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Review

A Critical Review of Fire Tests and Safety Systems in Road Tunnels: Limitations and Open Points

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Abstract: Fire tests are used to determine whether fire protection products meet the minimum performance criteria set out in codes and legislation, as well as to certify these products. Experimental large-scale fires are used to test the performance of safety systems in tunnels, which are confined environments with a high probability of accidents and significant consequences due to the evolution of the event and whether there is the capability of counteracting it by safety measures. In this study, we conducted a systematic literature review following PRISMA guidelines. We searched the Scopus and Web of Science databases for publications from 2013 to 2022, resulting in a selection of 72 articles. An analysis was conducted on the following main topics: tunnel fires, fire characteristics (measured variables, spread, and smoke), model-scale tests, automatic shutdown systems, and ventilation solutions. One of the most important contributions of this study is the suggestion that fire tests represent an effective method not only to prevent fire events in tunnels but also to ensure the resilience of the infrastructure. Based on this state-of-the-art literature review, future tunnels could be designed by linking new smart technology and artificial intelligence to create interactive and high-performing safety systems.

Keywords: tunnel fire; large-scale fire test; ventilation system; automatic shutdown; water mist solutions; computational fluid dynamics; systematic literature review

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1. Introduction

Fires in the confined infrastructure of tunnels are critical hazards due to the potential for fatalities and damage to the structures. Road tunnels have a central utility in transportation and logistics connections [1,2]; in fact, in the Sustainable Development Goals (SDGs) of its 2030 Agenda, the United Nations declared transportation to be essential for building community connections and resilience, in accordance with SDG 9. To ensure the availability of the infrastructure, fire safety needs to be designed with an awareness of the risks involved. Risk-based design is a key method that not only represents a fire safety design model but also establishes a connection between risk management and emergency planning.

The concept of the resilience of critical infrastructure should be incorporated into the planning and designing phase according to the risk assessment [3,4]. It is important to emphasize the importance of fire safety design, detection, and fire suppression in tunnels [5].

Retracing major historical tunnel fire events is important to understand why designing punctual fire safety systems is necessary for infrastructure such as tunnels, as shown in Figure 1. We can analyze the worst fire events in road tunnels [6–8]: the Mont Blanc tunnel (Italy–France) in 1999, with 39 fatalities; the Tauren tunnel (Austria) in 1999, with 12 fatalities; and the Gotthard tunnel in 2001, with 11 fatalities.

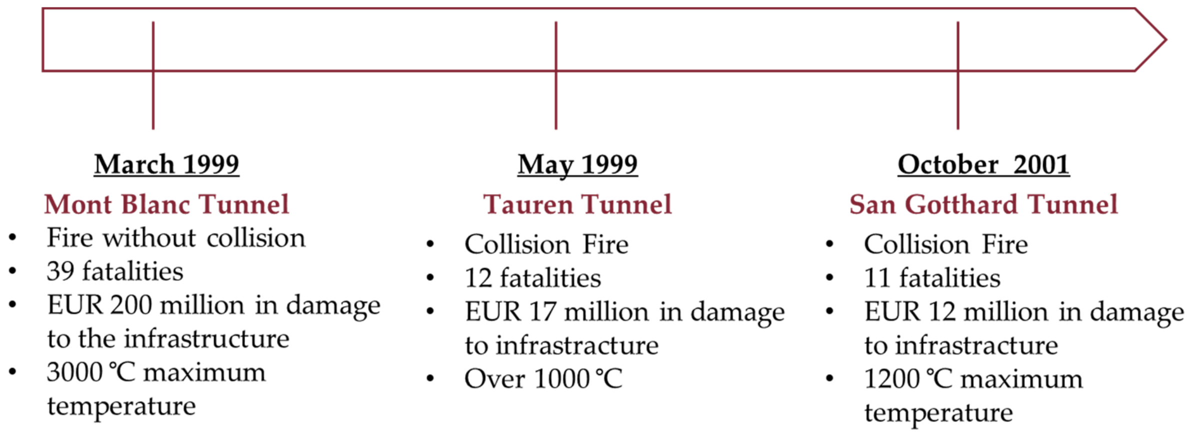

Figure 1. Timeline of critical fire events in road tunnels.

These are just a few examples of major accidents that led to the emergence of Directive 2004/54/EC [9] on minimum safety requirements for tunnels in the trans-European road network. This directive was created to ensure uniformity, safety, and connection in the transport infrastructure in Europe (TEN-T).

Real-scale fire tests are useful for measuring relevant parameters and characterizing fires using sensors that promptly measure quantities of interest (such as temperature and visibility) and associate the measurements with space–time coordinates. Modeling fires in a simulated environment allows for the validation of the experimental results. Once the model has been validated, it can be used in the pre-design stage to anticipate the evolution of fires in different conditions than the experimental ones. However, it is necessary to define the range of variability of characteristic parameters such as peak thermal power, wind speed, and tunnel geometry. Selecting a set of case studies, such as large-scale fire tests, allows for the calibration and validation of simulation models to predict the interaction of safety systems responsible for fire control and different fire outbreaks.

An important part of modeling fires is the ability to perform numerical simulations using specialized computational fluid dynamics software (FDS), among which fire safety engineering is the most commonly used [10,11]. These simulations require input parameters such as tunnel shape, fire protection systems, fire characteristics, and the evolution of the event.

Computational fluid dynamics software is widely used to simulate fire events in various situations and with different parameters. There are also new proposals to merge numerical simulations and fire tests using machine learning techniques [12], including neural network and deep learning techniques, to further improve the accuracy and effectiveness of fire safety design [13–16]. As one example of these new technologies, smart sensors applied to machine learning can be used to forecast tunnel hazards. A large amount of real-time data serve as the input for processing machine learning algorithms and building models for fire prediction in road tunnels [17,18]. The analysis must occur in real-time and be fast in order to provide tunnel operators with enough time to make quick decisions during critical situations.

The objective of the present study, which investigated case studies from 2013 to 2022, was to create a database of fire scenarios that could be used to test an experimental holistic model for fire safety design, as described previously, both ex ante and ex post. The data collection was based on an analysis of articles published in scientific journals from 2013 to October 2022. A decade of studies provides an overview of state-of-the-art research, with a particular focus on searching for a model to validate the fire test approach, including both numerical simulations and experimental activities.

The main questions asked while conducting the systematic literature review were as follows:

- ➢ Q1. What are the basic characteristics of the fire test models that have been developed in the scientific community?
- ➢ Q2. What are the positive aspects of the interaction of safety systems in road tunnels?
- ➢ Q3. What are the negative aspects of the interaction of safety systems in road tunnels?

The present systematic literature review is structured as follows: First, an introduction to the study is presented (Section 1), and the historical background of tunnel fires is provided (Section 2); in the second part, the focus is on the methodology of the systematic literature review (Section 3), while in the third part, a bibliometric analysis of the material on the topic is presented (Section 4). The results of the meta-analysis are then discussed (Section 5). Finally, a critical analysis of the studies is provided, along with an explanation of their limitations (Section 6), followed by conclusions and hypothetical future developments (Section 7).

2. Background

Historical data about fires in road tunnels are important to understand the causes of fire accidents and the consequences in terms of fatalities and infrastructure damage. Forensic engineering is the application of technical knowledge to post-event analysis and reconstruction [19,20]. Thanks to the forensic approach, it is possible to establish relationships between the stages of the fire response, including fire alarm, mobilization, arrival and access to the scene, and rescue and firefighting efforts. Additionally, in-depth research has been conducted on the challenges of dealing with fire and rescue situations in tunnels. Lessons learned from accidents that occurred before the implementation of safety regulations should be taken into account to improve the knowledge of actions during and after a fire event in tunnels. Most accidents in road tunnels occur due to vehicle collisions, braking, speed, and cargo, as well as reasons that are unclear [21]. For instance, an accident in the Frejus tunnel, a bidirectional tunnel connecting France and Italy, occurred in 2005 when a heavy goods vehicle (HGV) carrying tires caught fire and caused damage to vehicles, people, and the structure. As a result of the fire, 2 people died, and 21 people were treated for smoke inhalation.

Such experiences have prompted the scientific community to reflect on the critical points during and after a fire event. Safety systems are fundamental for managing fire events to reduce the intensity of the fire and provide people with the possibility of evacuation. After the event, investigations are needed to determine the causes, resume normal traffic flow, and assess fire damage to the structure. The aim of the present study was to highlight the latest research on safety systems and model-scale testing in order to collect a database of useful information to test a risk-predictive model and assess the performance of protective systems.

3. Materials and Methods

We conducted a systematic literature review following the Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [22], investigating model-scale tests in road tunnels and how safety systems work in case of a fire emergency.

