



# A bibliometric performance and network analysis of red-light camera impact on signalized intersection safety

Samaila Garba , Pengyu Zhu <sup>\*</sup>

Division of Public Policy, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

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## ABSTRACT

**Introduction:** Red-light running (RLR) at signalized intersections poses a significant threat to traffic safety, contributing to thousands of fatalities and injuries globally each year. Despite the introduction of red-light cameras (RLCs) to mitigate these violations, their effectiveness remains contentious, with inconsistent results across studies. This article utilizes bibliometric performance and network analysis (BPNA) alongside a systematic literature review (SLR) to evaluate the impact of RLCs on signalized intersection safety. **Method:** By analyzing literature from 1975 to 2024, the study reveals a complex landscape of research themes, highlighting both the successes and challenges associated with RLC implementation. **Results:** The findings identified prominent research themes, influential authors, institutions, and gaps in the literature, emphasizing the need for comprehensive strategies that combine RLC implementation with community engagement and driver education to enhance traffic safety. It also illustrates the necessity for continued exploration of RLC efficacy and the development of innovative approaches to enhance compliance, ultimately informing policymakers and traffic safety advocates about the critical importance of addressing RLR in urban areas. **Conclusions and Practical Applications:** The study advocates for the integration of RLC systems with emerging technologies, such as vehicle-to-infrastructure (V2I) communication. As connected vehicles become increasingly prevalent, the synergy between RLCs and V2I systems could facilitate a more comprehensive understanding of traffic environments, thus enabling real-time updates and enhanced driver assistance functionalities for improving traffic safety and efficiency at signalized intersections.

## 1. Introduction

Red-Light Cameras (RLCs) have been introduced as a countermeasure to mitigate red-light running (RLR) at signalized intersections and to reduce related traffic crashes (Retting et al., 2003). Operational since the 1970s in Europe and introduced in the early 1990s in the United States, RLCs function by comparing the status of traffic signals with data from vehicles approaching signalized intersections (Retting et al., 1999). Most systems employ electromagnetic sensors embedded in the pavement to detect violations (Fig. 1), capturing images of offending vehicles along with critical information such as time, date, vehicle speed, and the interval between the activation of the red signal and the vehicle's crossing of the stop line (Fig. 2). Typically, two photographs are taken: one as the vehicle crosses the stop line and another as it proceeds through the signalized intersection (Fig. 3). These images are used to issue citations to vehicle owners (Retting et al., 2003).

RLCs act as remote enforcement mechanisms, enabling law

enforcement agencies to monitor compliance with traffic signals and potentially deterring drivers from running red lights (Retting et al., 2002). McCart and Hu (2013) posited that RLR is a prevalent traffic violation globally, accounting for over 300,000 injuries and an average of 7500 fatalities annually. While assessing the safety efficacy of photo enforcement programs is critical in intelligent transportation, the impact of RLCs on driver behavior globally remains a subject of ongoing debate. Minor infractions, often occurring within the first second after the light turns red (referred to as the “dilemma zone”) (Fig. 4), may not pose significant safety risks (McCart & Hu, 2013). In contrast, intentional RLR by reckless drivers, particularly when occurring 1.5 s or more after the light has turned red, presents a considerable risk of fatality (McCart & Hu, 2013). This reckless behavior of drivers who run red lights or ignore other traffic controls has become a prominent factor in urban traffic crashes and is associated with injuries in 40% of such incidents (IIHS, 2022). Although many drivers comply with traffic signals, violations persist, often due to distractions, aggressive driving behaviors, or deliberate disregard for signals. A study by Zaal (1994) suggested that

<sup>\*</sup> Corresponding author.

E-mail address: [pengyuzhu@ust.hk](mailto:pengyuzhu@ust.hk) (P. Zhu).

Nomenclature	
BPNA	Bibliometric Performance Network Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RLCs	Red Light Cameras
RLR	Red Light Running
SciMAT	Science Mapping Analysis Tool
SLR	Systematic Literature Review
V2I	Vehicle-to-Infrastructure
WoS	Web of Science

eliminating these traffic violations can help substantially in reducing road crashes, potentially decreasing them by as much as 35%.

The Insurance Institute for Highway Safety (IIHS, 2022) estimates that about 1.8 million RTCs occur yearly at intersections in the United States, with RLR accounting for 1149 fatalities and approximately 144,280 injuries in 2022. The IIHS study also found that RLCs have reduced the number of deaths as a result of RLR related crashes in large cities by 21%, while the overall occurrence of fatal crashes at signalized intersections reduced by 14% (IIHS, 2022). This traffic violation is further underscored by a study conducted by Hill and Lindly (2003), which revealed an average violation rate of 3.2 per intersection per hour across 19 signalized intersections in four states. Similarly, another study by Retting et al. (1999) analyzed five heavily trafficked signalized intersections in Fairfax City, Virginia, reporting an average of 3 violations per intersection per hour.

Research by Brittany et al. (2004) examined 9951 fatal crashes at

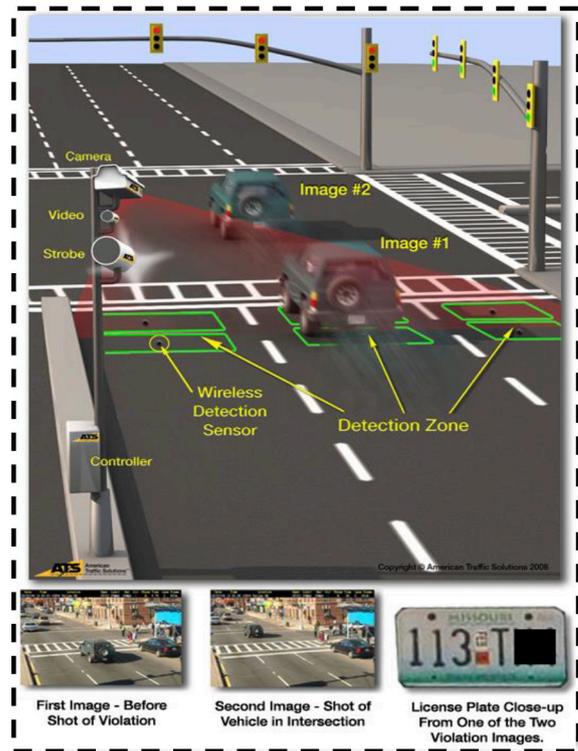


Fig. 2. Capturing critical information at a signalized Intersection.

signalized intersections from 1999 to 2000, indicating that 20% of drivers did not comply with traffic signals. Additionally, the Federal

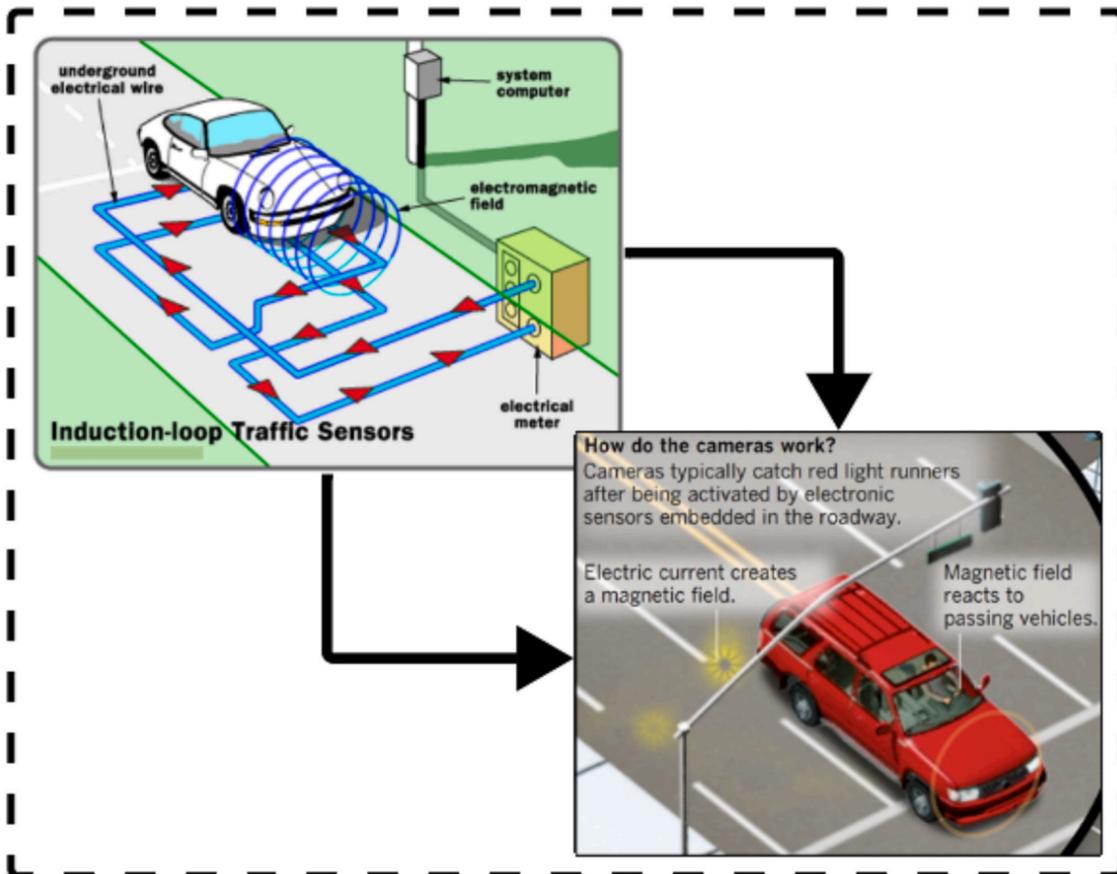


Fig. 1. Electromagnetic sensors for detecting traffic violation at signalized intersection and how it works.

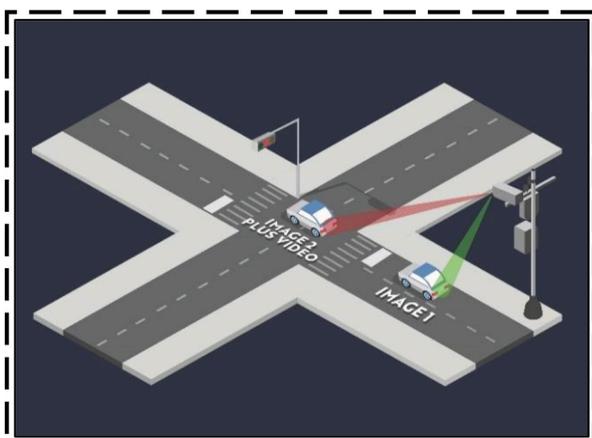


Fig. 3. Sequence of the Two photographs captured. (*Image 1: captures the vehicle behind the stop bar while light is red; Image 2: captures the vehicle proceeding through the intersection while the light is red.*) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

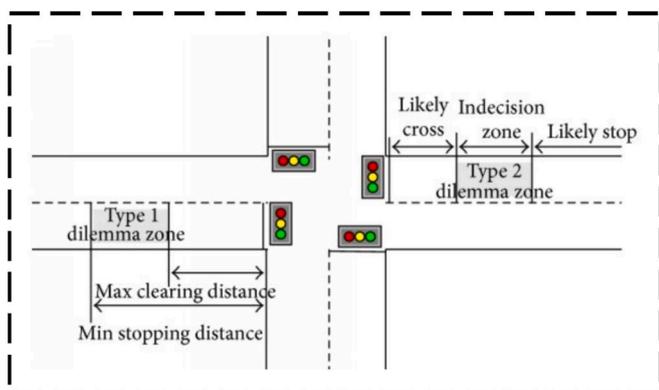


Fig. 4. Dilemma zones at signalized intersection.

Highway Administration (FHWA) 2013 (Erke, 2009) reported that 50.7% of Americans acknowledge having run red lights, with over 85% expressing concern about the likelihood of a collision with a vehicle running a red light when entering a signalized intersection.

Notwithstanding the potential benefits of RLCs in deterring traffic violations at signalized intersections and improving safety, law enforcement agencies face considerable challenges, highlighting the need for innovative and effective strategies for managing and enforcing traffic regulations (Insurance Institute for Highway Safety, 2017). Notably, while several papers have addressed various aspects of this topic (Retting et al., 2003; Retting et al., 1999; Retting et al., 2009; Retting et al., 2008; Ahmed-Aty, 2015; Helai et al., 2008; Shin & Washington, 2007; McGee & Eccles, 2003; Retting & Kyrchenko, 2002; Golob et al., 2002; Ng et al., 1997) findings regarding the effectiveness of RLCs on signalized intersection safety and crash rates are mixed. Some studies indicate a significant reduction in RLR violations (Garber et al., 2007; Garber et al., 2005; Council et al., 2005; Fox, 1996), while others report minimal impact or even an increase in overall crash frequency (Burkey & Obeng, 2004; Yaungyai, 2004; Cusack & Tait, 2001; Gallagher & Fisher, 2020).

This inconsistency highlights the contentious nature of RLCs' effectiveness in improving safety at signalized intersections and emphasizes the urgent need for strategies that enhance compliance and safety at traffic signals (Hill & Lindly, 2003). Regardless of the growing interest in RLCs and their impact on signalized intersection safety, there remains a notable absence of systematic analyses utilizing knowledge-based tools,

such as scientometric analysis, to evaluate this relationship. To the best of our understanding, no study has undertaken a comprehensive analysis of the entire body of academic literature on RLCs from 1975 to 2024. The use of scientometric analysis facilitates the characterization of RLCs within this context, revealing a range of pertinent topics and enabling their classification based on both external and internal coherence within the thematic network. This analysis not only elucidates the origins of these themes and their constituent terms but also enhances the plausibility and logical interpretation of the findings. To address this gap, this study conducts a bibliometric performance and network analysis (BPNA) with systematic literature review (SLR) to gain a thorough understanding of the literature on RLCs. The aim is to offer a comprehensive overview of the current research landscape regarding RLCs within the context of signalized intersection safety.

The findings from this study offers a robust foundation for contextualizing existing contributions in the field while identifying emerging trends and outlining directions for future research. It also provides insights into the evolution of themes over time, as well as the most influential journals, institutions, and productive authors contributing to the literature. Therefore, this study contributes to the field in three significant ways. Firstly, it elucidates the knowledge structure surrounding RLCs in relation to signalized intersection safety from 1975 to 2024. Secondly, it develops a comprehensive scientometric analysis model that encompasses multiple aspects and highlights the research hotspots covering both the past and the present within this domain. Lastly, it proposes several directions for future research, thereby paving the way for continued exploration and advancement in this area. This study is structured as follows: Section 2 outlines the methodology employed in this research; the results and discussions are presented in Section 3; the methodological evaluation and key critiques in RLC research are discussed in Section 4; challenges and limitations of RLC is provided in Section 5; while Section 6 explores potential future research directions. Finally, Section 7 offers a conclusion of the research conducted.

## 2. Materials and methods

To accomplish the objectives for this study, a BPNA supported by SLR was conducted using scientometric mapping. For the BPNA, we utilized the SciMAT tool for data analysis. The SLR was guided using PRISMA protocol to examine literature focused on identifying the challenges associated with RLCs. The overall workflow is depicted in Figs. 5 and 6, showcasing the science mapping approach, which includes bibliometric data search and retrieval, pre-processing analysis, import and scientometric analysis involving network extraction, normalization and mapping, as well as discussion, conclusions and future directions. In this study, we pose the following research questions:

- i. What themes have been studied most frequently and are currently receiving attention in this domain?
- ii. How is the intellectual structure of knowledge in the area of RLCs organized?
- iii. What key emerging and declining research themes are associated with RLCs that may reveal unexplored avenues for future research?
- iv. Which authors, journals, and institutions have the greatest influence in the field of RLC in relation to signalized intersection safety?
- v. What are the key limitations of RLCs research?

We proposed that the research landscape of RLCs in signalized intersection safety reveals a dynamic intellectual framework thus highlighting an increasing focus on integrating technology with human behavior. However, themes such as "Emerging" suggest that there are still unexplored avenues for future research. While influential authors, journals, and institutions significantly help in shaping the discourse.

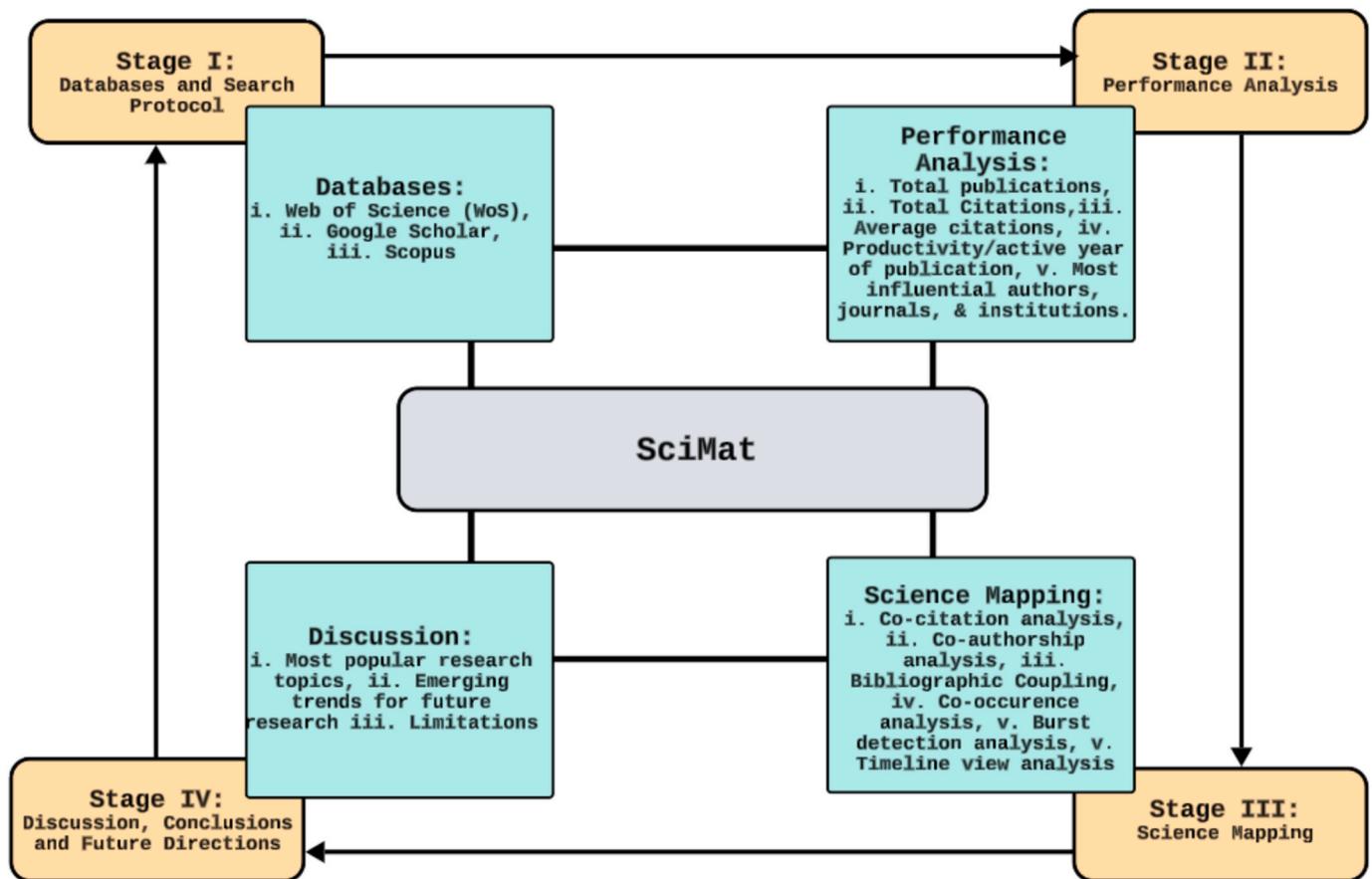


Fig. 5. Methodological framework.

