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Trend analysis of machine learning techniques for traffic control based on bibliometrics

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ABSTRACT

Machine learning in traffic control for intelligent transportation systems (ML-ITSTC) aims to enhance user coordination and safety within transportation networks, ultimately improving overall traffic system performance. ML-ITSTC is achieved by leveraging data to execute machine learning algorithms in intelligent transportation management and optimizing traffic flow to prevent or reduce congestion. This paper conducts bibliometric analysis to explain the research status, development trajectory, and challenges of ML-ITSTC, drawing insights from literature in the Scopus database literature covering 2013 to November 2023. The bibliometric analysis of ML-ITSTC includes: performance analysis, science mapping analysis, and citation analysis. The evaluation of ML algorithm trends over the 10-year span indicates that traffic prediction (TP), neural networks, and deep learning are frequently used keywords. Further, an examination of keywords used over the entire period and in 2023 (up to November) shows that reinforcement learning (RL) is the latest popular approach for traffic control in transportation. The results provide a comprehensive view of the opportunities and challenges in ML-ITSTC, covering data, models, and applications, offering researchers insights into the current and future directions of ML-ITSTC research.

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1. INTRODUCTION

Intelligent transportation systems (ITS) are built to increase safety and efficiency in transportation by addressing various traffic-related issues, such as traffic management, accident prevention, toll roads, parking systems, and pollution control [1], [2]. The advantage of ITS is its cost-effectiveness through a method of controlling traffic operations without requiring additions or modifications to existing road facilities [3], [4]. ITS combines advanced technologies such as electronic sensor technology, data transmission technology, and intelligent control technology, resulting in big data [5], [6]. However, problems with big data include data storage, data analysis, and data management. Combining diverse and big data obtained from ITS with machine learning (ML) increases accuracy and expedites data analysis [7].

The ML algorithm processes data through several stages, including regression, classification, clustering, and determining association rules [8]. It identifies relationships between features and outputs, namely labelling, patterns, and makes decisions based on particular data, involved in the transportation sector. In recent years, many papers worldwide have focused on exploring the research status of ML algorithms applied in ITS. For instance, ML is used in urban transportation to prevent vehicle congestion through predictive vehicle analysis [9], [10]. Chen *et al.* [11] introduced deep learning (DL) for real-time vehicle counting, which can further predict traffic flow using convolutional neural network (CNN) and graph convolutional neural network (GCNN) [12], [13]. Moreover, ML can be applied on highways for vehicle trajectory prediction while line changing [14].

Based on the multitude of studies about ML-ITS topics, a bibliometric review study is essential to providing a holistic understanding of the research landscape in this area. Bibliometric review is a method to explore and analyze large amounts of scientific data, providing an overview of journal development and evolution [15]. Several studies have explored bibliometric analysis in the ITS area, such as big data topics in ITS [16], ML in general as the primary topic [17], and reinforcement learning (RL) for transportation [18]. Other studies have used database IEEE transactions on intelligent transportation systems (T-ITS) with varying spans of years to see research trends related to ITS [19], [20]. According to Tomaszewska and Florea [21], bibliometric using to identify trends based on urban smart mobility scientific literature based on Web of Science and Scopus databases.

However, none of these studies has been conducted on bibliometrics regarding the use of ML in traffic control for intelligent transportation systems (ML-ITSTC). This study quantitatively and visually analyzes the academic landscape, research trends, and knowledge dissemination paths in ML-ITSTC. Bibliometric analysis involves ranking and evaluating the journal's lifespan over 10 years, guiding to readers, authors, and reviewers with an overview of the development and evolution of ML-ITSTC topic journals. Clustering based on keywords is done to illustrate the growth trend of publications and research patterns in ML-ITSTC spans 2013 to November 2023.

This paper is organized as follows: an explanation of the data source and method used in this bibliometric study is presented in section 2. Section 3 reviews the results of the bibliometric analysis, which has been divided into three sections: section 3.1 focuses on the statistical performance, section 3.2 presents the visualization of bibliographic coupling, and section 3.3 examines the research publication trends. Finally, the conclusion of our findings and points for some future recommendations are given in section 4.

