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A bibliometric mapping study on advances in the operational safety of maglev trains

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ABSTRACT

Magnetic levitation (maglev) trains represent a pivotal advancement in high-speed transportation. However, research on their aerodynamics and operational safety is complex and fragmented across various disciplines, creating a barrier to a holistic understanding of the field's progress. This study aims to systematically analyze the global research landscape of maglev train safety to construct a comprehensive knowledge map, identify key research clusters, and forecast emerging trends. A bibliometric mapping approach was employed, analyzing 491 relevant publications sourced from the Web of Science (WOS) core collection from 1990 to 2025. The study utilized VOSviewer and CiteSpace to conduct a multi-faceted analysis, including spatio-temporal distribution, collaboration networks, keyword co-occurrence, and citation bursts. The analysis reveals a rapid expansion in publication output since 2013, with China emerging as the dominant country in research volume. A collaborative network of key institutions, primarily in China, leads research with distinct thematic specializations. Research hotspots have evolved from foundational topics like "suspension system" and "nonlinear control" to current frontiers such as "high-speed maglev", "simulation", "vehicle dynamics", and "superconducting magnets". The findings underscore an interplay where aerodynamic factors like ambient wind, lateral/vertical aerodynamic load, drag and wake flow directly impact safety aspects including levitation stability and guidance performance. This study provides a quantitative and visual overview of the field, revealing a clear research trajectory moving from foundational technical verification toward solving complex safety challenges in high-speed, commercial-scale applications.

1. Introduction

High-speed rail transport plays a pivotal role in the modern global transportation system [1–6]. According to the 2024 Railway Statistical Bulletin issued by the National Railway Administration of China, by the end of 2024, China's railway operation mileage had reached 162,000 km, including 48,000 km of high-speed railway, ranking first in the world and exceeding the total length of high-speed railway operation in other countries in the world [7,8]. While conventional wheel-rail technology is mature, its inherent contact model introduces friction, mechanical wear, and vibrational noise [9]. These factors impose a physical bottleneck on operational speed. As a revolutionary terrestrial transport technology, maglev trains have demonstrated great potential in high-speed operation [10]. By utilizing a unique non-contact suspension, propulsion, and guidance system, maglev fundamentally eliminates wheel-rail friction. This offers significant advantages, including higher operational speeds, lower noise, and reduced maintenance costs, making it a highly promising technology for future ultra-high-speed transportation. The successful operation of commercial projects, such as the Shanghai maglev Train Line, has already verified the feasibility and reliability of this technology in ultra-high-speed passenger transport [11].

However, this high-speed, non-contact mode gives rise to an extremely complex aerodynamic environment [12–15]. Consequently, it poses a series of unprecedented challenges to operational safety and has become a critical technical bottleneck that currently hinders the further development of maglev technology [16,17]. Current research

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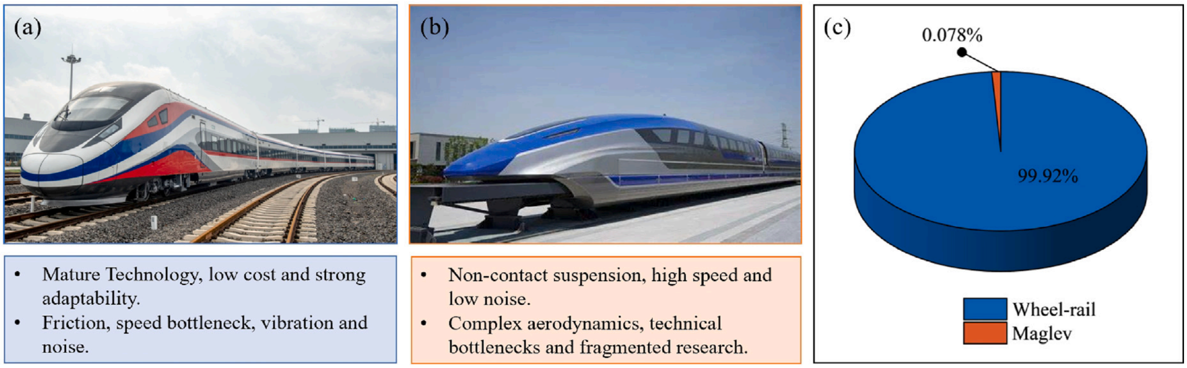


Fig. 1. The comparison of wheel-rail and maglev in train research: the advantages and disadvantages of (a) wheel-rail trains and (b) maglev trains; (c) the proportion of research on wheel-rail trains and maglev trains.

on maglev trains primarily focuses on their aerodynamic characteristics (including drag reduction and shape optimization) as well as operational safety, such as stability, guidance systems, superconducting magnets performance, and adaptive control strategies [18–28]. These research efforts have been mainly investigated through four different approaches: (1) numerical simulations, particularly Computational Fluid Dynamics (CFD) used to simulate the airflow around the train; (2) wind tunnel experiments, which involve simulating the airflow conditions in a manually controllable wind tunnel environment; (3) moving-model tests, where a scaled train model is operated at set speeds on a simulated track; and (4) full-scale tests, utilizing prototypes identical in size to actual trains to replicate real-world performance [29–48]. A critical appraisal of these approaches reveals not only their respective contributions but also their inherent limitations, which collectively shape the current understanding of maglev train aerodynamics.

Numerical simulations (such as CFD) have been instrumental in visualizing complex flow structures and optimizing train shapes for drag reduction and stability, particularly under crosswind conditions [49–52]. However, the accuracy of CFD is contingent upon turbulence modeling and computational resources, often requiring validation from experimental data. Conversely, wind tunnel tests provide high-fidelity benchmark data for force and pressure measurements but struggle to accurately simulate the moving ground effect and real-world dynamic scenarios like train-tunnel interactions. The moving-model test stands out in capturing these transient aerodynamic phenomena, such as pressure waves generated during tunnel entry or train meets, offering a closer representation of actual operations. But its main constraints lie in the limited test duration and the challenges associated with model scaling. Finally, while full-scale testing delivers the most reliable performance data under real conditions, its exorbitant cost, uncontrollable environmental variables, and inherent risks render it unsuitable for fundamental parametric studies.

Despite a rapid expansion in research output since 2013, the field remains characterized by a highly fragmented knowledge structure. The relevant literature is scattered across multiple disciplines, including "Materials science", "Engineering, mechanical", "Engineering, civil", and "Automation & Control Systems", forming relatively independent "knowledge silos". This fragmentation has significantly impeded holistic progress in two ways. First, the lack of effective interdisciplinary integration means that valuable insights from one domain often fail to inform related challenges in another. For instance, advancements in materials science for lighter carriages may not be fully leveraged by control engineers to optimize energy efficiency and stability algorithms. Second, this siloed approach limits the translation of fundamental research findings into practical, integrated engineering solutions, potentially delaying technological breakthroughs and commercial deployment.

Furthermore, when compared to the vast body of research on wheel-rail technology, studies on maglev safety are relatively new and the number is small. A search of the WOS core collection revealed that wheel-rail research accounted for 99.92% of publications on train safety, whereas maglev research constituted a mere 0.078%, as shown in Fig. 1. Notably, no prior bibliometric study has systematically mapped this field's intellectual structure. This gap, coupled with the field's fragmentation and nascent state, makes it difficult for researchers to grasp its developmental trajectory, key knowledge bases, and emerging frontiers.

Therefore, a systematic, quantitative review is urgently needed to integrate this fragmented knowledge and map the macroscopic intellectual structure of the "operational safety of maglev trains" field. By employing a bibliometric mapping approach, this study aims to [53–59]:

- Systematically map the overall development history and evolutionary pathways of the field.
- Precisely identify the most influential countries, research institutions, core researchers, and foundational publications to outline the global research network.
- Reveal the core research themes, hotspots, and their intellectual connections through comprehensive keyword and citation analysis.

This bibliometric mapping aims to be more than a retrospective but also a framework for tackling future challenges. The findings are expected to identify pathways for cross-disciplinary integration, highlight unresolved technical and safety issues at ultra-high speeds, and ultimately serve as a strategic map to guide collaborative research and accelerate future breakthroughs. To achieve these objectives, this study analyzes 491 records retrieved from the WOS core collection for the period of 1990–2025. In Section 2, it utilizes a combination of bibliometric and visualization tools, namely VOSviewer [60,61] and CiteSpace [62], to conduct a multi-angle analysis. In Section 3, the research is conducted from several perspectives: the spatio-temporal distribution of publications (Section 3.1), main sources (researchers, and journals) of publications (Section 3.2), and an analysis of research hotspots (main documents, keyword co-occurrence, co-citation networks, and citation bursts) in (Section 3.3). Through this in-depth analysis, (Section 3.4) ultimately reveals the coupled relationship between the core themes of aerodynamics and operational safety, constructing a comprehensive and profound picture of the field's knowledge structure. In the final Section 4, the study summarizes the key research conclusions in the article and provide a comprehensive perspective on future research work.

Table 1
Types of documents of this data collection.

Rank	Type	TP	SOTC	CA	Proportion%	h-index
1	Article	320	4121	2899	65.24%	31
2	Proceeding Paper	176	533	490	35.79%	10
3	Early Access	10	1	1	2.04%	1
4	Review Article	6	247	245	1.23%	5

TP: total publications; SOTC: sum of times cited; CA: citing articles; h-index: h articles have been cited for at least h times.

2. Methodology

Bibliometric analysis applies mathematical and statistical methods to quantitatively examine literature distributions, relationships, and clusters using bibliometric theory [63–66]. Within this framework, knowledge mapping visualizes comprehensive domain knowledge through data mining, information analysis, scientific measurement, and graphical representation.

2.1. Data source

The WOS Core Collection was used as the data source. Four sub-databases from WOS were included: Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI) and Conference Proceedings Citation Index - Science (CPCI-S). In this paper, a topic-based search strategy was used with key search terms. The complete query string is shown as follow:

("maglev train" or "magnetic levitation train" or "maglev rail" or "maglev high-speed train") AND ("safety" OR "safe" OR "aerodynamics" OR "stability" OR "security" OR "stable" OR "unstable" or "instability")

The retrieval time was from 1990 to 2025 and the search languages include English and Chinese. After removing the Retraction document type and using CiteSpace for duplicate removal, a total of 492 records from 31 countries, 354 research institutions, 320 journals, and 1133 authors were obtained. The results contain four different types of documents (see Table 1). Among them, TP represents the number of papers from each type; SOTC represents the sum of times cited, CA represents the number of citing articles, and Proportion represents the proportion of each type in the total number of documents. The h-index means that h articles have been cited for at least h times, which is a measure of both the productivity and citation impact of the publications.

To evaluate the potential bias introduced by including Early Access and Review Articles, which together account for only about 3.27% of the data, we excluded these two types of documents and re-ran the citation analysis. The results showed that the h-index values for the overall citation patterns remained consistent with the original analysis (31). This indicates that the inclusion of Early Access and Review Articles did not introduce significant bias to our citation analysis, thus reinforcing the integrity and timeliness of the results.