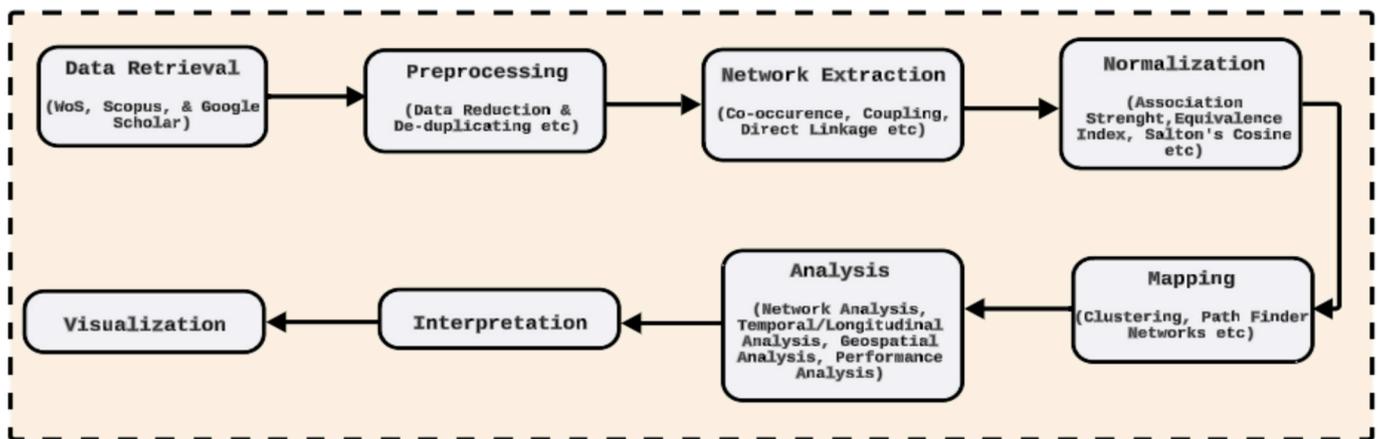


Fig. 6. Science mapping framework.

Nonetheless, key limitations remain that impede a full understanding of the role of RLCs in traffic safety.

### 2.1. Bibliometric search

To create an extensive map of the knowledge framework in the area of RLCs within the context of signalized intersection safety, we implemented a database search following a well-established systematic review protocol, aligned with recent advancements in bibliometric research (Alshater et al., 2023; Anuar et al., 2022; Dabić et al., 2020). Data extraction for the bibliometric analysis was conducted on December 30, 2024, using “Publish or Perish” software while adhering

to PRISMA protocol (Fig. 10) as recently updated by Page et al. (2021). Originally introduced in 2009 to improve transparency and rigor in systematic reviews, the PRISMA protocol (Fig. 10) has evolved to reflect advancements in methodology, providing researchers with a comprehensive checklist to improve bibliometric analyses and reporting (Cobo et al., 2011). This review explores current and emerging research trends related to RLCs while identifying potential future research directions. The following research database including (i) Web of Science (WoS) core collection database of Clarivate Analytics UK, (ii) Google Scholar, and (iii) Scopus were chosen for this study. We selected WoS for its full coverage of high-quality peer-reviewed literature, while Google Scholar provided an extensive array of scholarly materials and citation metrics,

while Scopus was included for its focus on credible publications and frequent updates. The reliability of every bibliometric study is greatly influenced by the precision of the search criteria employed for the data retrieval. As a result, we developed a comprehensive list of expressions (keywords) pertinent to Red-Light Camera interventions aimed at reducing traffic violations and crashes, which includes: ‘Red-Light Camera,’ ‘Red-Light Running,’ ‘Intersection,’ and ‘Signalized Intersection.’ To ensure a thorough search, the selected keywords were required to be present in the abstracts, titles, or keywords of the retrieved articles.

### 2.2. Data pre-processing

In this case, data retrieved from bibliometric sources often contains errors, such as misspellings in author names, journal titles, reference lists, or author affiliations. This makes it necessary to supplement the original data with further information, particularly if an author’s name is duplicated by using the last name as the first name in different publications. This calls for a process called de-duplication. Consequently, science mapping analysis cannot be applied directly to the retrieved data; a pre-processing step is essential. This pre-processing phase is critical for enhancing the quality of the units of analysis, primarily keywords and authors, which are pivotal for achieving more accurate and reliable outcomes in the subsequent scientometric analysis. Therefore, this action was conducted on the retrieved data before the commencement of data analysis. The SciMAT software was used, as it offers several advantages, with its robust pre-processing module being paramount, since data extracted from the database requires meticulous pre-processing to ensure quality outcomes.

### 2.3. Data processing

The initial search identified 9529 documents (WoS: 1846; Google Scholar: 2850; Scopus: 4833) published up to November 2024. Approximately 5243 documents were removed as duplicates. After applying exclusion criteria, this number was narrowed down to 4036 articles and reviews in English language relevant to the search topics (red-light camera, red-light running, and signalized intersection), while 1000 irrelevant publications from out-of-scope journals were excluded. Following the methods established by Khan et al. (2020), Caputo et al. (2021), and Alshater et al. (2023), an interpretive refinement assessed article relevance, resulting in the retention of 2,136 articles, with 900 excluded for irrelevance. This ensured that only articles discussing the searched keywords within the broader context of intersection safety were included in the final dataset. Upon completion of the search procedure, the final sample of articles was exported in both plain text and comma-separated values (CSV) formats for use in the bibliometric analysis software employed in this study. A detailed overview of the search procedure is presented in Table 1.

### 2.4. Scientometric analysis

Cobo et al. (2011) evaluated nine bibliometric software applications and identified a significant gap in the literature: no single software was capable of analyzing all key elements of science mapping. This limitation necessitated the use of multiple software applications concurrently to achieve a comprehensive bibliometric analysis. To address this issue, the authors (Cobo et al., 2011) developed SciMAT, a comprehensive tool that facilitates bibliometric process. This study also considered this limitation, which is a reason why we used the SciMAT software tool. This study employs scientometric analysis, also known as science mapping analysis, in order to accomplish the different tasks involved in the stages of its analysis. This analytical approach enabled the summarization of the extensive bibliometric data we extracted, facilitating the description and identification of the intellectual structure and emerging trends associated with the RLC research area. The science mapping analysis provided the study with a visual framework for assessing the

**Table 1**  
Detailed overview of search procedure.

S/ No.	Item	Criteria
1.	Search Topics Used	“Signalized Intersection” or “Red Light Running” or “Red Light Camera”
2.	Period (Years)	Only articles published from 1975 to 2024
3.	Access	Open Access & Non-Open Access included
4.	Area of Interest (AOI)	Subject area covers; Red-Light Cameras, Intersection Safety and Signalized Intersection.
5.	Medium of communication	All Non-English articles were excluded and only those in English language were selected
6.	Data Type	The search for the data was limited to: Published Articles, Proceeding Papers, and Review Articles.
7.	Eligibility by means of both automated and manual review	The abstracts and titles of the documents comprising of published articles, conference proceedings, and review articles were manually examined, while those deemed irrelevant were excluded.
8.	Final Pool of entries that fully fit the topic used for the search	–

Source: (Author’s Analysis, 2024).

relationships between themes through the spatial representation of their thematic networks, thereby facilitating the exploration of these relationships. This enabled the construction of scientific maps grounded in the co-occurrence of the searched keywords, enhancing our understanding of the underlying connections within the literature. The extracted data were loaded into the SciMAT tool, facilitating the analysis across five distinct time periods (Table 2), and submitted to various stages of analysis.

These stages included selecting the unit of analysis, performing data reduction through minimum frequency selection, and choosing co-occurrence as the matrix type. Additionally, edge value reduction was applied during network reduction, while the association strength served as the measure of normalization. The “simple centers algorithm” was utilized for clustering, and maximum and minimum network size were adjusted, with the core and intersection mapper selected for document mapping. Quality measures, such as the g-index, h-index, q<sup>2</sup>-index, average citations and sum of citations, were selected alongside the association strength for longitudinal evolution mapping and the inclusion index for longitudinal overlapping mapping. This process resulted in the clustering of keywords into conceptual nodes, termed as themes, leading to the creation of 28 networks based on these co-occurring keywords. Each theme was then plotted in a two-dimensional (2-D) space layout using Callon’s centrality and density indicators (Fig. 7), allowing for classification into four quadrants: highly developed or isolated themes, motor themes, basic and transversal themes, and emerging or declining themes. Finally, the number of documents and citations were employed as bibliometric indicators to analyze the thematic areas. The SciMAT software tool generates strategic diagrams (Fig. 7) that visually depicts the most significant themes, along with conceptual network structures (Fig. 8) that clarify the relationships among authors, keywords, and

**Table 2**  
Study time period (1975–2024).

Year	Subperiod
1975–1984	p <sup>1</sup>
1985–1994	p <sup>2</sup>
1995–2004	p <sup>3</sup>
2005–2014	p <sup>4</sup>
2015–2024	p <sup>5</sup>

Source: (Author’s Analysis, 2024).

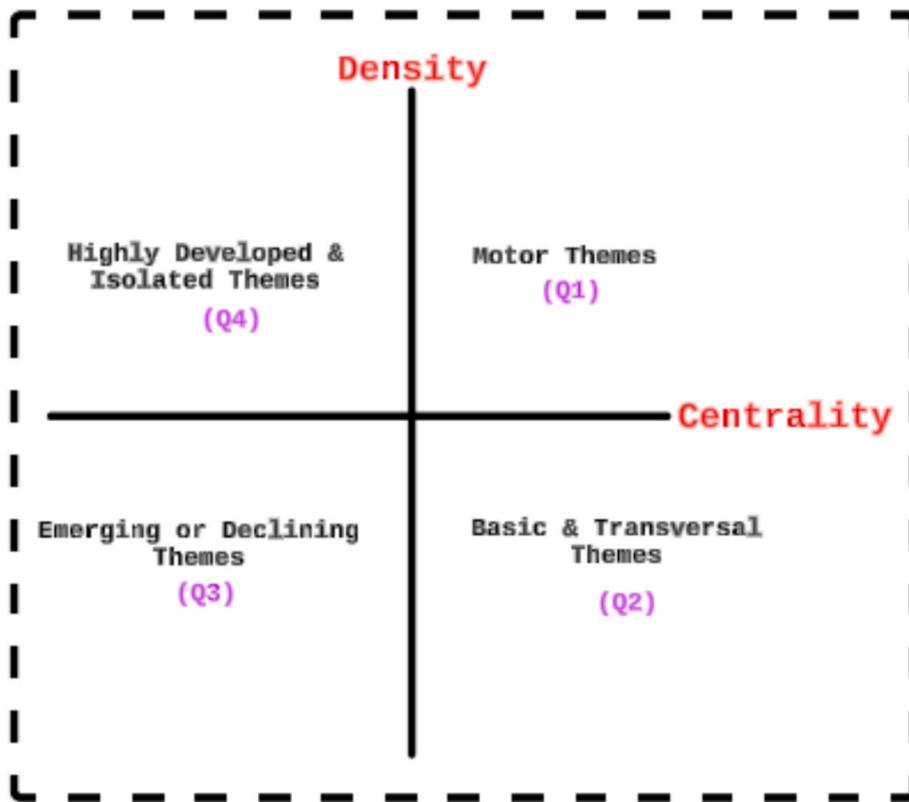


Fig. 7. SciMAT strategic diagram based on Callon's centrality & density indicators.

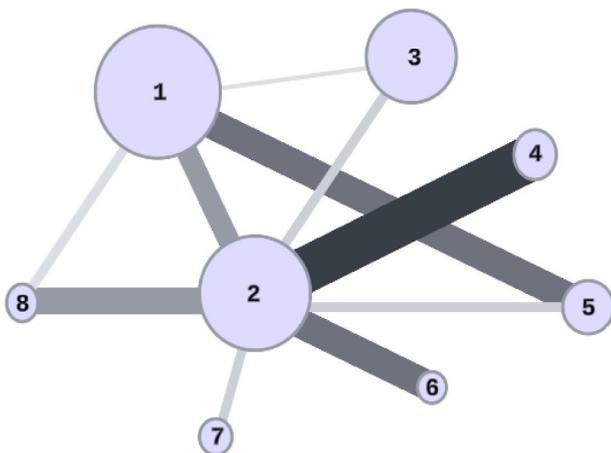


Fig. 8. Thematic network structure.

citations.

The strategic diagram groups the themes or keywords into quadrant and illustrates the identified clusters for each period in a two-dimensional (2-D) space, categorizing them based on Callon's density and centrality measures (Fig. 7), as previously mentioned. Each cluster within the strategic diagram is enhanced using selected bibliometric measures from the SciMAT, while the corresponding network for each cluster is displayed, offering a graphical representation of the relationships between its components (sub-themes) (Fig. 8). Furthermore, it provides a thematic evolution structure (Fig. 9) that facilitates an understanding of how the field has progressed overtime. The SciMAT thematic evolution structure is used to illustrate the findings from the temporal and longitudinal analysis (Fig. 9). It reveals two distinct evolution areas, marked by differently shaded colors. In this illustration,

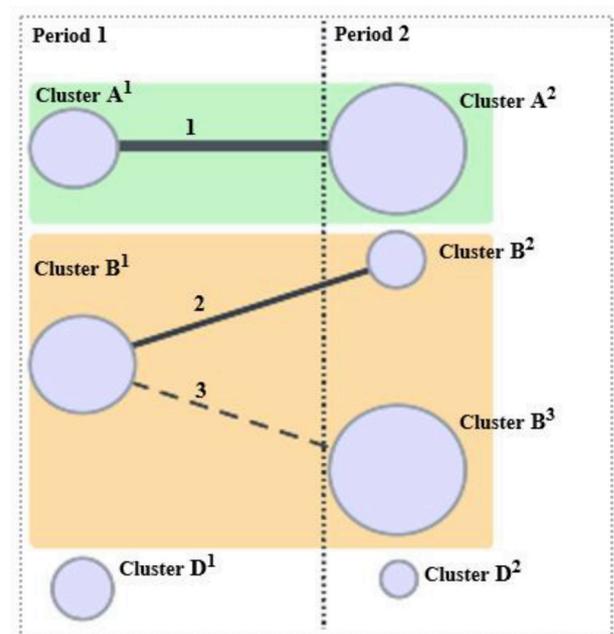


Fig. 9. Thematic evolution structure.

one area includes Cluster A<sup>1</sup> and Cluster A<sup>2</sup>, while the other encompasses Clusters B<sup>1</sup>, B<sup>2</sup>, and B<sup>3</sup>. Additionally, Cluster D<sup>1</sup> is no longer active, and Cluster D<sup>2</sup> is identified as a new cluster.

### 2.5. Systematic literature review

The SLR conducted in this study aimed to identify the challenges associated with RLC themes in relation to signalized intersection safety.

This review follows the guidelines outlined in PRISMA (Page et al., 2021). The PRISMA framework comprises of four stages: identification, screening, eligibility, and inclusion [Fig. 10]. For this review, we employed criteria similar to those used in the BPNA regarding the database, time frame, and document types. From the initial pool of 9,529 publications exported from the three databases (WoS, Google Scholar and Scopus), 5,243 duplicates were removed. During the screening phase, we searched for documents with titles containing keywords such as “red-light camera challenges,” “limitations,” “difficulties,” and “barriers” resulting in 1,300 relevant articles. However, articles lacking these keywords in their titles were removed, resulting in a total of 675 publications. In the eligibility stage, the 1,300 selected documents were reviewed, leading to the exclusion of 436 that were only vaguely related to the topic. Ultimately, 54 documents were deemed suitable for qualitative analysis. The PRISMA flowchart utilized in this study is presented in Fig. 10.

2.6. Qualitative discussion

Following the science mapping and analysis, a qualitative discussion was conducted to identify three key issues: summarizing current

research themes, identifying research gaps, and suggesting directions for future studies. The qualitative approach employed for this analysis involved a thematic examination of the content from the collected scientific literature. This approach facilitated recognition of recurring patterns and trends within the data, yielding valuable insights into existing research themes, limitations, and potential areas for further exploration.