2. METHOD

This study aims to determine the research status, development, and trends of ML-ITSTC by analyzing literature from the Scopus database. Scopus is regarded as one of the largest curated databases selected through a content selection process with continuous re-evaluation [22], [23]. Figure 1 illustrates the flow of research methods and protocols. In this bibliometric study, we did not directly address the ML algorithm topic but focused on the areas encompassed by the topic, including DL, supervised learning (SL), unsupervised learning (UL), RL, and evolutionary learning (EL) [10]. Consequently, the bibliometric method was implemented using the specified keywords: (TITLE-ABS-KEY(intelligent AND transportation AND system) AND TITLE-ABS-KEY(traffic AND control) AND TITLE-ABS-KEY(deep AND learning) OR TITLE-ABS-KEY(supervised AND learning) OR TITLE-ABS-KEY(unsupervised AND learning) OR TITLE-ABS-KEY(reinforcement AND learning) OR TITLE-ABS-KEY(evolutionary AND learning)).

The selected bibliometric analysis utilizes co-word analysis, focusing on describing thematic relationships among words that frequently appear together in "author's keywords," "article title," and "abstract" [15]. The document search is limited to a 10-year period from 2013 to 2022. Subsequently, subject categorizations were focused on computer science, engineering, and mathematics, while the remainder covered social science, energy, environmental science, and neuroscience. The application of keywords and limitations in the search on Scopus yielded 494 documents, including 236 conference proceedings, 215 journals, and 43 book series, all written in English. The dataset, collected in comma-separated values (CSV) format, was processed using Microsoft Excel to examine trends and patterns of research publications over a specific period [23].

In the following processing stage, keyword pre-processing was carried out by combining synonyms and terms into a standard form using OpenRefine. This software is used to clean and filter data through various methods while offering compatibility with several secondary data sources [24], [25]. In this study, the evolution of ML-ITSTC publications over a certain period can be seen using keywords. VOSviewer was used as a co-occurrence network mapper to create a bibliometric map to visualize the relationship between keywords in each publication within the bibliometric network for future examination [17], [18]. The research involved analyzing and mapping article data related to trends in the number of papers each year, authors, locations, institutions, publishers, citations, and keywords. This study conducted a co-occurrence analysis, emphasizing the frequency of keyword occurrences (OC) in core papers that significantly impact the ML-ITSTC field within the network [26]. Furthermore, measure the range and intensity of influence of a node in the network using total link strength (TLS) [27]. Following the analysis, the results were organized and presented in map form, complete with network connections and color differentiation. In a network map, larger circles of the same color signify greater influence and relevance of a keyword compared to others [28], [29]. If two or more papers cite the same document, connections are established between these papers, forming new clusters. We restricted the search scope by adding the specific keyword "traffic control" in the ML-ITSTC Scopus database from 2013 to 2022. This approach aimed to identify the most influential publications solely on the application of traffic control within the ML-ITSTC domain.

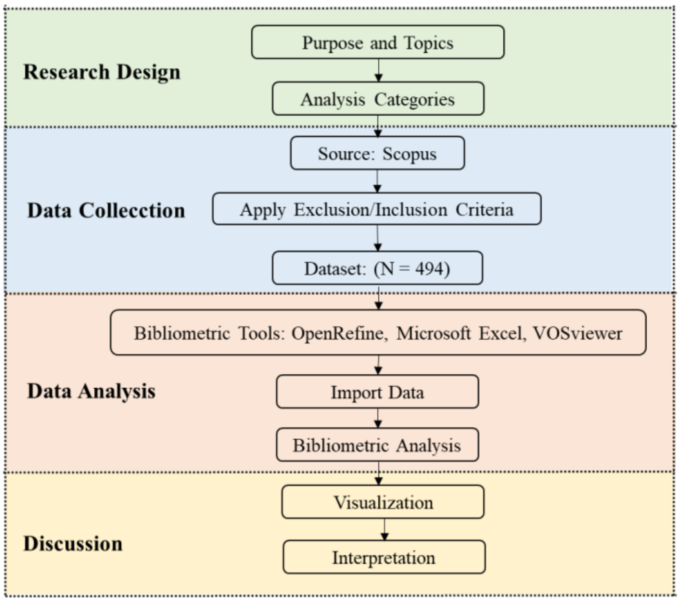


Figure 1. Research methodology flowchart

3. RESULTS AND DISCUSSION

3.1. Performance bibliometric analysis of ML-ITSTC

Figure 2 illustrates the annual trend in document production from 2013 to 2022, highlighting the growth in publications related to ML-ITSTC. This trend, spanning 10 years, can be categorized into three distinct phases: the emerging phase, the pick-up phase, and the rapid development phase [30]. From 2013 to 2015, there was a low increase of less than five additional documents per year, characterizing this period as the emerging phase. Then, in the pick-up phase from 2016 to 2018, an increase in the document count occurred, surpassing 10 to 30 documents per year. The rapid development phase from 2019 to 2022 is marked by substantial growth, exceeding 60 to 100 documents per year.