2.2. Analytical tool

Knowledge domain mapping visually represents the developmental trajectory and structural relationships of scientific knowledge. Exhibiting dual characteristics of both "graph" and "genealogy", it functions not only as a visual knowledge graph but also as a sequential knowledge lineage. This approach reveals implicit complex relationships — including networks, structures, interactions, intersections, evolutions, and derivations — among knowledge units or clusters. Understanding these relationships facilitates novel knowledge generation. Citation analysis employs mathematical and statistical methods to examine inter-document citation relationships, thereby uncovering quantitative patterns and underlying regularities within literature corpora. Cluster analysis classifies multivariate data using similarity metrics to measure association strength between entities. Co-occurrence analysis quantifies the joint appearance of information elements to expose content linkages and latent semantic features. Intermediary centrality is often used to measure the degree to which a point located at the center of other "point pairs" in a graph, and it can be calculated as follows [67,68]:

$$BC_i = \sum_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}} \quad (1)$$

where g_{st} is the number of shortest paths from node s to node t, and n_{st}^i is the number of shortest paths that pass through node i among g_{st} shortest paths from node s to node t. VOSviewer excels in clustering technology, mapping and processing large-scale data. It can perform coupling analysis, co-occurrence analysis, co-citation analysis and clustering analysis of literature data, while CiteSpace is suitable for detecting the frontier of corrosion research in petrochemical equipment. The combination of the two can meet the analysis requirements of both horizontal clustering and vertical evolution.

The search Settings of CiteSpace are as follows:

- Links: Select the calculation method for link strength as "Cosine" and set the link range to "Within Slices".
- Selection Criteria: Node selection is carried out using g-index. The number of included nodes is increased or decreased by adjusting the value of scale factor "k". The current k value is set to 25 in this article.
- Pruning: Check "Pathfinder", "Pruning sliced networks" and "Pruning the merged network".

In VOSviewer, the Minimum Cluster Size (MCS) will determine the number of clusters in each network. In this paper, different MCS values and minimum node thresholds will be selected based on different analysis contents and the number of nodes to make the results more intuitive. The corresponding Settings of MCS, minimum node threshold, total number of nodes and the number of finally divided clusters for each VOSviewer cluster graph display will be supplemented.

The research methodology and contents of this paper can be concluded as Fig. 2.

3. Result and discussion

3.1. Spatio-temporal distribution of publications

Understanding the growth trajectory of maglev research requires analyzing its temporal phases and geographic hubs. This subsection categorizes publications into stages of development and identifies leading countries and institution, revealing how global collaboration and regional expertise have shaped the field.

3.1.1. Yearly distribution of research

Quantitative variations in scholarly publications serve as a key metric for tracking developmental trends within a research field and reflecting shifts in knowledge depth. By analyzing publication volumes over time through multivariate statistics, researchers can assess current research activity and forecast future trajectories in a given domain. The temporal distribution of operational safety of maglev trains research literature is shown in Fig. 3.

This analysis focuses on the annual publication output of research on maglev train operational safety. Based on the citation burst from 1990 to 2025 (for specific analysis, see Section 3.3.3 of the article), it can be observed that before 2009, only four keywords emerged, and their popularity persisted until around 2009. During this period, the

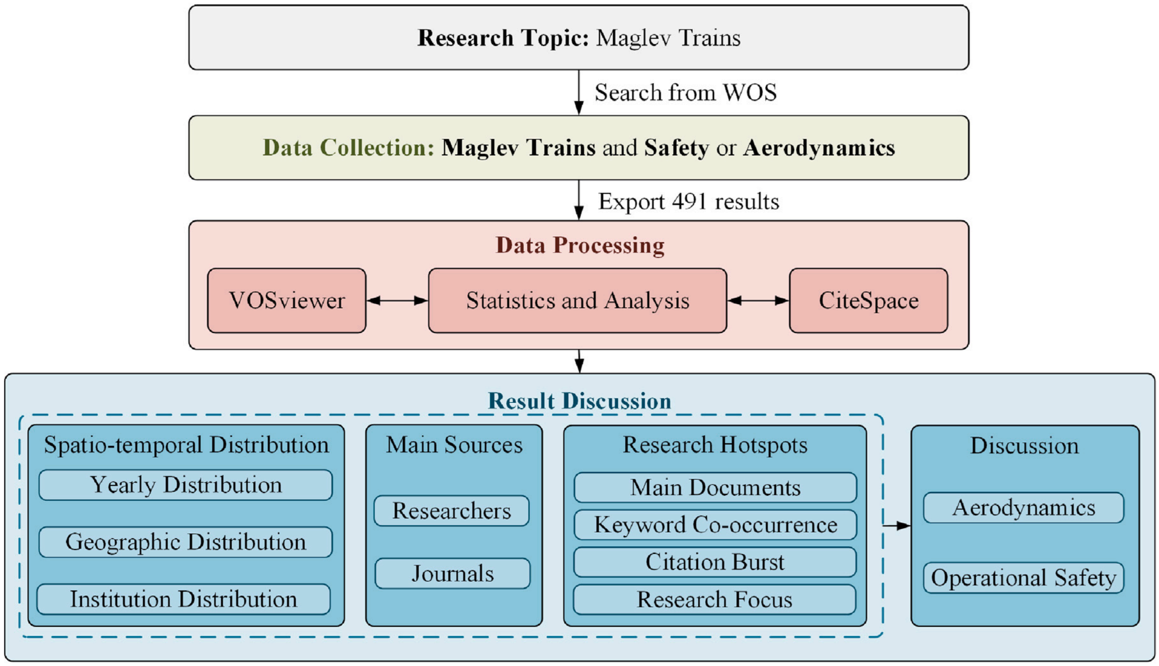


Fig. 2. Research methodology and contents of this paper.

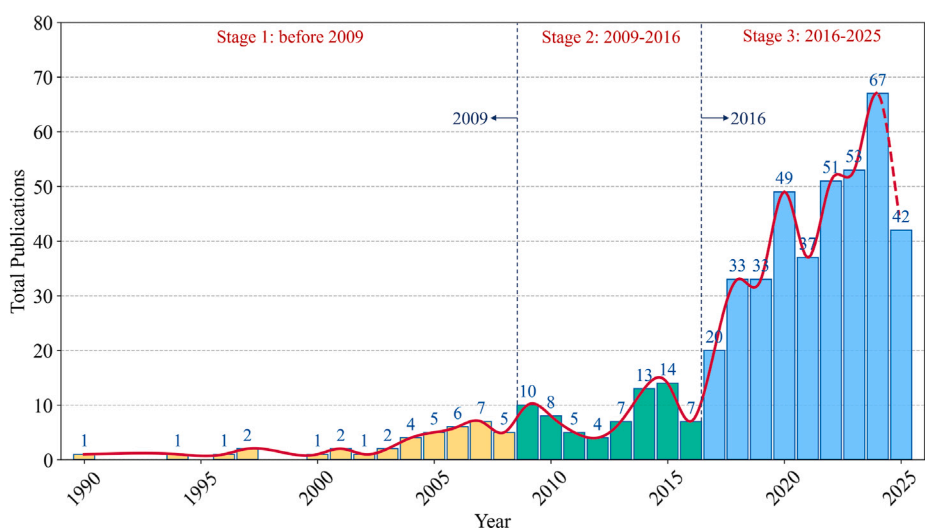


Fig. 3. Growth trend of publications around the world (The data in 2025 is still updating).

average number of emerging keywords per year was approximately 0.21. From 2009 to 2016, the emergence of key words increased. On average, about 0.57 key words emerged each year, and the popularity of these emerging key words mostly lasted until 2016. Since 2016, the phenomenon of keyword emergence has become more prominent, with a large number of emerging keywords. On average, the number of emerging keywords each year has reached 1.56, and the popularity of these keywords has continued to this day. This phased change reflects the development characteristics and the shift of hotspots in the research field at different times, which echoes the research trends in the field. Therefore, 2009 and 2016 are respectively selected as thresholds to divide the three stages of the research. By dividing the timeline into three distinct stages, a clearer understanding of the research trend can be achieved as follows.

• Stage 1: Initial Exploration (before 2009)

In the early years, the number of publications was relatively low. During this period, research on the operational safety of maglev trains was in its infancy. The annual number of publications was mostly in single-digit, indicating that the research field was not yet highly active. There were only sporadic studies, likely due to the relatively new nature of maglev train technology and the limited resources and research focus dedicated to these specific aspects at that time.

• Stage 2: Gradual Growth (from 2009 to 2016)

From 2009 to 2016, the overall trend of the number of published papers showed fluctuations, but there was a significant increase compared with the previous stage. This phase suggests that the research community started to pay more attention to the operational safety of maglev trains. As maglev train technology began to develop further and gain more practical applications in some regions, researchers became more interested in these critical aspects, leading to an increase in research output.

• Stage 3: Rapid Expansion (from 2016 to 2025)

The period from 2016 to 2025 witnessed a significant and rapid growth in the number of publications. The annual publication quantity soared, reaching much higher levels compared to the previous

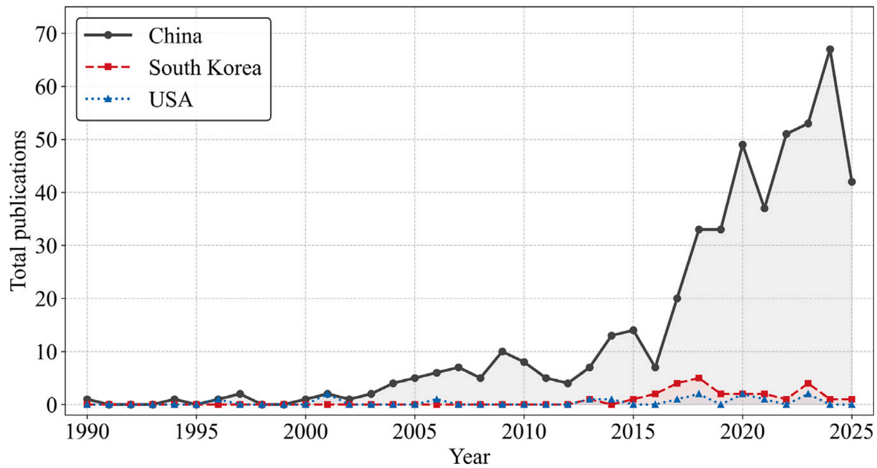


Fig. 4. Publication growth trend of top three countries (China, South Korea and USA).

Table 2
The top 5 research countries ranked by TP, 1990 to 2025.

Rank	Country	Region	TP	Percentage	ACI	h-index
1	China	Asia	413	84.11%	8.98	30
2	South Korea	Asia	26	5.30%	13.54	9
3	USA	America	14	2.85%	59.57	9
4	Japan	Asia	13	2.65%	37.15	7
5	German	Europe	11	2.24%	49.82	5

TP: total publications; ACI: the average times cited per item; h-index: h articles have been cited for at least h times.

phases. This rapid expansion can be attributed to several factors. Firstly, the continuous improvement and widespread deployment of maglev train technology made the study of operational safety more crucial. Secondly, advancements in research methods and tools such as CFD simulation, along with increased international cooperation in the field, contributed to a boom in research activities. More research institutions and scholars joined the exploration, resulting in a substantial increase in the volume of publications.

3.1.2. *Geographic distribution of research*

The spatial distribution of scholarly publications enables researchers to rapidly identify global research trends, thereby facilitating the dissemination of scientific findings and fostering collaboration. In this part, 31 countries and regions were obtained from the WOS core database. The statistics of the top 5 countries in the number of published papers are shown in Table 2.

Among them, TP represents the number of papers published by each country, percentage represents its percentage in the total number of documents, ACI represents the average number of articles cited in a country, which reflects the quality of a country's articles. h-index means that h articles have been cited for at least h times. The greater the h-index, the greater the influence of the paper. Among the top five countries, three belong to Asia (China, South Korea and Japan), so Asia constitutes the main research force in this field. It can be seen from the table that among the top 5 countries, China has the highest number of papers (413 papers, accounts for 84.11%) and h-index (30), reflecting its core position in the research field of maglev trains. Although the number of papers published in the USA ranked third (14 papers, accounts for 2.86%), its ACI ranked first (59.57), indicating that its early theoretical research has a continuous influence, followed by German (49.82) and Japan (37.15).