Based on the PRISMA checklist strategy [23], the study structure can be summarized in the following steps:

(1) Identify sources of information for the research material, such as databases, registers, and websites;
(2) Select the literature based on content filtering according to the purpose stated in the abstract;
(3) Establish eligibility criteria for the review and synthesis group in line with the research scope;
(4) Conduct a full review of articles, including meta-analysis.

3.1. Information Sources

For the first item of the Methods section, we specify the initial data sources: databases, websites, and the reference period. In accordance with the guidelines, the following choices were made:

(1) Definition of scope: Fire tests in road tunnels;
(2) Databases and time frame: Scopus and Web of Science, from 2013 to 2022;
(3) Eligibility criteria: Performance criteria were established for the abstract review;

In this stage, the selection of articles was made by reading titles and abstracts. The minimum requirement for selection was whether the title and content contained the following topics: safety systems in road tunnels (water mist, sprinkler), safety ventilation systems, setup of fire tests, setup of model-scale (micro or large), and computational fluid dynamics. All of the information on the inclusion criteria is described in Table 1.

Table 1. Set of inclusion criteria for the systematic literature review.

Inclusion Criteria	Description
Keywords	Tunnel fire, ventilation system, longitudinal ventilation, tunnel fires, smoke back layering, natural ventilation, model-scale tests, CFD simulations, water-based firefighting system, automatic sprinkler, water mist
Language	English
Source type	Peer-reviewed articles published in Scopus or Web of Science
Time interval	2013–2022

(4) Categorization: After the selection process, each article was assigned to a specific category or trend.

A presentation of the collected database is provided below.

When conducting a review, the choice of database is fundamental. For this study, we opted to use the Scopus [24] and Web of Science [25] databases to collect relevant studies. After the initial data collection, the core of the study was the data screening, which is described in detail in Figure 2. The third stage of a systematic literature review involves conducting a critical analysis of the collected data. The aim of this stage is to identify the main themes discussed in the articles to create maps and visual trends.

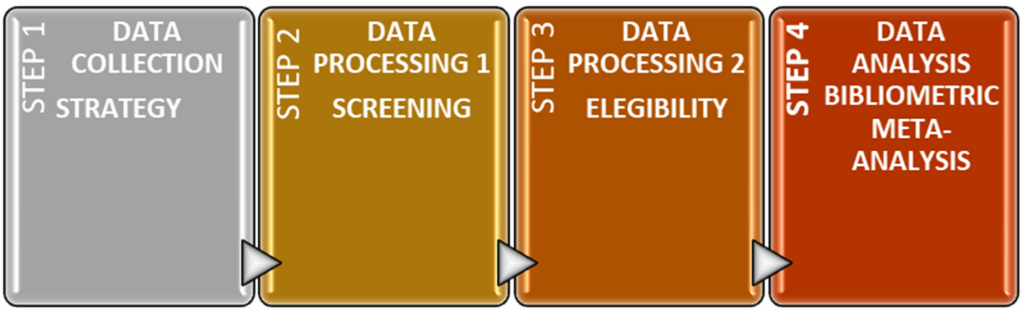

Figure 2. Data processing methodology.

3.2. Selection Process: Formulation and Databases

The data extraction process began with the Scopus and Web of Science databases. First, relevance was determined by matching streams using Boolean operators. Papers that fell outside the parameters were excluded. Articles published in English between 2013 and 2022 were searched using the following strings: for Scopus: "TITLE-ABS-KEY (("fire test tunnel ventilation" OR "tunnel test fire safety" OR "fire test tunnel large scale" OR "fire test tunnel water mist"))"; and for Web of Science: "(TS = (("fire test tunnel ventilation" OR "tunnel test fire safety" OR "fire test tunnel large scale" OR "fire test tunnel water mist")))". As a result, 458 documents were collected from Scopus and 421 documents from

Web of Science. An initial screening was done considering the limitation of the research area, which was engineering. After this limitation, a total of 792 articles were collected. Then, duplicated articles were removed, leaving 639 articles. The data were available in comma-separated values (CSV) format. We downloaded the full articles and removed duplicates using Excel software.

3.3. Eligibility

For each manuscript, the initial relevance was determined by the title and keywords. With the help of Scopus, we obtained the full reference, including author, year, title, and abstract, for further evaluation. Then, following the PRISMA guidelines, we defined the sets of inclusion and exclusion criteria. This step is crucial, as it narrows down the range of information and helps to determine whether the articles meet the inclusion criteria [26].

After completing the data screening process and excluding four inaccessible documents, 72 documents were reviewed. The purpose of the study was to collect knowledge in the field of fire tests for road tunnels and connect the experimental data found in the state-of-the-art in a progressive vision with a focus on safety. A summary of the work done in step 1 (data collection) and step 2 (data processing) is presented in Figure 3.

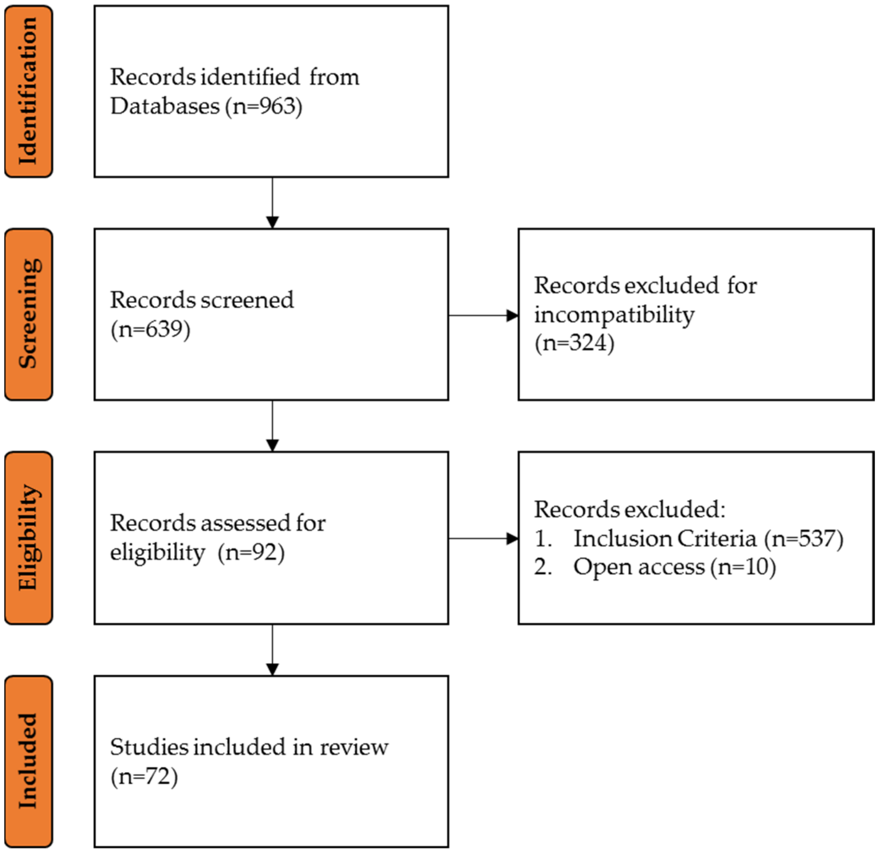

Figure 3. Search design following PRISMA guidelines [27].

3.4. Full-Text Review

The full-text review step represents the core of the analysis: meta-analysis aims to underline the heterogeneity or homogeneity of the state-of-the-art collected and to summarize similarities and differences directly related to the research topic in the various articles. Through this process, we can formulate a synthesis by pooling results from different studies to derive a single summary effect estimate. The data analysis is divided into the following sections: bibliometrics (Section 4), results (Section 5), and discussion (Section 6). For the synthesis in Section 5, we focused on the content of the articles and performed a deep analysis during the meta-analysis stage [28].

4. Bibliometric Findings

This section reports the bibliometric analysis of the 72 relevant articles [29,30]. Road tunnel fires are a frequently discussed topic with a consistent number of publications. A bibliometric analysis in this area has to provide a clear picture in order to identify research trends and future directions [31,32]. Bibliometrics is a useful tool for analyzing data and presenting results visually. It allows researchers to compare articles, identify trends in the state of the art, and suggest solutions for eliminating gaps. The effectiveness of bibliometric analysis depends on the scientific domain and the topics being analyzed [32]. Software analysis can provide insights into research themes, citations, and author information. Data can be downloaded from Scopus and Web of Science and analyzed using bibliometric software or graphically [33–35]. While some publications on tunnel fires from 1990 were found, our aim was to highlight the most recent applications and innovations available in the field of large-scale fire tests in road tunnels.

The bibliometric analysis included sources, country distribution and collaboration, articles over time, and highly cited papers. At the end of the section, subcategories are defined to classify categories and synthesize them in the Results section (see Section 5).