3. Results

3.1. Bibliometric performance analysis of RLCs

Fig. 11, offers an overview of the journal articles focused on the searched topics. These topics include ‘red-light camera,’ ‘red-light running,’ ‘intersection,’ and ‘signalized intersection.’ This summary indicates a consistent rise in the number of articles published between 1975 and 2024. Notably, the volume of articles doubled between 2018 and 2019 and nearly doubled again in 2021, although there was a slight decline in 2022 and 2023. By November 2024, a total of 65 articles had already been published, with additional publications expected by the end of the year. Among the three searched topics, red-light camera

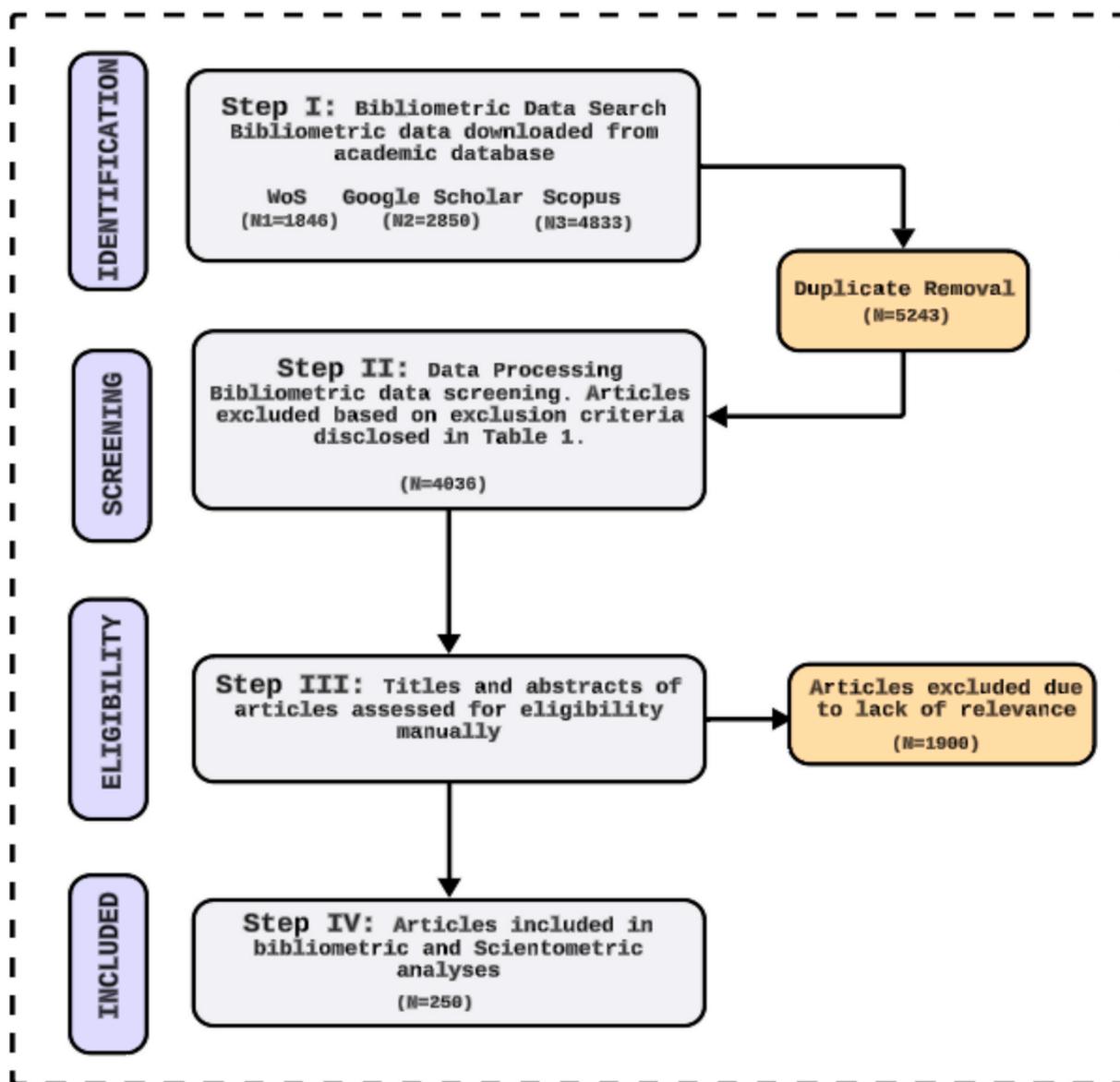


Fig. 10. Systematic review flow-chart.

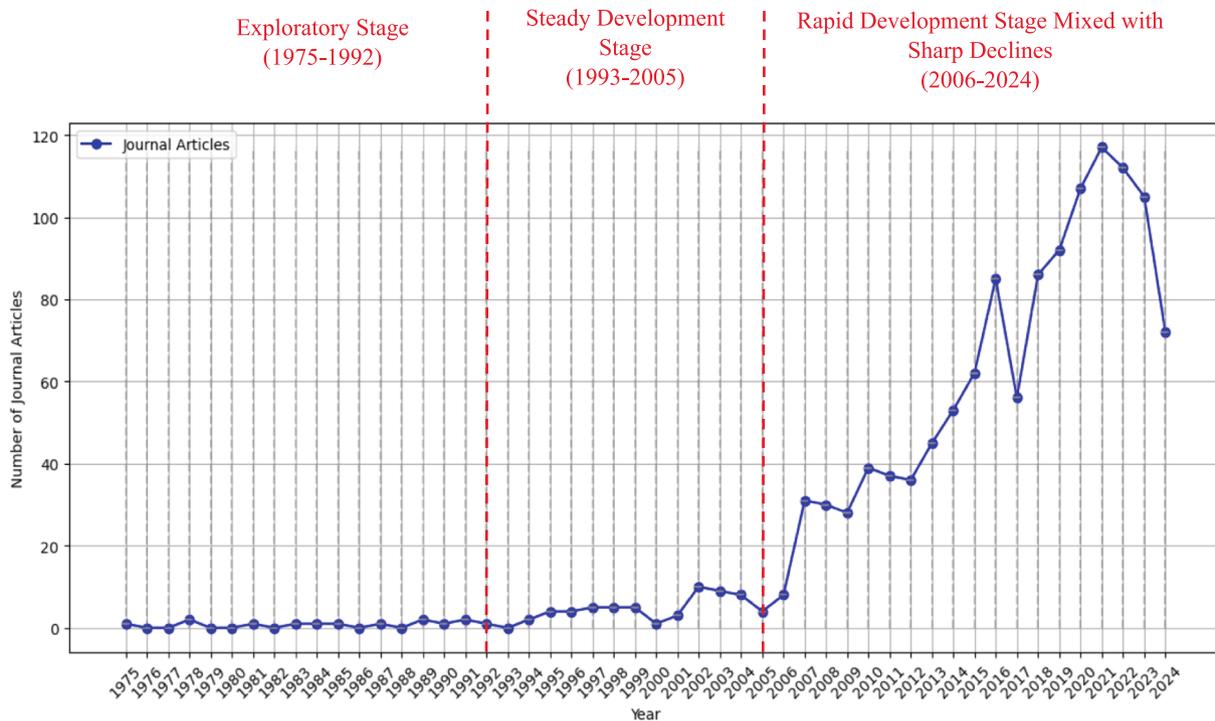


Fig. 11. Related Journal Articles Published over Years after exclusion (1975–2024).

research had the fewest publications, totaling only 60 articles, compared to 297 articles on red-light running and 678 articles on signalized intersection [Fig. 14]. Additionally, there has been a significant rise in the number of conference papers in the years 2013, 2017, and 2020, contrasted by sharp declines in 2014, 2015, 2021, and 2023 (Fig. 12). The drop in 2021 is attributed to the impact of COVID-19. Specifically, the conference papers include only 10 for RLCs, 39 for RLR, and 250 for signalized intersection (Fig. 15).

These findings indicate a steady growth in interest in the topics of RLR and signalized intersections, while the growth in RLC research remains low. It also indicates that although researchers are actively

engaging with the critical areas of RLR and signalized intersections, the focus on RLCs is significantly limited. The research analysis over the past 50 years has been divided into three distinct stages that highlight how RLC research focuses have evolved, (i) the exploratory stage (1975–1992), (ii) the steady development stage (1993–2005), and (iii) the rapid development stage (2006–2024) for the published articles (Fig. 11). Although, the time frames for the conference papers slightly differs. The exploratory stage last from 1975 to 1988. Following that, the steady development stage takes place between 1989 and 2003, while the rapid development stage runs from 2004 to 2024 (Fig. 12). This classification enhances the understanding of how research priorities and

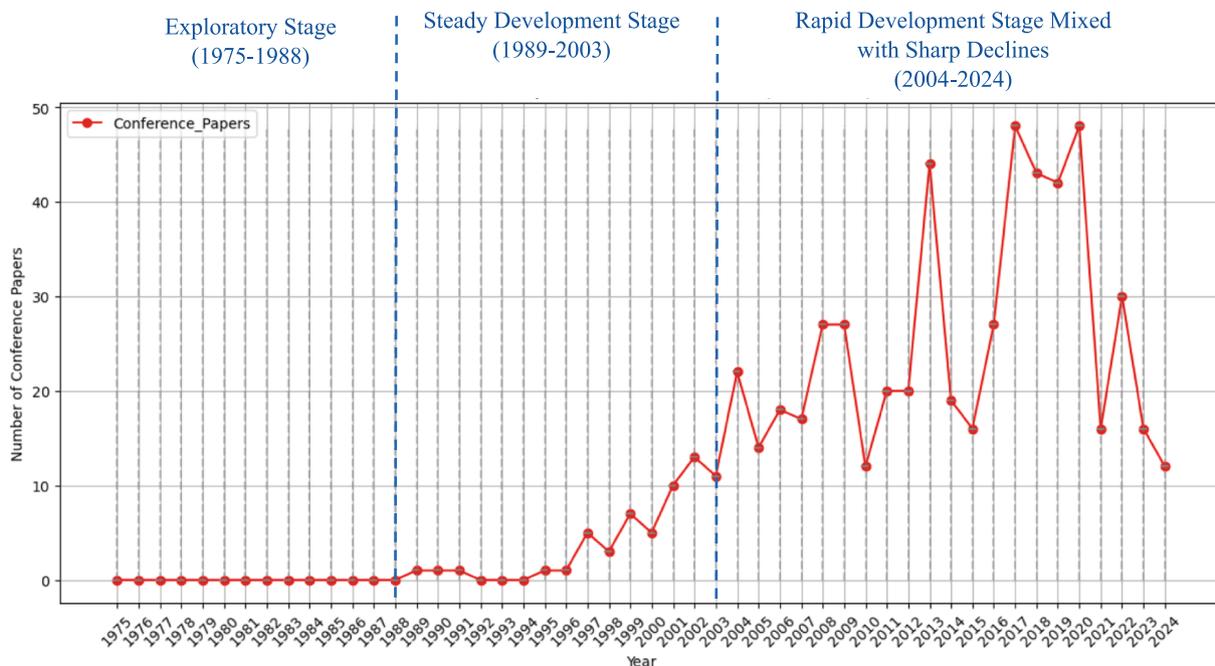


Fig. 12. Related Conference Papers over the Years after exclusion (1975–2024).

methodologies have evolved throughout these periods.

The publication and citation performance for RLCs demonstrates an upward trend, indicating promising prospects in this research area, although with a decline in 2021 (Fig. 13), which can be attributed to the Covid-19 pandemic. Ten most cited authors are displayed in Table 3, with Retting, RA, Farmer, CM, and Chin, HC as the top contributors. Furthermore, Tables 4, 5 and 6 outline the 10 most prominent journals and institutions publishing RLC research, with Accident Analysis and Prevention (AAP) ranking first, followed by the Journal of the Institute of Transport Engineers (ITE), and the Journal of Safety Research. Among institutions, the Insurance Institute for Highway Safety emerges as the most productive, followed by Texas A&M University and Nanyang Technological University, China.

3.2. Bibliometric network analysis of RLCs from 1975 – 2024

In this section, we present the bibliometric network analysis of RLCs from 1975 to 2024, illustrated through three key components: the strategic diagrams (Figs. 16, 17, 18, 20 and Appendix 1–3), the thematic network structures (Fig. 21 and Appendix 4–6), the overlapping map and the thematic evolution structure (Figs. 22 and 23). Each topic is described in detail in subsequent sub-sections to facilitate a deeper understanding of the analysis.

3.2.1. Bibliometric performance and network analysis of RLCs

The strategic diagrams for periods P<sup>1</sup> (1975–1984) and P<sup>2</sup> (1985–1994) revealed no clusters representing any themes related to the searched keywords. This absence can be attributed to the data reduction methods employed, specifically the selection of frequency reduction, where the minimum frequency occurrence for keywords was set at 2 rather than 1. Until the 1990 s, none of the databases we consulted contain any publications related to RLCs. In contrast, period P<sup>3</sup> (1995–2004) identified four clusters (Fig. 16). This include RED-LIGHT RUNNING BEHAVIOR, TRAFFIC CONTROL, REAL-TIME SIGNAL CONTROL, and QUEUE. Given the significance of RED-LIGHT RUNNING BEHAVIOR in this analysis, P<sup>3</sup> is included as a focal period. Moving to period P<sup>4</sup> (2005–2014), the analysis shows a total of 11 clusters (Fig. 17), namely RISKY BEHAVIOR, RED LIGHT CAMERA, TRAFFIC

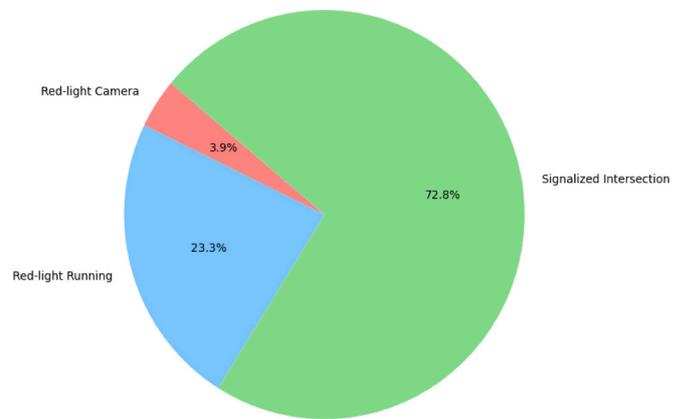


Fig. 14. Red-Light Camera Article Publications (1975–2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

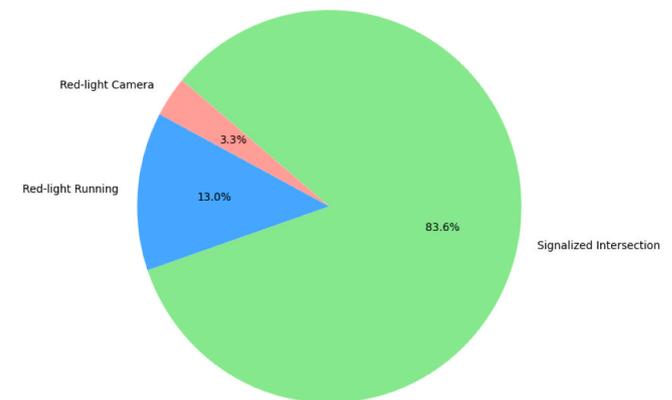


Fig. 15. Red-Light Camera Conference Papers (1975–2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

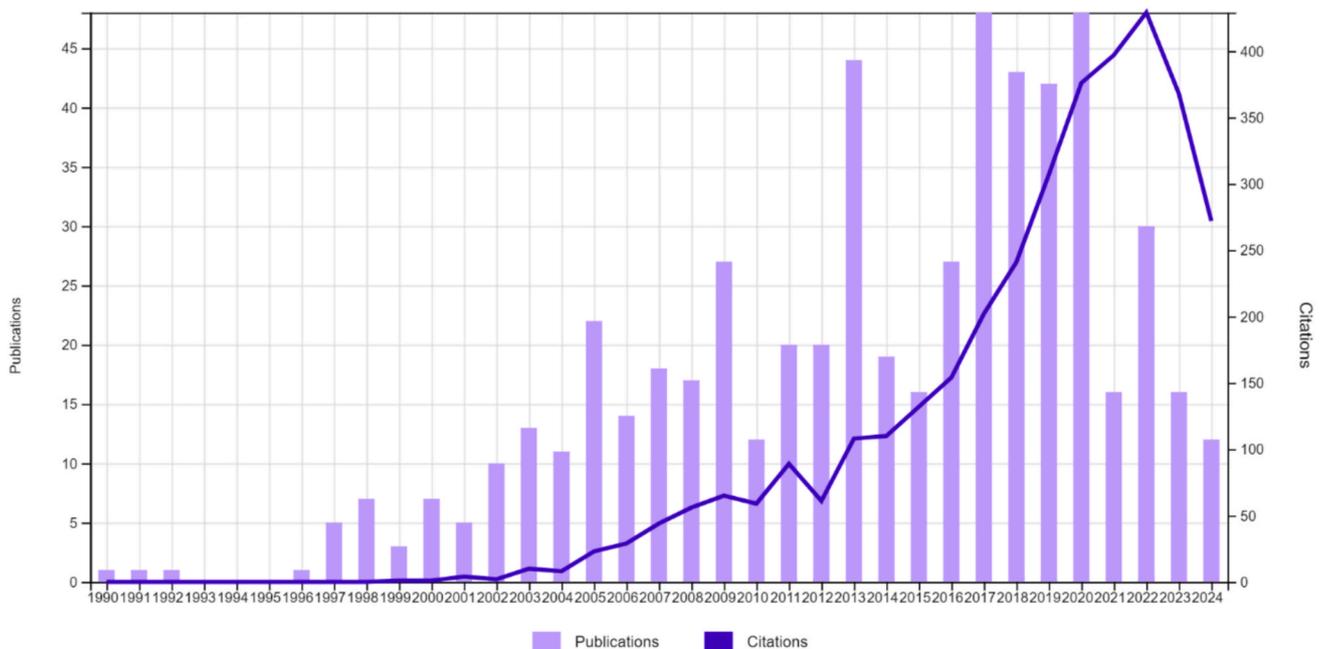


Fig. 13. Red Light Camera Publications and Citations Over the Years (1990–2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 3**  
Most cited authors for RLCs.

S/No	Most Cited Authors	Cits
1.	Retting, RA	286
2.	Farmer, CM	222
3.	Chin, HC	134
4.	Tay, R	112
5.	Haque, MM	109
6.	McCartt, AT	90
7.	Council, FM	61
8.	Persaud, B	61
9.	Wong, YD	52
10	Lum, KM	52

**Table 4**  
Journals that publish RLC research papers.

S/No	Journals	Docs
1.	Accident Analysis and Prevention	13
2.	ITE Journal Institute of Transport Engineers	6
3.	Journal of Safety Research	6
4.	Traffic Injury Prevention	4
5.	IEEE Transactions on Intelligent Transportation Systems	4
6.	Journal of Transportation Engineering-ASCE	3
7.	Journal of Advanced Transportation	3
8.	Transportation Research Record	2
9.	Transportation Research Part F	1
10	Transport Policy	1

**Table 5**  
Universities that conduct RLC research.

S/No	Universities	Docs
1.	Insurance Institute Highway Safety	8
2.	Texas AM University	6
3.	Nanyang Technological University	4
4.	State University System of Florida	4
5.	Auburn University	4
6.	Morgan State University	3
7.	National University Singapore	3
8.	University of Hong Kong	3
9.	BMI SG	3
10.	FHWA	2

SIGNAL OPTIMIZATION, SIGNAL, BEHAVIOR, TRAFFIC SIMULATION, SIGNALIZED INTERSECTION, TRAFFIC SIGNALIZATION, NON-SIGNALIZED INTERSECTION, TRAVEL TIME and SATURATION FLOW RATE. Finally, period P<sup>5</sup> (2015–2024) reveals 13 clusters (Fig. 18) encompassing PROBE, WALKING, YELLOW SIGNAL, MOTORCYCLIST BEHAVIOR, ALGORITHM, INTERSECTION CRASHES, LANE, ECO DRIVING, BEHAVIOR, TRAFFIC SIGNALIZATION, DATA ANALYSIS, and SIGNALIZED INTERSECTION.

