Y. Zhang, P. Arcaini, Z. Jin, H. Zhao, F. Ishikawa, R. Wu, and T. Xie, “Targeting requirements violations of autonomous driving systems by dynamic evolutionary search (HOP at GECCO’22),” in *Proceedings of the Genetic and Evolutionary Computation Conference*, Boston, Massachusetts, 2022, pp. 33–34. https://doi.org/10.1145/3520304.3534064

[18] Y. Luo, X. Y. Zhang, P. Arcaini, Z. Jin, H. Zhao, L. Zhang, and F. Ishikawa, “Hierarchical assessment of safety requirements for configurations of autonomous driving systems,” in *IEEE 30th International Requirements Engineering Conference (RE)*, Melbourne, Australia, 2022, pp. 88–100. https://doi.org/10.1109/RE54965.2022.00015

[19] P. Arcaini, X. Y. Zhang, and F. Ishikawa, “Less is more: Simplification of test scenarios for autonomous driving system testing,” in *IEEE Conference on Software Testing, Verification and Validation (ICST)*, Valencia, Spain, 2022, pp. 279–290. https://doi.org/10.1109/ICST53961.2022.00037

[20] T. Laurent, P. Arcaini, F. Ishikawa, and A. Ventresque, “Achieving weight coverage for an autonomous driving system with search-based test generation (HOP track at GECCO 2021),” in *Proceedings of the Genetic and Evolutionary Computation Conference Companion*, Lille, France, 2021, pp. 33–34. https://doi.org/10.1145/3449726.3462723

[21] P. Arcaini, X. Zhang, and F. Ishikawa, “Targeting patterns of driving characteristics in testing autonomous driving systems,” in *IEEE Conference on Software Testing, Verification and Validation (ICST)*, Porto de Galinhas, Brazil, 2021, pp. 295–305. https://doi.org/10.1109/ICST49551.2021.00042

[22] E. Castellano, A. Cetinkaya, and P. Arcaini, “Analysis of road representations in search-based testing of autonomous driving systems,” in *2021 IEEE 21st International Conference on Software Quality, Reliability and Security (QRS)*, Hainan, China, 2021, pp. 167–178. https://doi.org/10.1109/QRS54544.2021.00028

[23] S. Klikovits and P. Arcaini, “Handling noise in search-based scenario generation for autonomous driving systems,” in *2021 IEEE 26th Pacific Rim International Symposium on Dependable Computing (PRDC)*, Perth, Australia, 2021, pp. 1–6. https://doi.org/10.1109/PRDC53464.2021.00011

[24] P. Arcaini, A. Calò, F. Ishikawa, T. Laurent, X. Y. Zhang, S. Ali, F. Hauer, and A. Ventresque, “Parameter-based testing and debugging of autonomous driving systems,” in *2021 IEEE Intelligent Vehicles Symposium Workshops (IV Workshops)*, Nagoya, Japan, 2021, pp. 197–202. https://doi.org/10.1109/IVWorkshops54471.2021.9669254

[25] T. Laurent, P. Arcaini, F. Ishikawa, and A. Ventresque, “Achieving weight coverage for an autonomous driving system with search-based test generation,” in *2020 25th International Conference on Engineering of Complex Computer Systems (ICECCS)*, Singapore, 2020, pp. 93–102. https://doi.org/10.1109/ICECCS51672.2020.00018

[26] A. Calo, P. Arcaini, S. Ali, F. Hauer, and F. Ishikawa, “Generating avoidable collision scenarios for testing autonomous driving systems,” in *2020 IEEE 13th International Conference on Software Testing, Validation and Verification (ICST)*, Porto, Portugal, 2020, pp. 375–386. https://doi.org/10.1109/ICST46399.2020.00045

[27] A. Calo, P. Arcaini, S. Ali, F. Hauer, and F. Ishikawa, “Simultaneously searching and solving multiple avoidable collisions for testing autonomous driving systems,” in *GECCO ’20: Proceedings of the 2020 Genetic and Evolutionary Computation Conference*, Cancún, Mexico, 2020, pp. 1055–1063. https://doi.org/10.1145/3377930.3389827

[28] N. Kolb, F. Hauer, and A. Pretschner, “Fitness function templates for testing automated and autonomous driving systems in intersection scenarios,” in *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, Indianapolis, IN, USA, 2021, pp. 217–222. https://doi.org/10.1109/ITSC48978.2021.9564591

[29] A. Pretschner, F. Hauer, and T. Schmidt, “Tests für automatisierte und autonome fahrsysteme: Wiederverwendung aufgezeichneter Fahrten ist nicht zu rechtfertigen,” *Informatik Spektrum*, vol. 44, no. 3, pp. 214–218, 2021. https://doi.org/10.1007/s00287-021-01364-w

[30] F. Hauer, T. Schmidt, B. Holzmuller, and A. Pretschner, “Did we test all scenarios for automated and autonomous driving systems?” in *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, Auckland, New Zealand, 2019, pp. 2950–2955. https://doi.org/10.1109/ITSC.2019.8917326

[31] F. Hauer, A. Pretschner, and B. Holzmüller, “Fitness functions for testing automated and autonomous driving systems,” in *Computer Safety, Reliability, and Security: 38th International Conference, SAFECOMP 2019*, Turku, Finland, 2019, pp. 69–84. https://doi.org/10.1007/978-3-030-26601-1_5

[32] M. Cheng, Y. Zhou, and X. Xie, “Behavexplor: Behavior diversity guided testing for autonomous driving systems,” in *Proceedings of the 32nd ACM SIGSOFT International Symposium on Software Testing and Analysis*, Seattle, WA, USA, 2023, pp. 488–500. https://doi.org/10.1145/3597926.3598072