4.1. Sources

The bibliometrics process was basically limited by the data extraction in the Scopus and Web of Science websites. The aim of the systematic literature review (SLR) was to provide an overview of fire tests in tunnels. A graphical display of the article sources is presented in Figure 4, with the sources split into conference papers and articles, providing some valuable insights. A list of 14 journals closely related to the field of fire safety engineering that match the selected publications is given in Table 2. These journals are listed in alphabetical order, and a specific value has been assigned to each one based on the quartile citation values provided by the Scimago website and the H-index for each journal [36]. In a systematic literature review, the method of journal ranking is helpful in presenting the state-of-the-art that has been reviewed. As we can see in the table, most of the journals have a top-quartile citation (Q1).

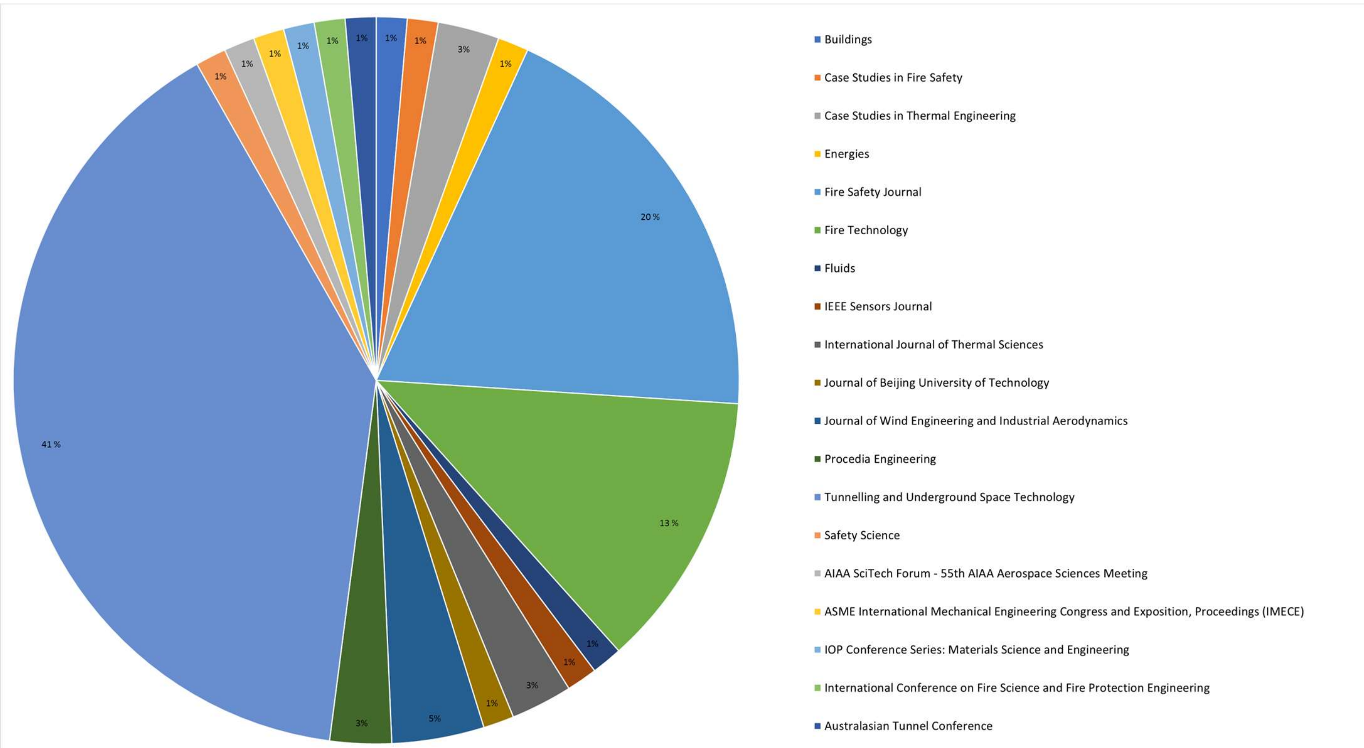

Figure 4. Number of articles from each journal/conference.

Table 2. Journals, H index values, and quartile citations.

Journals	H-Index	Quartile Citation
Buildings	35	Q1
Case Studies in Fire Safety	9	-
Case Studies in Thermal Engineering	47	Q1
Energies	111	Q1
Fire Safety Journal	85	Q1
Fire Technology	47	Q1
Fluids	18	Q2
IEEE Sensors Journal	132	Q1
International Journal of Thermal Sciences	127	Q1
Journal of Beijing University of Technology	17	Q4
Journal of Wind Engineering and Industrial Aerodynamics	115	Q1
Procedia Engineering	88	-
Tunnelling and Underground Space Technology	113	Q1
Safety Science	125	Q1

A list of five conference proceedings related to the field of fire safety that match the selected publications is given in alphabetical order in Table 3.

Table 3. Conference proceedings.

Conference Proceedings
AIAA SciTech Forum—55th AIAA Aerospace Sciences Meeting
ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)
IOP Conference Series: Materials Science and Engineering
International Conference on Fire Science and Fire Protection Engineering
Australasian Tunneling Conference

In terms of dissemination, articles from more than 20 journals and conferences were found. Figure 4 shows the number of articles from each journal/conference. Among the most prolific journals are Tunneling and Underground Space Technology, Fire Safety Journal, and Fire Technology. Tunneling and Underground Space Technology appears to have the highest number of publications, accounting for 40% of the total. This international journal covers a wide range of research topics related to fire safety in tunnels and experimental fire tests.

For the present study, we collected a total of 72 articles, including both journal articles and conference papers. An initial observation showed that the majority of articles were from journals (93%), with only five conference papers (7%). The results presented in Tables 2 and 3 and Figure 4 indicate the existence of extensive research on fire tests in road tunnels globally, with articles published in various journals and conferences.

4.2. Country Distribution

The country distribution of the first author's affiliation is shown in Figure 5. China stands out with the highest number of papers on the subject, accounting for 49% of publications, followed by Sweden (17%) , Japan (5.1%), USA (3%), Italy (3%), New Zealand (3%) and Poland (3%). The remain-ing proportion (16.9%) is divided among other countries. Table 4 presents the number of articles from each country, showing that China and Sweden have the highest number of publications.

The countries with fewer publications are France, Saudi Arabia, the United Kingdom, Australia, Austria, Iran, Greece, Spain, Egypt, Finland, the Czech Republic, and Portugal, as shown in the graph.

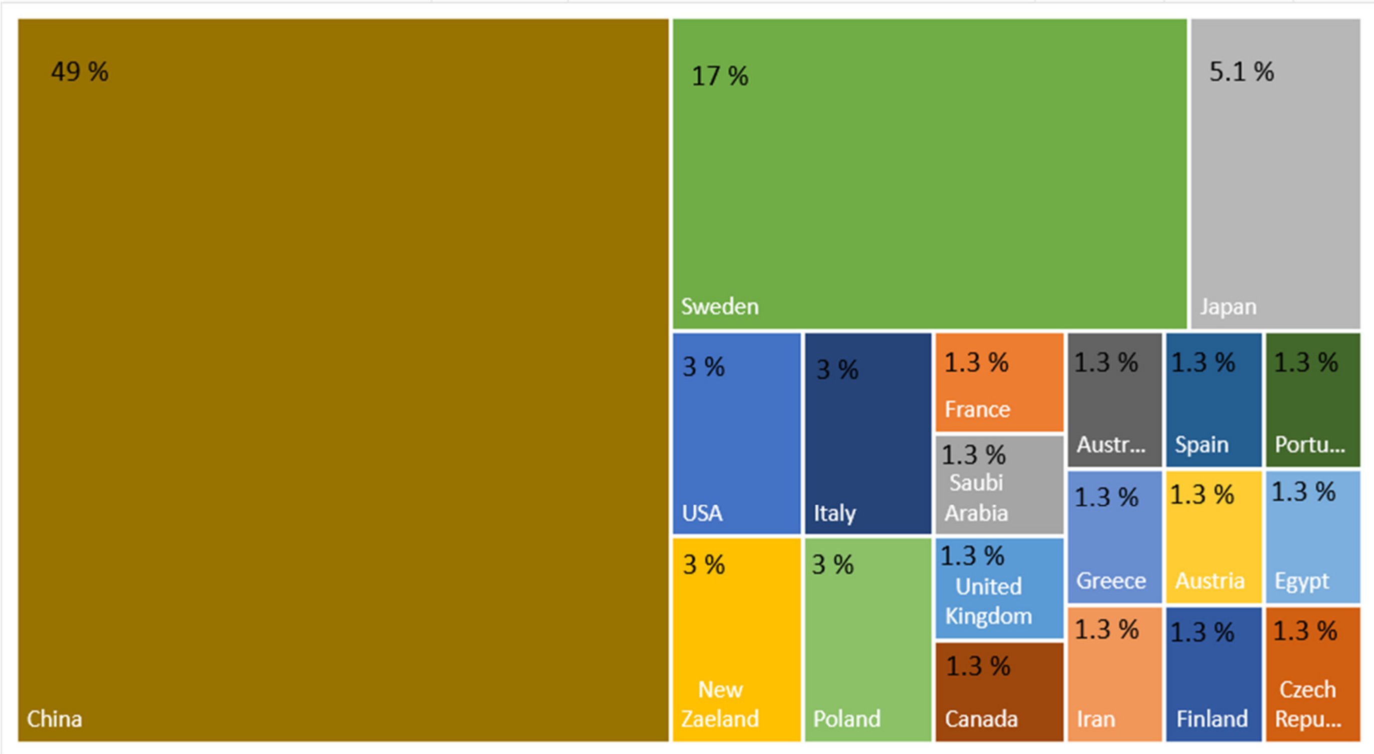

Figure 5. Mapping of first author affiliation.