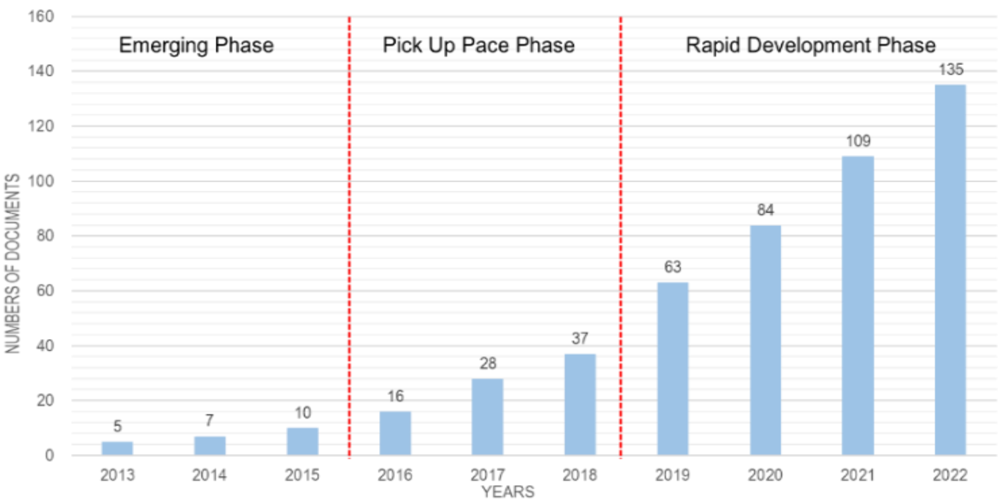
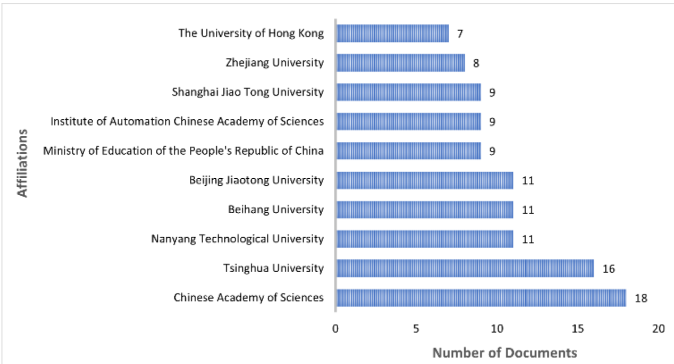
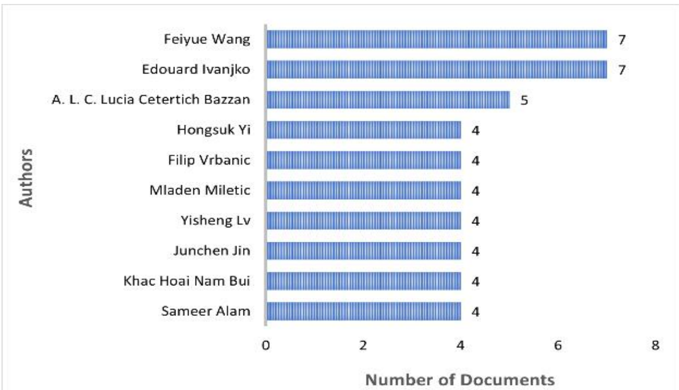