[33] Y. Zhou, Y. Sun, Y. Tang, Y. Chen, J. Sun, C. M. Poskitt, Y. Li, and Z. Yang, “Specification-based autonomous driving system testing,” *IEEE Trans. Softw. Eng.*, vol. 49, no. 6, pp. 3391–3410, 2023. https://doi.org/10.1109/TSE.2023.3254142

[34] S. Tang, Z. Zhang, J. Zhou, Y. Zhou, Y. Li, and Y. Xue, “Evoscenario: Integrating road structures into critical

scenario generation for autonomous driving system testing," in *2023 IEEE 34th International Symposium on Software Reliability Engineering (ISSRE)*, Florence, Italy, 2023, pp. 309–320. https://doi.org/10.1109/ISSRE59848.2023.00054

[35] X. Han, Y. Zhou, K. Chen, H. Qiu, M. Qiu, Y. Liu, and T. Zhang, "Ads-lead: Lifelong anomaly detection in autonomous driving systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 1, pp. 1039–1051, 2023. https://doi.org/10.1109/TITS.2021.3122906

[36] Y. Tang, Y. Zhou, Y. Liu, J. Sun, and G. Wang, "Collision avoidance testing for autonomous driving systems on complete maps," in *2021 IEEE Intelligent Vehicles Symposium (IV)*, Nagoya, Japan, 2021, pp. 179–185. https://doi.org/10.1109/IV48863.2021.9575536

[37] Y. Tang, Y. Zhou, T. Zhang, F. Wu, Y. Liu, and G. Wang, "Systematic testing of autonomous driving systems using map topology-based scenario classification," in *2021 36th IEEE/ACM International Conference on Automated Software Engineering (ASE)*, Melbourne, Australia, 2021, pp. 1342–1346. https://doi.org/10.1109/ASE51524.2021.9678735

[38] X. Han, K. Chen, Y. Zhou, M. Qiu, C. Fan, Y. Liu, and T. Zhang, "A unified anomaly detection methodology for lane-following of autonomous driving systems," in *2021 IEEE Intl Conf on Parallel and Distributed Processing with Applications, Big Data and Cloud Computing, Sustainable Computing and Communications, Social Computing and Networking (ISPA/BDCloud/SocialCom/SustainCom)*, New York City, NY, USA, 2021, pp. 836–844. https://doi.org/10.1109/ISPA-BDCloud-SocialCom-SustainCom52081.2021.00119

[39] C. Lu, T. Yue, and S. Ali, "Deepscenario: An open driving scenario dataset for autonomous driving system testing," in *2023 IEEE/ACM 20th International Conference on Mining Software Repositories (MSR)*, Melbourne, Australia, 2023, pp. 52–56. https://doi.org/10.1109/MSR59073.2023.00020

[40] C. Lu, H. Zhang, T. Yue, and S. Ali, "Search-based selection and prioritization of test scenarios for autonomous driving systems," in *13th International Symposium on Search-Based Software Engineering (SSBSE 2021)*, Bari, Italy, 2021, pp. 41–55. https://doi.org/10.1007/978-3-030-88106-1_4

[41] A. Stocco, B. Pulfer, and P. Tonella, "Model vs system level testing of autonomous driving systems: A replication and extension study," *Empir. Softw. Eng.*, vol. 28, no. 3, p. 73, 2023. https://doi.org/10.1007/s10664-023-10306-x

[42] A. Stocco, B. Pulfer, and P. Tonella, "Mind the gap! A study on the transferability of virtual versus physical-world testing of autonomous driving systems," *IEEE Trans. Softw. Eng.*, vol. 49, no. 4, pp. 1928–1940, 2023. https://doi.org/10.1109/TSE.2022.3202311

[43] A. Stocco and P. Tonella, "Confidence-driven weighted retraining for predicting safety-critical failures in autonomous driving systems," *J. Softw. Evol. Process*, vol. 34, no. 10, p. e2386, 2022. https://doi.org/10.1002/smr.2386

[44] A. Stocco, P. J. Nunes, M. D'Amorim, and P. Tonella, "Thirdeye: Attention maps for safe autonomous driving systems," in *Proceedings of the 37th IEEE/ACM International Conference on Automated Software Engineering*, Rochester, MI, USA, 2022, p. 102. https://doi.org/10.1145/3551349.3556968

[45] A. Stocco, M. Weiss, M. Calzana, and P. Tonella, "Misbehaviour prediction for autonomous driving systems," in *ICSE '20: Proceedings of the ACM/IEEE 42nd International Conference on Software Engineering*, Seoul, South Korea, 2020, pp. 359–371. https://doi.org/10.1145/3377811.3380353

[46] E. Ferrandino, A. Capillo, E. De Santis, F. M. F. Mascioli, and A. Rizzi, "Improving simulation realism in developing a fuzzy modular autonomous driving system for electric boats," in *International Joint Conference on Computational Intelligence*, Valletta, Malta, 2023, pp. 163–184. https://doi.org/10.1007/978-3-031-46221-4_8

[47] E. Ferrandino, A. Capillo, E. De Santis, F. M. F. Mascioli, and A. Rizzi, "A comparison between crisp and fuzzy logic in an autonomous driving system for boats," in *2022 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, Padua, Italy, 2022, pp. 1–8. https://doi.org/10.1109/FUZZ-IEEE55066.2022.9882868

[48] E. Ferrandino, A. Capillo, E. De Santis, F. M. F. Mascioli, and A. Rizzi, "A modular autonomous driving system for electric boats based on fuzzy controllers and q-learning," in *International Joint Conference on Computational Intelligence*, 2021, pp. 185–195. https://doi.org/10.5220/0010678100003063