Fig. 4 shows the changes in the research trend in the three main countries (China, South Korea and USA). In the initial stage (before 2009), the annual number of publications in China was less than 10; from 2009 to 2016, it accelerated to 5–15 papers annually; from 2016 to 2025, it showed explosive growth, with the number expected to exceed 80 in 2025, increasingly dominating global research in this field, which aligns well with Table 2. Research output in South Korea stabilized gradually after 2012, maintaining 0–5 publications annually, peaking at 5 in 2018, showing a steady trend. The average annual publication of the USA remains at 0 to 2 papers, and it has an early advantage in the theoretical research of maglev trains.

Fig. 5 is a world map visualizing the distribution of research on maglev train operational safety across countries. China stands out with the deepest color, indicating it has the highest number of publications in this field (413), showing its leading position. South Korea, the USA, Japan and Germay also have certain research outputs, but at a lower level than China. Overall, the map reflects that Asia, led by China, is the core area of this study, while Europes (including countries such as Germany, the UK and France) and America (represented by the USA and Brazil) play secondary roles. This spatial distribution aligns with the data in Table 2 and the trends in Fig. 4. China relies on top universities and enterprises to form an innovation chain and accelerate the transformation of scientific research into practical applications. China's research status makes it possible for it to influence international standards. On the other hand, over-reliance on its dominant standards poses risks. It is necessary to build an inclusive platform, and the long-term healthy development of the field requires broader global participation.

3.1.3. *Institutions distribution of research*

Cooperation network analysis identifies the most productive organizations and specialized research groups within a discipline. According to the retrieved results, the studies on operational safety of maglev trains come from 200 organizations.

Fig. 6 showcases main institutions in the field of maglev train operational safety. In this figure, each node represents an institution, and the lines on the node represent cooperation between institutions. A greater number of connecting lines corresponds to stronger or more frequent cooperation. The node size in Fig. 6 is set to be related to frequency—the larger the node, the more papers affiliated with that institution. Leading institutions such as the National University of Defense Technology (NUDT), Southwest Jiaotong University, Tongji University, and Beijing Jiaotong University have the largest nodes, signifying their substantial contributions and high research activity in this field. Together with enterprises (e.g., CRRC Corporation) and research institutes (such as branches of the Chinese Academy of Sciences), these core universities form an interconnected domestic network.

By contrast, international universities such as the University of Cambridge, Monash University, and the University of Glasgow appear as comparatively smaller nodes that nevertheless show collaborative ties

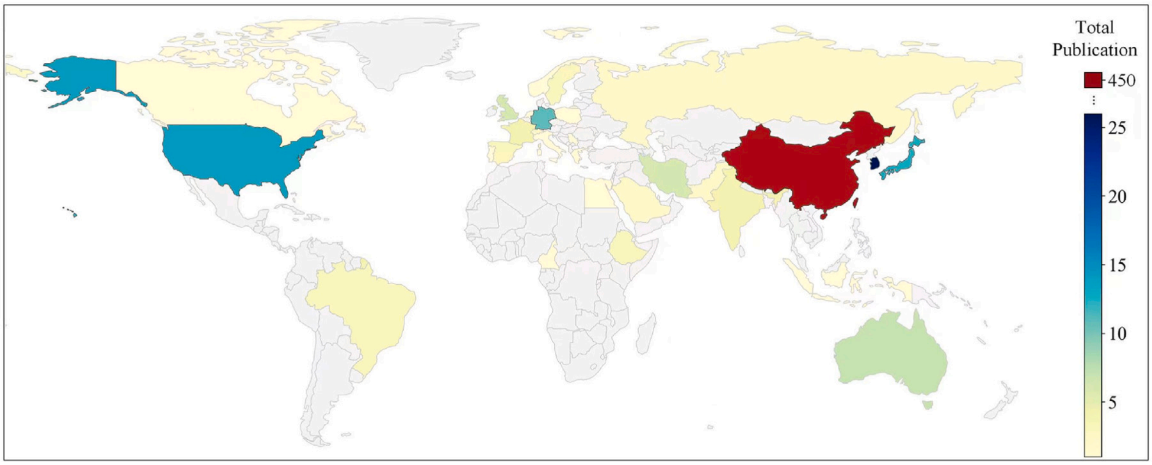


Fig. 5. Distribution of main research countries in operational safety of maglev trains.

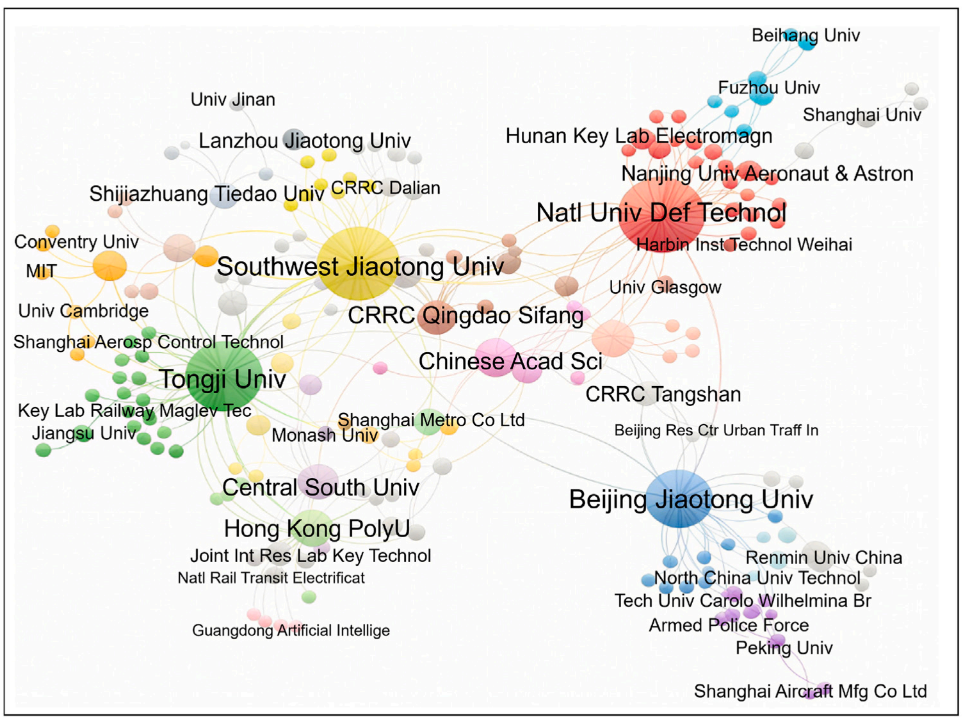


Fig. 6. Main research institutions in operational safety of maglev trains.

to major Chinese centers. Examination of representative co-authored publications indicates that these international contributions are frequently realized through joint studies with Chinese partners, often addressing topics such as superconducting magnet design, dynamic modeling, and control theory. In several cases the first authors are affiliated with Chinese institutions, which suggests that Chinese groups commonly take the lead in organizing and implementing applied research projects, while overseas partners contribute complementary theoretical and methodological expertise.

The clustering pattern mainly reflects China's long-term investment in maglev infrastructure and prototype development, which has concentrated much of the engineering-oriented research within domestic institutions. From an international perspective, this situation means that research activities are not evenly distributed across regions. Nevertheless, such concentration also promotes closer collaboration and faster knowledge exchange within the main research community. In recent years, cooperation with institutions in Europe, Asia, and North America has gradually increased. These collaborations are expected to broaden the research scope and strengthen global connections in the field of maglev safety.

The subject-based cluster labels of main institutions, as shown in Fig. 7(a), reveal a comprehensive multidisciplinary landscape in the field of operational safety of the maglev trains. Institutions are involved in diverse disciplines such as "Materials science, multidisciplinary", "Engineering, civil", "Engineering, mechanical", and "Transportation science & Technology". Fig. 7(b) shows the keyword-based cluster labels of main institutions such as "Superconducting magnets", "Adaptive control" and "Medium-speed maglev train".

Based on the results in Figs. 6 and 7, Table 3 was obtained. Table 3 systematically profiles the top five institutions in maglev train research, delineating their research focuses through publication metrics, centrality, and clustered themes. NUDT leads with 99 papers, followed by Southwest Jiaotong University (91) and Tongji University (72). This shows their long-term commitment to the field. Centrality can measure

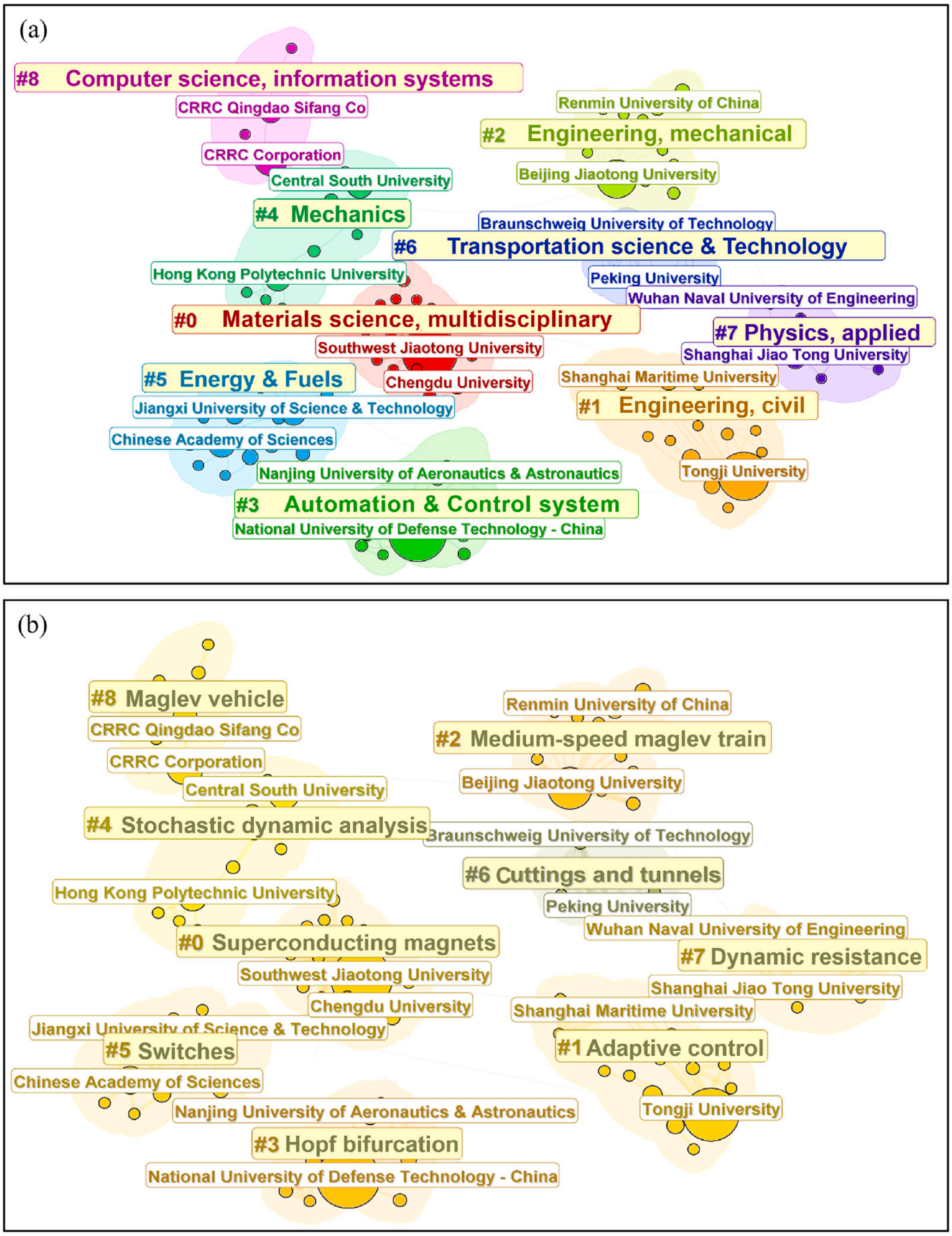


Fig. 7. Cluster labels of main institutions: (a) subject-based; (b) keyword-based.

