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Fire Safety in Metro Systems: Risks, Solutions, and Global Standards

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Abstract: Metro systems play a critical role in the sustainability of urban life. However, emergencies such as fires pose significant threats to both passenger safety and occupational health and safety (OHS) for workers. This study examines 52 metro fire incidents worldwide through statistical and analytical approaches. Findings reveal that 52% of the fires stemmed from electrical faults, 19% from human errors, 15% from technical deficiencies, and 13% from environmental factors.

The research addresses various engineering and administrative solutions for preventing and mitigating fire incidents. Engineering measures include the use of fire-resistant materials, effective ventilation systems, and the integration of innovative detection and suppression technologies. Administrative controls involve emergency planning, regular staff training, and fire drills. Within the framework of OHS, these measures are emphasized as critical for creating a safe environment for both employees and passengers.

Historical and geographical analyses indicate that fire incidents occur more frequently in densely utilized metro networks, underscoring the importance of regional safety standards. The study advocates for the development of global standards and the implementation of localized safety strategies. This comprehensive analysis highlights the need for a holistic approach to fire safety dynamics in metro systems, providing stakeholders with a roadmap for improvement.

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1. Introduction

Fires are among the most destructive and life-threatening hazards, impacting diverse environments from urban structures to industrial facilities. Underground fires, such as those in mining operations, tunnels, and metro systems, pose unique challenges due to confined spaces, limited ventilation, and high temperatures, which exacerbate the spread of smoke and toxic gases (Külekçi & Uçak, 2023). Historical incidents have demonstrated the devastating consequences of such fires, as seen in the Centralia mine fire, which has burned for decades, and urban tunnel fires that disrupt critical transportation networks (Jackson, 2019). The literature highlights that underground fires often require specialized prevention, detection, and response strategies, leveraging technologies like advanced ventilation systems and automated suppression mechanisms (Mao et al., 2022; Tanaka, 2021). Furthermore, lessons from major fire incidents underline the importance of robust risk assessments, early warning systems, and adherence to stringent safety protocols to mitigate the risks associated with these events (Kaya, 2021).

Urban metro systems have become indispensable components of modern city infrastructure, offering efficient, high-capacity alternatives to road traffic, particularly in rapidly growing metropolitan areas. Since the establishment of the London Underground in 1863, the world's first metro system, and Istanbul's Beyoğlu-Karaköy Tunnel in 1875, metro networks have undergone significant expansion, with over 600 metro lines now operating in more than 200 cities across 60 countries (UITP, 2024). These systems play a vital role in reducing traffic congestion, supporting sustainable urban development, and transporting millions of passengers daily.

Despite these advantages, metro environments pose unique safety challenges due to their complex infrastructure and high passenger density. Fire hazards, in particular, represent one of the most critical risks, stemming from factors such as electrical faults, flammable materials, and operational errors (Yılmaz, 2023). Historical incidents like the King’s Cross fire in London (1987), the Daegu Metro fire in South Korea (2003), and the Baku Metro fire in Azerbaijan (1995) illustrate the catastrophic consequences of inadequate fire safety measures, including significant loss of life and extensive infrastructure damage (Jackson, 2019; Li et al., 2020).

This study builds upon the growing body of literature that emphasizes the importance of proactive fire safety strategies in metro systems. It incorporates comprehensive statistical analyses of 52 major metro fire incidents, categorizing root causes into electrical failures, human errors, technical deficiencies, and environmental factors. These findings align with the recognition that electrical faults remain the primary contributor to metro fires, accounting for 52% of the analyzed incidents (Külekçi, 2023).

In addition to examining historical and geographical distributions of fire incidents, this research highlights the need for a multifaceted approach to fire safety. Engineering controls, such as the use of fire-resistant materials and advanced ventilation systems, are critical for mitigating risks. Similarly, administrative measures, including regular staff training, fire drills, and emergency planning, play a crucial role in enhancing both passenger and employee safety (Zhang et al., 2022). The integration of cutting-edge technologies, such as automated detection and suppression systems, further strengthens metro fire safety frameworks (Yang et al., 2021).

