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A Systematic Patent Review of Connected Vehicle Technology Trends

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Abstract: Governments and manufacturers anticipate that connected vehicle deployments will reduce accidents, optimize traffic flow, and enhance the driving experience. Although extensive studies focus on the technical aspects of connected vehicles, a gap exists in systematically analyzing the invention trends shaping the field. Insights into these trends is a strategic imperative for policymakers, researchers, and investors alike. This study presents a systematic patent review (SPR) as a robust and adaptable methodological framework for patent analysis. Adapted from the established systematic literature review (SLR), the SPR offers detailed insights into both the thematic and temporal trajectories of innovation in any technology field. The SPR identifies 220 U.S. patents from 2018 to 2022 and classifies them into specific objective categories such as computing resources, cybersecurity, and driving safety, among others. The study notes an increasing focus on driving safety and secure wireless communications, which aligns with broader goals of enhancing safety and situational awareness in transportation. Both the methodological framework and findings address an existing gap in the literature, guide future research, policymaking, and investment in the field of connected vehicles.

Keywords: cybersecurity; driving safety; wireless communications; invention trends; thematic analysis; innovation landscape; methodological framework; policymaking

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1. Introduction

Connected vehicle (CV) technology promises revolutionary enhancements in driving safety, efficiency, and convenience. CVs have the potential to reduce accidents, optimize traffic flow, and enhance the driving experience by communicating with each other (V2V) and with everything else (V2X) [1]. In 2020, the U.S. Federal Communications Commission (FCC) repurposed 60% of the spectrum in a safety band dedicated to vehicle use, causing uncertainty and stalled investments [2]. Therefore, understanding this landscape will guide future research, policymaking, and investment decisions.

The current literature focuses on the technical aspects and applications of connected vehicles, such as driving safety and wireless communications. While these studies are invaluable, there is a gap in the systematic analysis of invention trends within this domain. Understanding these trends is crucial for identifying research gaps, and potential areas for technological advancements, and providing a roadmap for efforts in policymaking and standardization.

The goal of this research is to fill this knowledge gap by introducing a novel methodology for analyzing invention trends with a case study of connected vehicle technology. This research develops a systematic patent review (SPR), a new methodological approach based on a unique adaptation of the established systematic literature review (SLR) but tailored to patent analysis. The author designed the SPR methodology to be rigorous and adaptable, capable of both quantitatively and qualitatively evaluating patents to discern temporal and thematic trends.

This study utilizes a comprehensive dataset from the United States Patent and Trademark Office (USPTO), focusing on patents awarded from 2018 to 2022. The SPR workflow identified and classified 220 patents into distinct objective categories such as computing resources, cybersecurity, and driving safety, among others. The outcome offers a detailed understanding of the current state of connected vehicle technology and offers insights into its evolutionary trajectory.

The study contributes in two ways. First, it contributes to the SPR as a robust tool for patent analysis, providing a framework that researchers can apply to other emerging technologies. Second, it contributes a detailed analysis of invention trends in connected vehicle technology, including demonstrating the utility of the SPR in providing stakeholders with insights about emerging capabilities and deficiencies to plan for EV adoption.

The paper proceeds as follows: Section 2 reviews the literature on connected vehicle technology development. Section 3 describes the SPR workflow developed. Section 4 presents the workflow results. Section 5 discusses the implications, further insights, and limitations of the work. Section 6 concludes the research and suggests future work.

2. Literature Review

Connected vehicle technology is interdisciplinary, encompassing theories of transportation, computing, and engineering. Researchers have deeply explored the landscape of connected vehicles to understand the architectures, enabling technologies, applications, and development areas. Siegel et al. (2017) provided a comprehensive survey that summarized the state of the art in connected vehicles, discussing the challenges and opportunities in terms of privacy, security, scalability, and extensibility [3]. Yang et al. (2018) delved into the status and future perspectives of CVs, focusing on key technologies needed for their future deployment [4]. Ahmed et al. (2022) assessed the technological developments and impacts of connected and autonomous vehicles (CAVs), including government guidance, legislation, and regulations affecting their applications [5]. These works lay the groundwork for specialized studies in various aspects of connected vehicles, as described in the next subsections.

2.1. Networking

Amadeo et al. (2016) advocated a paradigm shift from traditional IP-based networking to information-centric networking to meet the challenges of maintaining wireless communications link speed, quality, and reliability in vehicular networks [6]. Soto (2023) examined road safety and traffic efficiency applications based on cellular-V2X technologies, emphasizing the role of digital communication in enhancing vehicular operations. Arthurs et al. (2021) examined edge cloud computing that enables vehicles to connect existing sensors such as road cameras, traffic density sensors, traffic speed sensors, emergency vehicle transmissions, and public transport transponders [7]. Nkenyereye et al. (2023) explored the fusion of fifth-generation (5G) cellular networks to enable software-defined vehicular cloud computing, an emerging technology where clusters of vehicles can share resources, sensor data, and complete tasks in a mobile ad hoc cloud environment [8].