Table 4. Number of publications by country.

Country	Number
China	35
Sweden	12
Japan	4
Italy, Poland, New Zealand, USA	2
France, Saudi Arabia, UK, Australia, Iran, Greece, Canada, Egypt, Finland, Spain, Czech Republic, Portugal, Austria	1

4.3. Articles over Time

The trend for the number of articles published on fire tests is shown in Figure 6. As the graph indicates, between 2013 and 2018, fewer than 30 articles were published. In contrast, between 2019 and 2022, the number increased to more than 40, indicating a rapid growth in interest in fire tests.

4.4. Highly Cited Papers

Citation is one of the most critical indicators of a publication's relevance [34]. Table 5 lists the most cited publications during the 10-year reference period. It is noteworthy that most of the publications were written by researchers from China and Sweden, with the authors Ying Zhen Li and Haukur Ingason being highly cited both individually and as a part of research groups. Tunneling and Underground Space Technology and Fire Technology are significant sources for these citations.

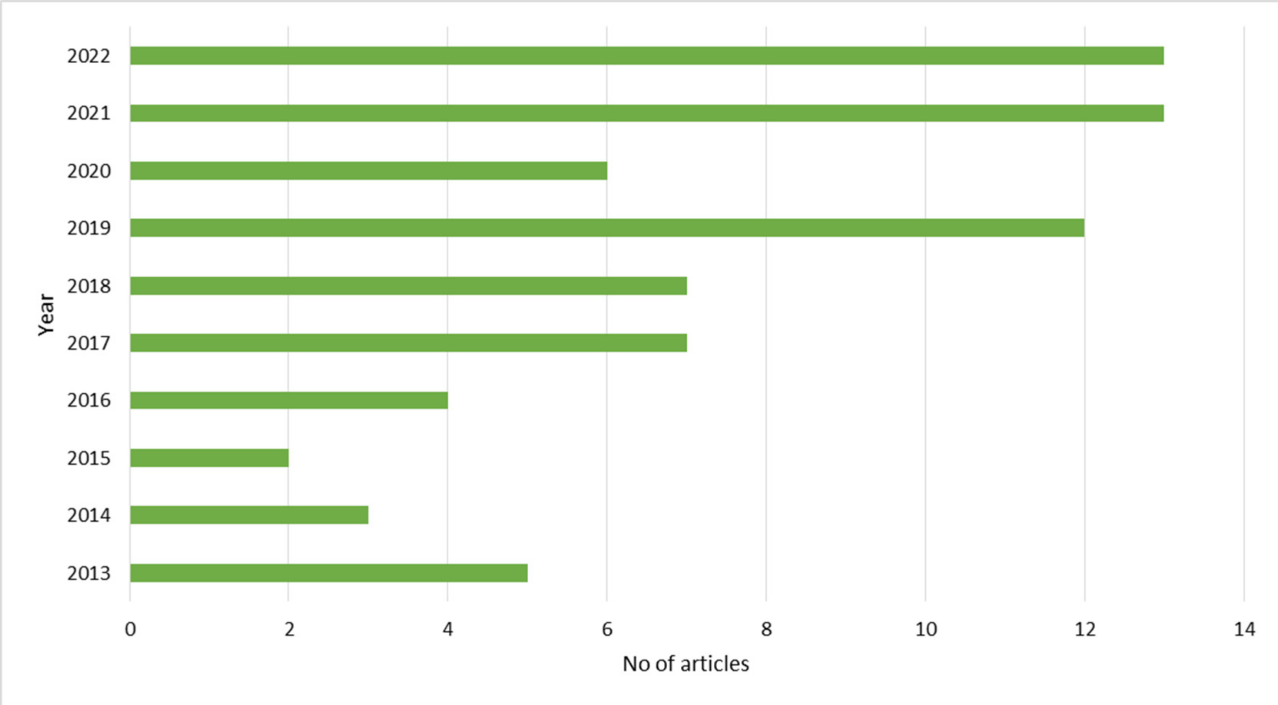

Figure 6. Number of publications per year.

Table 5. Most cited papers.

Rank	Title	Authors	Journal	Country	Number
1	Experimental investigation of pool fire behavior to different tunnel-end ventilation opening areas by sealing [37]	Chang-kun Chen, Huang Xiao, Nan-nan Wang, Cong-ling Shi, Cong-xiang Zhu, Xuan-ya Liu	Tunnelling and Underground Space Technology	China	65
2	Effect of cross section and ventilation on heat release rates in tunnel fires [38]	Ying Zhen Li, Chuan Gang Fan, Haukur Ingason, Anders Lönnermark, Jie Ji	Tunnelling and Underground Space Technology	Sweden	61
3	Model-scale tunnel fire tests with automatic sprinkler [39]	Ying Zhen Li, Haukur Ingason	Fire Safety Journal	Sweden	52
4	Full-scale measurements of the operation of fire ventilation in a road tunnel [40]	Małgorzata Król, Aleksander Król, Piotr Koper, Paweł Wrona	Tunnelling and Underground Space Technology	Poland	43
5	Position of Maximum Ceiling Temperature in a Tunnel Fire [41]	Ying Zhen Li, Haukur Ingason	Fire Technology	Sweden	42
6	Experimental and Numerical Study of the Interaction Between Water Mist and Fire in an Intermediate Test Tunnel [42]	E. Blanchard, P. Boulet, P. Fromy, S. Desanghere, P. Carlotti, J.P. Vantelon, J.P. Garo	Fire Technology	France	40
7	Experimental study of the effectiveness of a water system in blocking fire-induced smoke and heat in reduced-scale tunnel tests [43]	Jiayun Sun, Zheng Fang, Zhi Tang, Tarek Beji, Bart Merci	Tunnelling and Underground Space Technology	China	33
8	Testing the predictive capabilities of evacuation models for tunnel fire safety analysis [44]	Enrico Ronchi	Safety Science	Italy	30

Table 5. *Cont.*

Rank	Title	Authors	Journal	Country	Number
9	Experimental studies on the gas temperature and smoke back-layering length of fires in a shallow urban road tunnel with large cross-sectional vertical shafts [45]	Qinghua Guo, Hehua Zhu, Zhiguo Yan, Yao Zhang, Yinping Zhang, Tianrong Huang	Tunnelling and Underground Space Technology	China	29
10	Heat Release Rate of Heavy Goods Vehicle Fire in Tunnels with Fixed Water-Based Firefighting System [46]	M.K. Cheong, W.O. Cheong, K.W. Leong, A.D. Lemaire, L.M. Noordijk	Fire Technology	Japan	27

4.5. Subcategories and Targets

The data in the present systematic literature review were divided into two groups to discriminate between theoretical issues and applied studies (Figure 7). Conceptual studies outnumber empirical ones. One reason is that scale fire tests are expensive and complex to carry out. Instead of conducting real tests, it is common to use computational fluid dynamics software, which allows for the representation of a large structure and its safety systems at a reduced cost. However, experimentation plays a crucial role, and real-scale tests in tunnels not only enable us to study the response of safety systems but also to predict and characterize other cases where it is necessary to standardize the fundamental parameters of the fire. Additionally, this allows for experimentation with new technologies for future developments.

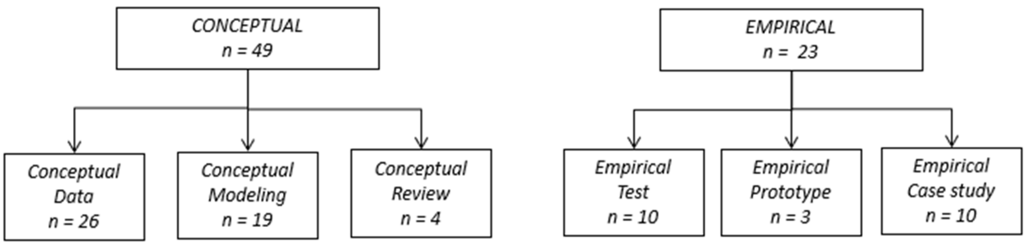

Figure 7. Conceptual and empirical papers.