influence in academic networks. Tongji University (0.37) and Beijing Jiaotong University (0.27) rank highest, indicating they act as key connectors in maglev research collaborations. NUDT (2003) and Beijing Jiaotong University (2004) are early entrants, laying foundational research; CRRC Corporation (2017) is a latecomer, representing the R&D acceleration at the industry level. Each institution has distinct thematic clusters. NUDT, with the earliest initiation year (2003) and a keyword cluster of "Hopf bifurcation", emphasizes theoretical control systems, underpinning dynamic stability analysis within the "Automation & Control system" discipline. Southwest Jiaotong University, clustering around "Superconducting magnets" and aligned with "Materials science, multidisciplinary" concentrates on material-science advancements critical to superconducting maglev technology. Tongji University, boasting the highest centrality (0.37) and a "Adaptive control" keyword cluster, rooted in Engineering, civil. Essential for real-time adjustment of maglev systems to ensure safety (such as train- rail interaction). Beijing Jiaotong University, focusing on "Medium-speed maglev trains" and situated in "Engineering, mechanical", reflects its role in advancing practical, medium-speed transit solutions. CRRC Corporation, the latest entrant (2017) with a "Maglev vehicle" cluster, leverages "Computer science, information system" to validate industrial-scale applications. CRRC's low centrality stems from its late entry (2017) and industry-specific focus (testing), resulting in a narrower collaboration scope (such as partnering mainly with universities for validation).

Each institution's keyword cluster matches its disciplinary strengths, showing a specialized collaboration model in maglev research. In summary, the table reveals a layered ecosystem: foundational theory (NUDT), material innovation (Southwest Jiaotong University), civil engineering integration (Tongji University), mechanical system

Table 3
The top 5 institutions ranked by TP, 1990 to 2025.

Rank	Institution	TP	Centrality	Starting year	Keywords cluster	Subject cluster
1	National University of Defense Technology-China	99	0.11	2003	Hopf bifurcation	Automation & Control system
2	Southwest Jiaotong University	91	0.17	2005	Superconducting magnets	Materials science, multidisciplinary
3	Tongji University	72	0.37	2007	Adaptive control	Engineering, civil
4	Beijing Jiaotong University	46	0.27	2004	Medium-speed maglev train	Engineering, mechanical
5	CRRC Corporation	28	0.15	2017	Maglev vehicle	Computer science, information system

TP: total publications; Centrality: betweenness centrality.

Table 4
The top 5 researchers ranked by TP, 1990 to 2025.

Rank	Researcher	TP	Centrality	Starting year	Cluster label
1	Long Zhiqiang	44	0.02	2006	Guidance system
2	Deng Zigang	26	0.04	2013	High-temperature superconductors
3	Xu Junqi	24	0.02	2019	Couplings
4	Lin Guobin	21	0.02	2015	Couplings
5	Sun Yougang	18	0.01	2019	Couplings

TP: total publications; Centrality: betweenness centrality.

development (Beijing Jiaotong University) and industry transformation (CRRC Corporation). This structure supports the field’s evolution from basic science to commercial deployment, with interdisciplinary collaboration as a key driver.

3.2. Main sources of the publications

The vitality of maglev research derives from synergistic collaboration among institutions and researchers. This section profiles top contributors, their collaborative networks, and the interdisciplinary journals that disseminate cutting-edge findings.

3.2.1. Quantitative analysis of main researchers

Fig. 8 showcases key researchers in the field of maglev train operational safety. The diameter of each researcher’s node represents the quantity of their published articles, with larger diameters indicating a greater volume of research output. The connecting lines between researchers denote collaboration, and the thickness of these lines reflects the intensity of cooperation, with thicker lines indicating closer partnerships. Larger node diameters, like those of Long Zhiqiang, Deng Zigang, etc., signify more extensive research outputs. Long Zhiqiang also has dense connections, indicating active collaboration, which aligns with the idea that collaboration fosters knowledge exchange, as seen in related engineering research fields. From the keyword cluster labels in Fig. 9, distinct research hotspots emerge. The "Guidance system" cluster, centered on Long Zhiqiang, mainly explores control and levitation system ensuring maglev train stability and operational safety, a critical aspect for reliable operation [69,70]. Deng Zigang’s "High-temperature superconductors" cluster may investigate material applications to enhance maglev train performance, as superconductors impact magnetic levitation and propulsion [67,71,72]. The "Couplings" cluster, with Xu Junqi and Lin Guobin, probably studies train-rail coupling, vital for smooth train operation [73–75]. Other clusters, such as "High temperature superconducting maglev" and "Dynamic simulation", supplement the research landscape, covering technology application and simulation-based safety analysis.

Table 4 shows the detailed data of the top 5 researchers. Centrality measures a researcher’s role as a collaborative bridge in the research network. It reflects how frequently a researcher connects otherwise disconnected research groups, facilitating knowledge exchange and resource integration. As shown in the table, Long Zhiqiang ranks first with 44 publications, starting research in 2006 and associated with the "Guidance system" cluster. Deng Zigang follows with 26 publications, commencing in 2013 and linked to "High-temperature superconductors". Xu Junqi, Lin Guobin, and Sun Yougang have 24, 21, and 18 publications respectively, all starting in 2015 or 2019 and clustered under "Couplings". The number of publications reflects their research productivity, with more publications generally indicating greater contributions to knowledge accumulation in the field.

The research directions of main researchers are closely related to the background of the Times and the orientation of the country, such as:

- guidance system: in 2006, the Shanghai Maglev Train demonstration operation line project officially passed the national acceptance inspection and entered the operation optimization stage. The stability of the guidance system is a core technical bottleneck for commercial operation safety and passenger comfort. This clustering research provides theoretical support for engineering operation and maintenance.
- high-temperature superconductors: during the 12th Five-Year Plan period, the Ministry of Science and Technology of China provided continuous support for the research and development of high-speed maglev transportation system technology through channels such as the National Key Research and Development Program.

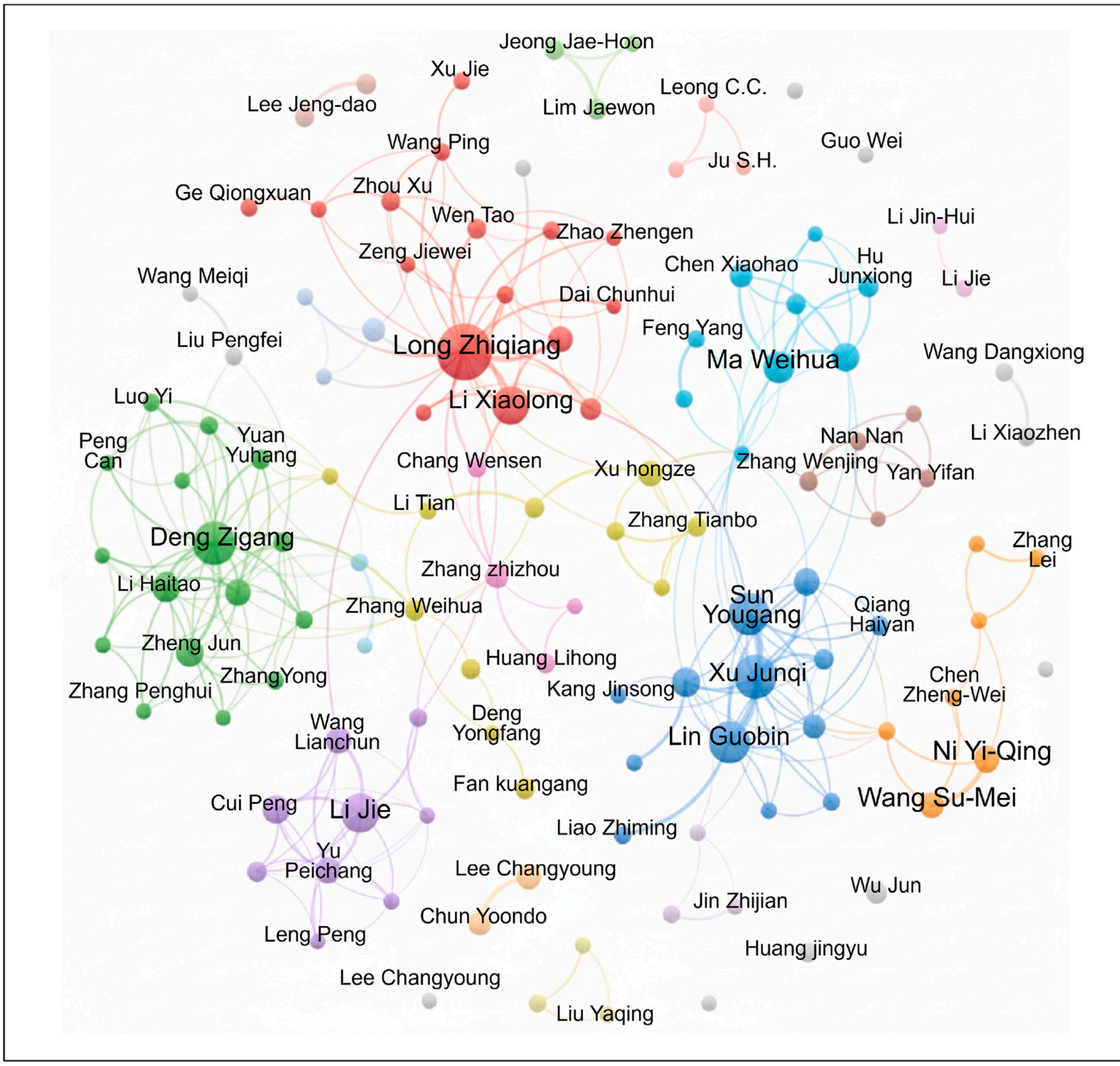


Fig. 8. Main researchers in field of maglev trains: cooperation network.

- couplings: the domestic maglev lines have been extended to intercity transportation, and "coupled dynamics" has become the key to solving the stable coordination of high-speed maglev trains and tracks. This clustering research has supported the expansion of engineering scenarios.

3.2.2. Quantitative analysis of main journals

Academic journals serve as vital knowledge repositories. They disseminate major scientific discoveries and research advances, functioning as primary channels for scholarly communication. Consequently, research institutions universally prioritize publication output in authoritative journals as a key metric for evaluating academic achievements. Based on the retrieved results, 491 articles were published by a total of 319 journals, covering Engineering, Automation Control, Transportation, Mechanical Engineering, Physics Applied, Computer Science and other research domains. Journals with high quantity of maglev trains operational safety articles are listed in Table 5.