2.2. Security and Cybersecurity

Security remains a crucial concern in the connected vehicle ecosystem. Shichun et al. (2023) provided a detailed review of cybersecurity techniques for CVs, discussing threat analysis, risk assessment, and intrusion detection [9]. Rathore et al. (2023) scrutinized challenges in in-vehicle communication cybersecurity [10]. Ju et al. (2022) surveyed attack detection and resilience from a vehicle dynamics and control perspective [11]. Hildebrand et al. (2023) presented a comprehensive review of the integration of blockchain technology in-vehicle networking to add trustworthiness and immutability [12]. Khan et al. (2023) proposed a secure communication system for CAVs using blockchain technology, focusing on privacy and protection against cyber threats like distributed denial of service attacks [13].

2.3. Traffic Management

Alanazi (2023) performed an SLR focusing on how autonomous vehicles manage traffic at junctions, categorizing approaches into rule-based, optimization, hybrid, and machine-learning procedures [14]. Shi et al. (2023) devised a real-time control algorithm for CAVs in signalized corridors, aiming to minimize fuel consumption and avoid idling [15]. Gholamhosseinian and Seitz (2022) completed a comprehensive survey on cooperative intersection management for CVs [16]. Xu et al. (2023) proposed an origin-destination-based partition technique to improve arterial signal coordination using data from CVs [17]. Zhu et al. (2022) conducted a comprehensive review of merging control strategies at freeway on-ramps [18]. Wang et al. (2022) discussed the development of CV cooperative driving systems, focusing on vehicle collaborative control algorithms and communication optimization [19].

2.4. Road Safety

Cui et al. (2022) reviewed cooperative perception technologies that aimed to fuse local and edge-sensing data to improve situational awareness and eliminate blind spots [20]. Khanal et al. (2023) used CV data to develop crash prediction models for intersections and road segments, offering a proactive approach to road safety [21]. Gao et al. (2023) provided a review and outlook on predictive cruise control of vehicles under cloud control systems, emphasizing the role of predictive algorithms in enhancing traffic efficiency and safety [22]. Islam and Abdel-Aty (2023) used CV data to predict traffic conflicts [23]. Schwarz et al. (2022) examined the role of digital twin simulations in traffic management centers, digital maps, onboard diagnostics, and route planning [24].

Overall, the existing literature spans assorted topics from foundational understanding, networking paradigms, and security concerns to traffic management algorithms, safety measures, and emerging technologies. While the industry has made considerable progress, challenges in security, real-time control, and traffic management persist, requiring future research to realize the full potential of CVs.

3. Methodology

A SLR systematically collects literature on a specific topic from across multiple databases for evaluation, integration, and interpretation [25]. This study presents a systematic patent review (SPR) that mirrors the general SLR process but highlights key distinctions. Table 1 contrasts the key steps in an SLR and an SPR. Both methods require defining a focused objective, searching a comprehensive set of databases, screening and selecting relevant documents, analyzing the main themes, and interpreting the results relative to achieving the objective. The first two steps of defining terms and using them to search established document databases are similar. However, the remaining steps utilize different approaches. The SLR screening process is qualitative because it relies on reading titles and abstracts whereas the SPR specifies a quantitative approach based on term frequency and term position distributions. Empirical observations found that patents peripherally related to a topic seldom mentioned a key term or mentioned it extremely late in the text.

The step to select documents is similar for both SLR and SPR because it requires qualitative evaluation by the researcher or a subject matter expert (SME). The author served as the SME in this research by leveraging his 30 years of industry experience as an electrical engineer with expertise and patents related to connected vehicles and intelligent transportation systems. The analysis step could be similar, depending on the objective of the document review. The SPR in this research specified classifying patent objectives to identify both temporal and thematic trends. The interpretation step may also be similar for both SLR and SPR. However, this research specified utilizing a word cloud to visualize thematic patterns within each of the SME-defined categories.

Table 1. Contrasting the Key Steps in SLR and SPR.

Step	SLR	SPR
Objective	Define a specific and answerable research question within a focused topic area.	Specify a topic area based on well-established terms used by the patent filing system.
Search	Retrieve literature from scholarly databases (e.g., Scopus, Google Scholar) that matched specified inclusion and exclusion criteria.	Access a patent database from the official patent office of a specified country and extract all documents containing the defined keywords.
Screen	Judge validity for inclusion based on pre-defined criteria for relevancy.	Extract documents that are relevant based on a quantitative assessment of their term frequency and position distributions.
Select	Read the full text to exclude documents that do not address the research question.	Exclude low-relevance documents via qualitative assessment by a subject matter expert.
Analyze	The data synthesis should provide a comprehensive and informative answer to the research question.	Subject matter expert classification of patent objectives.
Interpret	Synthesize the available evidence, identify gaps, and generate new theories.	Visualize a denoised word cloud of documents within each objective class to interpret themes and trends.