The strategic diagrams (Figs. 16–18) illustrate the most researched and cited themes for each of the three periods: P<sup>3</sup> (1995–2004), P<sup>4</sup> (2005–2014), and P<sup>5</sup> (2015–2024). These diagrams reveal a clear trend indicating that research in RLCs originated from studies focused on ‘RED LIGHT RUNNING BEHAVIOR’ during the third period (P<sup>3</sup>), as depicted in Fig. 19, which shows its thematic network. Table 7 presents the centrality and density metrics based on Callon’s measures, the h-index, sum citations and core documents. The theme ‘RED-LIGHT RUNNING BEHAVIOR,’ with a centrality of 21.17 and a density of 29.51, is positioned firmly within the motor theme quadrant (Fig. 16). This indicates that ‘RED-LIGHT RUNNING BEHAVIOR’ is frequently cited and linked to diverse array of other themes (Fig. 19), highlighting its significance in the field of RLCs research. However, given the established nature and relevance of this theme, it is crucial for understanding the overall dynamics of the research area surrounding signalized intersection safety, as it addresses fundamental questions and challenges within the

discipline.

However, the evolution of themes (P<sup>1</sup> to P<sup>5</sup>) related to signalized intersection safety reflects a progression from foundational concepts to advanced interventions (Figs. 16–18). At the core is ‘RED-LIGHT RUNNING BEHAVIOR’ (Fig. 16), which identifies the factors leading to driver’s violation of traffic signals, such as time pressure and distraction. This understanding informs the design and operation of ‘INTERSECTIONS’ and ‘SIGNALIZED INTERSECTIONS,’ where effective traffic management is crucial. The results indicate that complex intersection configurations can increase violations while consistent signal timing can help reduce confusion and compliance. Therefore, enhancements in ‘TRAFFIC SIGNALIZATION’ such as adaptive controls and countdown timers, will aid in informing drivers and mitigating RLR incidents, similar to the report by IIHS (2022).

As research advanced (P<sup>3</sup>), the implementation of ‘RED LIGHT CAMERA’ emerged as a motor theme and a significant enforcement mechanism aimed at deterring traffic violation such as RLR (Fig. 17). These RLCs contribute significantly to broader ‘ENFORCEMENT PROGRAMS’ (Fig. 19) that combine automated and traditional policing strategies to promote compliance and educate the public. Ultimately, the research at this level, as depicted in the interconnectivity between the themes, aims to reduce intersection crashes (Fig. 21d). In P<sup>4</sup>, studies show that cities implementing comprehensive safety measures, including RLCs and optimized signal management, experience significant decreases in red light violations and intersection crashes, demonstrating the effectiveness of an integrated approach to enhancing safety at signalized intersections. Consequently, ‘SIGNALIZED INTERSECTION’ emerged as the most extensively researched theme in P<sup>4</sup> and maintained its status as the leading theme in P<sup>5</sup>. However, it transitioned from a ‘motor theme’ to a ‘basic and transversal theme’ (Figs. 17 and 18), while still retaining the highest number of core documents and citations (Table 7).

### 3.2.2. Thematic network of RLCs

Fig. 20 displays 28 clusters, of which 6 are categorized as highly developed and isolated themes, 7 as emerging or declining themes, 5 as basic and transversal themes, and 11 clusters are categorized as motor themes. However, the size of each cluster corresponds to the number of the selected performance measures linked to the respective theme. Table 8 presents the performance analysis of the motor themes in RLC research, detailing their core documents, sum citations, and h-index. The analysis identified 11 motor themes: “RED LIGHT RUNNING BEHAVIOR,” “TRAFFIC CONTROL,” “REAL TIME SIGNAL CONTROL,” “RED LIGHT CAMERA,” “SIGNALIZED INTERSECTION,” “BEHAVIOR,” “RISKY BEHAVIOR,” “MOTORCYCLIST BEHAVIOR,” “YELLOW SIGNAL,” “PROBE,” and “DATA ANALYSIS.”

Altogether, these themes encompass 458 core documents that have been cited 11,495 times. These motor themes represent key research topics that are well-established and significantly impact signalized intersection safety, characterized by a high degree of connectivity and influence within the RLC literature. The 11 motor themes are typically developed, supported by substantial literature. They reflect areas of active research that have generated a considerable body of knowledge. This indicates they are likely to continue to evolve. These RLC motor themes not only have high citation counts, but also significantly influence the emergence and development of other themes in the field. Consequently, they serve as foundational concepts upon which other research topics are built. Given their established nature and relevance, the RLC motor themes are essential for understanding the overall dynamics of the research area, as they often address fundamental questions and challenges related to signalized intersection safety).

Fig. 21 illustrates the thematic network structure of the motor themes related to the researched area, as outlined in Table 8. A thorough analysis of keyword co-occurrence was conducted and is presented here to reveal underlying patterns in relation to signalized intersection safety.

**Table 6**

Performance analysis of the researched themes according to their periods and quadrants and their respective sum citations, average citations, core documents, *h* and *g* indices over the years.

S/No.	Quadrant	Period	Theme	Core Docs	<i>h</i> -Index	<i>g</i> -Index	Sum Cits	Ave. Cits
1.	Q1	p <sup>3</sup>	RED LIGHT RUNNING BEHAVIOR	13	9	11	601	46.23
2.	Q1	p <sup>3</sup>	TRAFFIC CONTROL	6	3	5	73	18.25
3.	Q1	p <sup>3</sup>	REAL TIME SIGNAL CONTROL	4	3	3	67	11.17
4.	Q1	p <sup>4</sup>	RED LIGHT CAMERA	43	21	35	1247	29
5.	Q1	p <sup>4</sup>	SIGNALIZED INTERSECTION	80	25	50	2601	32.51
6.	Q1	p <sup>4</sup>	BEHAVIOR	22	13	20	680	30.91
7.	Q1	p <sup>4</sup>	RISKY BEHAVIOR	19	13	19	1048	55.16
8.	Q1	p <sup>5</sup>	MOTORCYCLIST BEHAVIOR	88	25	36	1554	17.66
9.	Q1	p <sup>5</sup>	YELLOW SIGNAL	63	19	27	1910	14.44
10.	Q1	p <sup>5</sup>	PROBE	59	17	26	838	14.2
11.	Q1	p <sup>5</sup>	DATA ANALYSIS	61	16	26	876	14.36
12.	Q2	p <sup>4</sup>	TRAFFIC SIMULATION	43	14	27	782	18.19
13.	Q2	p <sup>4</sup>	SIGNAL	30	11	24	580	19.33
14.	Q2	p <sup>5</sup>	SIGNALIZED INTERSECTION	488	40	57	6825	13.99
15.	Q2	p <sup>5</sup>	TRAFFIC SIGNALIZATION	122	19	30	1219	9.99
16.	Q2	p <sup>5</sup>	BEHAVIOR	98	25	40	1893	19.32
17.	Q3	p <sup>3</sup>	QUEUE	2	2	2	177	88.5
18.	Q3	p <sup>4</sup>	TRAFFIC SIGNALIZATION	48	21	40	1633	34.02
19.	Q3	p <sup>4</sup>	NON-SIGNALIZED INTERSECTION	3	2	2	90	30
20.	Q3	p <sup>4</sup>	SATURATION FLOW RATE	2	2	2	44	22
21.	Q3	p <sup>5</sup>	INTERSECTION SAFETY	117	24	36	1707	14.59
22.	Q3	p <sup>5</sup>	INTERSECTION CRASHES	59	18	32	1132	19.19
23.	Q3	p <sup>5</sup>	ALGORITHM	41	13	20	463	11.29
24.	Q4	p <sup>4</sup>	TRAFFIC SIGNAL OPTIMIZATION	28	11	25	748	26.71
25.	Q4	p <sup>4</sup>	TRAVEL TIME	2	2	2	45	22.5
26.	Q4	p <sup>5</sup>	ECO DRIVING	134	27	46	2518	18.79
27.	Q4	p <sup>5</sup>	WALKING	39	16	28	828	21.23
28.	Q4	p <sup>5</sup>	LANE	60	13	24	685	11.42

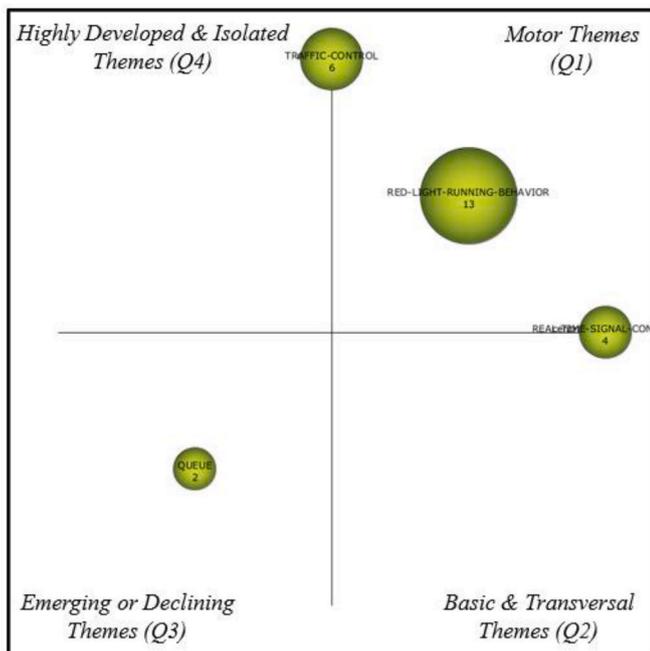


Fig. 16. RLC Strategic Diagram for P3 (1995–2004) showing Core Documents.

3.2.2.1. Motor themes (Q1).

a. Signalized Intersection

The cluster ‘SIGNALIZED INTERSECTION’ (Fig. 21a) emerged as the most extensively researched theme in P<sup>4</sup> and maintained its status as the leading theme in P<sup>5</sup>. This motor theme is the most significant theme in the RLC strategic diagram (Fig. 20), as evidenced by its performance metrics: 80 core documents, a *g*-index of 50, a *h*-index of 25, and a total of 2,601 citations (Table 8). ‘SIGNALIZED INTERSECTION’ is integral to

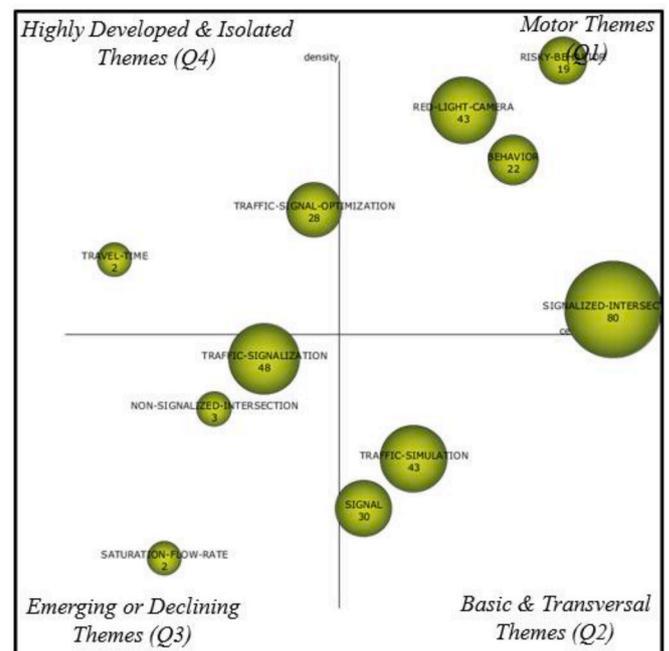


Fig. 17. RLC Strategic Diagram for P4 (2005–2014) showing Core Documents.

advancing traffic safety research, particularly regarding the role of RLCs as tools for improving compliance and reducing crashes, as they are equipped with traffic lights to manage the flow of vehicles and pedestrians (Zhu et al., 2013). Their design and operation are crucial for enhancing overall traffic safety. By exploring the relationship between technological interventions such as RLCs and intersection design, researchers can develop effective strategies to enhance safety at signalized intersections. In this context, we can explain the emergence of the most cited sub-themes within its thematic network, such as ‘INTERSECTION SAFETY,’ ‘TIME,’ ‘CAPACITY,’ ‘QUEUE DYNAMICS,’ ‘U-TURNS,’

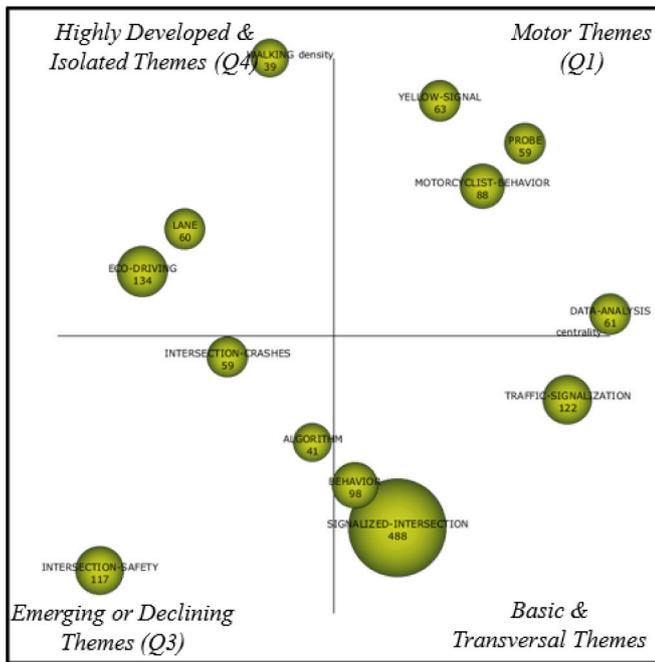


Fig. 18. RLC Strategic Diagram for P5 (2015–2024) showing Core Documents.

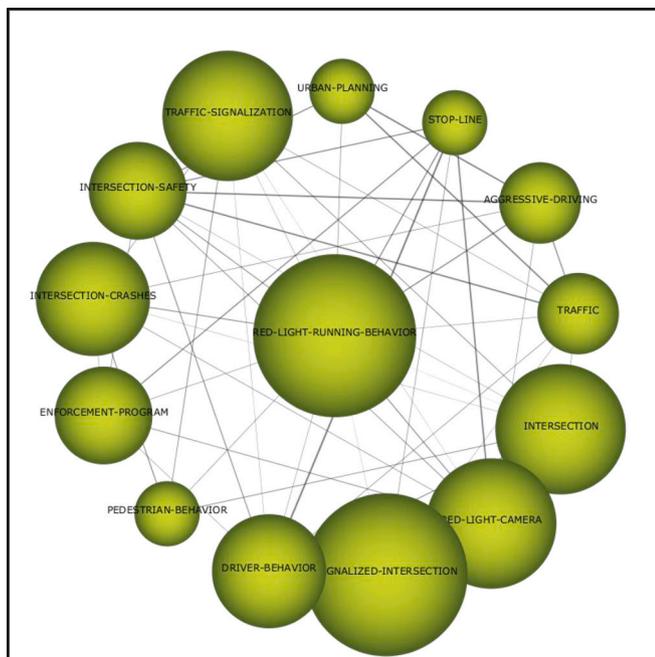


Fig. 19. Thematic Network Structure of Red-Light Running Behavior in P3 (2015–2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

‘RIGHT TURNS,’ ‘DETECTION SYSTEMS,’ ‘COUNTERMEASURES,’ ‘HIGHWAYS,’ and ‘INFLUENCING FACTORS.’ Hence every sub-theme plays a significant role in understanding and mitigating safety risks associated with signalized intersections. For instance, optimizing signal timing can reduce waiting times and improve compliance (Retting et al., 2002), while effective detection systems enhance traffic flow and safety for all users (Hillier et al., 1993). Additionally, examining queue dynamics helps address driver impatience that may lead to hazardous maneuvers (Gallagher & Fisher, 2020), and design considerations for U-turns and right turns focus on minimizing conflicts with pedestrians and

other vehicles (Persaud et al., 2005).

b. Yellow Signal

The cluster ‘YELLOW SIGNAL’ (Fig. 21b) has emerged as one of the most critically researched and cited themes after the ‘SIGNALIZED INTERSECTION’ cluster in the RLC strategic diagram (Fig. 20), as it influences driver behavior and decision-making. This motor theme is pivotal in signalized intersection safety research, focusing on the role of yellow traffic signal in regulating vehicle and pedestrian behavior at intersections. The yellow signal serves as a transitional phase between the green and red lights, indicating to drivers that they should prepare to stop unless they are too close to the intersection to do so safely (Retting et al., 2008). This motor theme has a substantial total citation count of 1910 and includes 63 core documents, a h-index of 19 and a g-index of 27 (Table 8). Understanding the dynamics of the ‘YELLOW SIGNAL’ is essential for improving safety outcomes at signalized intersections (Cusack & Tait, 2001). RLCs are often implemented as a countermeasure to the risks associated with RLR, which is closely linked to the behavior of drivers during the yellow signal phase (Cusack & Tait, 2001). Therefore, the relationship between yellow signals and RLCs illustrates how technological interventions can reinforce safe driving behavior, ultimately contributing to improved safety at intersections. The most relevant sub-themes within its thematic network include, ‘DILEMMA ZONE,’ which highlights the challenges drivers face when deciding whether to stop or to proceed (Almutairi & Wei, 2021); ‘ONSET’ of the yellow signal, which affects reaction times (Ahmed & Abdel-Aty, 2015); and ‘COUNTDOWN TIMERS,’ which provide crucial information to drivers (Hebert-Martinez & Porter, 2006). Other sub-themes include ‘MIXED TRAFFIC CONDITIONS,’ ‘SPEED CAMERAS,’ ‘GREEN SIGNAL,’ ‘AMBER SIGNAL,’ ‘DECISION ZONE,’ which illuminate the complexities of driver responses (Lum & Wong, 2003), ‘TRAFFIC VIOLATIONS,’ ‘ALL-RED,’ ‘TRAFFIC MANAGEMENT SYTEMS.’