Figure 2. Numbers of papers in the field of ML-ITSTC

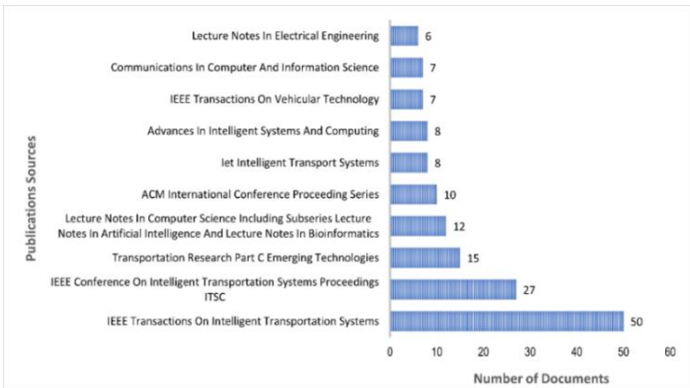
Further exploration was conducted to provide in-depth bibliometric analysis by observing the most significant variables in the field of ML-ITSTC. Figure 3 displays bar graphs presenting the top 10 rankings based on affiliated colleges or institutions, authors, and publication sources. Figure 3(a) shows the top 10 leading affiliated colleges or institutions, resulting in the Chinese Academy of Sciences leading with 18 papers in 10 years. Notably, most of the top 10 affiliate rankings are occupied by colleges or institutions from China. Figure 3(b) illustrates the top 10 authors most productive with ML-ITSTC topics. Over the past decade, the most prolific writers have been Feiyue Wang and Edouard Ivanjko, who have produced seven documents specifically related to TC using ML. Wang is associated with the Chinese Academy of Sciences in Beijing, China, while Edouard Ivanjko is affiliated with the University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia. Concurrently, Figure 3(c) shows the top 10 leading sources delivering the IEEE Transactions on Intelligent Transportation Systems emerge as the most significant publication source, contributing 50 documents to the Scopus dataset.



(a)



(b)



(c)

Figure 3. Number of publications indexed from 2013 to 2022, (a) top 10 leading affiliations, (b) top 10 leading authors, and (c) top 10 leading sources, in the field of ML-ITSTC

3.2. Science mapping analysis of ML-ITSTC

Figure 4 illustrates a VOSviewer map representing network relationships between keywords from the author's work. In the Scopus database, which comprises 494 documents, requiring a minimum of 5 OC for inclusion, a threshold of 46 was obtained. Figure 4 shows three clusters: ITS-RL, DL-traffic flow prediction (TFP), and traffic forecasting (TF). In the ITS-RL map network, the 4 keywords with the strongest relationships are ITS (OC=141, TLS=263), RL (OC=62, TLS=102), ML (OC=42, TLS=83), and traffic signal control (TSC) (OC=28, TLS=55). For the DL-TFP group, the top keywords are DL (OC=146, TLS=224), TFP (OC=54, TLS=93), CNN (OC=28, TLS=59), and short-term memory (STM) (OC=24, TLS=59). In the smallest network map, traffic forecasting consists of TF (OC=13, TLS=27), deep neural networks (DNN) (OC=10, TLS=15), recurrent neural networks (RNN) (OC=6, TLS=15), and graph convolutional network (GCN) (OC=17, TLS=32).

To visualize the research development trends during 2013 to 2022, keyword network maps were created by dividing them into period 1 (2013 to 2017) and period 2 (2018 to 2022) using VOSviewer, as seen in Figure 5. Figure 5 shows period 1, with 66 documents limited to requiring a minimum of 5 OC for inclusion, a threshold of 8 was obtained. This resulted in 8 main clusters, dominant keyword trends include TFP (OC=6, TLS=9), DL (OC=4, TLS=17), and CNN (OC=5, TLS=8). Figure 6 displays period 2 with 428 documents applying a threshold of 42, which required a minimum of 5 OC for inclusion, resulted in 24 main clusters. The majority of research progress related to ML-ITSTC at the end of 2021 to 2022 encompasses topics such as deep reinforcement learning (DRL) (OC=31, TLS=45), TSC (OC=26, TLS=49), multi-agent systems (MAS) (OC=8, TLS=19), artificial intelligence (AI) (OC=12, TLS=24), and GCN (OC=9, TLS=11).