Figure 1 illustrates the SPR workflow developed in this research. The author coded all procedures in the Python programming language. The study employed a database of patent summaries from the United States Patent and Trademark Office (USPTO) of patents awarded from 2018 to 2022 [26]. To minimize size, the USPTO database contained only the patent number and a text summary of each patent. That is, the database excluded information such as the patent title, inventor, organization, geographic location, and other details. The lack of such information did not affect the SPR's goal of identifying thematic and temporal patterns in inventions concerning connected vehicle technology. That is, the summary of the patent alone provided all the information needed to identify the objective of the invention.

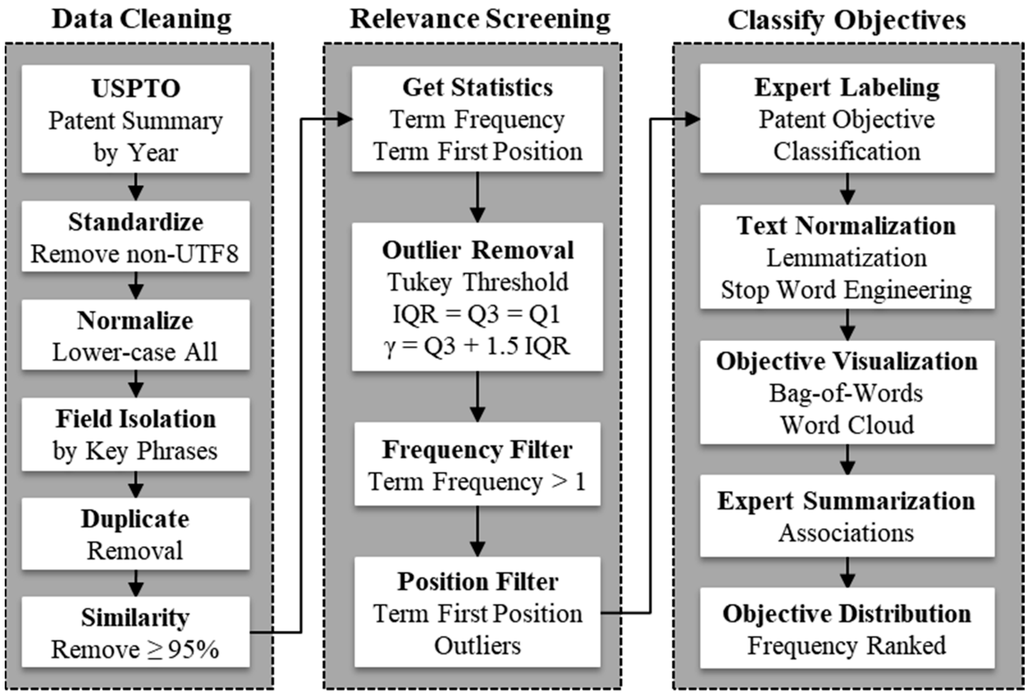

Figure 1. SPR workflow.

The SPR workflow comprised three sets of procedures: data cleaning, relevance screening, and classification of patent objectives. Data cleaning eliminated non-standard characters, isolated patents that contained the key phrase "connected vehicle" or its plural form, and removed duplicate or similar patent descriptions. The measure of similarity was the cosine similarity expressed as

$$cos(\theta) = \frac{\sum_{i=1}^{n} X_i Y_i}{\sqrt{\sum_{i=1}^{n} X_i^2}\sqrt{\sum_{i=1}^{n} Y_i^2}} \quad (1)$$

where the word vectors X and Y represent a document pair and n is the number of word representations in each vector. The word representations are tokens derived from a natural language processing procedure that breaks down text into smaller units for more efficient processing [27]. The theory is that the angle between vectors of similar documents will approach zero in multidimensional feature space. This SPR specified a similarity threshold of 95% to mirror the p-value threshold that is customary in hypothesis testing [28].

Relevance screening isolated and removed documents that were outliers in the term frequency and the term position's first mention. The outlier frequency is a single mention of the term "connected vehicle" or its plural form and the outlier position was the Tukey threshold

$$\gamma = Q_3 + 1.5 \times [Q_3 - Q_1] \quad (2)$$

where Q_1 and Q_3 are the first- and third-quartile values, respectively, of the ordered position values [28].

The procedures to classify patent objectives utilized SME's understanding of the patent objective, which was the specific problem that the patent was addressing. Each objective class featured a word cloud to visualize its main themes. The word cloud is a graphic that displays a cluster of words with font sizes proportional to their frequency of occurrence in the document set. Effective visualization necessitates text normalization to remove punctuation, numbers, single-character words, symbols, and "stop-words" that do not convey meaning. Lemmatization increased the efficiency and quality of the word cloud by reducing all words to their base meaning, such as their singular form.