By addressing the interplay between occupational health and safety (OHS) considerations and global safety standards, this study aims to provide a comprehensive roadmap for improving fire safety in metro networks. It advocates for the adoption of localized safety strategies informed by global best practices, ensuring that metro systems worldwide can meet the demands of modern urbanization while safeguarding lives and infrastructure.

2. Research and Findings

2.1. Major Metro Fire Incidents:

1969 Beijing Metro Fire: Metro fires have gone down in history as complex and hazardous events that can cause significant loss of life and property over time. The first recorded metro fire occurred on November 11, 1969, in Beijing due to an electrical fault. The fire occurred during peak hours, severely hindering intervention efforts. During this period of metro development in China, the lack of firefighting equipment and emergency protocols emerged as a major issue. (Figure 1)

Figure 1 1969 Beijing Metro Fire (URL 1)

One of the subsequent severe incidents was the **1973 Paris Metro Fire**, which occurred on August 10, 1973, on “Paris Metro Line 5” between Gare de Lyon and Bastille stations. The fire resulted in 10 fatalities and over 50 injuries. The cause was identified as an electrical fault; however, the rapid spread of the fire was attributed to the flammable properties of plastic and synthetic materials used inside the train. This highlighted the consequences of improper material selection. Following the fire, measures were taken to make train materials fire-resistant, improve emergency protocols, and strengthen ventilation and fire suppression systems. (Figure 2)

Figure 2 1973 Paris Metro Fire (URL 2)

After the fire, the French government and the Paris Public Transport Authority (RATP) conducted a comprehensive review of safety standards to improve metro security and developed more robust pre-fire and fire detection systems. This event became a significant milestone in the evolution of metro safety systems worldwide.

The King’s Cross Fire occurred in 1987 at London’s King’s Cross St. Pancras Underground Station, resulting in the deaths of 31 people. The exact cause of the fire was unclear, but it was believed to have originated from an electrical fault in the station's underground sections, particularly in old, poorly maintained escalators. Initially perceived as a small amount of smoke, the fire rapidly escalated into a major blaze due to underground airflows. Following the fire, wooden escalators in the metro were gradually replaced with metal ones. (Figure 3)

Figure 3 King's Cross Fire, 1987 (URL 3)

The Daegu Metro Fire (South Korea, 2003): This fire, which occurred on February 18, 2003, in the Daegu metro, remains one of the largest public transportation disasters in South Korea's history. The fire was caused by the ignition of a bag containing flammable materials. It led to the deaths of 192 people and injuries to 151 others. After the incident, safety standards were raised, and emergency plans were reviewed and improved. (Figure 4)

Figure 4 Daegu Metro Fire, 2003 (URL 4)

The Baku Metro Fire (Azerbaijan, 1995): On October 28, 1995, a fire broke out in a metro car in Baku, resulting in the deaths of 289 people and injuries to many others. The significant loss of life was attributed to inadequate ventilation and the absence of emergency exits. Following the disaster, it was recognized that safety standards in the Baku metro needed to be revisited and improved. (Figure 5)

Figure 5 Baku Metro Fire, 1995 (URL 5)

These events underscore the importance of fire safety in metro systems and emphasize the measures that need to be taken to prevent similar incidents in the future. Each incident offers valuable lessons for improving emergency management and fire safety standards. The fires have had profound impacts on both the safety of individuals and the operation of public transportation systems.

2.2 Statistical Analysis of Metro Fires:

Since 1863, many important metro fires have occurred. Data on some of these incidents have survived to the present day, while others have been lost in the pages of history. This historical accumulation of metro fires constitutes an important source for the development of fire safety measures and understanding of existing risks. In this context, in order to determine the causes of metro fires and to create safer work areas, statistical analyses were performed by selecting 52 cases from the past. These analyses play an important role in revealing critical data such as the source, effects and preventability levels of fires. The selection of these cases was based on various parameters such as the homogeneous distribution of fires around the world, differences in the number of deaths and injuries, the variety of causes of fires, the environmental conditions in which they occurred and the severity of the accident. These criteria were determined in order to ensure that the analyses were more comprehensive and representative.