After the first division, a second one was proposed, as shown in Figure 7. Most conceptual studies deal with data collection, analysis, and modeling, while empirical studies focus on large- and micro-scale tests and case studies in general. Only a few articles propose prototypes. Regarding reviews, a few are recognized, which is useful in differentiating the present study from past reviews on the same topic. As previously mentioned, the following subcategories were addressed: empirical studies proposing new prototypes (E-P), empirical studies based on experimentation on real equipment (E-T), and empirical studies based on a case study (E-S). For conceptual works, the following subcategories were defined: studies based on data extraction, collection, and analysis (C-D), studies based on software for simulation and modeling (C-M), and the literature reviews (C-R).

The identification of research targets for fire tests in road tunnels is based on the type of case study analyzed, keywords, and proposed innovations. As a result of a combination of bibliometric findings and an initial deep reading of publications, research targets can be grouped into three macro areas: fire suppression, ventilation systems, and water-based firefighting systems. Each was subdivided into content groups according to the previously conducted meta-analysis. The first research target, Fire Suppression (T.1), includes all articles related to the main characteristics of tunnel fires and how to perform a model-scale fire test. The second one, Ventilation Systems (T.2), covers topics about different kinds of ventilation (natural, forced). The last one, Water-Based Firefighting Systems (T.3), addresses issues relating to water shutdown.

5. Results

This section presents a summary of the articles' content. In the Appendix A, the entire group of articles and their corresponding references is reported. The targets listed in Table 6 are the subheads of the following paragraphs.

Table 6. Research targets, sub-targets, and the number of articles.

Research Target	Sub-Targets	Code	Number of Articles
T.1 Fire Suppression	Model-scale Test	T.1.1	13
	Smoke Dynamics and Critical Velocity	T.1.2	15
	Fire Location and Product of Combustion	T.1.3	8
T.2 Ventilation System	Natural Ventilation	T.2.1	4
	Forced Ventilation	T.2.2	13
T.3 Water-Based Firefighting System	Water Mist and Water Spray	T.3.1	16
	Automatic Sprinkler	T.3.2	3

5.1. *T.1 Fire Suppression*

This section includes publications about fire tests and investigations on smoke and combustion products. Model-scale tests are conducted to investigate fire suppression on combustion products and their influence on smoke dynamics in a fire. Fire suppression systems are fundamental for reducing the quantity of combustion products, but sometimes a model-scale test is needed to determine the activation settings.

5.1.1. T.1.1. Model-Scale Test

The aim of experimental fire testing is typically to provide practical evaluations of specific phenomena, such as smoke movement in tilted tunnels, the back-layering effect, and safety system activation. On-site tests are often replaced by simulated tunnels using computational fluid dynamics (CFD) software. Despite the time-consuming nature of CFD simulations, they are still widely used in simulating fires in tunnels and developing ventilation and emergency systems management [47]. Small-scale model tests can be useful for studying the back-layering length of fire smoke and critical velocity with canyon crosswind by changing wind velocity, longitudinal ventilation velocity, and fire position in the tunnel. By manipulating fire positions and pressure induced by longitudinal ventilation, a correlation between critical velocity and wind velocity becomes evident [48].

The study of fire dynamics in tunnels is important for safety not only during operation but also during construction. Yao et al. [49] proposed a study using a model-scale tunnel to investigate the effects of various parameters, such as tunnel geometry, fuel type, fire size, fire location, and ventilation rate, on fire development during tunnel construction. By changing different parameters of the fire, such as ventilation velocity, location, and fire size, the investigation revealed their influence on the fire dynamics in a tunnel during construction. The same authors conducted an experimental model and medium-scale test [50] to expand the knowledge of under-ventilated fires in tunnels with entrance openings of different sizes in order to understand the influence of ventilation rate and fire characteristics.

Due to the high cost of fire tests, it is important to understand that model-scale tests conducted using software can accurately simulate what happens. A case study [51] compared model CFD results and the experimental data of a tunnel fire. The validity of CFD results was illustrated by a graphical temperature field analysis, which was detailed through the sensitive study of the geometry and boundary tunnel model. Boundary conditions, external temperature pressure, and velocity of air parameters are fundamental inputs for validating simulations and understanding the impact of factors causing natural airflow in tunnels [40]. In simulated tests, scaling theory cannot maintain all terms obtained, and only the most important and relevant terms are preserved. For example, HRR, time, flow rate, energy content, and mass are usually scaled in simulated tests [41].

One of the most important parameters used in model-scale tests is the heat release rate per unit area (HRRPUA). This parameter influences the survival level related to combustion products, soot yield, gas temperature, and radiation [52]. Focusing on the temperature field, in a model-scale test, it is important to use a thermocouple system to accurately measure the on-site conditions and damage induced by a fire event [53]. The accuracy required in simulations, as described in previous work, depends on the mesh resolution, which is the domain in which the CFD software can perform numerical analysis. Janardhan et al. [54] demonstrated the validity of using a local fire test of wood pallets in a simulated case study of a fire tunnel. Their results showed that the computational cost of simulating fire spread could be reduced using coarser mesh, and sufficient accuracy can be achieved by adjusting the area parameter in the fire source. Small-scale tests are conducted to investigate methods that study smoke and fire using training data. One study [55] proposed a regression method for recording gas concentration and temperature in tunnel fires during steady burning stages, and the regression was found to agree well with the small amount of training data. For all tunnel fires, the models estimating fire dynamics can be used to determine the time needed to escape [56]. Ronchi [44] conducted a study that tested the predictive capability of different evacuation modeling approaches to simulate tunnel fire evacuations. Model-scale test studies mostly help us to understand fire dynamics, particularly smoke dynamics.

5.1.2. T.1.2. Smoke Dynamics

Model-scale tests are used to investigate experimental and theoretical findings in tunnel fires. Smoke movement is one of the major phenomena investigated in tunnel fire studies. Zhang et al. [57] studied smoke back-layering and critical velocity through numerical analysis and small-scale experimental tests to demonstrate the effect of the tunnel aspect ratio on smoke buoyancy. The importance of smoke dynamics is related to the need for a ventilation system, the characteristics of which must be adapted to the characteristics of fire, such as air velocity, thermal temperature, and smoke stratification [58,59]. Tunnel geometry is relevant to smoke movement, and one important characteristic is the slope of the tunnel. Tunnel slopes are crucial for calculating critical velocity under different heat release rate conditions [60,61].

Zhao et al. [62] conducted a simulation study of tunnel slopes to redirect smoke flow in an inclined tunnel fire. In their study on simulated tunnel fire, Krol and Krol [63] investigated how the temperature and hot gases generated by the fire impacted the airflow within the tunnel, ultimately affecting the overall safety conditions. The sensors used for temperature detection are typically thermocouples, which must be accurately calibrated to ensure their reliability [64]. As previously mentioned, airflow is an important design parameter. Airflow velocity can be designed using a simplified mathematical model based on continuity and Bernoulli equations, as proposed by Jan et al. [65] and tested on complex road tunnels. The back-layering in tunnels can be controlled at a lower velocity than the critical velocity by activating automatic shutdown and ventilation systems, as described in a data analysis of model tunnels [66]. Fire dynamics also involves controlling the mass burning rate, as described in a data analysis study [67] correlating the type of burning fuel with damage to the tunnel structure. All studies mentioned thus far proposed methods to investigate the heat release rate, maximum temperature, back-layering length, and critical velocity through experimental simulations or tests.

Yi et al. [68] conducted a model-scale test and provided data on temperature, critical velocity, and back-layering field. They demonstrated that the gas temperature becomes asymmetric when the ventilation system is activated. Tang et al. [69] proposed a model simulation involving two fire sources and found that the critical longitudinal ventilation velocity decreased as the separation distance between the fires increased. These studies provide insight into fire modeling and the design of model tests. A study by Guo et al. [45] focused on the smoke back-layering length and shaft height. That study showed that back-layering length decreases with shaft height for a given fire HRR and certain shaft intervals, while it increases with fire-shaft intervals for a given fire HRR and shaft height. Li and Liu [34] emphasized that smoke thermodynamics, smoke extraction, and model-scale tests are among the most critical issues in tunnel fire publications. When a fire occurs, smoke spreading along the tunnel is one of the most fatal factors, leading to reduced visibility, elevated temperatures in the ceiling, and fire interacting with the ventilation system.