Stop-word engineering eliminated common English words, common field terminology, and domain-specific words that did not contribute towards distinguishing among themes. Examples of common English stop-words are "and", "the", and "it". The field-specific stop-words were "connected" and "vehicle" because they appear in all the patent summaries due to the search criteria. Domain-specific words were those commonly used in patent documents such as "invention", "embodiment", "method", "apparatus", "claim", "said", and "according". The word cloud visualization helped the SME refine the classification of patent objectives by iterating the workflow.

4. Results

The USPTO database holds a total of 1,637,725 patents across the five-year period, which amounted to an annual average of 327,545 patents. The SPR workflow identified 220 relevant patents from that period. These data revealed that the USPTO awarded an average of 44 patents annually that focused on connected vehicles, a 50% increase from 2018 to 2022. Table 2 summarizes the results of the data-cleaning and relevance-screening portions of the SPR workflow. Term frequency-based relevance filtering reduced the number of patents that focused on connected vehicles by an average of 58.5%, yielding 254 patents in total. Further filtering to eliminate term position outliers further reduced the number of relevant patents to 224. Figure 2a shows the distribution of the term frequency and Figure 2b shows the distribution of the first position of mention for the term. Each figure's inset displays a box plot of the distribution statistics. Specifically, the term "connected vehicle" appeared on average 4.65 times with a standard deviation of 11.2. The first quartile ended with a frequency of 1, and the third quartile began with a frequency of 3. SME analysis identified four patents that were not relevant because of term confusion. The confused patents discussed methods to physically "connect" a vehicle to an object or another vehicle in tow.

Table 2. Results of the Data Cleaning and Relevance Screening.

Procedure	2022	2021	2020	2019	2018	Mean
USPTO Summaries	283,075	330,645	355,647	357,790	310,568	327,545
Field Isolation	166	145	136	104	71	124
Duplicate Removal	164	144	135	100	64	121
Similarity Reduction	160	141	135	100	64	120
Frequency Filter	75	60	54	42	23	51
% reduction	53.1%	57.4%	60.0%	58.0%	64.1%	58.5%
“connected vehicle” < pos count	67	51	50	37	19	45
“connected vehicle” < pos thresh	698	488	690	811	332	604
SME Relevance Analysis	66	50	50	35	19	44