When the 52 metro fires were examined, the factors causing the fire were classified under four main headings. First, technical faults such as short circuits, overloads and insulation problems in the electrical infrastructure were addressed under the heading of electrical faults. Second, situations resulting from passengers' or personnel's failure to comply with safety procedures, negligence or incorrect behavior were defined as human-induced errors. The third category, technical errors, includes structural or mechanical deficiencies in the design, construction or maintenance processes of metro systems. Finally, events resulting from natural disasters, external interventions and environmental conditions were examined under the heading of environmental effects. This classification provides an important framework for systematically analyzing the causes of metro fires. When the causal distribution of 52 studies is examined, it was determined that 27 were caused by electrical faults, 10 by human errors, 7 by environmental effects and 8 by technical errors. These findings reveal that electrical faults are the most common cause of metro fires, while other factors also have a significant effect. (Figure-6)

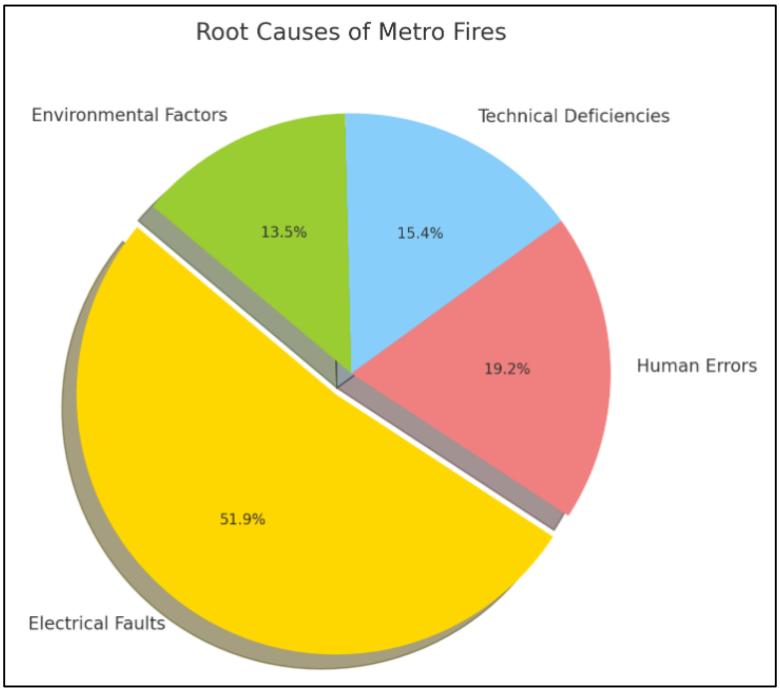

Figure 6: The root causes of metro fires as analyzed

The continuous operation of the electrical infrastructure and the high energy consumption are the main causes of fires in metro systems. Short circuits, inadequate insulation materials and aging infrastructures trigger these problems. As stated in the literature, such failures are usually associated with inadequate maintenance or installations that do not comply with standards (Tanaka, 2021; Külekçi, 2023). For example, the 1995 Baku Metro fire showed the devastating consequences of serious deficiencies in the electrical infrastructure.

Human Errors (19.2%): Almost one-fifth of the fires are caused by human errors, such as non-compliance with safety procedures, prohibited behaviors such as smoking, and incorrect interventions in emergency situations. The human factor is especially evident in regions where the safety culture is inadequate (Smith & Anderson, 2018).

Technical Deficiencies (15.4%): Defects in the design and construction stages increase the risk of fire in metro systems. Inadequate ventilation systems and the use of flammable materials can cause fires to spread more quickly (Wong et al., 2019). The Paris Metro Fire (1973) is an example of the tragic consequences of such deficiencies.