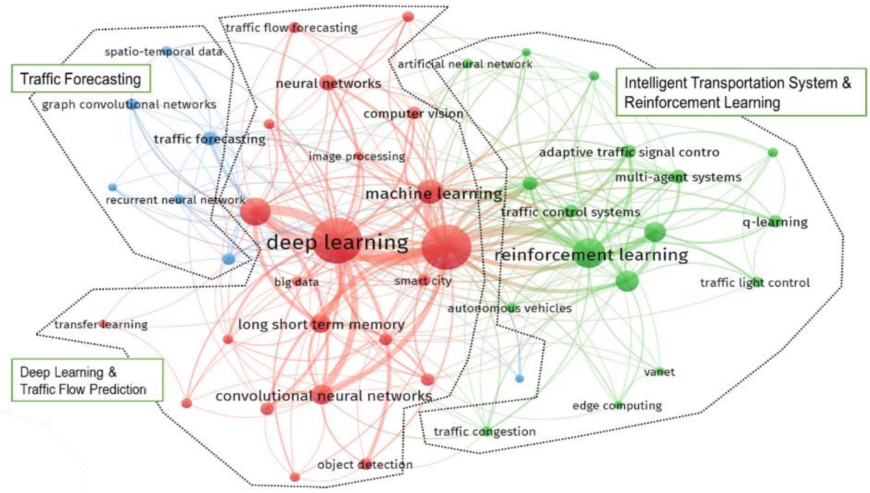


Figure 4. Co-occurrence network of keywords for the period 2013 to 2022

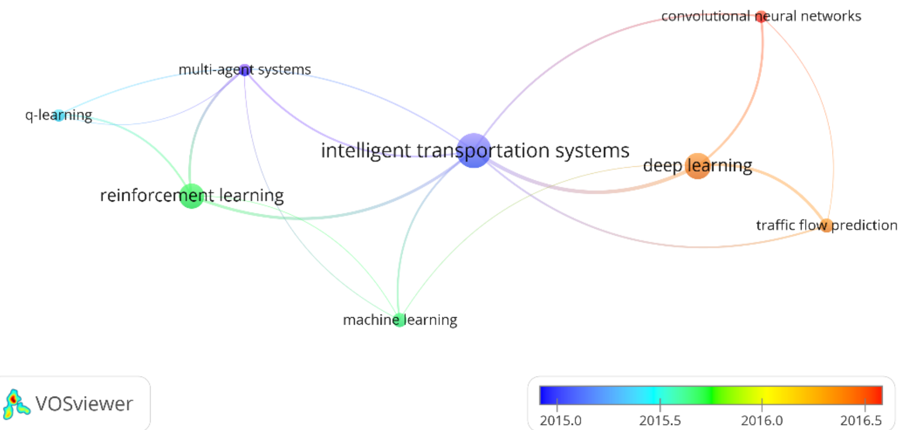


Figure 5. Co-occurance network of keywords period 1 (2013 to 2017)