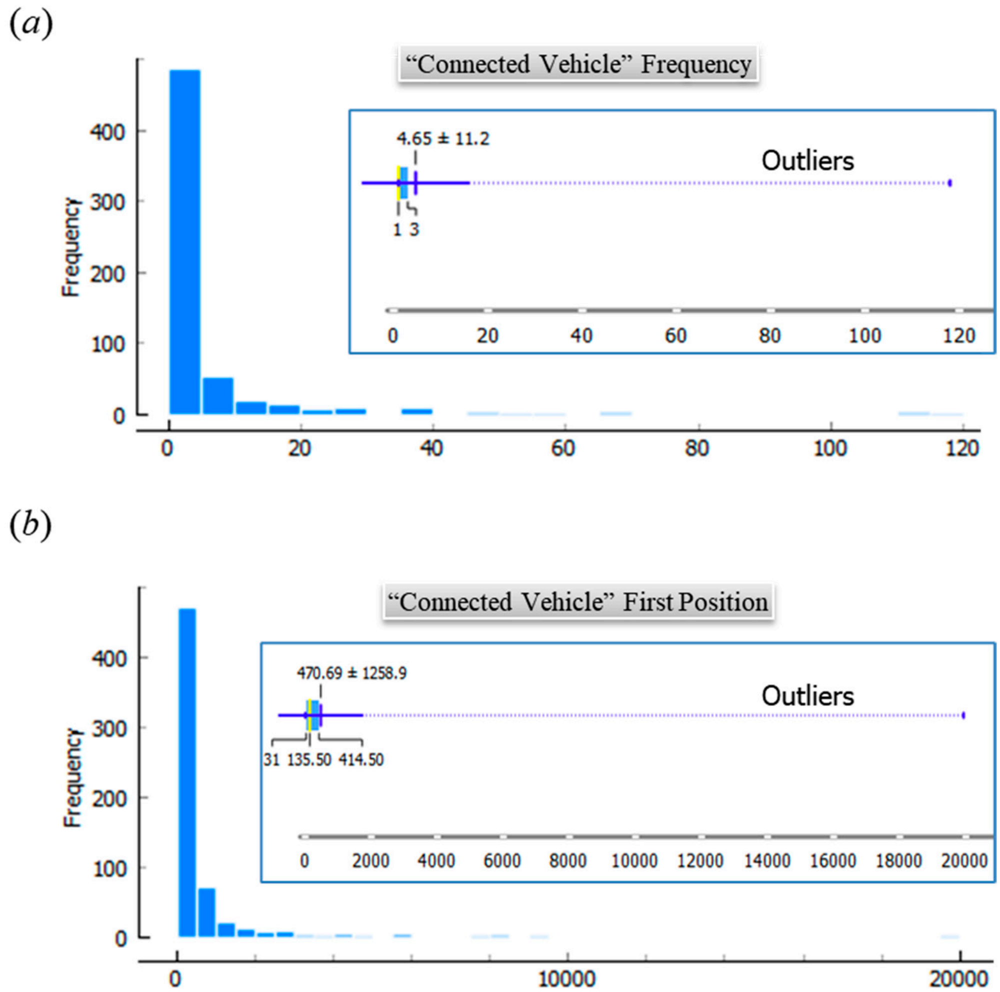

Figure 2. Distribution of (**a**) key phrase frequency and (**b**) first position of occurrence.

Table 3 categorizes the SME classification of patent objectives and describes the general focus and methodologies employed within each category. Figure 3 shows the distribution of each objective class by frequency, year, and temporal trend per class. Patents concerning CVs have risen steadily since 2018. The dominant objective of enhancing driving safety increased since 2019. Figure 4 shows individual word clouds for each of the objective categories. Dominant keywords within each word cloud, upon inspection, aligned well with the SME description of patent objectives for each category.

Table 3. SME Classification of General Patent Objectives.

Objective	General Description
Computing Resource	Communications traffic to exchange sensor data and a wide range of other information, including the need for low latency to meet real-time demands place additional burdens on available computational resources. Objectives target optimal resource allocation and usage of onboard and cloud-based computing resources and optimizes communications across multiple network interfaces and servers.
Cybersecurity	Growing wireless connectivity between vehicles and other things, including other vehicles, expands the vulnerability surface for cyber-attacks. Objectives address enhanced cybersecurity including encryption, authentication, and intrusion detection methods.
Driving Safety	Objectives utilize vehicle-to-everything connectivity and sensors on other vehicles to enhance visibility and situational awareness. Safely navigating in complex environments, including through intersections and among pedestrians, and avoiding collisions.
Information Management	Demand for efficient management of information across software applications and services scales with increased vehicle connections. Objectives assure that systems present relevant information to vehicle operating and in-cabin infotainment systems to prevent data overload and prioritize information that is essential for vehicle operation, safety, and user experience.
Multi-vehicle Networking	Vehicle clusters can form and maintain micro vehicular clouds to efficiently share and exchange information. Objectives address the efficient use of resources among vehicles to enable capabilities such as distributed data storage, collaborative computing, reliable communications, and service provisioning.
Platooning	The streamlined aerodynamics of vehicles following each other more closely than normal (platooning) results in better fuel efficiency and improved traffic flow. Objectives address various ways to utilize wireless, sensors, and real-time control mechanisms to enable safer and more cost-efficient platooning and alerting law-enforcement.
Smart Parking	Locating parking spaces in crowded and complex environments can be challenging and contribute to congestion. Objectives facilitate cooperative parking space searches, including charging for the "ego" vehicle by using sensors and micro vehicular clouds or centralized services.
Traffic Signaling	Suboptimal traffic signal timing can exacerbate congestion. Objectives leverage wireless communications and sensors among vehicles to assess conditions and predict arrival times while dynamically optimizing traffic signaling for overall traffic impact.
Vehicle Monitoring	Objectives aim to enrich in-cabin experiences for passengers through display devices that provide various forms of information and entertainment. Methods of preventing motion sickness by monitoring and predicting ride quality.
Vehicle Navigation	Objectives update electronic maps with real-time data from vehicles for more accurate navigation. Detecting environmental changes dynamically such as topography, emergency situations, and seasonal conditions like flooding or snow to inform alternative routes.
Wireless Communications	Objectives address advancements in wireless communications such as lower latency cellular networks, quality of service, resilience in noisy environments, and interference.

The next sections illuminate how dominant keywords align with the patent objectives in each SME-defined category:

Computing resource: dominant keywords include "speed", "terminal", "edge server", and "digital twin". These pertain to methods of offloading computing burden to edge servers and other terminals to increase the speed of information processing or employing digital twin simulations to inform the optimization of resources for enhanced reliability of information exchanges.

Cybersecurity: dominant keywords include "security", "authentication", and "pseudonym certificate". These refer to enhancing the integrity of data exchanges through authentication and methods of reducing the computational burden of message signing by using pseudonym certificates to enhance privacy or detect malicious activities.