c. Motorcyclist Behavior

The cluster ‘MOTORCYCLIST BEHAVIOR’ (Fig. 21c) focuses on the unique challenges faced by motorcyclists at signalized intersection. Key aspects include the perception of traffic signals, compliance rates with red lights, and interactions with other vehicles and pedestrians. All of these significantly influence accident risks. Studies (Almutairi & Wei, 2021; Jensupakarn & Kanitpong, 2018; Satiennam et al., 2018) highlight that motorcyclists often misjudge signal timing or accelerate through yellow lights, increasing their vulnerabilities at intersections. Safety interventions, such as improved signage and dedicated lanes, are vital for enhancing motorcyclist safety. The integration of RLCs serves as a relevant countermeasure, deterring red light violations and encouraging compliance among motorcyclists. Studies (Almutairi & Wei, 2021; Jensupakarn & Kanitpong, 2018; Satiennam et al., 2018) also indicate that installation of RLCs can lead to behavioral changes, fostering more cautious approaches to intersections and potentially reducing collision rates. Key sub-themes include ‘RED LIGHT RUNNING BEHAVIOR’ and ‘RED LIGHT VIOLATIONS,’ ‘TRAFFIC ACCIDENTS,’ ‘STOP LINE,’ ‘HAZARD PERCEPTION,’ ‘INJURIES,’ and ‘INFLUENCING FACTORS.’ RLR behavior significantly increases the risk of crashes, particularly at intersections. The stop line serves as an essential reference point for compliance. Whereas hazard perception also plays a crucial role in how effectively motorcyclists identify potential dangers in their environment. This motor theme has a substantial total citation count of 1,554 and includes 88 core documents, with a h-index of 25 and a g-index of 36 (Table 8).

d. Red Light Camera

The cluster ‘RED LIGHT CAMERA’ (Fig. 21d) is a focal point in signalized intersection safety research, as these automated enforcement

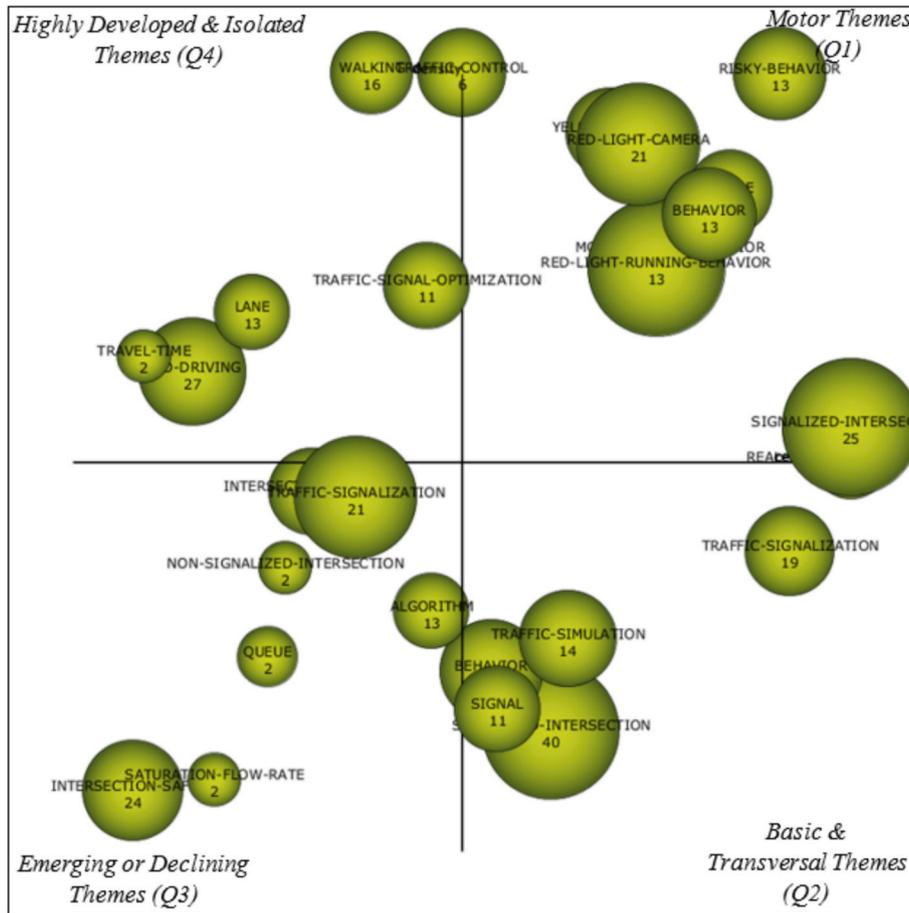


Fig. 20. RLC strategic diagram (1975–2024).

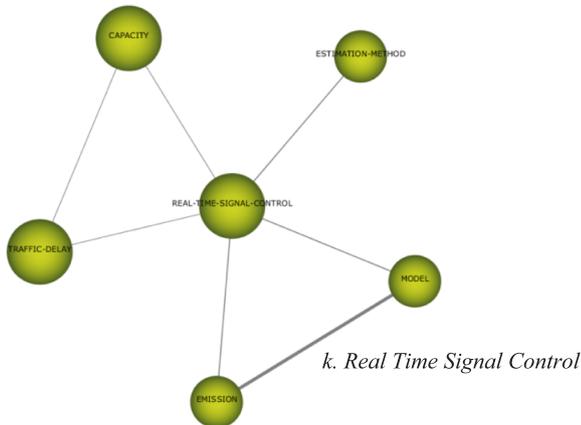


Fig. 21. Thematic network of the RLCs motor themes (a–k).

systems are designed to reduce violations of traffic signals, specifically RLR. RLCs capture images of vehicles that enter an intersection after the traffic light has turned red. This is to deter against such violations while contributing to overall traffic safety. Ongoing research into their efficacy, public perception, and legal considerations will continue to inform best practices implementing RLCs as part of comprehensive traffic safety strategies. Relevant sub-themes within its thematic network include, ‘RED LIGHT RUNNING BEHAVIOR,’ ‘RED LIGHT VIOLATIONS,’ ‘TRAFFIC LIGHTS,’ ‘ENFORCEMENT PROGRAMS,’ ‘INTERSECTION CRASHES,’ ‘INJURY,’ ‘DETERRENCE THEORY,’ ‘REGRESSION MODELS,’ ‘COUNT DATA MODELS,’ ‘BEFORE-AFTER STUDIES,’ and ‘JUNCTION.’ The effectiveness of RLCs is closely tied to the operation of traffic lights, as improved adherence to signal changes can enhance overall traffic flow (Retting et al., 1998; Sun et al., 2012; Vanlaar et al., 2014; Bonneson & Son, 2003; Almutairi & Wei, 2021). Furthermore, RLCs are integral to broader enforcement programs that combine traditional policing with public awareness campaigns, significantly impacting intersection crashes and injury rates (Khan et al., 2020; Lum

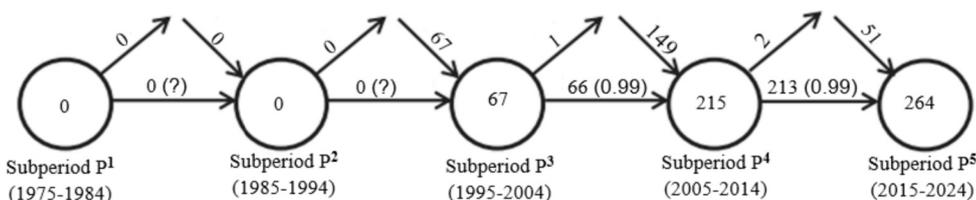


Fig. 22. Overlapping Map of RLCs (1975–2024).

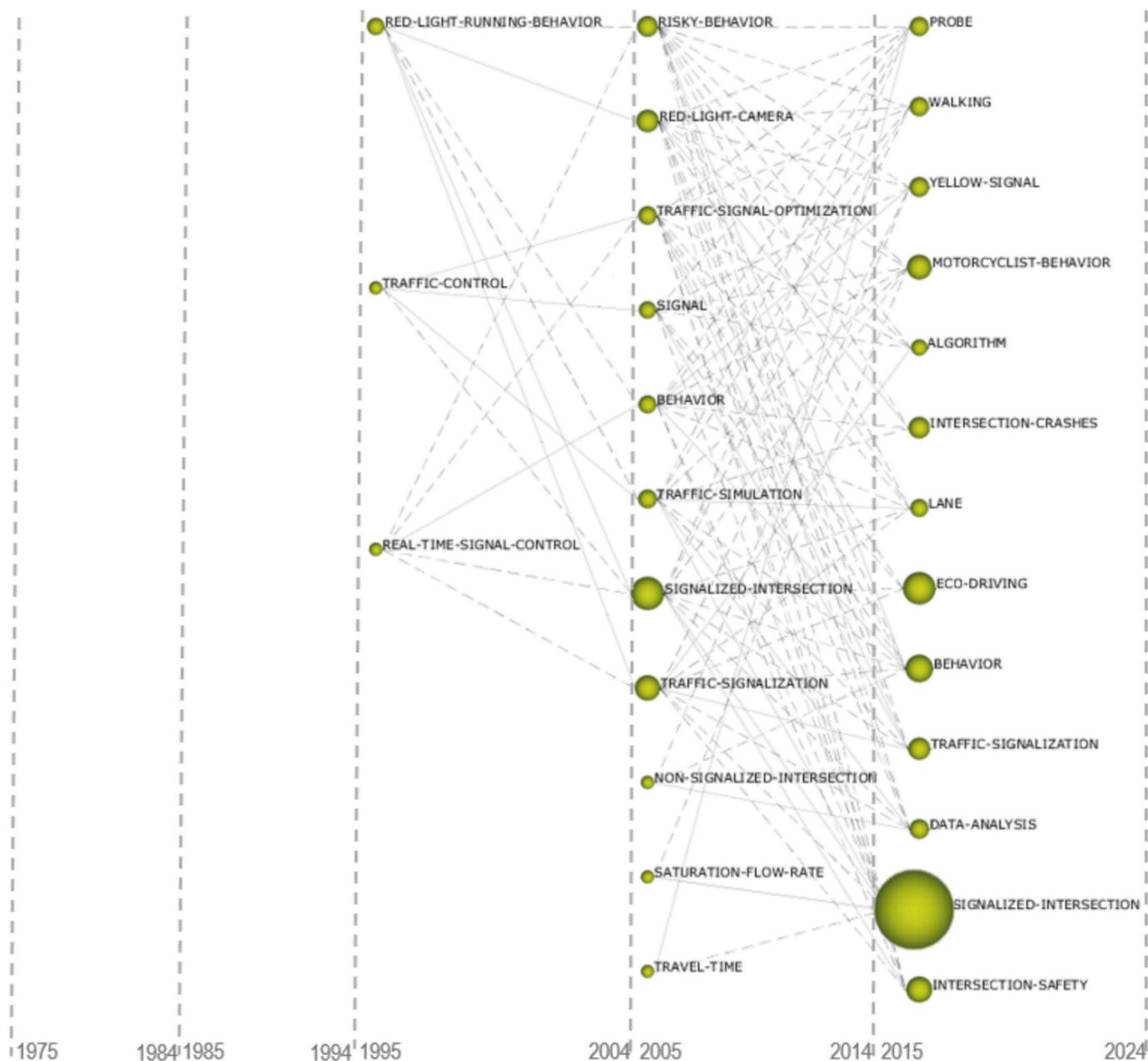


Fig. 23. Thematic evolution structure of RLCs (1975–2024).

Table 7

Most researched and cited themes over the years.

Period	Year	Theme	Most researched theme	Core documents	Centrality	Density	Sum citations	h-Index
p <sup>1</sup>	1975–1984	–	–					
p <sup>2</sup>	1985–1994	–	–					
p <sup>3</sup>	1995–2004	Motor Theme	Red Light Running	13	21.17	29.51	601	9
p <sup>4</sup>	2005–2014	Motor Theme	Signalized Intersection	80	78.93	6.28	2601	25
p <sup>5</sup>	2015–2024	Basic & Transversal Theme	Signalized Intersection	488	38.60	1.10	6825	40

& Wong, 2003). Grounded in deterrence theory, RLCs increase the perceived likelihood of penalties, thus encouraging compliance among drivers and motorcyclists. This motor theme is supported by a substantial body of research, comprising 43 core documents, a h-index of 21, a g-index of 35, and a total of 1247 citations (Table 8).

e. Risky Behavior

The cluster ‘RISKY BEHAVIOR’ (Fig. 21e) involves various behavior that can lead to increased traffic violations and accidents at signalized intersections. It also focuses on the actions and decisions of drivers that leads to the risk of crashes at signalized intersections. It also highlights how reckless driver behaviors such as running red lights, improper lane changes, and distracted driving can compromise safety for all road users, including other vehicles and pedestrians. Understanding these factors is

**Table 8**  
Performance analysis of the motor themes (Q1).

Theme	Core Docs	h-Index	g-Index	Sum Cits	Ave. Cits
SIGNALIZED INTERSECTION	80	25	50	2601	32.51
YELLOW SIGNAL	63	19	27	1910	14.44
MOTORCYCLIST BEHAVIOR	88	25	36	1554	17.66
RED LIGHT CAMERA	43	21	35	1247	29.00
RISKY BEHAVIOR	19	13	19	1048	55.16
DATA ANALYSIS	61	16	26	876	14.36
PROBE	59	17	26	838	14.2
BEHAVIOR	22	13	20	680	30.91
RED LIGHT RUNNING BEHAVIOR	13	09	11	601	46.23
TRAFFIC CONTROL	06	03	05	73	18.25
REAL TIME SIGNAL CONTROL	04	03	03	67	11.17

also critical for addressing the causes of crashes at signalized intersections. By examining these behaviors, researchers can develop targeted strategies for enhancing safety. Hence RLCs serves as a valuable tool that helps in deterring risky actions while encouraging compliance. Key sub-themes include, 'DRIVING BEHAVIORS,' 'AGGRESSIVE DRIVING,' 'HUMAN FACTORS,' 'BAYESIAN' and 'POISSON MODELS,' and 'VULNERABLE ROAD USERS.' In this regard, aggressive driving, and human factors have significant impacts on decision-making processes at signalized intersections. The implications for vulnerable road users, including pedestrians and cyclists, are particularly significant, highlighting the need for targeted interventions (Bonneson & Son, 2003; Chen et al., 2015). This theme is supported by 19 core documents, a h-index of 13, a g-index of 19, and a total of 1048 citations (Table 8).

#### f. Data Analysis

The cluster 'DATA ANALYSIS' (Fig. 21f) focuses on the systematic examination of traffic data to inform decision-making and improve safety outcomes. However, in the context of signalized intersection safety, data analysis involves various methodologies and techniques used to understand traffic patterns, driver behavior, and accident rates, ultimately aiming to enhance safety for all road users. Therefore, the motor theme 'DATA ANALYSIS' is essential for advancing safety research at signalized intersections, providing the foundation for informed decision-making and targeted interventions. This theme is a significant component in RLC research analysis and is associated with several interrelated sub-themes, including, 'TRAFFIC FLOW,' 'HUMAN FACTORS,' 'VEHICLE EMISSIONS,' 'TRAFFIC DELAY,' 'LEFT' and 'RIGHT TURNS,' 'REGRESSION ANALYSIS,' and 'ORDERED PROBIT MODEL.' Techniques such as regression analysis and the ordered probit model have been utilized to identify relationships between various factors affecting signalized intersection safety and providing valuable insights for traffic management. This motor theme is supported by 61 core documents, a h-index of 16, a g-index of 26, and a total of 876 citations (Table 8).

#### g. Probe

The cluster 'PROBE' (Fig. 21g) is essential for advancing the understanding of traffic dynamics and safety at signalized intersections. In the context of signalized intersection safety research, 'PROBE' refers to the methodologies and technologies used to collect, analyze, and interpret traffic data. The use of various probing techniques, researchers can gain insights into traffic behavior, congestion patterns, and safety issues, ultimately informing more effective and efficient traffic management strategies. It is also associated with different interrelated sub-themes within its thematic network, including, 'TRAFFIC VOLUME,' 'QUEUE

DYNAMICS,' 'DETECTORS,' 'REAL-TIME SYSTEMS,' 'LOCATION,' 'REAL-TIME SIGNAL CONTROL,' 'MATHEMATICAL MODELS,' 'STATISTICAL TESTS,' 'SHOCKWAVE THEORY,' 'DATA ANALYTICS,' 'HIDDEN MARKOV MODELS,' and 'TRAJECTORIES.' Probe helps in the measuring traffic volume, monitoring of queue dynamics, and the use of detectors for accurate data collection. The theme also highlights the role of real-time systems in traffic management, the significance of location in data accuracy, and the assessment of travel time to inform signal optimization. Additionally, the integration of real-time signal control with probing data enhances intersection safety, while mathematical models and statistical tests are employed to analyze and validate this data. This motor theme is supported by 59 core documents, a h-index of 17, a g-index of 26, and a total of 838 citations (Table 8).

#### h. Behavior

The cluster 'BEHAVIOR' (Fig. 21h) is important for understanding how various factors influence the actions of drivers and pedestrians at signalized intersections, significantly impacting safety outcomes. Behavior is a fundamental aspect of signalized intersection safety research, focusing on the actions and decision-making of drivers and pedestrians at critical moments and junctions (Retting et al., 1998; Smith et al., 2000; Obeng & Burkey, 2008; Almutairi & Wei, 2021). It helps identify risk factors and improve compliance with traffic signals. Key sub-themes include, 'GREEN,' 'YELLOW SIGNALS,' 'CROSSING BEHAVIOR,' 'COUNTDOWN TIMERS,' 'TRAFFIC CONFLICTS' and 'COLLISIONS,' 'WAITING TIME,' 'TRAFFIC LIGHT VIOLATIONS,' 'REAL TIME SIGNAL CONTROL,' 'DECISION ZONE,' 'STOP LINE,' and 'ADVERSE WEATHER.' It also illustrates clear road user responses to green and yellow signals, the crossing behavior of pedestrians, and the influence of countdown timers on decision-making. It also addresses traffic conflicts and collisions. However, factors such as waiting time and traffic light violations are crucial for understanding compliance and the likelihood of dangerous actions (Lum & Wong, 2003; Bochner & Walden, 2010). This theme is supported by 22 core documents, an h-index of 13, a g-index of 20, and a total of 680 citations (Table 8).