Among them, TP represents the number of papers published by each journal, CA represents the number of citing articles, ACI represents the average number of articles cited in a journal, which reflects the quality of a journal's articles. h-index means that h articles in this journal have been cited for at least h times. The greater the h-index, the greater the influence of the paper. IEEE Transactions on Applied Superconductivity leads with 29 publications, highest TP, CA (514), ACI (19), and h-index (11), showing its core role in superconducting tech for maglev. Other journals like IEEE Access, International Journal of Structural Stability and Dynamics, Actuators, and Energies follow, with varying TP, CA, ACI, and h-index, reflecting their contributions to different maglev research aspects.

Fig. 10 is a network visualization of source citation via full counting, mapping connections between various journals in the maglev-related research field.

In Fig. 10, the size of the node is determined by the average citation value. The larger the node, the higher the average number of citations per article in the journal. The thickness of the connection lines between nodes indicates the strength of the relationship between the documents. The thicker the connection line is, the stronger the co-citation relationship of the literature will be. The MCS is set to 4 and minimum number of documents is set to 5. The 21 nodes in the figure are scattered into 3 clusters of different colors (red, green and blue), and different color clusters show interdisciplinary links, with green, blue, and red groupings connecting journals focused on structural stability, material, and transportation themes. IEEE Transactions on Applied Superconductivity emerges as a central hub for superconducting technology, while IEEE Access bridges electronics, transportation, and aerodynamics, indicating their central role in knowledge dissemination. The network reflects how research spreads across areas like engineering dynamics, superconductivity science, and intelligent transportation

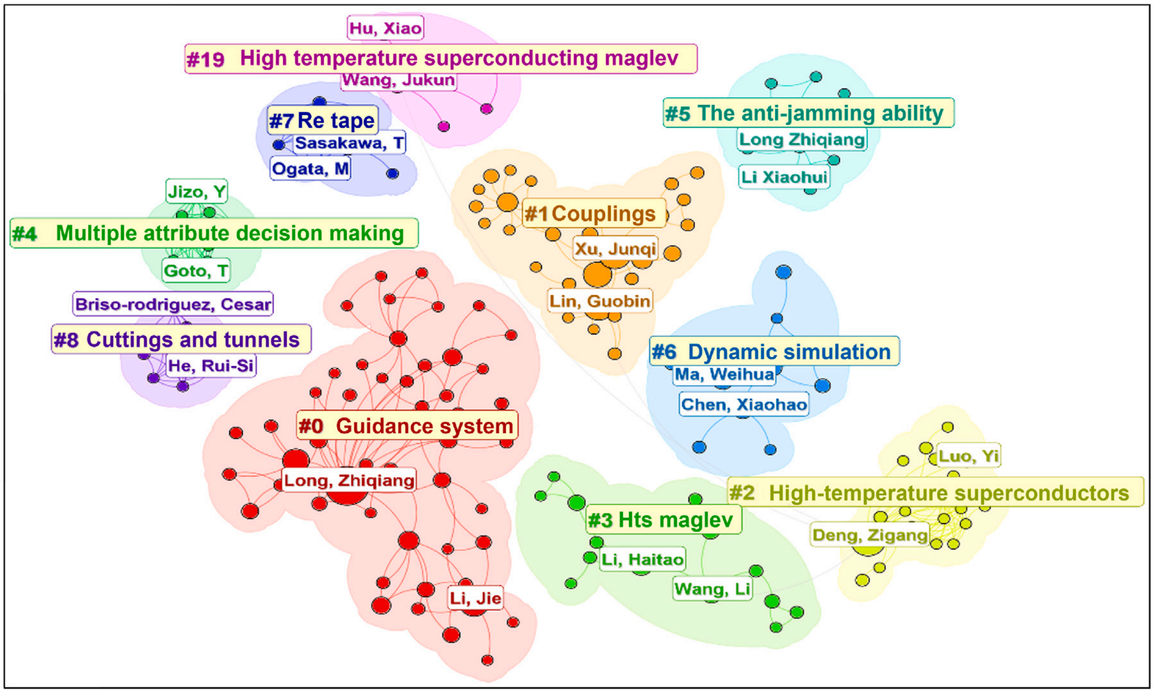


Fig. 9. Main researchers in field of maglev trains: keyword-cluster labels.

Table 5
The top 5 journals ranked by TP, 1990–2025.

Rank	Journal	TP	CA	ACI	h-index
1	IEEE Transactions on Applied Superconductivity	29	514	19	11
2	IEEE Access	15	162	12.53	8
3	International Journal of Structural Stability and Dynamics	10	60	6.5	4
4	Actuators	9	18	2.33	3
5	Energies	7	44	6.75	4

TP: total publications; CA: citing articles; ACI: the average times cited per item; h-index: h articles have been cited for at least h times.

systems. Overall, it visualizes the collaborative and multi-disciplinary nature of maglev train research through journal citations.

Table 6 presents the top 5 journals in the maglev train research field, ranked by cited count, along with key metrics like centrality, starting year, keyword clusters, and subject clusters, offering insights into their influence.

In Table 6, IEEE Transactions on Magnetics leads, with 177 publications, a centrality of 0.16, starting in 2003, and focuses on "Electromagnetic suspension" in the "Computer science, information system" cluster, showing its long-standing role in core magnetic research. IEEE Transactions on Applied Superconductivity follows, having 148 publications, a 0.09 centrality, starting in 2005, with "Online compensation" in "Engineering" clusters, highlighting its contribution to superconducting tech. IEEE Transactions on Industrial Electronics, with 138 publications, 0.05 centrality, starting in 2004, also ties to "Online compensatio" in "Engineering", indicating overlap in research themes. The Journal of Sound and Vibration, with 135 publications, a notable 0.38 centrality, started in 2001, centered on "Guidance system" in "Environmental studies", reflecting its focus on dynamic analysis and guidance for maglev operational safety. Vehicle System Dynamics, the fifth, has 108 publications, starting in 2014, focusing on "Crosswind" in "Mechanics", reflecting emerging research on environmental factors impacting maglev operation. Overall, these journals cover diverse themes from maglev foundations to environmental dynamics, showcasing the interdisciplinary nature of maglev train research and the varying influences of journals in advancing different technological aspects.

3.3. Research hotspots

Building upon the aforementioned spatio-temporal distribution and primary knowledge sources, identifying research hotspots must integrate the distinctive attributes of interdisciplinary convergence. The following analyzes the core research context of operational safety from keyword and main references.

3.3.1. Quantitative analysis of main documents

A knowledge base is formed by the production of highly cited documents in a certain discipline. These documents represent the academic knowledge of scholars engaged in scientific research over a long period of time and are the driving force to promote the development of related research and knowledge innovation. Table 7 shows the top 5 references ranked by SOTC. SOTC represents the sum of times cited. ACY means the average cited per year.

In Table 7, the one with the highest SOTC is the article "Challenges Toward Wireless Communications for High-Speed Railway" (386) published by Ai Bo in the journal "IEEE Transactions on Intelligent Transportation Systems" in 2014. Sun Yougang has two articles in the table,

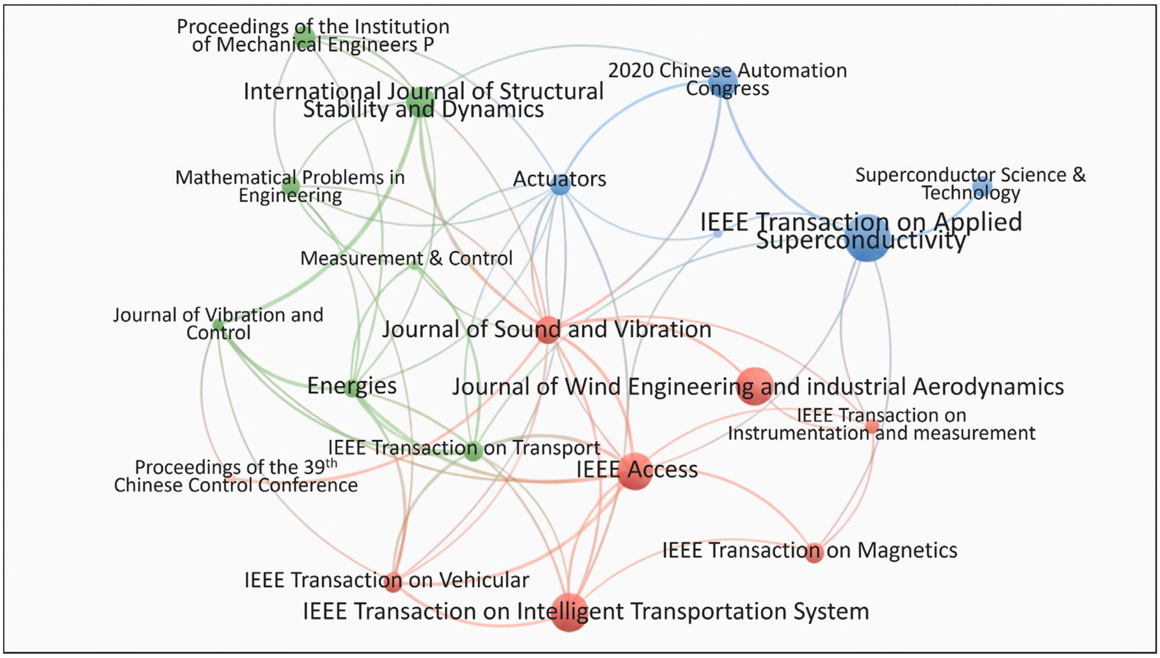


Fig. 10. Main sources citation via full counting.
Note: The size of the node is determined by the average citation value. The thickness of the connection lines between nodes indicates the strength of the relationship between the journals. The green, blue and red nodes represent the theme of structural stability, material, and transportation respectively.

Table 6
The top 5 journals ranked by cited count, 1990–2025.

Rank	Journal	TP	Centrality	Starting year	Keywords cluster	Subject cluster
1	IEEE Transactions on Magnetics	177	0.16	2003	Electromagnetic suspension	Computer science, information system
2	IEEE Transactions on Applied Superconductivity	148	0.09	2005	Online compensation	Engineering
3	IEEE Transactions on Industrial Electronics	138	0.05	2004	Online compensation	Engineering
4	Journal of Sound and Vibration	135	0.38	2001	Guidance system	Environmental studies
5	Vehicle System Dynamics	108	0.00	2014	Crosswind	Mechanics

TP: total publications; Centrality: betweenness centrality.

namely "RBF Neural Network-Based Supervisor Control for Maglev Vehicles on an Elastic Track with Network Time Delay" (2022, the highest ACY of 37) and "Deep Learning Based Semi-Supervised Control for Vertical Security of Maglev Vehicle With Guaranteed Bounded Airgap" (2021, ACY of 23.8). The key is showing annual citation trends, with the 2022 Sun paper having the most notable ACY, reflecting its potentially high ongoing research impact, while older works like the 2001 one have lower but still relevant long-term citation rates. Beyond raw publication counts, the citation patterns of highly cited papers reveal how maglev train research has evolved in maturity and influence over time. Several highly cited studies mark important turning points where new technologies or theoretical approaches emerged. For instance, Schetz (2001), "Aerodynamics of High-Speed Trains", represents a foundational contribution that established the aerodynamic framework for high-speed and maglev transportation systems. Another representative milestone is Maeda (2014), "Recent Developments in High-Temperature Superconducting Magnet Technology", which reflects the technological transformation of maglev systems driven by advances in material science. Sun (2021 and 2022) applied deep learning and neural network-based supervisory methods to maglev vehicle control, drawing considerable attention and leading to a wave of related studies. The increasing citation rates of such works indicate that the field has entered a stage of consolidation and interdisciplinary integration, reflecting the overall maturity of maglev safety research.