Driving safety: dominant keywords include "ego", "driver", "pedestrian", "sensor", "change condition", and "environment". These refer to methods of exchanging sensor data, using the focus or "ego" vehicle for orchestration, to improve situational awareness and visibility for both pedestrians and drivers and to detect changes in traffic or environmental conditions that inform driving adaptation.

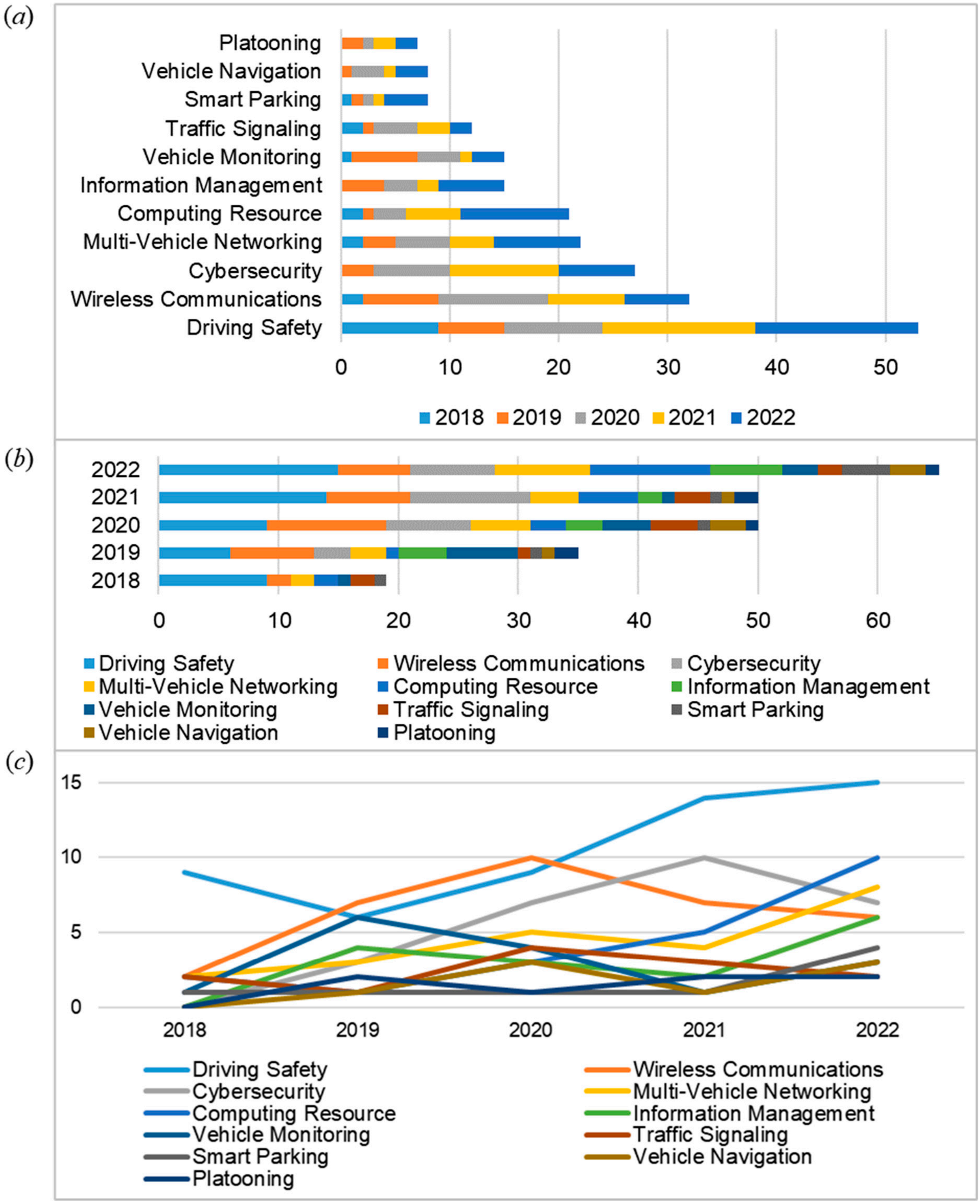

Figure 3. Distribution of patent objectives by (**a**) classes, (**b**) by year, and (**c**) temporal class trend.

Information management: dominant keywords include "advertisement", "cluster", "travelable range", "monitor module", "wireless", and "processor". These refer to using the wireless communications of vehicles within clusters such as at an event to broadcast relevant advertisements or to predict travel range through diverse processing and monitoring techniques.

Multi-vehicle networking: dominant keywords include “micro cloud”, “micro vehicular cloud”, “access point”, and “server”. These refer to means of collaboratively forming a virtual cloud computing facility by utilizing the computing resources and wireless communications of a vehicle group.

Platooning: dominant keywords include “following”, “gateway processor”, “interface controller”, and “platoon”. These refer to methods of controlling the “following” vehicle in a convoy to reduce air gaps by utilizing an interface controller and/or a gateway processor to synchronize vehicle movements.