Environmental Factors (13.5%): Natural disasters and external interventions increase the risk of fire, especially depending on geographical features. High temperatures or humidity changes can cause electrical systems to fail (Mao et al., 2022).

Electrical failures; Electrical failures, which are the most common cause with a slice of 52%, constitute 27 of the 52 metro fire cases. *Table-1* provides a chronologically ordered table of 27 electrical failure-related fires. According to the table, fires; Electrical failures are generally caused by short circuits, overloads, insufficient insulation materials, aging electrical infrastructure and lack of maintenance. In particular, the intense energy consumption and continuous use of metro systems create a serious burden on the electrical infrastructure and pave the way for failures. In addition, non-standard arrangements in electrical installations or overheating are among the main triggers of such fires. These factors reveal how important regular control and maintenance of electrical systems are.

Table 1: Chronological Order of Fires Caused by Electrical Faults

Location	Year	Cause of Fire	Death Toll	Injured	Description
Beijing / China	1969	Electric locomotive failure	6	200	Fire caused by a fault in the electric system of the locomotive.
Montreal / Canada	1974	Short circuit	0	0	Fire caused by a short circuit in electrical cables, with no casualties.
Boston / USA	1975	Tunnel lighting line failure	0	0	A small fire caused by a lighting system failure in the metro tunnel.
San Francisco / USA	1979	Short circuit	1	56	Fire due to a short circuit in electrical equipment on the metro line.
Philadelphia / USA	1979	Transformer failure	0	178	Fire caused by a transformer malfunction, resulting in many injuries.
London / UK	1982	Short circuit	0	15	Fire due to a short circuit in the metro’s electrical cables.
Nagoya / Japan	1983	Rectifier failure	3	3	A technical failure in the electric rectifier caused the fire.
Munich / Germany	1983	Circuit failure	0	7	Fire caused by a circuit failure on the metro line.
Zurich / Switzerland	1991	Short circuit in metro locomotive	0	58	Fire due to a short circuit in the locomotive’s electric system.
Taipei / Taiwan	1994	Transformer station fire	0	3	Fire due to a malfunction in the transformer station; minimal damage reported.
Baku / Azerbaijan	1995	Electrical failure	289	270	A severe electrical fault caused a major tragedy in the metro system.
Kyiv / Ukraine	2012	Chandelier line fire	0	0	Fire caused by overloading in lighting system cables.
Moscow / Russia	2013	Short circuit	0	52	Fire due to a short circuit on the metro line, causing multiple injuries.
Washington, D.C. / USA	2015	Electrical failure	1	86	Fire caused by an electric fault at L'Enfant Plaza station; dense smoke led to the station’s closure.
Hong Kong / China	2017	Burning device	0	18	Fire quickly controlled, but passengers were affected by smoke.
London / UK	2017	Short circuit	0	0	Fire at Oxford Circus station caused the station's closure.
Moscow / Russia	2017	Short circuit	0	0	Fire on the platform, with successful evacuations carried out.
Tehran / Iran	2018	Transformer overload	0	0	Fire caused by an overload in the transformer.
Cairo / Egypt	2019	Electrical infrastructure issues	10	100+	Fires due to outdated systems and lack of maintenance caused casualties.
Shanghai / China	2019	Short circuit	0	7	Fire quickly controlled; seven people sustained minor injuries.
Mexico City / Mexico	2020	Electrical failure	26	70+	Damage from the fire led to a later structural collapse.
New York / USA	2022	Electrical failure	0	5	Fire caused by an electrical fault; five people suffered minor smoke inhalation.
Barcelona / Spain	2023	Battery failure	0	8	Fire due to a battery fault; quickly brought under control.
Seoul / South Korea	2023	Electrical failure	0	0	Fire occurred at Daechi Station; passengers affected by smoke.
Seoul / South Korea	2024	Battery failure	0	18	Fire caused by a maintenance train's battery.
Istanbul / Turkey	2024	Electrical failure	0	0	Evacuations conducted promptly; no casualties reported.
Mumbai / India	2024	Electrical failure	0	0	Fire occurred during the station's construction phase.