#### i. Red LIGHT RUNNING behavior

The cluster 'RED LIGHT RUNNING BEHAVIOR' (Fig. 21i) is a complex and significant research theme for understanding the safety dynamics at signalized intersections, where violations of traffic signals can lead to serious accidents. Researchers can develop effective strategies for promoting safer driving practices by examining the causes and implications of this behavior (Retting et al., 1999; McCartt & Hu, 2013; Hill & Lindly, 2003; Insurance Institute for Highway Safety, 2017; Retting et al., 2008; Ahmed & Abdel-Aty, 2015; Helai et al., 2008; Shin & Washington, 2007; McGee & Eccles, 2003; Retting & Kyrychenko, 2002; Jantosut et al., 2021). However, the relationship between RLCs and red-light running behavior provides an effective means of automated enforcement in deterring violations at signalized intersections (Hebert-Martinez & Porter, 2006; Helai et al., 2008; Ng et al., 1997; Retting & Kyrychenko, 2002; Vanlaar et al., 2014; Wong, 2014; Aeron-Thomas and Hess, 2005; Bochner and Walden, 2010; Golob et al., 2002; IIHS, 2017; McGee and Eccles, 2003; Shah, 2010). This motor theme is a critical focus within signalized intersection safety research. Analysis in this area addresses the actions of violators who enter an intersection after the traffic light has turned red. This behavior is a significant contributor to crashes at signalized intersections, often resulting in severe collisions, particularly side-impact crashes involving vehicles and pedestrians (Vanlaar et al., 2014; Wong, 2014; Hebert-Martinez & Porter, 2006). The theme is associated with several interrelated sub-themes, including 'INTERSECTIONS,' 'RED LIGHT CAMERA,' 'DRIVER,' 'PEDESTRIAN BEHAVIOR,' 'ENFORCEMENT PROGRAMS,' 'INTERSECTION CRASHES,' 'TRAFFIC SIGNALIZATION,' 'STOP LINE,' 'AGGRESSIVE DRIVING,' and 'TRAFFIC CONDITIONS.' This motor

theme is supported by 13 core documents, a h-index of 9, a g-index of 11, and a total of 601 citations (Table 8).

j. Traffic Control

The cluster ‘TRAFFIC CONTROL’ (Fig. 21j) is a vital area within signalized intersection safety research. It focuses on the systems and measures implemented to manage the flow of traffic at signalized intersections. It shows that effective traffic control plays a vital role in reducing crashes while improving traffic efficiency, and enhancing safety for all road users (Retting et al., 2002; Retting et al., 2008; Helai et al., 2008; Almutairi & Wei, 2021; Jantusut et al., 2021). The theme is key to understanding how the flow of vehicles and pedestrians at signalized intersections is managed. Key sub-themes include, ‘TRAFFIC SIGNALS,’ ‘TRAFFIC CONTROL NETWORK,’ ‘CONTROL SYSTEMS,’ ‘DETECTION TECHNOLOGIES,’ ‘LEFT’ and ‘RIGHT TURNS,’ ‘TRAFFIC SIMULATION,’ and ‘DATA ANALYSIS.’ This theme is very crucial in the design and operation of traffic signals, the structure of the traffic control network, and the implementation of advanced control systems. It also addresses the complexities of managing left and right turns at intersections (Hill & Lindly, 2003; McGee & Eccles, 2003; Golob et al., 2002). This motor theme is supported by 6 core documents, a h-index of 3, a g-index of 5, and a total of 73 citations (Table 8).

k. Real Time Signal Control

The cluster ‘REAL TIME SIGNAL CONTROL’ (Fig. 21k) focuses on the dynamic management of traffic signals based on real-time traffic conditions. This motor theme emphasizes the significance of using technology and data to optimize traffic flow, enhance safety, and reduce congestion at intersections (Zhu et al., 2013; Li et al., 2009); however, by focusing on adaptive signal control, traffic flow optimization, and data-driven decision-making, researchers and traffic managers can improve safety at intersections. Key sub-themes include ‘TRAFFIC DELAY,’ ‘CAPACITY,’ ‘EMISSIONS,’ ‘MODELING TECHNIQUES,’ and ‘ESTIMATION METHODS.’ Real time signal control helps reduce traffic delays through optimized signal timings, enhances the capacity to accommodate varying traffic volumes, and mitigates vehicle emissions by improving traffic flow. However, advanced modeling techniques are employed to simulate the effects of real time control, while various ‘estimation methods’ assess the performance and effectiveness of these systems. This motor theme is supported by 4 core documents, a h-index of 3, a g-index of 3, and a total of 67 citations (Table 8).

3.2.2.2. Basic and transversal themes (Q2).

a. RLCs Basic and Transversal Themes

The analysis identified several central themes within the basic and transversal quadrant (Q2) (Table 9). High centrality indicates the prominence of these themes within the overall RLC research network. It reflects how central these themes are in connecting with other themes, thus demonstrating a significant influence on RLC research in relation to signalized intersection safety. We identified several key themes such as

**Table 9**  
Performance analysis of the basic and transversal themes (Q2).

Theme	Core docs	h-Index	g-Index	Sum Cits	Ave. Cits
SIGNALIZED INTERSECTION	488	40	57	6825	13.99
BEHAVIOR	98	25	40	1893	19.32
TRAFFIC SIGNALIZATION	122	19	30	1219	9.99
TRAFFIC SIMULATION	43	14	27	782	18.19
SIGNAL	30	11	24	580	19.33

‘SIGNALIZED INTERSECTION’ (Centrality: 38.6, Density: 1.11); ‘BEHAVIOR’ (Centrality: 35.84, Density: 1.44); ‘TRAFFIC SIGNALIZATION’ (Centrality: 43.47, Density: 2.38), ‘TRAFFIC SIMULATION’ (Centrality: 55.82, Density: 3.8); SIGNAL (Centrality: 54.33, Density: 3.58). The findings reveal that themes such as ‘TRAFFIC SIMULATION’ and ‘TRAFFIC SIGNALIZATION’ possess high centrality and density, indicating their critical roles in enhancing signalized intersection safety and efficiency. For example, research on traffic signal optimization can lead to significant improvements in traffic flow, while dynamic models that integrate real-time data can help predict the impacts of signal changes. Therefore, the relationship among the main themes and the sub-themes (See Appendix 4) within their thematic networks provides valuable insights for guiding future research and policy initiatives aimed at improving safety at signalized intersections.

3.2.2.3. Emerging and declining themes (Q3).

a. RLCs Emerging and Declining Themes

The analysis also identified several themes within the emerging or declining themes quadrant (Q3) (Table 10). Using the Callon’s density and centrality measures, the analysis indicates their emerging or declining status in the current RLC research related to signalized intersection safety (See Appendix 5). The theme ‘INTERSECTION SAFETY’ (Centrality: 19.2, Density: 0.33) indicates an emerging interest but lacks integration, focusing on aspects such as video surveillance and driver emotions. In contrast, ‘TRAFFIC SIGNALIZATION’ (Centrality: 42.79, Density: 5.0) demonstrates high centrality and density highlighting its established role in optimizing traffic flow through intelligent transportation systems and machine learning applications. Similarly, the theme ‘INTERSECTION CRASHES’ (Centrality: 32.3, Density: 2.5) is moderately central, with a comprehensive approach to analyzing crash data using methods like causal inference and studies on RLCs. The analysis reveals that themes such as ‘ALGORITHM’ (Centrality: 34.92, Density: 2.22) and ‘NON-SIGNALIZED INTERSECTION’ (Centrality: 10.4, Density: 4.69) are growing areas of interest, emphasizing advanced algorithms for traffic management and gap acceptance modelling, respectively. Conversely, the themes ‘QUEUE’ (Centrality: 5.42, Density: 9.26) and ‘SATURATION FLOW RATE’ (Centrality: 9.03, Density: 1.89) show low centrality and density, indicating a decline in prominence. However, the results for emerging and declining themes, depicts dynamics that can guide future research initiatives and inform policy efforts aimed at enhancing safety at signalized intersections while ensuring a more effective approach to traffic management and accident prevention.

3.2.2.4. Highly developed and isolated themes (Q4).

a. RLCs Highly Developed and Isolated Themes

The analysis also revealed several areas that are highly developed yet relatively isolated from other research domains (Table 11) (See Appendix 6). The theme ‘ECO DRIVING’ (Centrality: 30.25, Density: 2.99)

**Table 10**  
Performance analysis of the emerging and declining themes (Q3).

Theme	Core Docs	h-Index	g-Index	Sum Cits	Ave. Cits
INTERSECTION SAFETY	117	24	36	1707	14.59
TRAFFIC SIGNALIZATION	48	21	40	1633	34.02
INTERSECTION CRASHES	59	18	32	1132	19.19
ALGORITHM	41	13	20	463	11.29
QUEUE	02	02	02	177	88.50
NON-SIGNALIZED INTERSECTION	03	02	02	90	30.00
SATURATION FLOW RATE	02	02	02	44	22.00

**Table 11**  
Performance analysis of the highly developed and isolated themes (Q4).

Theme	Core Docs	h-Index	g-Index	Sum Cits	Ave. Cits
ECO-DRIVING	134	27	46	2518	18.79
WALKING	39	16	28	828	21.23
TRAFFIC SIGNAL OPTIMIZATION	28	11	25	748	26.71
LANE	60	13	24	685	11.42
TRAVEL TIME	02	02	02	45	22.50

emphasizes environmental considerations, focusing on sub-topics such as automated vehicles and driving assistance systems, while research on proactive predictive cruise control illustrates its practical implications for optimizing vehicle performance and reducing emissions at signalized intersections. Similarly, the 'WALKING' theme (Centrality: 33.29, Density: 7.68) addresses pedestrian behavior and safety, highlighting issues like phone distractions and visual attention at signalized crosswalks, which can inform safety measures to accommodate distracted pedestrians. The theme of 'TRAFFIC SIGNAL OPTIMIZATION' (Centrality: 49.47, Density: 7.68) stands out for its influence within the research community, focusing on improving traffic flow through advanced optimization techniques. For example, utilizing optimization models to reduce start-up lost time can enhance traffic efficiency in mixed traffic scenarios. Themes such as 'LANE' (Centrality: 31.3, Density: 3.34) and 'TRAVEL TIME' (Centrality: 6.81, Density: 7.14), indicate important considerations in lane management and travel time analysis, respectively. The 'LANE' research theme employs technologies like lidar sensor for real-time monitoring, the 'TRAVEL TIME' theme focuses specifically on arterial intersections. However, the findings further highlight the need for targeted research efforts to enhance safety and efficiency at signalized intersections, leveraging the strengths of each theme while addressing their isolation.

### 3.3. Thematic evolution structure of RLCs from 1975 to 2024 (evolution and overlapping map)

In our analysis, the evolution map illustrates how RLC research themes evolved over the years (1975–2024). The results show the progression of RLC research themes based on their centrality and density measurements, highlighting how certain themes within the RLC research cluster gained prominence or declined in importance. However, the links between the themes in different periods provide crucial insights into the relationships and transitions of the RLC research themes across different time periods. The results reveal significant transitions in the research themes related to RLC concerning signalized intersection safety from P<sup>3</sup> (1995–2004) to P<sup>4</sup> (2005–2014). During this period, key themes included 'RED LIGHT RUNNING BEHAVIOR,' 'TRAFFIC CONTROL,' 'REAL TIME SIGNAL CONTROL,' and 'QUEUE,' reflecting initial concerns about intersection safety and management of traffic dynamics (See Appendix 1, Fig. 23). The result highlights the emergence of broader themes in P<sup>4</sup>, such as 'RISKY BEHAVIOR,' 'RED LIGHT CAMERA,' and 'TRAFFIC SIGNAL OPTIMIZATION,' indicating a more sophisticated understanding of the interplay between human factors and traffic safety. The connections among these research themes, particularly the non-broken lines linking 'RED LIGHT RUNNING BEHAVIOR' to 'RED LIGHT CAMERA,' 'SIGNALIZED INTERSECTION,' and 'TRAFFIC SIGNALIZATION,' suggest strong continuities that have influenced ongoing research efforts (Fig. 23).

Transitioning to P<sup>5</sup> (2015–2024), the results identify new research themes, including 'PROBE,' 'WALKING,' 'YELLOW SIGNAL,' 'MOTORCYCLISTS BEHAVIOR,' alongside established themes like 'SIGNALIZED INTERSECTION' and 'TRAFFIC SIGNALIZATION.' This expansion points to a shift towards integrating technology and human behavior in traffic safety discussions. However, the relationships between many of the traditional themes from P<sup>4</sup> and the new themes are marked by broken

lines, indicating weaker or less stable connections. For instance, the links from 'RISKY BEHAVIOR' to themes such as 'PROBE' and 'WALKING' are represented by broken lines, indicating a diminished direct influence as the focus of the new research landscape evolves.

Furthermore, the results also reveal that while traditional themes like 'RED LIGHT CAMERA' and 'TRAFFIC SIGNAL OPTIMIZATION' continue to be relevant, their connections to emerging themes are predominantly broken lines, reflecting challenges in maintaining their significance in contemporary discussions. For example, although the relationship between 'RED LIGHT CAMERA' and 'INTERSECTION CRASHES' remains strong, many other connections indicate a need for these themes to adapt to the evolving landscape of signalized intersection safety research. Conversely, the non-broken lines connecting 'BEHAVIOR' to itself and 'TRAFFIC SIMULATION' to 'LANE' and 'DATA ANALYSIS' highlights areas where continuity and relevance remain strong within the research domain, suggesting that understanding these interactions is crucial for informing future research.

The result of the evolution map analysis also highlight an important evolution in the thematic landscape of signalized intersection safety from P<sup>4</sup> to P<sup>5</sup>. The prevalence of broken lines signifies that many traditional themes are struggling to maintain their relevance in the face of newer research challenges and technological advancements. Nonetheless, the presence of non-broken lines in certain areas emphasizes the importance of foundational concepts such as understanding 'BEHAVIOR' and the relationship between RLCs and 'INTERSECTION CRASHES.' Therefore, the results further depict the necessity for researchers to adapt their focus to align with the dynamic complexities of urban transportation systems and emerging considerations.

## 4. Methodological evaluation and key critique in RLC research

The effectiveness of RLC as a traffic safety intervention necessitates a thorough methodological evaluation to ensure the validity and reliability of reported outcomes. In this section, we critically review the robustness of the principal analytical approaches applied in RLC research. Specifically, we examine: Before-and-after designs (with and without control groups), Regression and count-data statistical models, Machine-learning techniques, Simulation and modeling approaches, Saturation analysis, as well as Geometric and hierarchical methods. These techniques are grouped according to their functional similarities as identified in the literature (Table 12). Our evaluation reveals substantive methodological limitations and interpretive challenges that must be addressed to accurately assess RLC impacts on traffic safety.

The Empirical Bayes (EB) method is widely adopted for estimating RLC safety impacts, yet it is heavily dependent on the validity of Safety Performance Functions (SPFs) and fails to account adequately for spatial spillover effects. Such spillover can bias estimated safety impacts, while any misspecification or poor fit of the SPF introduces residual heterogeneity (Erke, 2009; Council et al., 2005; Hauer, 1997; Washington et al., 2020; Sacchi & Sayed, 2016; Washington & Shin, 2005). Moreover, EB analyses require substantial statistical expertise and data resources; their accuracy hinges on the quality and contextual relevance of the SPFs employed. Our scientometric analysis further highlights the EB method's prominent association with the emerging theme "INTERSECTION CRASHES," and sub-themes including "RED LIGHT CAMERA," "ENFORCEMENT PROGRAMS," and "BEFORE-AFTER STUDY" (see Appendix 7a), highlighting method's relevance in intersection-related safety research. Overall, these complexities and dependencies inherent in the EB method emphasize the need for careful implementation and transparency when using it to evaluate RLC effectiveness.

The Before-After with a Control Group (BA-CG) design compares crash trends at RLC-treated intersections against those at similar untreated sites over the same period. However, in the absence of controls for RTM, BA-CG studies may overestimate RLC benefits as indicated by Erke (2009). For instance, findings may suggest a 16% reduction in crashes, a figure likely inflated by RTM effects. Additional limitations