Smart parking: dominant keywords include “electric”, “charging pad”, “park”, “event”, and “account”. These refer to utilizing the sensors of connected vehicles to share information about parking spot availability for example, at events, and to identify parking spots with vehicle-compatible electric chargers, including means to automatically bill an account.

Traffic signaling: dominant keywords include “intersection”, “road”, “light”, “signal”, and “timing”. These refer to adapting the signal timing of traffic lights based on sensing the queue length and traffic flow to increase intersection safety and throughput.

Vehicle monitoring: dominant keywords include “roadway segment”, “condition”, “onboard sensor”, “processor”, “interface”, and “custom configuration”. These refer to using sensors, processing, and computing interfaces to monitor the condition of vehicle and roadway segments for adaptive or custom configurations that will enhance the ride experience.

Vehicle navigation: dominant keywords include “emergency”, “coordinate”, “scenario vector”, “moving object”, “map”, and “geofence”. These refer to coordinating geospatial and map information among vehicles for situational analysis and route planning, including avoiding interference with emergency vehicles and slow-moving objects.

Wireless communications: dominant keywords include “geographical region”, “geographical resource”, “radio resource”, “channel interference”, “adjacent channel”, “access point”, “VX”, and “base station”. These refer to designing V-to-X (VX) communications systems that incorporate access points and base stations to minimize wireless interference and to adapt operations for improved channel reliability based on radio resources available in different geographical regions. Key objectives of the V-to-X inventions included increasing the reliability and decreasing the latency of wireless communications, especially while moving. Methods achieving those objectives included dedicating access points to a mobile user, switching between cellular and short-range wireless channels, dynamically optimizing network control parameters, selecting networks dynamically to minimize usage cost and loading, packet priority tagging, splitting femtocells to support multiple in-vehicle operators, keeping track of noisy locations to predict when to pre-load streaming content, mapping pre-determined radio resource locations to optimize performance, and leveraging satellite radio to increase the broadcast area for messages.

The aggregate summary reveals dominant keywords such as “micro cloud”, “wireless”, “receiving”, “driver”, and “perform action”. This suggests that at the aggregate level, the dominant invention themes involve improving the reliability of wireless communications, forming vehicular micro clouds to exchange information, receiving messages, and taking action to improve driving safety. These observations are consistent with the finding that the dominant themes were driving safety and wireless communications, as shown above in Figure 3.