Nearly one-fifth of metro fires result from human errors, including failure to comply with safety procedures, prohibited behaviors like smoking, and incorrect interventions during emergencies. The human factor is especially prominent in regions with insufficient safety cultures (Smith & Anderson, 2018). Human error-related fires constitute 10 out of the 52 cases analyzed, making up 19.2% of the total. *Table 2* provides a chronological listing of these incidents. These errors stem from non-compliance with safety protocols, carelessness, misuse, or negligence. In particular, incorrect actions during emergencies, misuse of safety equipment, and lack of training among operating personnel increase fire risks. Additionally, user behaviors like smoking in prohibited areas or using devices that could ignite fires are among the leading causes of human-induced incidents. These findings underscore the critical importance of enhancing education and safety awareness to reduce fire risks.

Table 2: Chronological List of Fires Caused by Human Errors

Location	Year	Cause of Fire	Death Toll	Injured	Description
Cologne / Germany	1978	Cigarette butts	0	8	Fire caused by cigarette butts, injuring some passengers.
New York / USA	1979	Cigarette butts	0	4	Fire caused by passengers smoking in the metro.
London / UK	1980	Cigarette butts	2	0	Fire started due to passengers smoking.
Bonn / Germany	1981	Staff operation error	0	0	Fire caused by staff error, with no injuries reported.
London / UK	1984	Warehouse fire	0	18	Fire broke out in a storage area due to staff error.
Paris / France	1985	Burning trash	0	6	Fire caused by burning trash inside the metro.
Daegu / South Korea	2003	Arson in metro train	192	151	Fire started after a bag was set on fire and exploded inside the metro.
Nanjing / China	2014	Flammable material brought by passenger	0	0	Small fire caused by flammable material brought by a passenger.
Hong Kong / China	2017	Burning liquid substance	0	19	Fire started after a flammable liquid was brought into the metro.
New York City / USA	2023	Burning trash	0	0	Fire caused by burning trash led to several hours of service disruption but no injuries.

Design and construction flaws significantly increase fire risks in metro systems. Inadequate ventilation systems and the use of flammable materials can cause fires to spread more rapidly (Wong et al., 2019). The **1973 Paris Metro Fire** is a tragic example of the consequences of such deficiencies.

Technical deficiencies account for 8 of the 52 analyzed incidents, representing 15.4%. *Table 3* lists these incidents chronologically. These issues typically arise from flaws in the design, construction, or maintenance processes of metro systems. Structural failures, use of materials not compliant with fire safety standards, inadequate ventilation systems, and incorrect placement of fire barriers contribute to the spread of fires. Preventing technical deficiencies requires regular maintenance and updates to metro systems, as well as meticulous implementation of fire safety measures at every stage.

Table 3: Chronological List of Fires Caused by Technical Deficiencies)

Location	Year	Cause of Fire	Death Toll	Injured	Description
Paris / France	1979	Metro car fire	0	26	Fire in a metro car caused injuries and significant material damage.
Lisbon / Portugal	1976	Locomotive malfunction	0	0	Minor fire caused by a locomotive malfunction, no casualties reported.
Tokyo / Japan	1985	Locomotive bearing failure	0	0	Mechanical wear in locomotive bearings caused a fire with no major consequences.
London / UK	1987	Technical malfunction	32	Over 100	A major fire caused by technical failure led to significant casualties and injuries.
Tokyo / Japan	2016	Flammable material in ventilation	0	0	A small fire occurred in the metro ventilation system, causing no significant damage.
Hyderabad / India	2019	Welding sparks	0	0	Fire caused by welding sparks during maintenance work inside the metro.
Delhi / India	2021	Welding sparks	0	0	Welding sparks triggered a fire during metro construction work.
Mexico	2021	Train collision on metro line	1	Many injured	Two metro trains collided due to driver error and signaling failure, causing multiple injuries.