**Table 12**  
Methodological limitations in RLC research.

Methods	Group	Key Critique in Practice	Implications & Mitigation Strategies	Authors
EMPIRICAL BAYES (EB) METHOD	Before-After Approach	Dependency on Safety Performance Function (SPF) validity, Inability to account for spatial spillover effects, Residual RTM bias, Operational and data demands.	Use of Hybrid Approaches (EB + Spatial Econometrics), SPF transparency, test EB robustness to RTM assumptions.	(Erke, 2009; Council et al., 2005; Hauer, 1997; Lord and Mannering, 2010; Washington et al., 2020; Sacchi and Sayed, 2016; Washington and Shin, 2005; Elvik, 2008)
BEFORE-AFTER WITH CONTROL GROUP (BA-CG)	Before-After Approach	Failure to control for RTM, Spillover effects biasing control groups, Poor control group matching, Inability to isolate RLC effects.	Matched controls (use same crash history), or EB adjustments. Control sites geographically distant to avoid spillover, Multivariate controls for site-specific confounders.	(Erke, 2009; Shin and Washington, 2007; Burkey and Obeng, 2004; Andreassen, 1995; Golob et al., 2002)
QUASI-EXPERIMENTAL DESIGN BEFORE-AFTER PROBIT	Before-After Approach Regression Models	Inadequate control for RTM, Failure to account for Spillover Effects, Selection Bias in site assignment, Insufficient adjustment for confounding trends. Inapplicability to crash frequency data (binary outcome focus), Inability to model severity-frequency interactions (ignores frequency-severity links), Sensitivity to distributional assumptions, Poor handling of rare events (rare event bias).	Spatial models + distant control sites, EB adjustments, Propensity Score matching, interrupted time series. Use of count models (NB, RPNB), Frequency severity joint models, Firth-corrected logistic regression.	(Erke, 2009; Council et al., 2005; Hauer, 1997; Elvik, 2008; Shadish et al., 2002) (Lord and Mannering, 2010; Washington et al., 2020; Mannering and Bhat, 2014; Savolainen et al., 2011; Helai, 2008)
LOGIT	Regression Models	Inability to quantify net safety impacts, Mismatch with frequency data, Independence of irrelevant alternatives (IIA) assumption violation, Poor calibration for rare severe crashes.	Use of count regression (NB, RPNB), Crash Modification Factors (CMFs), Nested logit / Mixed logit, Firth penalized-likelihood logit.	(Erke, 2009; Helai, 2008; Lord and Mannering, 2010; Washington et al., 2020)
ORDERED PROBIT	Regression Models	Misalignment with RLC safety trade-offs (ignores frequency trade-offs), Proportional odds assumption violation, Inadequate handling of unobserved heterogeneity, Underestimate probabilities of rare outcomes.	Use of joint frequency-severity models, Generalized ordered logit/probit, Random parameter ordered probit, Zero-inflated/hurdle models.	(Erke, 2009; Council et al., 2005; Washington et al., 2020; Mannering and Bhat, 2014; Savolainen et al., 2011; Helai, 2008; Lord et al., 2007; Yasmin et al., 2016; Anastasopoulos et al., 2012; Williams, 2006)
REGRESSION ANALYSIS	Regression Models	Failure to address endogeneity, Inadequate handling of spillover effects, Model misspecification, Ignores temporal dynamics, Over reliance on statistical significance.	Instrumental variables + EB adjustment, Spatial econometrics (SEM, SAR), Interrupted time series (ITS), Random parameters-NB / Zero-inflated NB.	(Erke, 2009; Council et al., 2005; Hauer, 1997; Lord and Mannering, 2010; Washington et al., 2020; Elvik, 2011)
NEGATIVE BINOMIAL (NB)	Statistical Models for Count Data / Regression Model	Failure to control for RTM, Inability to handle unobserved heterogeneity, Neglect of spatial spillover effects, Poor performance with zero-inflation, Inadequate temporal trend adjustment.	Use of Empirical Bayes (EB) Method, Random parameter NB, Spatial lag/error models, Zero-inflated NB, NB-Integrated time series.	(Erke, 2009; Hauer, 1997; Savolainen et al., 2011; Anastasopoulos et al., 2012; Pace and LeSage, 2009)
RANDOM PARAMETER NEGATIVE BINOMIAL (RPNB)	Statistical Models for Count Data / Regression Model	Inadequate handling of spillover and RTM, Sensitivity to distributional assumptions, Black box parameter interpretation, Computational intensity and practical barriers.	Use of hybrid models such as: Pair RPNB with EB for RTM correction, Integrate spatial lags/errors for spillover effects. Ensure transparency standards such as Report sensitivity analyses for distributional assumptions, Contextualize parameters with behavioral theory.	(Erke, 2009; Hauer, 1997; Washington et al., 2020; Mannering and Bhat, 2014; Anastasopoulos et al., 2012; Pace and LeSage, 2009)
RANDOM FOREST	Machine Learning Technique	Requires large datasets to capture rare events (such as fatal angle crashes), but RLC studies often have sparse data, Prevents transparent interpretation of how RLC influence crashes thus hindering policy insights, Causal inference limitations (inability to establish causality or model spatial dynamics), RF stochasticity yields non-replicable results, undermining policy decisions.	Use of RF with Quasi experimental designs, Spatial RF extensions, Synthetic data augmentation, Use of SHAP/LIME explainers translatable for engineering interventions.	(Erke, 2009; Washington et al., 2020; Mannering and Bhat, 2014; Abdel-Aty et al., 2004)
DEEP LEARNING	Machine Learning Technique	Extreme opacity and lacks interpretability, requires massive crash data but fatal and RLC relevant crashes are sparse, ignores spatial temporal confounders, conflates correlation with causation, Stochastic weight initialization causes non-replicable results.	Use of DL with quasi-experimental frameworks, synthetic minority oversampling, use of graph neural networks (GNNs), Use of explainable Ai (SHAP/LIME).	(Erke, 2009; Washington et al., 2020; Abdel-Aty et al., 2004; Cai et al., 2019)
PREDICTION MODEL	Machine Learning Technique	Confuses prediction with causal inference, Ignoring spillover and network effects, Overreliance on historical bias, extreme black-box opacity hampers policy use, generalizability across contexts.	Use of causal machine learning, graph neural networks (GNNs), Federated learning, Use of explainable Ai (SHAP/LIME).	(Erke, 2009; Cai et al., 2019; Pearl and Mackenzie, 2018; Athey et al., 2019)

(continued on next page)

Table 12 (continued)

Methods	Group	Key Critique in Practice	Implications & Mitigation Strategies	Authors
ARTIFICIAL NEURAL NETWORK	Machine Learning Technique	Requires massive crash datasets, provides no interpretable mechanisms linking RLCs to crash outcomes thus preventing actionable insights for traffic engineers, Spatial temporal blind spot (underestimates RLC spillover effects), Confounding RLC effects with selection bias, Computational overhead and reproducibility crisis (public sector RLC evaluations require replicable methods).	Use of synthetic data generation, ANNs with Quasi-experimental designs, use of explainable Ai, use of graphic neural networks (GNNs).	(Erke, 2009; Cai et al., 2019; Rudin, 2019)
NEURAL NETWORK	Machine Learning Technique	Fails to simulate adaptive driver behavior post RLC installation, NNs does not model spillover effects, Lack interpretability as it offers no insight into why RLC violations occur, this hinders policy refinement, Ignore regional driving cultures (weather or infrastructure variability), may optimize narrow metrics (violation capture rates) without aligning with broader safety goals.	Use NNs with Empirical Bayes methods to balance automation with interpretability, NNs models to be tested against behavioral feedback data (such as rear-end collision trends), Incorporate satellite data, weather, and socioeconomic variables to reduce geographic bias.	(Erke, 2009; Lum and Wong, 2003; Lum and Wong, 2003; Washington et al., 2020; Rudin, 2019)
MULTI-AGENT	Simulation and Modeling Approaches	Requires granular behavioral data that are empirically unavailable, leading to arbitrary parameterization (calibration & validation challenges), Over simplified behavioral assumptions, Computational intractability at scale, Causal opacity.	Use of hybrid data assimilation, Embed quasi-experimental designs within simulations (Causal MAS framework), Simulate corridor-level interactions first then scale via statistical emulators (Hierarchical abstraction).	(Erke, 2009; Garber et al., 2007; Council et al., 2005; Savolainen et al., 2011; Pace and LeSage, 2009; Pearl and Mackenzie, 2018)
CELLULAR AUTOMATA MODEL	Simulation and Modeling Approaches	Inadequate spillover modeling, geometric inflexibility, behavioral naivety, calibration validation gap, Oversimplified vehicle dynamics.	Use of hybrid CA microsimulation, Incorporate risk-perception heterogeneity via agent personality scores calibrated to traffic violation data, Simulate regional networks using macro–micro coupling.	(Erke, 2009; Council et al., 2005; Nagel and Schreckenberg, 1992)
HIDDEN MARKOV MODEL	Simulation and Modeling Approaches	Reduces complex driver decisions to discrete hidden states, ignoring continuous risk gradient, Ignores spatial–temporal dependencies (fails to model spillover effects and long-term adaptation), Unvalidated state interpretability, Requires extensive sequence of rare events such as RL violations for reliable training, Cannot establish causal links between RLCs and crash outcomes, confounding selection bias.	Use of spatio-temporal extensions, Causal enhancement (combine HMMs with synthetic control methods for counterfactual inference, Use of hybrid frameworks.	(Erke, 2009; Persaud et al., 2005; Mannering and Bhat, 2014; Pace and LeSage, 2009; Athey et al., 2019)
GEOMETRIC APPROACH	Geometric and Hierarchical Analysis	Isolates geometric factors while ignoring behavioral dynamics that dominates RLC outcomes, Treats intersections as static systems, fail to model driver learning or spillover route changes, Ignores spatial displacement of crashes, Retroactive justification bias, Geometrical optimal design are context-dependent and lack universal safety thresholds.	Integrate geometric factors with behavioral econometrics, Use spatial graph models to quantify spillover, Test geometric predictors before RLC installation.	(Erke, 2009; Garber et al., 2007; Council et al., 2005; Hauer, 1997; Washington et al., 2020; Elvik, 2011)
HIERARCHICAL APPROACH	Geometric and Hierarchical Analysis	Model imposes rigid nesting that may misrepresent spatial-behavioral processes, Fails to resolve unmeasured cross-level confounders, Requires large sample sizes per cluster for stable estimates, but RLC installations are sparse, Ignores spatial autocorrelation, conflating spillover effects with cluster-level variance.	Use of hybrid spatial hierarchical models, Bayesian regularization, Test hierarchy robustness through cluster-level predictive accuracy.	(Erke, 2009; Washington et al., 2020; Helai, 2008; Pace and LeSage, 2009)
SATURATION MODEL	Saturation Analysis	Arbitrary threshold specification (lacks theoretical basis and varies inconsistently across RLC studies), Assumes fixed saturation points, but driver adaptation evolves continuously with enforcement exposure, requires extensive data across multiple saturation levels, but few jurisdictions have graded RLC deployment, Models assume localized effects but miss system-wide behavioral shifts.	Integrate saturation concepts with spatial econometrics to capture network effects (hybrid frameworks), Use stated-preference survey to ground thresholds in driver psychology (behavioral calibration), Treat saturation points as distributions, not fixed values, to quantify uncertainty (Bayesian approaches).	(Erke, 2009; Council et al., 2005; Lord and Mannering, 2010; Pace and LeSage, 2009)

include selection bias, since identifying truly comparable control sites is challenging; and Spillover bias, whereby proximate control intersections dilute measured treatment effects. These biases can distort conclusions regarding RLC efficacy unless explicitly addressed in the study design (Erke, 2009; Shin & Washington, 2007; Golob et al., 2002; Burkey & Obeng, 2004).

The BA-CG method is linked to the major emerging theme 'INTERSECTION CRASHES,' along with related sub-themes such as 'RED LIGHT CAMERA,' 'ENFORCEMENT PROGRAMS,' 'SPILLOVER EFFECT,' 'CAUSAL INFERENCE,' and 'BAYESIAN MODEL' (see Appendix 7b). Similarly, the literature highlights the value of Quasi-Experimental Design for drawing causal inferences about effects of RLCs on traffic safety outcomes when randomized controlled trials are infeasible. This approach relies on the rigorous selection of comparable control sites. Nevertheless, studies (Erke, 2009; Shin & Washington, 2007; Golob et al., 2002) have identified several methodological concerns including RTM effects, confounding due to simultaneous changes in traffic-safety technologies and enforcement practices, and spillover effects that displace violations to adjacent intersections. The Quasi-Experimental design is also associated with the emerging theme 'INTERSECTION CRASHES,' and its sub-themes 'RED LIGHT CAMERA,' and 'ENFORCEMENT PROGRAMS' (see Appendix 7c).

Although, RLC evaluations predominantly employ regression models for crash counts, reflecting the discrete, non-normal and often over-dispersed nature of crash-frequency data. Commonly used specifications such as Probit, Ordered Probit, and Logit, rest on an assumption of independent observations, yet traffic safety data typically exhibit spatial autocorrelation that these models cannot accommodate (Erke, 2009; Council et al., 2005; Washington et al., 2020). Their non-linear functional forms also complicate the interpretation of marginal effects, placing additional demands on analytical expertise. Moreover, reliable estimation from these models requires large sample size data that RLC studies often lack, thus heightening the risk of overfitting when many predictors are included and thereby undermining external validity. While regression approaches excel in identifying associations, they do not, on their own, establish causal relationships, limiting the strength of inferences about RLC effectiveness. In binary and ordered categorical settings, they may further introduce systematic bias (Erke, 2009; Washington et al., 2020; Mannering & Bhat, 2014; Savolainen et al., 2011; Helai, 2008; Yasmin et al., 2016). The Probit-based analyses show a strong bibliometric linkage to the theme 'SIGNAL' and its sub-themes 'VEHICLE' and 'SPEED LIMIT' (see Appendix 7g), highlighting their prevalence in signal-related crash-risk research.

Negative Binomial (NB) models and their extension, the Random Parameter Negative Binomial (RP-NB), are indispensable for analyzing over-dispersed crash count data, a violation of standard Poisson assumptions. These models effectively capture excess variance but may over simplify complex interaction if applied incorrectly. In RLC evaluations, NB and RP-NB specifications estimate changes in crash frequencies while adjusting for covariates such as traffic volume, intersection geometry, and temporal trends. Their computational tractability and ability to accommodate clustered observations have made them popular in before-after study designs. However, conventional NB models assume homogeneous risk parameters across all sites, thereby neglecting unobserved heterogeneity and risking biased effect estimates when RTM or spillover effects are not addressed (Erke, 2009; Hauer, 1997; Washington et al., 2020; Mannering & Bhat, 2014; Anastasopoulos et al., 2012; Pace & LeSage, 2009). Erke (2009) demonstrates that NB analyses without RTM controls can overstate RLC safety benefits by 15–25%. In our scientometric analysis, the RP-NB model exhibits a strong, exclusive association with the emerging theme "INTERSECTION CRASHES", highlighting its direct applicability to intersection-specific crash assessments (see Appendix 7d).

Several key critiques of various methods employed in RLC research highlight concerns regarding complexity and interpretability, particularly with advanced techniques such as machine learning techniques,

simulation-based models, and analytical approaches. While these methods can manage large datasets and identify intricate patterns, their opaque nature can hinder researchers' ability to comprehend the underlying relationships within the data.

Advanced algorithms such as random forests and deep neural networks are good at processing large volumes of heterogeneous data and uncovering complex, non-linear relationships. However, their opaque nature impedes transparent interpretation of model outputs, complicating the elucidation of causal mechanisms. In addition, these methods demand substantial computational resources and extensive hyperparameter tuning, which may be prohibitive in data-or resource constrained research settings (Lum & Wong, 2003; Lum & Wong, 2003; Washington et al., 2020; Rudin, 2019). Simulation-based models, such as multi-agent systems and cellular automata, also provide the capacity to emulate individual driver behaviors and localized interactions, even though they rely on simplifying assumptions (such as rule sets or initial conditions) that may not generalize to real-world traffic dynamics. Without rigorous calibration and validation against observed data, these models risk misrepresenting the evolution of driver responses to RLC deployment (Garber et al., 2007; Council et al., 2005; Savolainen et al., 2011; Pace & LeSage, 2009; Pearl & Mackenzie, 2018). While in analytical approaches like geometric techniques and saturation models provide interpretable, tractable tools for assessing the spatial distribution of violations and compliance rates. Their relative simplicity, however, can limit flexibility as they frequently do not account for temporal variability or non-linear effects arising from changing traffic volumes, enforcement intensity, or adjacent intersection spillovers (Council et al., 2005; Hauer, 1997; Lord & Mannering, 2010; Washington et al., 2020; Elvik, 2011; Pace & LeSage, 2009). No single method fully captures the complex nature of RLC impacts. Additionally, integrating quasi-experimental designs (e.g., difference-in-differences, synthetic controls) with machine learning frameworks to strengthen causal inference, and utilizing explainable-AI (XAI) techniques (such as SHAP values or local interpretable model-agnostic explanations) to clarify variable importance and model decision pathways. Similarly, simulation models can be enhanced using hybrid data-assimilation schemes and spatio-temporal extensions, thereby improving calibration to empirical driver-behavior data and better representing dynamic traffic interactions.

## 5. Challenges and limitations in RLC research

### 5.1. SLR of the key challenges encountered in RLC research

This section presents a comprehensive SLR of the KEY challenges encountered in RLC research. A total of 75 articles were chosen for analysis, identifying 12 major issues that impact RLC research on signalized intersection safety. These key challenges include inconsistent data quality, methodological flaws, statistical analysis, variability in study design, contextuality variability, limited longitudinal studies, confounding variables, public perception and compliance, ethical and legal challenges, funding and resource constraints, technological limitations, and resistance to changes.

Inconsistent data quality presents a significant challenge in evaluating RLC effectiveness, as heterogeneity in data-collection protocols impairs both the validity and comparability of study findings. Divergent definitions of key metrics such as *red-light violations* and *crash rates*, complicate direct comparisons and erode confidence in reported outcomes (Llau & Ahmed, 2014; Wahl et al., 2010; Flannery & Maccubbin, 2002). This inconsistency not only undermines the credibility of individual studies but also hinders the broader synthesis of RLC impacts on traffic safety (Llau & Ahmed, 2014; Lund et al., 2009). Moreover, many evaluations contrast crash frequencies at camera-equipped intersections with those at nearby non-camera sites, a design that may understate RLC benefits due to spillover or halo effects, namely, reductions in violations and collisions at adjacent locations in response to enforcement presence

(Langland-Orban et al., 2016; Lund et al., 2009). Conversely, selection bias can arise when cameras are installed at intersections with historically high crash rates; ensuing RTM effects lead crash counts to revert toward baseline levels over time, thereby inflating apparent RLC effectiveness (Langland-Orban et al., 2014; Regan et al., 2006; Debnath et al., 2014).

Another critical challenge in RLC research is the complexity of statistical analysis. RTM can substantially bias effect estimates, making RLCs appear more effective than they truly are. Many studies fail to adequately adjust for RTM, resulting in potentially misleading conclusions about the impact of camera enforcement on traffic safety (Cunningham & Hummer, 2010; Lund et al., 2009; Cohn et al., 2020; Hallmark et al., 2011). In addition, inconsistent evidence regarding spillover effects further complicates assessment: RLC installation may influence not only targeted intersections but also adjacent, untreated sites (Lee et al., 2016; Lund et al., 2009). Some studies indicate that heightened enforcement presence leads to changes in driver behavior and reductions in right-angle collisions at nearby intersections; however, the variability of findings precludes a clear consensus on the magnitude and direction of these effects. This also indicates that methodological heterogeneity such as that ranging from simple before-after comparisons to controlled quasi-experimental designs poses challenges for synthesizing results and often yields conflicting interpretations of RLC effectiveness at signalized intersections (Høye, 2013; Hakkert & Gitelman, 2004).

Contextual variability further complicates the evaluation of RLCs. Effectiveness can vary substantially with geographic, cultural, and traffic conditions: urban and rural environments often exhibit divergent safety outcomes, driven by differences in traffic volume, intersection geometry, and prevailing flow patterns (ALTurki, 2014; Retting et al., 1999). The lack of longitudinal studies limits insight into the durability of RLC-induced safety gains; as post-installation traffic behaviors and crash evolve, extended observation periods and systematic data collection become essential (Burkey & Obeng, 2004; Eger et al., 2015; Joris et al., 2014). Robust assessment also requires careful identification and control of confounding variables such as local socioeconomic characteristics and simultaneous enforcement initiatives. This to a great extent will help in mitigating bias and strengthen internal validity (Retting et al., 2008; Shin & Washington, 2007; Garber et al., 2007; McCartt & Hu, 2014; Hu et al., 2011; Cohn et al., 2020). Implementation and research are further challenged by issues of public acceptance and compliance. This also include ethical and legal constraints, funding limitations, technological obstacles and institutional resistance. However, addressing these hurdles is critical to optimizing both the deployment of RLCs and the rigor of their evaluation.

5.2. Linking key challenges encountered in RLC research to bibliometric themes

This section outlines the connections between the KEY challenges encountered in RLC research and the bibliometric themes organized by their quadrants, as summarized in Table 14. A total of six challenges were extracted from the KEY challenges presented in Table 13.

6. Prospect of future research in RLC

The RLC research area in relation to signalized intersection safety stands at a critical juncture, ripe for more innovations and advancements. Recent studies highlight the myriad challenges that researchers face, from inconsistencies of environmental influences on light detection that affects most drivers to the complexities of accurately understanding road user behavior amidst cluttered urban settings, which has a significant influence on collected data (De Charette & Nashashibi, 2009; De Charette & Nashashibi, 2009). The demand for robust algorithms capable of handling variations in different conditions such as weather, lighting conditions, and occlusions is paramount as we transition

Table 13  
Challenges and limitations in RLC research.