5.1.3. T.1.3. Products of Combustion

On-site fire tests and model-scale tunnel fire tests, with and without fire suppression, are usually carried out to detect the effects of fire suppression on the production of key combustion products, including CO and soot. The type of fuel, gas or solid, influences the production of combustion products [70]. With the help of an algorithm model proposed by Zhang et al. [71], a model simulation of the products of combustion and process data can be used to detect and predict fire events. During a fire event, the effect of the fire's location is usually investigated to understand the link between ventilation and the geometry of the tunnel [72]. The location of the fire influences the design of ventilation for smoke propagation and the quantity of combustion products. Combustion products are influenced by the fire suppression system. Li and Ingason [73] performed a scale test to evaluate the effect of fire suppression on combustion products. They found out that after the suppression system was activated, the measured data for soot production and yield could be higher than the real values due to the presence of water in droplets and vapor. Combustion products depend on the chemical characteristics of the fuel, whether the fuel is solid or liquid [38]. For example, a study [37] showed that in a methanol pool fire, a possible depression effect of different sealing ratios for combustion inside tunnels could be observed, which was found to be related to the fuel area. By analyzing a CFD simulation, it is possible to evaluate the impact of products of combustion (in terms of CO level, soot visibility, and high temperature) on humans [74,75].

5.2. T.2 Ventilation Systems

In this section, we present publications related to fire tests and investigations on ventilation systems and strategies. The two common ventilation methods in tunnel fires are natural and mechanical ventilation. Studies on natural ventilation can also inform the design of mechanical ventilation systems. Therefore, first, we summarize studies on natural ventilation, followed by studies on mechanical ventilation systems.

5.2.1. T.2.1. Natural Ventilation

The investigation of natural ventilation in tunnels is crucial, as it is often necessary to address system design problems. Lu et al. [76] presented a case study that focused on the effect of ceiling temperature under natural ventilation in a tunnel. The results showed that the maximum temperature reached was independent of the fire location and bifurcation angle. However, a bifurcation angle equal to or greater than 90° affected the longitudinal temperature distribution. According to Tanno et al. [77], under natural ventilation, the heat release rate has almost no effect on the smoke layer thickness in the tranquil flow region within the range of experimental conditions. Therefore, the vertical temperature distribution within the smoke layer is influenced by the cross-sectional shape of the tunnel. Another study on the same topic [78], based on experimental test conditions, established the smoke flow and smoke exhaust efficiency in naturally ventilated tunnel fires. An important parameter in studying natural ventilation is the influence of wind. Galhardo et al. [79], through CFD simulations, validated a one-dimensional model to evaluate the influence of wind on human safety during a hazardous event.

5.2.2. T.2.2. Forced Ventilation

So far, we have summarized publications related to tunnel fires and natural ventilation. In this section, we focus on studies related to mechanical ventilation strategies in tunnels. One common approach is to use CFD simulations, which link 3D and 1D models and factor in heating, ventilation, and air-conditioning (HVAC) to simulate ventilation and external conditions [80]. These simulations use the characteristics of flow, radiative heat transfer, and wall conduction in models to focus on governing equations, discretization methods, flux computations, and boundary conditions [81]. In general, the problem of the ventilation strategy can be summarized as follows: The longitudinal ventilation strategy can be divided into three branches [82]: the critical velocity strategy, which aims to prevent back-layering and any upstream movement of smoke along the tunnel; the low-velocity strategy, which applies to tunnels with unidirectional traffic, where specific conditions remain unclear; and the near-zero velocity strategy, which is not applicable because it leads to a strong increase in local concentrations of toxic gases and temperature, resulting in a dramatic reduction in tenability near the fire zone.

Longitudinal ventilation systems are often adopted as a ventilation strategy, as they are safe and practical. However, it is important to study their total characteristics. For example, Jiang et al. [83] proposed a series of small-scale tests to validate a model for predicting critical velocity under the conditions of a smoke point extraction system and a longitudinal ventilation system. Wang et al. [84] verified the use of vertical shafts with longitudinal ventilation, which provide more smoke vents and a stronger stack effect. Others [85,86] investigated the effect of longitudinal velocity on the mass flow rate distribution of the fire plume in longitudinally ventilated tunnels. Liu et al. [87] performed a series of tests to understand the combustion rate, ceiling temperature, and critical velocity by varying parameters such as fire size, ventilation velocity, and fire elevation under longitudinal ventilation, showing how fire elevation influences these parameters. Yao et al. [88] studied longitudinal ventilation to test small tunnels in order to quantify the maximum temperature that the ceiling structure would reach in a fire event. Tanaka et al. [89] set a fire in a tunnel with multiple openings on the ceiling, under the condition of longitudinal external wind blowing above the openings, to examine the spread of smoke along the tunnel and the interaction with safety conditions for humans. In case of a fire event, analyzing ventilation pressure around the fire area is crucial [90] in order to identify the best ventilation system to adopt [91]. In another study [92], full-scale exhaust smoke tests were performed to investigate the effects of forced longitudinal ventilation using two movable fans on the propagation characteristics of buoyancy-driven thermal smoke. The results are discussed based on longitudinal and vertical temperature measurements. The outcome of the study showed a reduction in maximum longitudinal temperature, while the spread velocity of the thermal smoke was enhanced when one fan was placed upstream.

5.3. T.3 Water-Based Firefighting System

Although ventilation systems are an effective method to control smoke and temperature and protect human safety in case of a fire in a tunnel, as illustrated by the collected articles above, the effectiveness of safety measures to prevent a fire event depends on another important element: the firefighting system. In this section, various articles regarding firefighting systems, specifically water-based systems, are presented. As mentioned, the ventilation system is closely connected to the water-based firefighting system, as discussed below.

5.3.1. T.3.1. Water Mist and Water Spray

Many studies focus on water-based firefighting systems, each proposing a different theoretical or experimental approach. One such system is commonly known as the water mist system. It has several advantages, including that it uses less water than other firefighting systems, it is flexible and environmentally safe, and it has a space-saving design. Liu et al. [93] conducted an experimental investigation on the combined effect of longitudinal ventilation and water mist systems. The study found that the cooling effect of water droplets in the upper hot smoke, specifically in relation to imposed velocity, plays a critical role in reducing the maximum temperature. Similar results were obtained by Li and Ingason [94], who emphasized the effect of ventilation on the effectiveness of water suppression systems. Model-scale simulations have been applied to study the interaction of water mist with other safety systems, such as evaluating critical velocity with and without mist suppression and using the ratio between the water evaporation rate and fire burning rate as a fundamental parameter [95,96]. The designed direction of nozzles can also influence the suppression results [97], along with the balance of ventilation velocity and the water mist setting [98]. In the absence of a ventilation system, the spread of temperature and smoke along the tunnel is significantly reduced [42,43]. Yan et al. [99] proposed a water mist system with an additive extinguisher to improve fire control and extinguishing effects in road tunnels. High-pressure systems and suitable water mist additives were found to be effective at improving fire control and extinguishing effects in water mist systems.

Other studies [100,101] investigated the behavior of water spray systems. Water spray induces a water–air jet, which blocks incoming air and deflects the air stream toward the ceiling. The region upstream of the water spray close to the system is not affected, but it changes significantly around the fire source. Wang et al. [102] analyzed temperature field trends in a small-scale test under longitudinal ventilation and found that the maximum smoke temperature decreased, and longitudinal smoke temperature decayed faster with an increased water spray flow rate. The performance of a longitudinal ventilation and fixed firefighting system can be improved by activating the ventilation before the fixed firefighting system to achieve better fire control [103]. In large-scale fire tests, water-based systems using large droplets were installed, resulting in significant fire reduction and control of the temperature field at the ceiling [104,105]. For example, in a heavy and dangerous fire event [46], activating the suppression system could reduce the fire's development. However, it has a disadvantage: high concentrations of carbon monoxide (CO) were found in the suppression tests, indicating incomplete combustion due to water suppression.

5.3.2. T.3.2. Automatic Sprinkler

In this section, we provide a summary of articles related to sprinkler systems. Fixed fire protection systems can be either active or passive, and the significance of active protection systems was discussed earlier. To better understand the importance of sprinkler systems in tunnels, Mawhinney et al. [106] conducted a review of past research, focusing on the relationship between safety systems, tunnel structure, and people's safety. Automatic sprinklers are among the most commonly used fire suppression systems, particularly in buildings and industrial sites. Ingason et al. [107] conducted a series of scale tests with automatic sprinklers in tunnels, and they found that parameters such as water density, water flow rate, and ventilation flow velocity must be carefully defined. Li and Ingason [39] noted that for automatic sprinkler systems in tunnels, fire suppression could be divided into two modes: surface gas cooling and downstream gas cooling.

Table 7 provides a summary of each sub-target. The process began with a selected group of articles, which were identified after the screening and eligibility phase of the systematic literature review. As highlighted in the bibliometric section, the majority of contributions came from China and Sweden, and the most popular journal was Tunnel and Underground Space Technology.

Table 7. Summary of content of meta-analysis.