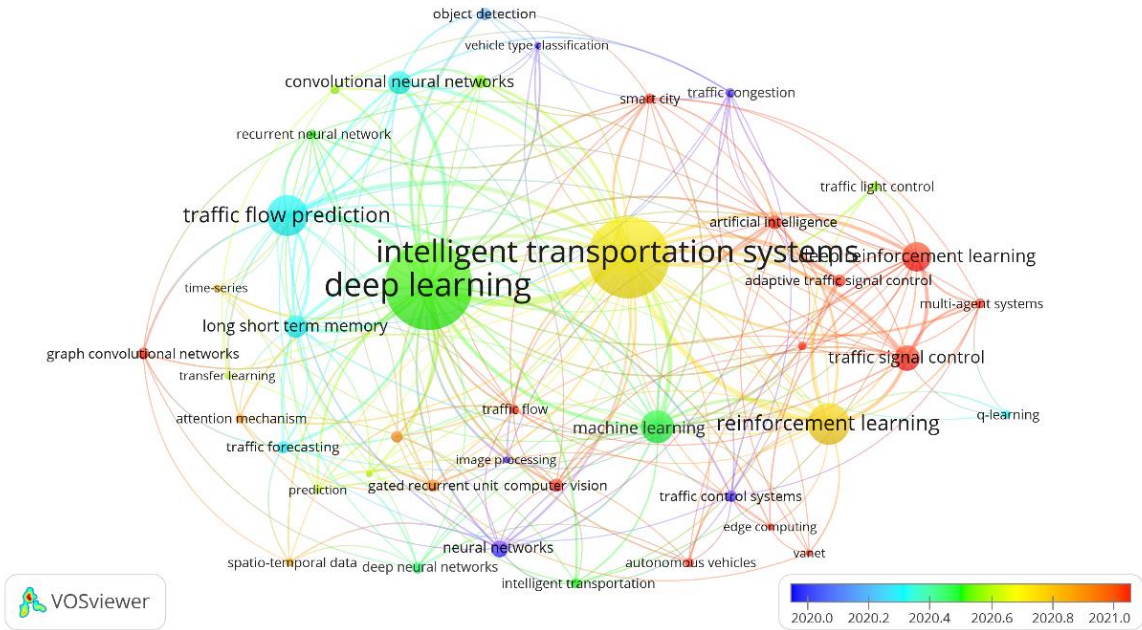


Figure 6. Co-occurance network of keywords period 2 (2018-2022)

In the end, we must know the newest keyword used in the ML-ITSTC topic as of 2023. Figure 7 illustrates the detailed evolution of ML-ITSTC research through keyword network mapping, which was conducted covering from January to November 2023. As a result, 119 papers related to ML-ITSTC have been published. Using VOSviewer with a minimum occurrence value of 5, 17 frequently appearing keywords were identified. The newly emerging keywords in 2023 with the highest frequencies include traffic prediction (TP) (OC=9, TLS=12), TC (OC=5, TLS=5), graph neural network (GNN) (OC=7, TLS=6), and long short-term memory (LSTM) (OC=5, TLS=7).

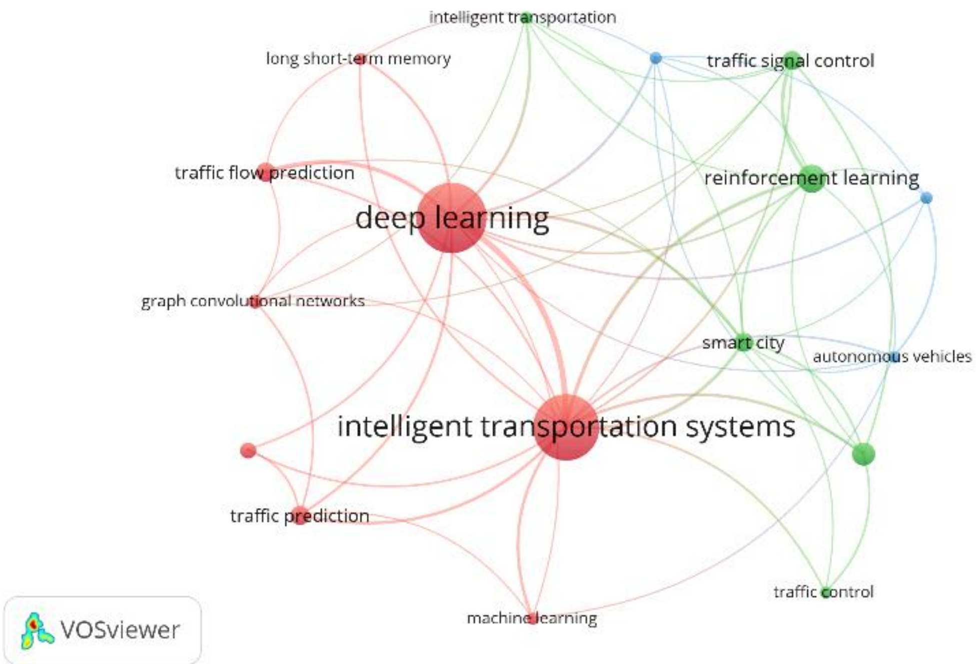


Figure 7. Co-occurrence network of keywords for 2023 (until November)

3.3. Citation analysis of ML-ITSTC

Citation analysis was conducted to identify the most influential publications specifically focused on traffic control applications within the ML-ITSTC domain. The top two most cited papers are research on communication systems, encompassing a survey of ML applications in networks and security for 6G [31] and the internet of connected vehicles (IoCV) in 5G networks for traffic control systems (TCS) [32]. The third and further highly cited papers are explorations into TC research. The studies about the smart traffic management platform (STMP) are a platform can analyze and control real-time and adaptive traffic using various heterogeneous data sources, including internet of things (IoT), smart sensors, and social media [7]. Other TC studies that control vehicles entering the freeway through reinforcement learning control agent (RLCA) algorithm in freeway ramp-metering [33]. A similar RL algorithm is used in the TC model to determine precise timing parameters in traffic scenarios [34]. Jin *et al*. [35] conducted urban TC research using a human-in-the-loop parallel learning framework. TCS not only has theoretical concepts, but it can also be built with a game called GamePlan, which prioritizes drivers based on their aggressiveness or impatience [36].