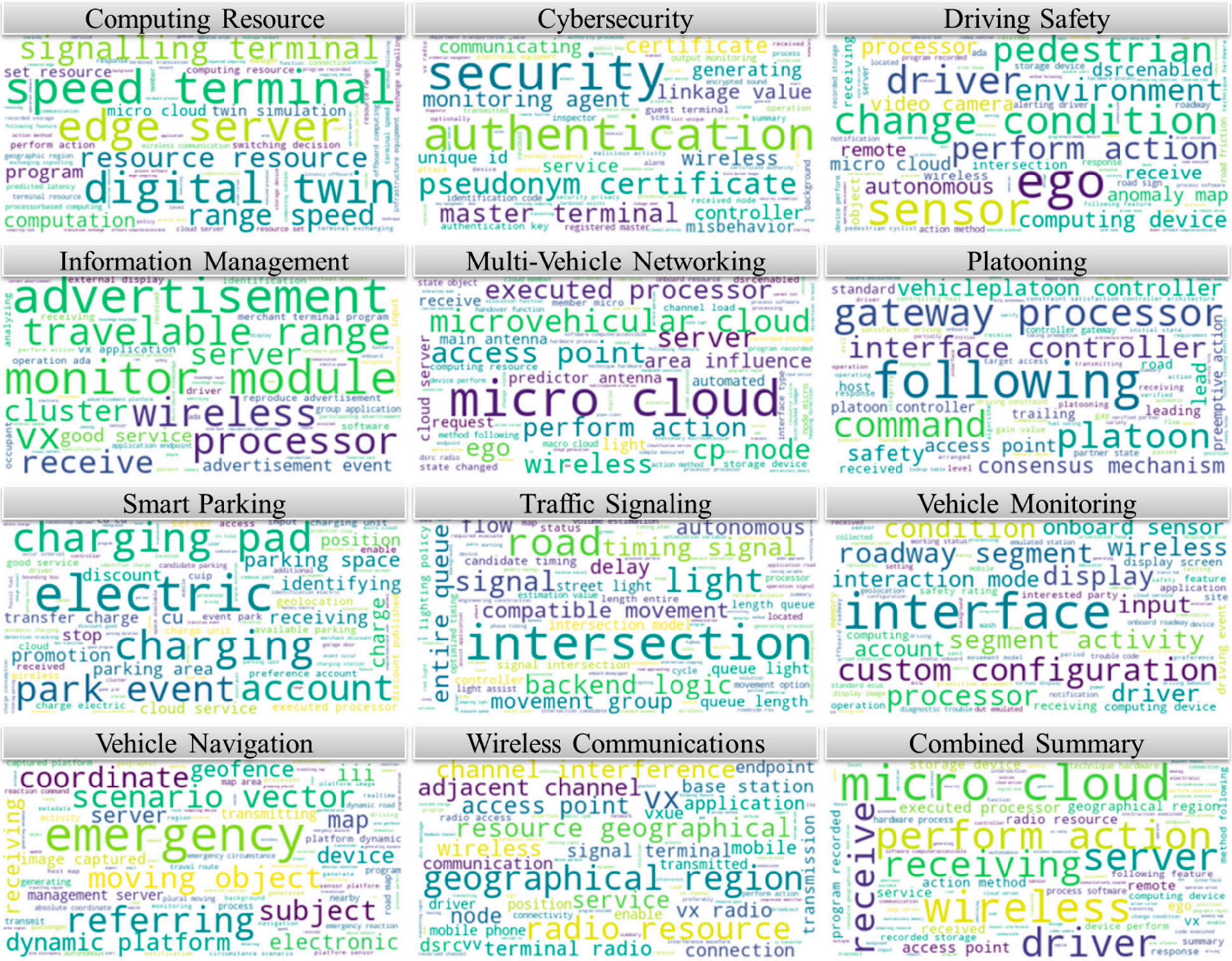

Figure 4. Word cloud for each objective category.

5. Discussion

This study addresses a critical gap in the existing literature by delivering a systematic analysis of CV-related technology invention trends. Results show an increasing focus on driving safety and wireless communications, domains aligning closely with CV technology's broader objectives to enhance situational awareness and road safety. Compared to optical sensors like cameras and LiDAR, radio technologies offer the advantages of greater range in wireless data exchange, bypassing blind spots and penetrating occlusions. Advancements in vehicular microcloud enable vehicles to share sensor data, which increases their collective ability to cooperatively observe and adapt to changing traffic, weather, and other environmental conditions.

The surge in V2X-related patents emphasizes the industry's focus on developing robust wireless networks to facilitate real-time data exchange between vehicles and their environment, despite spectrum allocation uncertainties. These innovations lay the groundwork for integration into autonomous vehicles, complementing their individual ability to navigate using onboard sensors and eliminating human error. This study confirms that recent inventions in CV technology represent a strategic focus that is integral to the future evolution of smart and sustainable mobility solutions.

The established SLR methodology inspired the development of the SPR methodology introduced in this research. The study contributes a nuanced approach to patent analysis by providing both quantitative and qualitative insights into the thematic and temporal trajectories of an innovation. SPR utility extends beyond academia, serving as a replicable framework with broad applicability in analyzing invention trends in other fields. Identified thematic and temporal trends can inform policy decisions, guide standardization efforts, and influence investment strategies.

While the SPR methodology and the insights it offers are robust, this study has limitations. This case study limited the dataset to USPTO patents from 2018–2022, possibly missing global trends or long-term evolutionary trajectories. However, selecting the past five complete years (excluding partial data for 2023) captured annual trends. Additionally, the study relies on one SME for patent classification, potentially adding bias. Future work will incorporate international patents and multiple SMEs to mitigate these limitations. Although representative, patents alone do not necessarily reveal the complete innovation trends in an area of technology development because companies may not commercialize products based on some inventions, and some companies may avoid patenting an invention to conceal trade secrets. Despite its limitations, this study serves as foundational work that future research can build upon.

6. Conclusions

Despite regulatory uncertainty, policymakers and manufacturers are pursuing CV technology development based on its transformative potential to enhance safety, efficiency, and user experience. This research clarifies the innovation landscape of this evolving field, aiming to inform subsequent research, policymaking, and investment decisions. This study introduced the Systematic Patent Review (SPR) as a methodological framework to analyze invention trends, with a case study of CV technology. The SPR used a comprehensive dataset from the USPTO, identifying 220 patents awarded from 2018 to 2022. An SME categorized them into defined classes such as computing resources, cybersecurity, driving safety, and others. The outcome provided detailed insight into the current state of CV technology, with insights into its evolutionary trajectory. The SPR's contribution lies in its robust and replicable framework for patent analysis in emerging tech sectors. Understanding areas of technology capability, availability, maturity, and readiness for commercialization will help the industry prepare relevant and effective standards and regulations to encourage broader adoption. These insights offer guidance to inform further research, policymaking, and investments, fulfilling the revolutionary promise of CVs. Future work will employ the SPR and use the SME classification as ground truth to assess the performance of unsupervised methods such as Latent Dirichlet Allocation and Non-negative Matrix Factorization.

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