Paragraph	Sub-Targets	Summary of Content
5.1 Fire Suppression	T.1.1 Model-scale Test	Model-scale tests are conducted to investigate the effect of fire suppression on combustion products and their influence on smoke dynamics during a fire.
	T.1.2 Smoke Dynamics and Critical Velocity	Smoke management and dynamics are related to the need for a ventilation system that can work optimally, with its characteristics adjusted to match the fire's characteristics, such as air velocity, thermal temperature, and smoke stratification.
	T.1.3 Fire Location and Product of Combustion	Fire suppression systems are essential for reducing the quantity of combustion products, but sometimes model-scale tests are needed to determine their activation.
5.2 Ventilation System	T.2.1 Natural Ventilation	Natural ventilation is the basis for analytically and numerically understanding fire development in tunnels.
	T.2.2 Forced Ventilation	Longitudinal ventilation systems are the most commonly used in road tunnels. Their performance must consider major characteristics such as air velocity, smoke plume, and interaction with other systems.
5.3 Water-Based Firefighting System	T.3.1 Water Mist and Water Spray	Water mist systems are innovative and offer advantages for fire suppression in tunnels. Research has focused on studying the interaction between ventilation and suppression systems.
	T.3.2 Automatic Sprinkler	Automatic sprinklers are commonly used in industrial and civil buildings. These firefighting systems can also be used in tunnels, but it is important to clearly identify the parameters for optimal use.

6. Discussion

The purpose of this research was to investigate fire tests in road tunnels, particularly concerning the behavior of safety systems, and to identify state-of-the-art model-scale tests and the interaction between ventilation systems and water-based firefighting systems. The objective of this systematic literature review was to create a holistic model that includes the design of road tunnels ex ante and ex post. Attention to this issue has increased in the last decade for several reasons: Firstly, as we highlight in the Introduction, accidents that occurred in the early 2000s prompted an investigation into fire hazards in road tunnels. Secondly, the need to counteract similar fire scenarios pushed nations to regulate road tunnels in order to prevent fire hazards. Thirdly, due to the regulations and requirements for safety systems in tunnels, it became necessary to conduct tests in order to understand the interactions between safety systems, mainly ventilation and fire suppression systems, in case of fire development. In fact, not every combination of these systems is effective at suppressing the growth of a fire while ensuring people's safety and the integrity of the structure.

Using the code attribution in Table 6 and the classification of articles by year, we analyzed the distribution of articles belonging to each target over time. The graphical distribution shown in Figure 8 provides some insights.

The principal topics discussed in the review are the setup of model-scale tests and fire development (smoke management, fire location), ventilation systems (natural or forced), and water-based firefighting systems. Based on these issues, some considerations were made to address the questions raised in the Introduction and understand the challenges and outputs of the state-of-the-art presented. These are summarized below:

- In this study, we collected 72 articles about fire tests and safety systems, which mostly show the complex interaction between longitudinal ventilation and water-based firefighting systems;
- Q1. The basic characteristics of fire test models developed in the scientific community to date are related to the construction of simulated tunnels using computational fluid dynamics;

- Q2. The positive aspects of the interaction of safety systems in road tunnels are the contemporary use of ventilation systems and extinguishing solutions to reduce the power of fire and help people evacuate;
- Q3. The negative aspects of the interaction of safety systems in road tunnels are related to the technical elements of the design and the lack of communication between individual systems when a fire occurs. Resolving this issue may require improving the design of the devices, as well as on-site or simulated scenario testing to demonstrate the efficiency of the integrated system;
- Most of the collected articles are conceptual, and simulations of fire in tunnels are more economical and easier to perform than on-site fire tests. Theoretical approaches and analyses of fire development are essential to understand the phenomenon and setting up safety systems;
- There are not many reviews about the issue [34,44,106], and each one covers different aspects of fire in road tunnels;
- The thematic analysis of fire management in road tunnels seems to mainly focus on the air velocity of the ventilation system [85,86] to manage the smoke flow;
- Full-scale experimental tests are very difficult to carry out [40,58] due to their cost, safety concerns, and environmental problems.

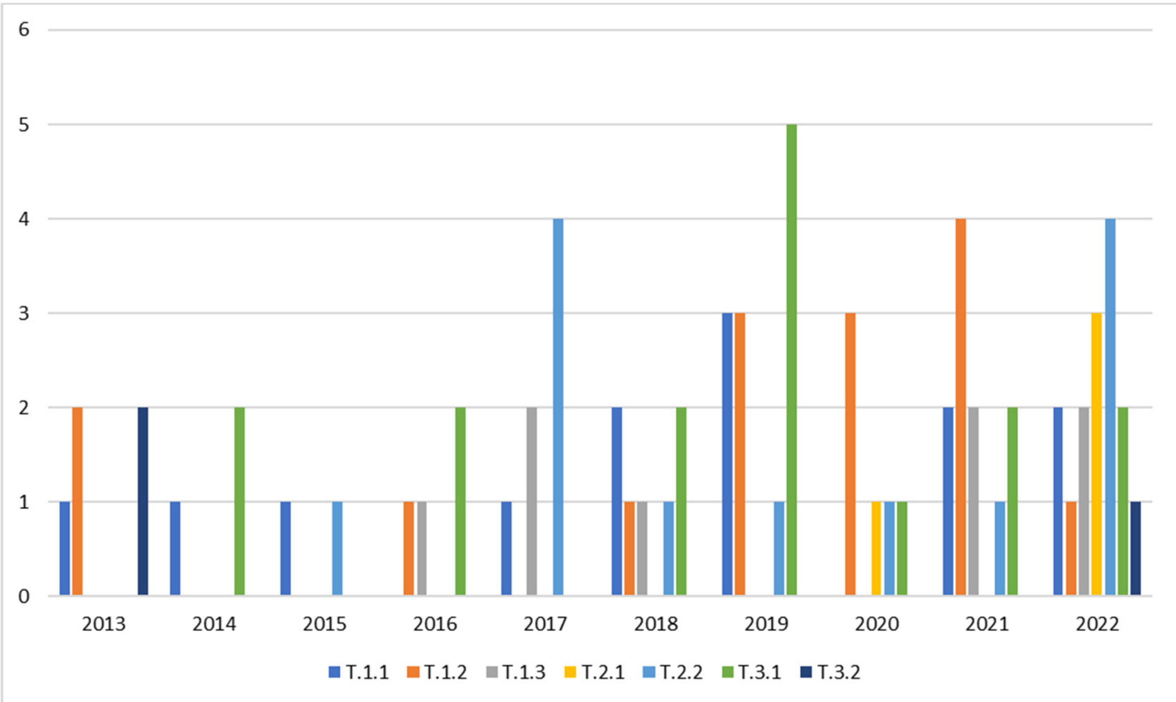

Figure 8. Trends of sub-targets by year.

The results of this study shed light on the importance of investigating fire risks in confined environments such as tunnels, given the serious consequences that could result. The goal is to determine the best way to optimize the use of safety systems to ensure the safety of human life and the structural integrity of the tunnel. Therefore, further research in this direction is needed to provide a clear understanding of individual tunnel models that is reproducible and applicable to existing and future tunnels. In fact, over the past year, machine-learning models adapted to fire in tunnels have been developed. Typically, the architecture of a machine learning algorithm is linked to a training dataset generated by CFD simulations. With the prediction and optimization of results, a feasibility model for fire prediction can be established [108]. Although data mining and validation have yielded highly accurate results, it is important to note that simulations cannot perfectly replicate real tunnels. However, simulations can provide scenarios for complex structures that cannot be tested in real-world conditions [109].

7. Conclusions

The main objective of this systematic literature review was to collect the state-of-the-art of different fire scenarios and safety system designs from 2013 to 2022 to test a model that encompasses the design ex ante and ex post, as described in the Sections 1 and 6. A synthesis of the results is presented in detail in the meta-analysis section and summarized in Table 7.

However, this systematic literature review has some limitations. The design of fire tests and safety systems has been discussed from various perspectives over the last decade. The decision to limit our consideration to the engineering field and focus on investigated road tunnel infrastructure was motivated by the need to verify the scientific validity of currently proposed solutions. The results of this study cannot be considered comprehensive because the topic of fire tests can be approached from other angles, and alternative solutions can be presented. The main outcome of this analysis is a clear display of what researchers have accomplished and what can be implemented as soon as possible.

An analysis must adopt a probabilistic approach to identify near misses and precursors of critical conditions (weak signals). Data from accidents with consequences in terms of human safety underline the need to make predictions on critical conditions based on weather and traffic forecasts using data analytics and machine learning, as well as designs based on risk.

Overall, this research leads to some points of reflection: Studies should focus on matching existing solutions and developing models that merge aspects regarding the performance of safety systems, collecting model-scale tests, highlighting gaps in the literature, and adding new value to what has been done until now on the topic of fire tests in road tunnels.

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Appendix A

List of selected documents categorized following the subject topic with referred code.