The intellectual foundation of a research field emerges through literature and journal co-citation networks. Co-citation occurs when two publications are jointly referenced by a third work, thereby establishing a co-citation relationship. Collectively, co-cited literature forms the field's knowledge base, while journals publishing such literature serve as its carriers. Highly co-cited journals constitute core sources that anchor advancing research frontiers. Fig. 11 depicts a co-citation network of references.

Table 7
The top 5 references ranked by SOTC, 1990–2025.

Rank	Title	Authors	Journal	Year	SOTC	ACY
1	Challenges Toward Wireless Communications for High-Speed Railway [76]	Ai Bo	IEEE Transactions on Intelligent Transportation Systems	2014	386	32.08
2	Recent Developments in High-Temperature Superconducting Magnet Technology [77]	Maeda Hideaki	IEEE Transactions on Applied Superconductivity	2014	270	22.5
3	Aerodynamics of high-speed trains [78]	Schetz JA	Annual Review of Fluid Mechanics	2001	185	7.4
4	RBF Neural Network-Based Supervisor Control for Maglev Vehicles on an Elastic Track With Network Time Delay [79]	Sun Yougang	IEEE Transactions on Industrial Informatics	2022	149	37
5	Deep Learning Based Semi-Supervised Control for Vertical Security of Maglev Vehicle With Guaranteed Bounded Airgap [80]	Sun Yougang	IEEE Transactions on Intelligent Transportation Systems	2021	112	23.8

SOTC: the sum of times cited; ACY: Average cited per year.

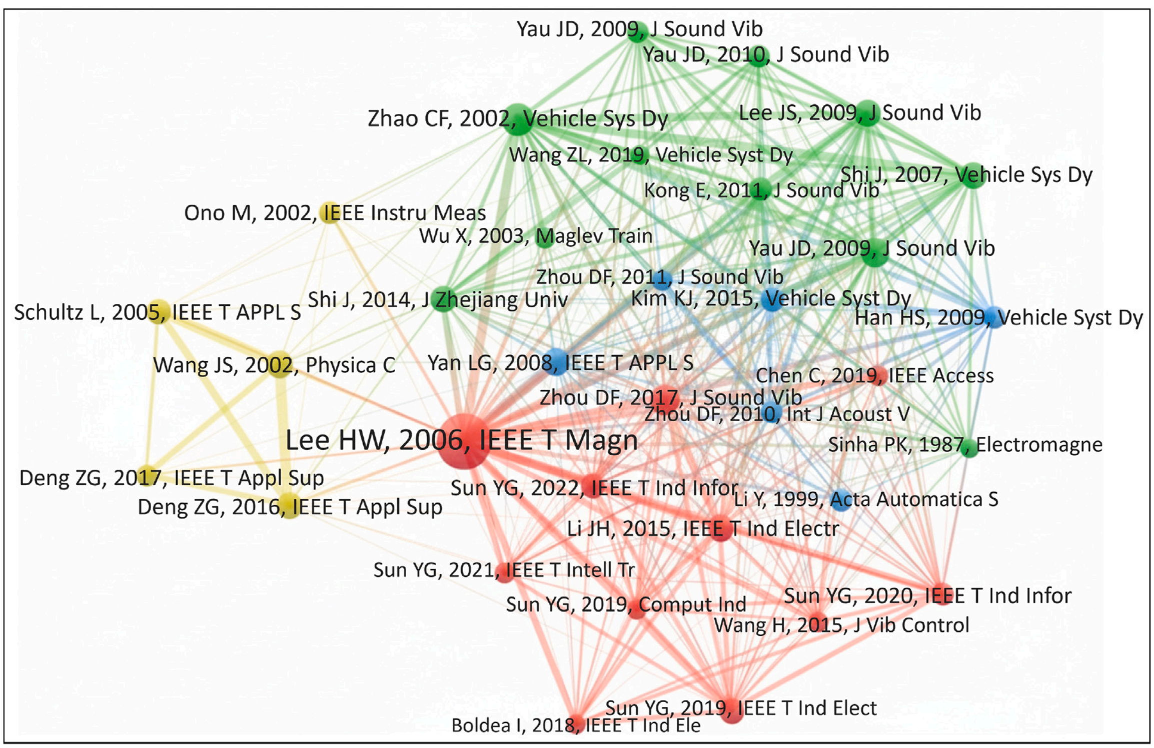


Fig. 11. Co-citation network of main references.
Note: The size of the nodes indicates the citation frequency of the co-cited literature. The links show co-citation relationships. Different colors of nodes signify various research themes, with green, blue, red and yellow groupings connecting documents focused on dynamic response, coupled vibration, control scheme and superconductivity.

The MCS is set to 5 and the minimum co-citation number is set to 15, and 33 nodes were obtained in the figure. Nodes represent individual references, and the size of the nodes indicates the citation frequency of the co-cited literature. The links show co-citation relationships, indicating how different studies are interconnected through being cited together. Different colors of nodes signify various research themes. The documents are divided into four clusters, with green, blue, red and yellow groupings connecting documents focused on dynamic response, coupled vibration, control scheme and superconductivity. For example, references with frequent co-citations form dense sub-networks, reflecting their joint influence in specific research areas, like maglev technology studies. This network helps identify core literatures and their interdisciplinary links in the research field.

Table 8 lists the top 5 co-citation references. SOTC represents the sum of Times Cited. The Links and Total link strength (TLS) attributes indicate, respectively, the number of links of an item with other items and the total strength of the links of an item with other items. The first, "Review of maglev train technologies" by Hyung-Woo Lee (2006, IEEE Transactions on Magnetics), has the highest citations (110) and TLS (51), showing its fundamental role in maglev research. Other entries, such as Chunfa Zhao's 2002 work on maglev vehicle/guideway vertical random response and ride quality and Jongar Yau's study on vibration

Table 8
The top 5 co-citation references, 1990–2025.

Rank	Title	Authors	Journal	Year	SOTC	TLS
1	Review of maglev train technologies [81]	Hyung-Woo Lee	IEEE Transactions on Magnetics	2006	110	51
2	Maglev vehicle/guideway vertical random response and ride quality [82]	Chunfa Zhao	Vehicle System Dynamics	2002	38	39
3	Vibration control of maglev vehicles traveling over a flexible guideway [83]	Jongdar Yau	Journal of Sound and Vibration	2009	30	31
4	An adaptive vibration control method to suppress the vibration of the maglev train caused by track irregularities [84]	Danfeng Zhou	Journal of Sound and Vibration	2017	32	28
5	The first man-loading high temperature superconducting maglev test vehicle in the world [85]	Jiasu Wang	Physica C: Superconductivity	2002	29	7

SOTC: sum of times cited; TLS: total link strength.

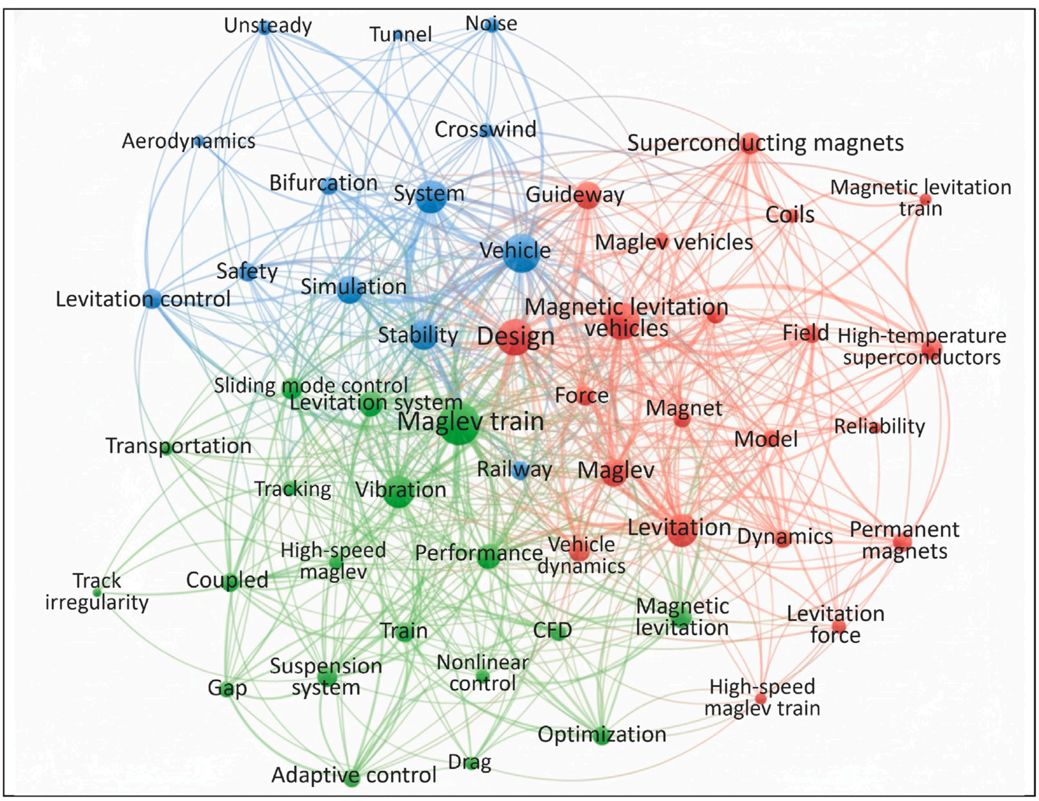


Fig. 12. Keyword co-occurrence network.
Note: Green, blue, and red groupings connecting keywords respectively focus on vehicles analysis, system stability assessment, and dynamic design as well as improvement.

control over a flexible guideway in 2009, are key in exploring maglev performance. Danfeng Zhou's 2017 adaptive vibration control paper reflects ongoing technical advancements, while Jiasu Wang's 2002 study on a superconducting maglev test vehicle marks an early practical milestone. These top references, with varied publication years and journals, highlight persistent research focuses like maglev dynamics and vibration, and their co-citation rankings reflect their centrality in the research landscape.

3.3.2. Keywords co-occurrence analysis

Keywords reflect the core content of an article. Therefore keyword co-occurrence analysis can be used to identify research hotspot related to knowledge domains. The literature on operational safety research based on maglev trains from 1990 to 2025 was analyzed. A total of 1851 keywords were found. Keywords with a frequency of no less than 7 occurrences were selected and checked. The keywords co-occurrence network is shown in Fig. 12. The size of the node represents the total link strength of the keyword, and thickness of the line between nodes represents the co-occurrence strength of the keywords. The color of the

Table 9
The top 20 co-occurrence keywords ranked by occurrences, 1990–2025.

Rank	Term	Count	TLS	Rank	Term	Count	TLS
1	Maglev train	107	210	11	Simulation	19	89
2	Vehicle	47	163	12	Guideway	19	75
3	Design	43	141	13	High-speed maglev train	19	21
4	System	38	119	14	Performance	17	65
5	Vibration	35	100	15	Sliding mode control	17	43
6	Maglev	32	58	16	Train	17	43
7	Levitation	30	107	17	Force	16	63
8	Stability	30	102	18	Suspension system	15	35
9	Magnetic levitation vehicles	28	144	19	High-speed maglev	14	28
10	Magnetic levitation	20	55	20	Vehicle dynamics	12	76

TLS: total link strength.

node represents the cluster to which the keyword belongs. The MCS is set to 10 and the minimum number of occurrences is set to 7. All 53 keywords are divided into 3 clusters, with green, blue, and red groupings connecting keywords focused on vehicles analysis, system stability assessment, and dynamic design as well as improvement.