Issues Raised	Related topics	Authors
INCONSISTENT DATA QUALITY	Data Collection Methods, Data Validation Techniques, Impact of data quality on research findings.	(Llau and Ahmed, 2014; Wahl et al., 2010; Cunningham and Hummer, 2010; Lund et al., 2009; Høye, 2013; Flannery and Maccubbin, 2002; Porter et al., 2013; Budd et al., 2011)
METHODOLOGICAL FLAWS	Research designs, Limitation of Cross-sectional Studies, Importance of control groups.	(Retting et al., 2003; Llau and Ahmed, 2014; Langland-Orban et al., 2014; Regan et al., 2006; Llau; Debnath et al., 2014; Langland-Orban et al., 2008; Li and Tian, 2009; Langland-Orban et al., 2011)
STATISTICAL ANALYSIS	Techniques for analyzing traffic safety data, Regression to the mean, Spillover effects,	(Cunningham and Hummer, 2010; Langland-Orban et al., 2016; Lee et al., 2016; Lund et al., 2009; Høye, 2013; Cohn et al., 2020; Hallmark et al., 2011)
VARIABILITY IN STUDY DESIGN	Comparative analysis across different studies, Influence of study design on outcomes, Standardization of research protocols.	(Høye, 2013; ALTurki, 2014; Hakkert and Gitelman, 2004; Retting et al., 1999; Cohn et al., 2020)
CONTEXTUALITY VARIABILITY	Geographic differences in RLC effectiveness, Impact of Local laws and culture, Case studies of RLCs implementations in diverse environments.	(Haque et al., 2010; Hakkert and Gitelman, 2004; Retting et al., 1999)
LIMITED LONGITUDINAL STUDIES	Importance of long-term data in traffic safety research, Challenges in conducting Longitudinal research.	(Burkey and Obeng, 2004; Haque et al., 2010; Regan et al., 2006; Eger et al., 2015; Alshater et al., 2020; Joris et al., 2014; Andreassen, 1995)
CONFOUNDING VARIABLES	Identifying and controlling for confounders, Impact of External factors on RLC effectiveness, Techniques for isolating RLC effects.	(Erke, 2009; Retting et al., 2008; Shin and Washington, 2007; Retting and Kyrychenko, 2002; Garber et al., 2007; Persaud et al., 2005; Langland-Orban et al., 2016; McCartt and Hu, 2014; Hu et al., 2011; Lum and Wong, 2002; Abdulsalam et al., 2017; Cohn et al., 2020; Baratian-Ghorghi et al., 2017; Claros et al., 2017; Lum and Wong, 2002)
PUBLIC PERCEPTION AND COMPLIANCE	Community attitude towards RLCs, Strategies for enhancing public compliance, Role of education and awareness campaigns.	(Retting et al., 1999; Retting et al., 2008; Garber et al., 2005; Satiennam et al., 2018; Retting et al., 1999; Quiroga et al., 2003; Cohn et al., 2020; Boakye et al., 2015; Retting and Williams, 1996; Lv et al., 2022; Tarawneh et al., 1999; Hooke et al., 1996; Eccles, 2012; Walker, 2014; Sze et al., 2011; Varet et al., 2021)
TECHNOLOGICAL LIMITATIONS	Advances in traffic monitoring technology, Limitations of current RLC technology, Future	(Wong, 2014; Llau and Ahmed, 2014; Eger et al., 2015; Cohn et al., 2020; Shin et al., 2005;

(continued on next page)

Table 13 (continued)

Issues Raised	Related topics	Authors
	innovations in traffic safety technology.	Baratian-Ghorghi et al., 2017; Center, 2009; Kent et al., 1995; Goldenbeld et al., 2019; Claros et al., 2017)
ETHICAL AND LEGAL ISSUES	Ethical considerations in traffic enforcement, legal challenges surrounding RLC implementation, Balancing safety and privacy concerns.	(Langland-Orban et al., 2014; Langland-Orban et al., 2016; Ruppell, 2012; Walker, 2014; Yang et al., 2013; Center, 2009; Wissinger et al., 2000; Hartzog et al., 2015; Li and Tian, 2009)
RESISTANCE TO CHANGES	Factors contributing to public resistance, strategies for overcoming resistance to RLC implementation, Case studies of successful RLC adoption despite opposition.	(Burkey and Obeng, 2004; Aldossari et al., 2023; Ruppell, 2012; Ruby and Hobeika, 2003; Christensen, 2010; Lehman, 2001; Kuncl, 2012; Saffarzadeh Parizi, 2023; Hayden, 2009)
FUNDING AND RESOURCE CONSTRAINTS	Impact of funding on research quality, Strategies for securing research funding, Resource allocation for traffic safety programs.	(ALTurki, 2014; Abdulsalam et al., 2017; Cohn et al., 2020; Hooke et al., 1996; Eccles, 2012; Tankasem et al., 2022; Balaci and Suh, 2024; Shin et al., 2005; Li and da Silva, 2022)

towards more autonomous transport networks. Future research should focus on developing advanced machine learning techniques, especially those that utilize deep learning architectures to enhance the accuracy and reliability of RLCs. By leveraging large annotated datasets, such as the extensive longitudinal data as proposed in recent studies (Burkey & Obeng, 2004; Regan et al., 2006; Haque et al., 2010), researchers can train models that generalize better across diverse scenarios, thus addressing the limitations of current methodologies.

In another instance, the integration of RLC systems with emerging technologies, such as vehicle-to-infrastructure (V2I) communication, will create an exciting avenue for future exploration within the context of signalized intersection safety. As connected vehicles become increasingly prevalent, the synergy between RLCs and V2I systems could facilitate a more comprehensive understanding of traffic environments, thus enabling real-time updates and enhanced driver assistance

Table 14  
Linking key challenges encountered in RLC research to bibliometric themes.

Challenges	Themes			
	Motor Themes (Q1)	Basic and Transversal Themes (Q2)	Emerging or Declining Themes (Q3)	Highly Developed and Isolated Themes (Q4)
DATA QUALITY ISSUES	Impacts reliability of analyses and findings.	Essential for valid compliance and interdisciplinary insights.	Hinders growth of emerging research areas; outdated results may decline.	Undermines credibility, reinforcing isolation from broader discourse.
TECHNOLOGICAL CONSTRAINTS	Limits the effectiveness of safety innovations.	Affects fundamental understanding in related fields.	May cause emerging technologies to stagnate without proper exploration.	Can lead to isolation if technologies are not integrated into broader studies.
INTERDISCIPLINARY APPROACHES	Enhances collaboration and innovation in solutions.	Critical for integrating diverse insights into core research.	Supports the rise of new interdisciplinary themes; lack may indicate decline.	Can bridge isolated themes, fostering collaboration and relevance.
PUBLIC ACCEPTANCE	Influences the implementation and effectiveness of policies.	Impacts foundational knowledge on societal behavior and norms.	Affects the traction of emerging themes; declining acceptance may hinder growth.	May isolate themes if public opinion diverges from established research.
FUNDING LIMITATIONS	Hinders implementation of safety initiatives and research.	Affects resource allocation across essential areas.	May cause decline in emerging topics due to lack of investment.	Limits innovation and exploration in niche research areas.
REGULATORY BARRIERS	Affects policy development and the implementation of safety measures.	Impacts compliance and legal frameworks in research.	Can stifle new methodologies and technologies, leading to decline.	Isolates innovative solutions due to strict regulations and lack of integration.

Source: Author’s Analysis 2025.

functionalities (Hawlder et al., 2023; Rammohan, 2023). This integration not only aims to improve traffic safety and efficiency at signalized intersections, but also paves way for the development of intelligent transportation within smart cities, where traffic management is dynamically optimized. Future studies should also consider the ethical and legal implications and societal impacts of implementing advanced RLC systems ensuring that innovations contribute positively to urban mobility and public safety.

### 7. Conclusion

The BPNA conducted in this study revealed a significant understanding of the impact of RLCs on traffic safety at signalized intersections. The results identified four distinct quadrants, each representing varying levels of research focus and effectiveness. The motor theme (Q1) highlighted studies demonstrating significant reductions in RLR violations and associated crashes, thus emphasizing the potential of RLCs as effective safety measures. Likewise, the basic and transversal themes (Q2) indicated minimal or mixed results, suggesting that RLCs alone may not sufficiently address the complexities of traffic safety. The emerging or declining themes (Q3) emphasized the importance of integrating community engagement and driver education in enhancing RLC effectiveness. However, the highly developed and isolated themes (Q4) drifted to emerging technologies such as vehicle-to-infrastructure (V2I) communication, as promising avenues for future research.

However, the thematic evolution of RLC research from 1975 to 2024 also reveals significant shifts in focus within the field of signalized intersection safety. Key transitions occurred between the P<sup>3</sup> (1995–2004) and P<sup>4</sup> (2005–2014) periods, as broader themes such as ‘RISKY BEHAVIOR’ and ‘TRAFFIC SIGNAL OPTIMIZATION,’ emerged, reflecting a deeper understanding of human factors in traffic safety. While traditional themes, such as ‘RED LIGHT RUNNING BEHAVIOR,’ remain relevant, many connections to new topics are marked by broken lines, indicating challenges in maintaining their significance amid evolving research landscapes. The P<sup>5</sup> (2015–2024) phase introduces new themes, such as ‘PROBE’ and ‘MOTORCYCLIST BEHAVIOR,’ into safety discussions.

Moreover, the methodological evaluation elucidated significant critiques of existing RLC research methodologies. Key limitations, including the dependency on the validity of SPFs and challenges in controlling for RTM, emphasize the need for more robust analytical approaches. The methodological challenges linked to bibliometric

themes revealed how issues such as inconsistent data quality and public perception can hinder research effectiveness and credibility. Hence, this comprehensive thematic analysis emphasizes the necessity for a holistic approach to traffic safety that integrates RLC implementation with innovative technologies and public involvement. RLC researchers should also focus on the dynamic complexities of urban transportation systems while retaining foundational concepts essential for future studies.

### CRedit authorship contribution statement

**Samaila Garba:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Pen-gyu Zhu:** Validation, Supervision, Software, Resources, Project administration.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsr.2025.12.009>.

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## Glossary

**Basic Themes:** These themes refer to the core research topics that are fundamental to a specific field of study in scientometric analysis. The motor themes represent established concepts, key questions, and foundational knowledge that underpin ongoing research efforts. They are essential for understanding the primary focus areas and the development of a discipline.

**Bibliometric Analysis:** A statistical analysis of published literature to assess the impact and development of research in a specific field.

**Callon's Centrality:** A measure used in scientometric analysis to access the influence and prominence of a research topic, an author, or institution, within a network. It is based on the concept of centrality in social network analysis, indicating how well connected an entity is thereby reflecting its role in facilitating collaborations and knowledge dissemination within the scientific community.

**Callon's Density:** A metric that evaluates the interconnectedness of nodes within a research network in scientometric analysis. It reflects the proportion of actual connections to possible connections among entities, indicating the overall cohesiveness and collaboration intensity within a specific research area.

**Citation Analysis:** The process of examining the frequency and context of citations in academic literature to assess impact and scholarly influence.

**Contextualizing:** The process of placing information, research findings, or phenomena within a specific framework or setting to enhance understanding. This involves considering the historical or situational factors that influence the interpretation and relevance of the data being analyzed, allowing for a more vivid comprehension of its implications and applications.

**Crash Rates:** This is the frequency of vehicle collisions in a specific area or under certain conditions, often expressed as incidents per unit of time or distance.

**Declining Themes:** These themes refer to research topics that are experiencing a decrease in scholarly activity, such as falling publication rates, reduced citations, or waning interest from the research community. In scientometric analysis, they signify areas that have become saturated, outdated, or less relevant over time.

**Dilemma Zone:** The area at an intersection where a driver must make a rapid decision about whether to stop or proceed through a traffic signal as it turns yellow. This zone poses challenges for drivers, as the decision-making process can lead to red-light running or sudden braking, increasing the risk of crashes.

**Emerging Themes:** These themes are research topics that are gaining attention and traction within the field. They typically show a rising trend in publications, citations, and scholarly interest, indicating new areas of inquiry or innovative developments. In scientometric analysis, they also reflect shifts in research focus and highlight the potential for future exploration. Collaboration, and impact on the discipline.

**Highly Developed Themes:** These themes are research topics that possess a significant body of literature, extensive citations, and well-established frameworks. In scientometric analysis, they demonstrate robust scholarly activity, indicating a mature area of study with a clear trajectory of advancement, strong theoretical foundations, and active engagement from the research community.

**Intervention Strategies:** Specific actions or measures taken to improve traffic safety, such as the installation of RLCs or education campaigns.

**Isolated Themes:** These themes refer to research topics that lack substantial connections to other areas of study or have limited scholarly interaction. In scientometric analysis, they are characterized by minimal citations, few collaborative efforts, and a narrow focus, which can hinder their development and integration within broader scientific discourse. Such themes may indicate niche areas of research that are underexplored or emerging fields that have not yet gained wider attention.

**Motor Themes:** These themes are central research topics that drive innovation and development within a field. They are characterized by high levels of activity, significant scholarly attention, a strong network of connections to other research areas. They often represent emerging trends or pivotal concepts that catalyze further exploration, collaboration and advancement in scientific knowledge. They play crucial role in shaping the future direction of research and influences related disciplines.

**Network Analysis:** A method used to study the relationships and connections between various entities, such as authors, institutions, or research themes in scientometric analysis.

**Network Extraction:** The process of identifying and isolating relationships and connections among entities, such as research topics, authors or institutions within a dataset in scientometric analysis. This involves creating a visual or data-driven representation of these relationships to explore collaboration patterns, citation networks, and the structure of knowledge within specific research field.

**Normalization:** This refers to the process of adjusting bibliometric data to account for various skew results, such as differences in publication volume across fields, citation practices etc. This adjustment helps provide a fair comparison of research impact and performance, enabling more accurate assessments of scholarly contributions across diverse contexts.

**PRISMA:** Preferred Reporting Items for Systematic Reviews and Meta-Analyses; A set of guidelines to improve the transparency and quality of reporting in systematic reviews.

**Red-Light Camera (RLC):** A traffic enforcement device that captures images of vehicles running red lights at intersections.

**Red-Light Running:** The act of a vehicle disregarding a red traffic signal at an intersection, resulting in the vehicle proceeding into the intersection while the light is not green.

This behavior poses significant risks to safety, often leading to collisions with other vehicles or pedestrians.

**Research Trends:** Patterns or shifts in research focus over time, identified through analysis of published studies and citation data.

**Safety Outcomes:** The results or impacts of interventions on traffic safety, including reductions in accidents, injuries, and fatalities.

**Safety Performance Indicators:** Metrics used to evaluate the effectiveness of traffic safety interventions and policies, such as RLC implementation.

**Scientometric Analysis:** This is the quantitative assessment of scientific literature and research outputs, focusing on measuring and analyzing patterns of publication, citation, and collaboration within a specific field. This analysis helps identify trends, research impact, and the development of knowledge over time, often using bibliometric techniques and tools.

**SciMAT Tool:** A software tool for conducting bibliometric analysis and visualizing scientific maps to explore the development of research fields over time.

**Signalized Intersection:** An intersection controlled by traffic signals to manage the flow of vehicles and pedestrians.

**Strategic Diagram:** This is a visual tool used to represent the relationships between various entities, such as authors, institutions, or research themes, in a structured way. It is also used in identifying strategic opportunities, collaborative networks, and areas of research strength or weakness in scientometric analysis.

**Systematic Review:** A methodological and comprehensive literature review that aims to summarize all relevant studies on a specific topic according to predefined criteria.

**Thematic Evolution:** Process by which research themes and topics develop and change over time, often identified through bibliometric analysis. It involves tracking the emergence, growth, and decline of specific research areas, highlighting shift in focus, trends, and the interconnections between different themes within a field.

**Thematic Network Structure:** This refers to the organization and interrelations of research topics and themes within the body of scientific literature. In scientometric analysis, the structure highlights how different themes are connected through citations, collaborations, and shared references, enabling researchers to visualize the landscape of knowledge in a specific field and identify key areas of research, emerging trends, and gaps in the literature.

**Traffic Enforcement:** Approaches used by the law enforcement to ensure compliance with traffic laws, including the use of RLCs and other monitoring methods.

**Traffic Signal Optimization:** Techniques and strategies aimed at improving the efficiency

and effectiveness of traffic signals to enhance traffic flow and safety.

**Transversal Themes:** These themes are interdisciplinary topics that connect multiple fields of research. In scientometric analysis, these themes highlight areas of overlap and collaboration across disciplines, addressing complex scientific issues that require insights from various domains.

**Mapping:** This refers to the visual representation of data to illustrate relationships, trends, and structures within scientific literature. This includes creating graphical displays, such as co-authorship networks, citation maps, or thematic clusters to illustrate how research topics, authors, or institutions are connected.

**Mr. Samaila GARBA** Mr. Samaila GARBA is a Research Postgraduate student in the Division of Public Policy at the Hong Kong University of Science and Technology (HKUST). He earned his Master's (M.Sc.) in Geographical Information Systems with Remote Sensing from the University of Greenwich London, United Kingdom. Mr. Garba teaches transport geography, transport Safety, GIS and Remote Sensing, His research interests include sustainable transportation, road accident analysis and prevention mechanisms, traffic safety policy, speed enforcement systems, automated enforcement for signalized intersections. He also utilizes spatial analysis to solve geospatial-related problems, planning and policy making.

**Professor Pengyu ZHU** Professor ZHU is a distinguish Professor in the Division of Public Policy at the Hong Kong University of Science and Technology (HKUST), a Co-Director of the Master of Public Policy Program, and Director of the Center for Applied Economic, Social and Environmental Reach. He was previously a faculty member at Boise State University from 2011 to 2016 and at the University of Hong Kong from 2017 to 2019. Prof. ZHU earned his Ph.D. in Public Policy, Planning and Development from the University of Southern California. His research focuses on the nexus between transportation, land use, and economic development policy. Key areas include travel behavior, location choice, and the implication of transportation infrastructure. Prof. ZHU employs spatio-temporal big data analytics to inform urban planning decisions. His works have been published in major academic journals and highlighted in media outlets such as the Wall Street Journal. In 2017, he ranked among the top 5% and 3% of researchers on Academia.edu based on article views. He has received several research grants and prestigious awards, including the 25<sup>th</sup> Charles M. Tiebout Prize in Regional Science.