Environmental factors, the least common cause of metro fires, account for 7 of the 52 incidents analyzed, representing 13.5%. These fires often result from natural disasters (e.g., floods, earthquakes) or external interferences (e.g., sabotage, terrorist attacks). Additionally, environmental conditions such as extreme temperatures, changes in humidity, or adverse weather conditions can place additional stress on electrical systems, leading to failures. Environmental factors increase risks, especially in open sections of metro systems. These conditions can affect the speed and severity of fire spread. To mitigate such risks, metro systems must be designed to withstand environmental conditions, emergency plans must be diversified, and environmental risks must be anticipated to implement necessary measures proactively. *(Table 4)*

Table 4: Chronological List of Fires Caused by Environmental Factors

Location	Year	Cause of Fire	Death Toll	Injured	Description
Paris / France	1973	Arson	2	0	Fire caused major damage to the metro line but resulted in minimal loss of life.
Toronto / Canada	1976	Arson	1	0	Fire caused limited damage, with no injuries reported.
Berlin / Germany	1991	Arson	0	18	Arson caused significant material damage, injuring 18 people.
Hong Kong / China	2004	Car Arson	0	14	Fire from car arson injured 14 people.
Shanghai / China	2016	Adjacent Shop Fire	0	0	A fire in a shop next to the metro line caused no major damage to the metro system.
Mexico City / Mexico	2021	Fire in Adjacent Building	1 (Firefighter)	Many Injured	Fire in the metro's electrical station led to casualties and injuries.
Quetta / Pakistan	2022	Terror Attack	27	62	A bombing incident caused a major fire, resulting in significant casualties and injuries.

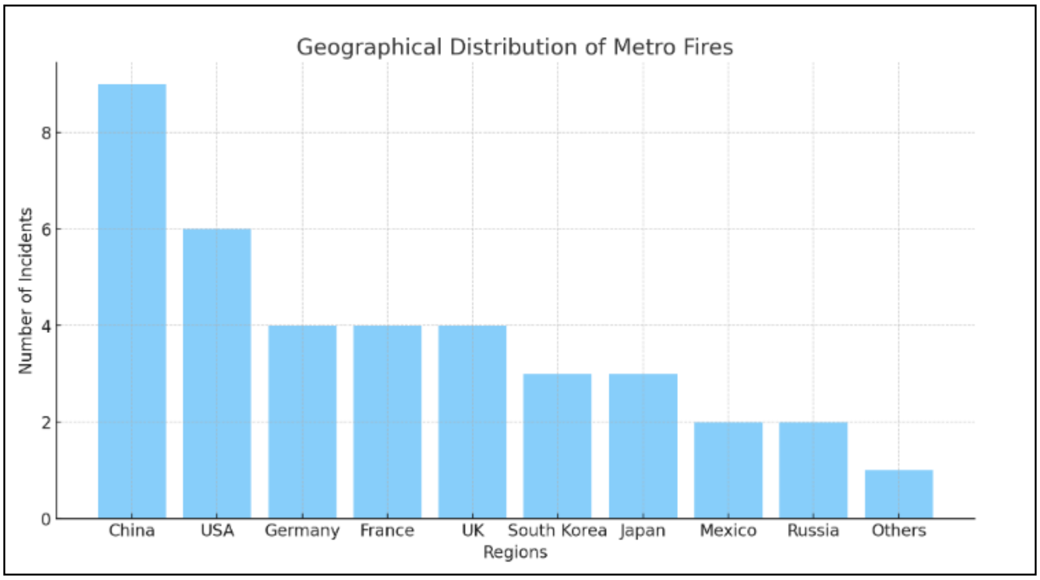

Figure 7: The number of incidents in different regions

Figure 7 demonstrates the geographic distribution of metro fire incidents, revealing significant regional variations: China leads with 9 incidents, followed by the United States with 6. Germany, France, and the United Kingdom each report 4 incidents, reflecting the historical development and high utilization rates of their metro systems. Countries like South Korea and Japan have 3 incidents each, while Mexico and Russia have 2. Other regions, including Turkey, Egypt, Saudi Arabia, and South Africa, report a single incident. This distribution correlates with the intensity of metro network usage and infrastructure conditions in these regions. Heavily urbanized areas with older metro systems face higher risks due to aging infrastructure, increased passenger loads, and operational complexities (Külekçi & Uçak, 2023). The relatively low number of incidents in less urbanized areas may reflect reduced metro usage but could also indicate underreporting or a lack of robust incident documentation. The geographic trends highlight the need for:

Region-specific safety standards: Countries with extensive metro systems must prioritize modernizing infrastructure and enforcing rigorous safety protocols (Mao et al., 2022). Risk mitigation in growing networks: Emerging metro systems in developing regions should incorporate best practices from highly utilized networks to preemptively address risks (Smith & Anderson, 2018).

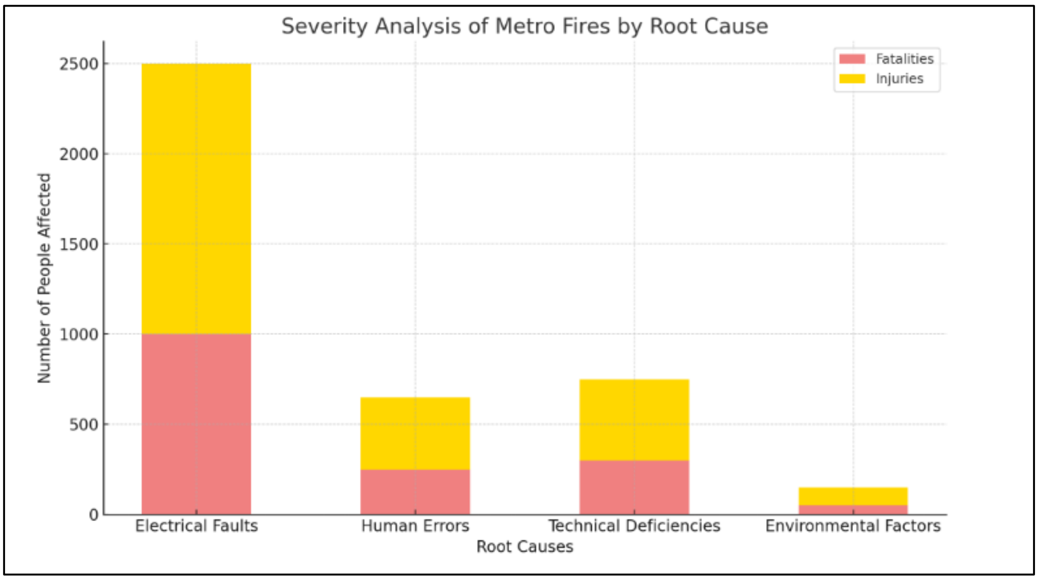

Figure 8: The timeline of fire incidents caused by electrical faults

Figure 8 provides a chronological analysis of fires caused by electrical faults, revealing critical trends, Electrical Faults as a Dominant Cause: These fires result in the highest fatalities and injuries, underscoring their criticality. This is consistent with global findings, where electrical faults, including short circuits and insulation failures, dominate fire incident statistics (Tanaka, 2021). Severity of Outcomes: The high casualty rates linked to electrical faults emphasize the need for advanced monitoring systems and predictive maintenance to identify vulnerabilities before incidents occur. The data supports the following interpretations:

Aging Infrastructure as a Key Risk Factor: Older metro systems face compounded risks due to worn-out electrical components and inadequate maintenance (Wong et al., 2019). Need for Proactive Measures: Regular electrical audits, compliance with international safety standards (e.g., NFPA 130), and modernization projects are essential to mitigate these risks (Liu, 2020). Global Best Practices: Examples from advanced systems, such as automated fault detection in Japan and South Korea, demonstrate the effectiveness of technological interventions in reducing fire risks (Yang et al., 2021). The findings from both figures collectively underscore the importance of regional and technical considerations in improving metro fire safety. Risk mitigation strategies should align with the unique challenges faced by each region, such as high passenger density in urban areas or outdated systems in older networks. Addressing electrical infrastructure vulnerabilities is crucial to reducing the prevalence and severity of incidents.