Document	Title	Year	Code
[39]	Model-scale tunnel fire tests with automatic sprinkler	2013	T.3.2
[66]	Study of smoke backlayering during suppression in tunnels	2013	T.1.2
[68]	Experimental studies on smoke movement in a model tunnel with longitudinal ventilation	2013	T.1.2
[44]	Testing the predictive capabilities of evacuation models for tunnel fire safety analysis	2013	T.1.1
[106]	Fixed Fire Protection Systems in Tunnels: Issues and Directions	2013	T.3.2
[42]	Experimental and Numerical Study of the Interaction Between Water Mist and Fire in an Intermediate Test Tunnel	2014	T.3.1
[41]	Position of Maximum Ceiling Temperature in a Tunnel Fire	2014	T.1.1
[46]	Heat Release Rate of Heavy Goods Vehicle Fire in Tunnels with Fixed Water-Based Firefighting System	2014	T.3.1

Document	Title	Year	Code
[56]	Limit-Based Fire Hazard Model for Evaluating Tunnel Life Safety	2015	T.1.1
[91]	Ventilation simulation of a large and complex road tunnel: A safe journey—E4 the Stockholm bypass project	2015	T.2.2
[65]	Model-based airflow controller design for fire ventilation in road tunnels	2016	T.1.2
[43]	Experimental study of the effectiveness of a water system in blocking fire-induced smoke and heat in reduced-scale tunnel tests	2016	T.3.1
[38]	Effect of cross section and ventilation on heat release rates in tunnel fires	2016	T.1.3
[105]	Large Scale Tunnel Fire Tests with Large Droplet Water-Based Fixed Fire Fighting System	2016	T.3.1
[40]	Full-scale measurements of the operation of fire ventilation in a road tunnel	2017	T.1.1
[89]	Smoke spreading characteristics during a fire in a shallow urban road tunnel with roof openings under a longitudinal external wind blowing	2017	T.2.2
[86]	Study of the critical velocity in tunnels with longitudinal ventilation and spray systems	2017	T.2.2
[82]	On the problem of ventilation control in case of a tunnel fire event	2017	T.2.2
[37]	Experimental investigation of pool fire behavior to different tunnel-end ventilation opening areas by sealing	2017	T.1.3
[81]	Numerical investigation of a tunnel fire under longitudinal ventilation	2017	T.2.2
[74]	Temperature distributions in an underground road tunnel: Effect of car fire heat release	2017	T.1.3
[51]	Interpretation of flow fields induced by water spray systems in reduced-scale tunnel fire experiments by means of CFD simulations	2018	T.1.1
[102]	Water spray flow rate effect on smoke temperature distribution under the ceiling in tunnel fires with longitudinal ventilation	2018	T.3.1
[73]	Influence of fire suppression on combustion products in tunnel fires	2018	T.1.3
[63]	Study on hot gases flow in case of fire in a road tunnel	2018	T.1.2
[55]	The Application of Support Vector Machine (SVM) Regression Method in Tunnel Fires	2018	T.1.1
[98]	CFD Simulations of the Interaction of the Water Mist Zone and Tunnel Fire Smoke in Reduced-scale Experiments	2018	T.3.1
[90]	Analysis on ventilation pressure of fire area in longitudinal ventilation of underground tunnel	2018	T.2.2
[64]	Measuring Air Speed with a Low-Power MEMS Ultrasonic Anemometer via Adaptive Phase Tracking	2019	T.1.2
[49]	Study of tunnel fires during construction using a model-scale tunnel	2019	T.1.1
[50]	The characteristics of under-ventilated pool fires in both model and medium-scale tunnels	2019	T.1.1
[97]	The effect of nozzle design on the fire heat release rates in tunnel deluge systems	2019	T.3.1
[92]	The effect of forced ventilation by using two movable fans on thermal smoke movement in a tunnel fire	2019	T.2.2
[96]	Experimental study of the effectiveness of a water mist segment system in blocking fire-induced smoke and heat in mid-scale tunnel tests	2019	T.3.1
[103]	Performance evaluation on fixed water-based firefighting system in suppressing large fire in urban tunnels	2019	T.3.1
[54]	Predictive Computational Fluid Dynamics Simulation of Fire Spread on Wood Cribs	2019	T.1.1
[104]	Large-scale tunnel fire tests with different types of large droplet fixed fire fighting systems	2019	T.3.1
[62]	Re-direction of smoke flow in inclined tunnel fires	2019	T.1.2
[45]	Experimental studies on the gas temperature and smoke back-layering length of fires in a shallow urban road tunnel with large cross-sectional vertical shafts	2019	T.1.2
[99]	Tunnel Fire Suppression Tests with Water Mist Fire Extinguishing System Containing an Additive	2019	T.3.1
[34]	Science Mapping of Tunnel Fires: A Scientometric Analysis-Based Study	2020	T.1.2
[87]	Analysis of experimental data on the effect of fire source elevation on fire and smoke dynamics and the critical velocity in a tunnel with longitudinal ventilation	2020	T.2.2
[78]	Theoretical and experimental studies on the fire-induced smoke flow in naturally ventilated tunnels with large cross-sectional vertical shafts	2020	T.2.1
[69]	Critical longitudinal ventilation velocity for smoke control in a tunnel induced by two nearby fires of various distances: Experiments and a revisited model	2020	T.1.2

Document	Title	Year	Code
[61]	Experimental approach to suppress smoke diffusion in sloped road tunnels	2020	T.1.2
[101]	Flow fields induced by longitudinal ventilation and water spray system in reduced-scale tunnel fires	2020	T.3.1
[57]	Experimental study of back-layering length and critical velocity in longitudinally ventilated tunnel fire with various rectangular cross-sections	2021	T.1.2
[72]	Experimental investigation on the smoke back-layering length in a branched tunnel fire considering different longitudinal ventilations and fire locations	2021	T.1.3
[58]	Full-scale experimental investigation on smoke spreading and thermal characteristic in a transversely ventilated urban traffic link tunnel	2021	T.1.2
[84]	Experimental and numerical studies on the smoke extraction strategies by longitudinal ventilation with shafts during tunnel fire	2021	T.2.2
[47]	Expanding the FDS Simulation Capabilities to Fire Tunnel Scenarios Through a Novel Multi-scale Model	2021	T.1.1
[59]	Study of the critical velocity of the tunnels using an analytical approach	2021	T.1.2
[93]	The combined effect of a water mist system and longitudinal ventilation on the fire and smoke dynamics in a tunnel	2021	T.3.1
[85]	Influence of longitudinal ventilation on the mass flow rate distribution of fire smoke flow in tunnels	2021	T.2.2
[60]	Study on temperature decay characteristics of fire smoke backflow layer in tunnels with wide-shallow cross-section	2021	T.1.2
[94]	Parametric study of design fires for tunnels with water-based fire suppression systems	2021	T.3.1
[48]	An experimental study on smoke back-layering and critical velocity in tunnel fires with canyon cross wind	2021	T.1.1
[88]	The maximum gas temperature rises beneath the ceiling in a longitudinal ventilated tunnel fire	2021	T.2.2
[75]	Characteristics of fire and smoke in the natural gas cabin of urban underground utility tunnels based on CFD simulations	2021	T.1.3
[70]	An experimental study on the intermittent flame ejecting behavior and critical excess heat release rate of carriage fires in tunnels with longitudinal ventilation	2022	T.1.3
[71]	Smart real-time forecast of transient tunnel fires by a dual-agent deep learning model	2022	T.1.3
[100]	Experimental and numerical study on the flow field of longitudinally ventilated tunnels with water spray system	2022	T.3.1
[80]	A coupled hybrid numerical study of tunnel longitudinal ventilation under fire conditions	2022	T.2.2
[76]	Study on smoke temperature profile in bifurcated tunnel fires with various bifurcation angles under natural ventilation	2022	T.2.1
[107]	Fire tests with automatic sprinklers in an intermediate-scale tunnel	2022	T.3.2
[83]	Critical velocity in point extraction for dual longitudinally ventilated tunnel fire	2022	T.2.2
[77]	Determination of smoke layer thickness using vertical temperature distribution in tunnel fires under natural ventilation	2022	T.2.1
[67]	Experimental investigation of mass loss rate and spatial temperature distribution of the pool fire in tunnel	2022	T.1.2
[52]	Numerical Study of Large-Scale Fire in Makkah's King Abdulaziz Road Tunnel	2022	T.1.1
[79]	The influence of wind on smoke propagation to the lower layer in naturally ventilated tunnels	2022	T.2.1
[53]	Fractal Analysis of Tunnel Structural Damage Caused by High-Temperature and Explosion Impact	2022	T.1.1
[95]	Estimation of the effects of water mist system on the tunnel critical velocity due to smoke cooling	2022	T.3.1

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