The top 20 co-occurrence keywords table (as shown in Table 9) and Fig. 12 jointly reveal the research focus and thematic structure of the maglev train field. In the network graph, keywords such as "Maglev train", "Vehicle", and "Levitation" form core nodes with dense connections, indicating their central status in the research. The table shows that "Maglev train" has the highest occurrence (107 times), which is consistent with its core position in the network, reflecting that the research is deeply centered on the maglev train itself. Other high-occurrence keywords like "Design", "System", and "Stability" are closely related, forming a research framework that encompasses vehicle design, system integration, and levitation technology. The results also reflect the interdisciplinary and multi-dimensional nature of the research. For example, "Vibration", "Stability", and "Reliability" involve the study of dynamic characteristics and operational safety, while "Simulation", "Sliding mode control", and "Optimization" represent the application of advanced technologies and scheme; "Sliding mode control", through robust design and active intervention, combined with the "Bifurcation" early warning mechanism, jointly builds a closed loop of engineering system safety from theory to practice. The co-occurrence relationships demonstrate that research in the maglev train safety field is not isolated but integrates multiple aspects such as mechanical design, control systems, and dynamic analysis, aiming to comprehensively improve the performance, safety, and efficiency of maglev trains. Overall, the keywords collectively outline a research landscape that is both focused on the core subject and extensive in interdisciplinary exploration.

3.3.3. *Citation burst*

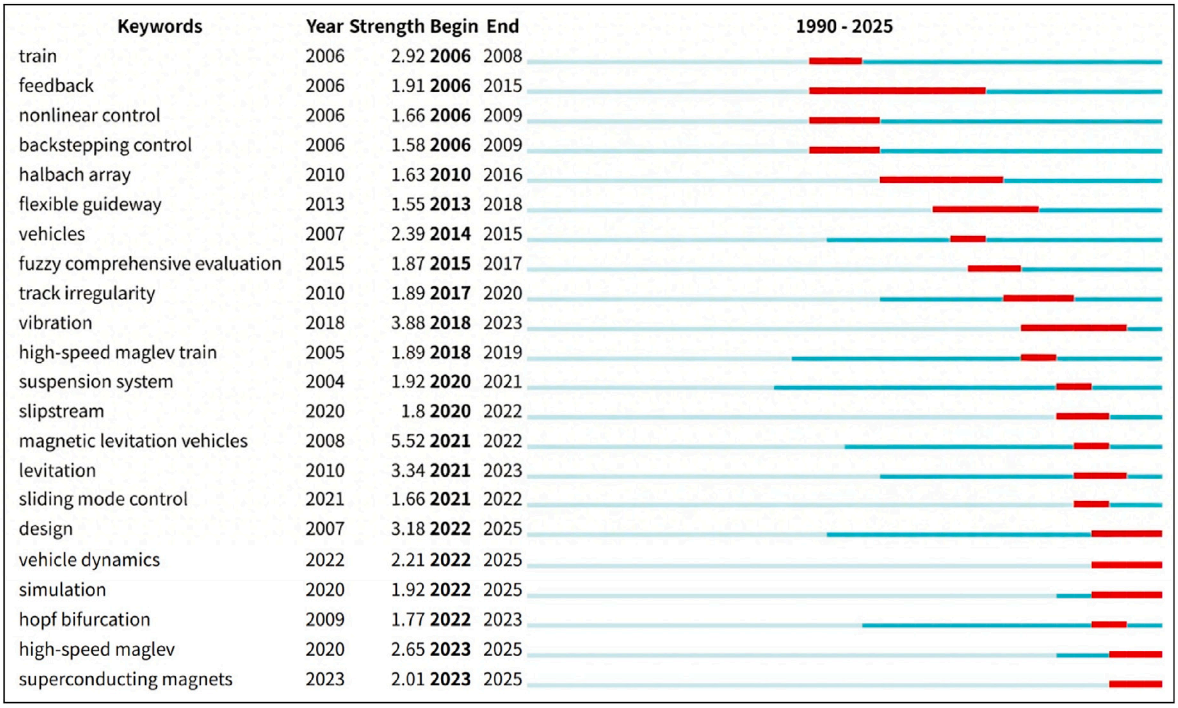
Citation burst denotes keywords exhibiting sudden frequency surges within a specific timeframe, signaling temporally concentrated scholarly attention. This analytical method detects emergent concepts and latent research questions within a field, revealing disciplinary turning points and mapping active research frontiers. In this part, "citation burst detection" was conducted. The detection scope includes the title, abstract, key words and table of contents of the articles and 22 emergent words that emerged from 1990 to 2025 were plotted in Fig. 13. Among them, Strength represents the emergent intensity, Begin represents the year when the emergent begins, and End represents the year when the emergent ends.

At the beginning of the 21st century, maglev trains, as a new type of transportation, saw accelerated research and development worldwide. The term "Suspension system" emerged in 2004 and re-emerged as a research burst in 2020 (with a strength of 1.92, lasting until 2021). In 2006, keywords such as "Train" (2.92), "Feedback" (1.91), "Nonlinear control" (1.66), and "Backstepping control" (1.58) showed concentrated bursts, but the duration periods were different. The essence of this phenomenon is the resonance between "Engineering practice demands" and "Development of control theory". At that time, the maglev train moved from theory to test, exposing a large number of problems regarding system stability and adaptability to working conditions. Theoretical tools such as nonlinear control and backstepping have matured, providing precise solutions to the above problems. For instance, the Shanghai Maglev Demonstration Line was officially put into operation in 2003. Its stable operation relies on suspension and control technologies, creating a demand for research on suspension system design and control algorithms (such as feedback and nonlinear control). These efforts laid the foundation for the operational safety and performance of maglev trains, making them core research hotspots in the early stage.

During 2007 to 2010, Keywords like "Vehicles" (2.39), "Design" (3.18), "Track irregularity" (1.89) and "Halbach array" (1.63) emerged successively. During this period, the engineering of maglev trains is accelerating. To adapt to operation and ensure safety and stability, the basic links such as train design and levitation control need to break through the traditional ones. The dynamic response between the train and the track has attracted attention. Meanwhile, suspension technology advanced from the system level to the study of magnet structures and vehicle integration design, reflecting the progression toward more refined research on the overall performance and safety of maglev trains.

During 2011 to 2015, Terms such as "Fuzzy comprehensive evaluation" (1.87), and "Flexible guideway" (1.55) became research bursts. During this period, maglev transportation explored large-scale and diversified applications. This reflects an upgrade from single-technology research to system integration and research adapted to working conditions. During the next five years, "Figh-speed maglev train" (with a strength of 1.89, first emerging in 2005 and re-emerging as a burst in 2019), "Slipstream" (1.8), and "Simulation" (1.92) became hotspots. There was an accelerated "High-speed" competition in global rail transit. Aerodynamic issues under high-speed operation became prominent. Simulation technology, as it can efficiently simulate complex working conditions, assisted in optimizing train performance and safety design, becoming a core research tool. This embodies the deepening of research on the coordination of safety driven by high-speed scenarios.

Keywords like "Magnetic levitation vehicles" (5.52), "Sliding mode control" (1.66), "Hopf bifurcation" (1.77), and "Levitation" (3.34) emerged as bursts during 2021 to 2023. As maglev technology moved from testing to preparation for commercial operation, there were strict requirements for the stability of the entire vehicle system and the dynamic behavior under complex working conditions. Advanced algorithms such as sliding mode control optimized suspension stability. Meanwhile, terms like "High-speed maglev" (2.65), and "Superconducting magnets" (2.01) showed concentrated bursts from 2022 to 2023. Terms such as "Design", "Vehicle dynamics", "Simulation", "High-speed maglev", and "Superconducting magnets" will continue to be popular.



Keywords	Year	Strength	Begin	End	1990 - 2025
train	2006	2.92	**2006**	2008	
feedback	2006	1.91	**2006**	2015	
nonlinear control	2006	1.66	**2006**	2009	
backstepping control	2006	1.58	**2006**	2009	
halbach array	2010	1.63	**2010**	2016	
flexible guideway	2013	1.55	**2013**	2018	
vehicles	2007	2.39	**2014**	2015	
fuzzy comprehensive evaluation	2015	1.87	**2015**	2017	
track irregularity	2010	1.89	**2017**	2020	
vibration	2018	3.88	**2018**	2023	
high-speed maglev train	2005	1.89	**2018**	2019	
suspension system	2004	1.92	**2020**	2021	
slipstream	2020	1.8	**2020**	2022	
magnetic levitation vehicles	2008	5.52	**2021**	2022	
levitation	2010	3.34	**2021**	2023	
sliding mode control	2021	1.66	**2021**	2022	
design	2007	3.18	**2022**	2025	
vehicle dynamics	2022	2.21	**2022**	2025	
simulation	2020	1.92	**2022**	2025	
hopf bifurcation	2009	1.77	**2022**	2023	
high-speed maglev	2020	2.65	**2023**	2025	
superconducting magnets	2023	2.01	**2023**	2025	

Fig. 13. The top 22 Keywords with the Strongest Citation Bursts, 1990–2025.
Note: Strength represents the emergent intensity; Begin represents the year when the emergent begins, and End represents the year when the emergent ends.

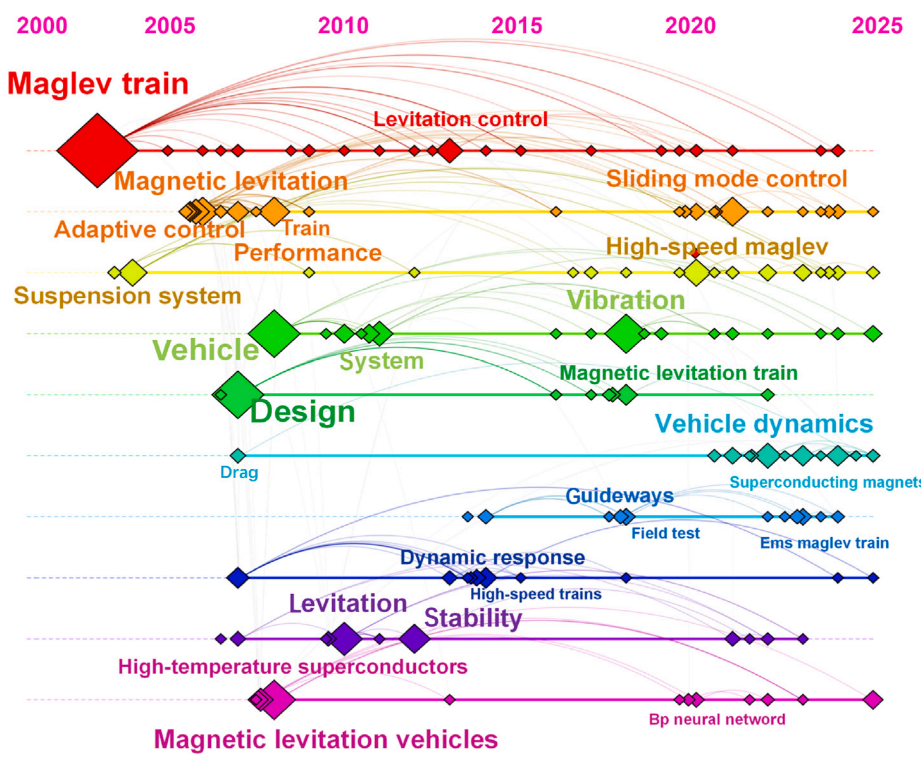


Fig. 14. Research timeline of maglev trains field, 1990–2025.
Note: The horizontal axis is the time axis, and the vertical axis is the clustering axis. Each node represents different keywords, the link between nodes represents a co-occurrence relationship, and the thickness indicates the intensity of co-occurrence.