Moreover, we identified publications using the same keyword previously mentioned in the ML-ITSTC Scopus database during the period January to November 2023 to examine the newest research trend. Out of the 119 documents we found, 7 publications relevant to this keyword are listed in Table 1. Based on the contribution of novel ML techniques to ITS applications from each publication listed in Table 1, we can observe that these publications focus on developing DRL methods. The publications focus on optimizing traffic light control (TLC) using different DRL techniques, such as LSTM algorithm as a single agent to control the centralized grid [37], [38], DNNs algorithm to train deep q-learning (DQN) agents [38], and combining TLC with autonomous vehicles (AV) using multi-agent hierarchical RL framework methods [39]. Furthermore, vehicle control methods can be applied on freeways, such as controlling maximum vehicle speed admission using variable speed limit (VSL) with a multi-agent proximal policy optimization (MAPPO) method [40] and optimizing traffic flow and minimizing delays by controlling ramp meters and adaptive headway cruise control (ACC) through adaptive headway RL and DRL controllers [41]. TC is not limited to urban road traffic; it can also be applied in railways as developing new mathematical traffic models for train and passenger dynamics using a new double deep q-network (DDQN) model [42]. Another study explored the basic TC strategy model using macroscopic fundamental diagrams (MFD), employing DRL agents, and applying Bang-Bang policies for two- and three-region perimeter control [43].

Table 1. The most influential ML-ITSTC publications (January to November 2023)

Author	Methods	Application
Wu *et al.* [37]	DRL, LSTM	TLC on urban road
SenthilPrabha *et al.* [38]	DQN, DNNs	TLC on urban road
Sun *et al.* [39]	GNN, DQN, GCN	TLC with AV
Zhang *et al.* [40]	MAPPO	VSL on freeways
Elmorshedy *et al.* [41]	DNNs, DRL, PPO	Ramp meters and ACC on freeways
Khozam *et al.* [42]	DDQN	Traffic control for train and passenger dynamics on mass transit
Zhou and Gayah [43]	C-RL, Bang-bang type deep-RL controller, domain control knowledge (DCK)	Regional traffic dynamics

4. CONCLUSION

This paper conducts a bibliometric analysis of the Scopus database in ML-ITSTC technology to evaluate the weighted and cumulative technology evolution during the 2013 to 2022 period, resulting in 494 documents. Performance bibliometric analysis shows a slow increase in the volume of published papers from 2013 to 2015, followed by rapid and nearly exponential growth since 2016, particularly in 2018. According to statistical data, China leads the top ten countries with the highest publication volume, with Feiyue Wang and Edouard Ivanjko stand out as the most prolific authors, and IEEE Transactions on Intelligent Transportation Systems became the top-pick publication source. Co-occurrence network of keyword maps was used for the science mapping analysis of ML-ITSTC, resulting in three clusters: ITS-RL, DL-TFP, and TF. Evaluation trends in ML algorithms over 10 years reveal that TP, neural network and DL are keywords that appear more frequently than others. Furthermore, analyzing frequently used keywords over a 10-year period and throughout 2023 (until November) reveals that RL algorithm is the latest popular technology in transportation traffic control using ML. The application of RL algorithms is not limited to urban roads but extends to the aviation sector, freeways, and railways. In the end, this study did not conduct a detailed literature review of ML-ITSTC, which suggests potential exploration in future research. Subsequent studies could enhance database retrieval by incorporating additional sources like Google Scholar, Microsoft Academic, PubMed, and Web of Science to gather comprehensive data on ML-ITSTC-related research.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Eko S. Hasrito	✓	✓	✓	✓	✓			✓		✓		✓		✓
Tri Widodo	✓	✓		✓					✓	✓		✓		✓
Sofwan Hidayat				✓	✓	✓				✓		✓	✓	✓
Okghi Adam Qowiy		✓	✓		✓	✓		✓	✓	✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author [HL], upon reasonable request.

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