3.3.4. Research focus

Timeline view analysis was performed, and the keyword Timeline view was generated after properly editing the keywords (as shown in Fig. 14). The Timeline view mainly focuses on the relationship between clusters and the historical span of keywords in a cluster to show the development of different research hotspots over time. In the keyword sequence diagram, the horizontal axis is the time axis, and the vertical axis is the clustering of different keywords. Each node represents different keywords, the connection between nodes represents a co-occurrence relationship, and the thickness indicates the intensity of co-occurrence. It can be used as a quantitative index to describe the relationship between two nodes. The larger the node is, the more frequent the keyword appears in the corresponding year.

In Fig. 14, ten timelines represent ten thematic clusters, with the three keywords showing the highest centrality being "Maglev train" (0.56), "Design" (0.16), and "Performance" (0.16). The first timeline contains the most keywords, among which the keywords with higher mutation strength are "Maglev train", "Levitation control", representing research related to the levitation frame. The frequently occurring terms are distributed across different clusters and time periods, reflecting the interdisciplinary integration of maglev train technology.

Several major research branches in the field of Maglev train research can be identified from the figure. Fundamental terms such as "Maglev train" form the basis of the field's development. Terms like "Levitation control" correspond to control technology, while "Design" and "System" relate to system design. "High-speed maglev" focuses on aerodynamic performance, and "High-temperature superconductors" reflect applications of superconducting materials. The Progress in superconducting materials and the maturity of control theory (e.g., adaptive/sliding mode control) have supported the continuous upgrading of maglev technology.

The temporal evolution of these clusters reveals three distinct research stages. During Stage 1 (before 2009), clusters such as high-temperature superconductors and suspension systems concentrated on fundamental mechanisms of levitation and propulsion, forming the technological foundation of the field. At this stage, the keyword "Maglev train" appeared 12 times with a centrality of 0.14, ranking third after "Design" and "Performance". In Stage 2 (from 2009 to 2016), the focus shifted toward control algorithms, vibration analysis, and levitation stability. The frequency of "Maglev train" increased to 26 and its centrality rose sharply to 0.58, ranking first, reflecting the transition from theoretical exploration to system-level optimization. In Stage 3 (from 2016 to 2025), clusters such as high-speed maglev, field test, and BP neural network became prominent, indicating growing interest in intelligent technologies and practical implementation. During this period, "Maglev train" remained the top-ranked keyword, with frequency 76 and centrality 0.42, suggesting that while it continues to dominate the field, research themes have diversified to include intelligent control, medium-speed operation, and safety evaluation.

Overall, the evolution of "Maglev train" and its associated clusters demonstrates a continuous transition of research focus—from fundamental design and performance analysis to control optimization, intelligent safety management, and large-scale application. This pattern indicates that maglev train research has evolved from a pioneering phase into a mature, multidisciplinary, and application-oriented field.

3.4. Discussion

The above results reflect the interdisciplinary integration of maglev train research, with aerodynamics and operational safety as the two core themes. Aerodynamics penetrates multiple research directions through keywords such as "Slipstream", "Performance", and "Drag". Operational safety, centered on "Stability" and "Vibration", runs through the entire life cycle of maglev train research, from component design to system integration. These two themes are deeply coupled: aerodynamic effects impact safety performance, and safety demands drive the optimization of aerodynamic design, jointly promoting the development of maglev train technology. The analysis of these studies reveals that the research on maglev trains is highly interdisciplinary, involving fields such as mechanical engineering, control systems, material science, and aerodynamics. The core themes of aerodynamics and operational safety are deeply intertwined, reflecting the industry's focus on high-speed performance and safety assurance. The following sections discuss the interdependence of aerodynamics and operational safety in maglev train research.

3.4.1. Aerodynamics

Aerodynamics is an important aspect in the field of maglev train research, which is reflected in keywords such as "High-temperature superconductors", "Performance" and "Drag".

(1) High-speed: Since the 2010s, with the development of high-speed maglev trains, aerodynamic issues such as air resistance, tail flow effects, and train-train interaction have become prominent. The "Drag" directly affects the "Performance" under aerodynamic forces, which is a key factor in high-speed maglev train design.

(2) Infrastructure-Train Interaction: The keyword "Guideways" involves the impact of aerodynamic forces on track structures. "Magnetic levitation vehicles" need to consider the interference of aerodynamic forces on "Levitation stability", which can be optimized through technologies like "High-temperature superconductors".

(3) Train Meeting and Tunnel Passage: In high-speed operations, the aerodynamic effects of train-train meeting and tunnel passage are critical safety issues. Research on "Slipstream" and "Vibration" in the clustering map corresponds to the need to solve pressure wave impacts and structural vibration problems during train meeting and tunnel passage, driven by the practical operation of demonstration lines.

(4) Drag Reduction: The clustering map's emphasis on "Performance" reflects the research on optimizing train aerodynamic shapes and applying bionic technologies to reduce energy consumption, aligning with global transportation's pursuit of green and efficient development.

3.4.2. Operational safety

Safety is the core of multi-cluster collaboration, covering the keywords such as "Levitation", "Stability", "System".

(1) Basic Safety: Focused on solving the basic safety issue of "levitation stability", ensuring the train (mainly including the suspension system) run stably. "Stability" and "Levitation" are the foundations of safety. "Magnetic levitation" technology (e.g., high-temperature superconducting magnets) directly affects the robustness of the levitation system, ensuring that the train does not lose contact under complex conditions.

(2) System Safety: "Vehicle" and "design" need to embed safety redundancy (such as train body structures resistant to aerodynamic impacts). The "System" involves the coordination of vehicle and the suspension system. With "Dynamic response" becoming hotspots, addressing the safety challenges of vehicle-track coupling control collaboration emerged as a critical topic.

(3) Scenario Safety: With the move towards commercial operation, safety research has extended to high-speed, heavy-load scenarios, which include vehicle, the suspension system and surrounding environment, such as bridge and tunnels. The keyword "Field test" and "High-speed maglev" reflects the need to ensure safety under different conditions.

The above analysis shows that the research on maglev train presents a demand-driven trend. Aerodynamics has become a key constraint on train performance and safety. Technologies such as drag reduction, train-train meeting control, and tunnel pressure wave mitigation are continuously advancing. Safety, from ensuring basic levitation stability to full-scenario security, reflects the industry's shift from "theoretical research" to "technical verification" and then to "commercial application". In conclusion, aerodynamics and running safety are interdependent and mutually reinforcing, jointly promoting the development of maglev trains towards higher speed, higher efficiency, and higher safety.

4. Conclusion

This study employs bibliometric mapping to analyze 491 publications on maglev train operational safety from 1990–2025. It examines spatio-temporal trends, key contributors (countries, institutions, researchers), and research hotspots through main documents, co-citation, keyword co-occurrence and research focus analysis.

4.1. Key findings

The main research conclusions are as follows.

• Spatio-temporal distribution: research progressed through three phases: initial exploration (before 2009), gradual growth (2009–2016), and rapid expansion (2016–2025). China leads global research (84.11% of publications), while the U.S. and Germany contribute high-impact theoretical studies. Key institutions (e.g., NUDT, Tongji University) drive advancements in control systems and material science.

• Main sources of publications: top journals (e.g., IEEE Transactions on Applied Superconductivity) focus on electromagnetic suspension and adaptive control. Researchers like Long Zhiqiang (guidance systems) and Deng Zigang (high-temperature superconductors) shape core themes. Industry players (e.g., CRRC Corporation) bridge academic research and commercial applications.

• Research hotspots: early studies emphasized suspension systems, while recent work prioritizes aerodynamics and stability. Keyword clusters reveal a shift from basic levitation technology to high-speed operational safety and simulation-based optimization. Citation bursts highlight emerging trends like superconducting magnets and sliding mode control.

• Research focus: aerodynamics and operational safety stand out as the two central and deeply interconnected themes. Aerodynamic effects, such as "drag", directly impact train "performance", while safety requirements, centered on "stability" and "levitation", drive the optimization of aerodynamic design.

4.2. Future works

Based on the above analysis, future research should be directed toward the following four areas: multi-physics coupling, safety under extreme conditions, intelligent control and health monitoring, standardization for commercial application.

• Multi-physics coupling: future work should move beyond identifying the link between aerodynamics and safety to developing integrated simulation platforms. Existing studies have laid a foundation for such development through specialized tools: MATLAB-Simulink has been widely used to model electromagnetic-control coupling in maglev systems, but lacks robust integration with aerodynamic models. COMSOL, on the other hand, has supported electromagnetic-structural coupling analyses, but exhibits weaknesses in real-time simulation for high-speed dynamic scenarios. Thus, future platforms should build upon these existing frameworks to achieve seamless integration of aerodynamics (e.g., incorporating CFD modules), vehicle-track dynamics, and electromagnetic control systems, filling the gap between specialized tools and the comprehensive, real-time simulation needs of maglev systems.

• Safety under extreme conditions: existing studies have primarily focused on single-factor or simplified scenarios (e.g., isolated crosswind effects on aerodynamics), while real-world challenges involve multi-factor coupling: for instance, heavy rain may simultaneously induce track-track adhesion degradation and aerodynamic disturbances, compounding safety risks. Additionally, complex traffic scenarios like multi-train operations introduce interactions-track interaction and control coordination issues, which lack systematic investigation compared to single-train studies. Future work should build on these initial explorations—integrating multi-physical field coupling models to address the gap between simplified simulations and real-world extreme conditions.

• Intelligent Applications: the rapid progress of intelligent technologies is opening new directions for maglev safety research. Machine learning algorithms have been increasingly applied for fault detection and condition monitoring, enabling early identification of abnormal vibration patterns and potential failures. Digital twin technology provides virtual simulation platforms for studying aerodynamic–safety coupling and predicting dynamic responses under different operating conditions. Moreover, AI-based optimization methods have shown potential for improving levitation control accuracy, enhancing system stability, and reducing energy consumption [86–90]. These approaches indicate that maglev research is gradually evolving from model-based analysis toward data-driven and intelligent system design, which will likely become a major focus of future studies.

• Standardization for commercial application: to bridge the gap between academic research and industrial deployment, more focus is required on reliability engineering, life-cycle analysis, and the development of international standards and safety certification protocols for maglev systems. Specifically, align reliability engineering with China's Standard for Technology of Maglev Railway (TB 10630-2019) to establish life-cycle analysis models covering design, operation, and decommissioning. Collaborate with international institution to extend ISO Railway Safety guidelines and leverage academic-industry partnerships to translate research findings into actionable standards.

In summary, the current research landscape for maglev train aerodynamics and safety is dynamic, highly interdisciplinary, and rapidly maturing. It has progressed from fundamental stability and control problems to a sophisticated, system-level focus on ensuring safety under complex operational conditions. Despite this growth, the field remains relatively niche compared to traditional wheel-rail research, highlighting a need for continued investigation to support its widespread commercial deployment. By constructing a comprehensive knowledge map, the study offers valuable insights into the evolution of research hotspots, from foundational technical topics to more complex challenges in high-speed, commercial-scale applications. This provides a clear roadmap for future research directions.

CRediT authorship contribution statement

Jia-Qi Fan: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Zheng-Wei Chen:** Writing – review & editing, Supervision. **Yi-Qing Ni:** Supervision. **Shanqiang Fu:** Resources. **Tiantian Wang:** Resources. **Rugang Tang:** Visualization.

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.

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