Figures 7 and 8 illustrate the multifaceted nature of metro fire risks, spanning geographic disparities and technical deficiencies. By adopting targeted regional strategies and prioritizing infrastructure modernization, stakeholders can significantly enhance safety outcomes. These findings align with broader safety literature, advocating for a proactive, data-driven approach to metro fire prevention and management.

2.3. Geographic Distribution of Metro Fires:

In addition to all these findings, the geographic distribution of fires has been examined to conduct a risk analysis in terms of occupational health and safety (OHS) and to consider regional differences. The examination of geographic distribution reveals how factors such as infrastructure, environmental conditions, safety culture, and local government fire safety measures affect the frequency and severity of fire incidents. These data enable the development of fire safety strategies tailored to local characteristics within the OHS framework, facilitate the more effective implementation of preventive measures, and allow for the proper allocation of resources. *(Figure 9)*

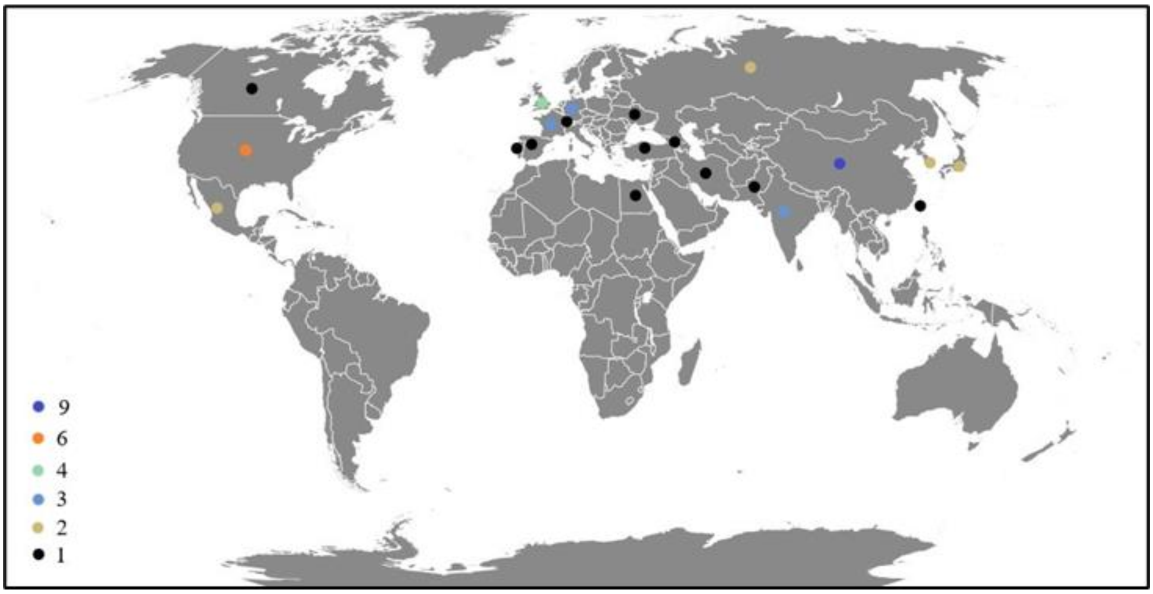

Figure 9: Geographic Distribution of Metro Fires

When the distribution of metro fires is analyzed, it becomes evident that 9 out of 52 fires occurred in China. The United States follows with 6 fires, while Germany, France, and the United Kingdom each recorded 4 fires. Additionally, South Korea and Japan experienced 3 fires each, whereas Mexico and Russia reported 2 fires each. Countries such as Turkey, Egypt, Saudi Arabia, and South Africa recorded only one metro fire each, representing lower rates. *(Figure 9)*

These data demonstrate the impact of factors such as metro system usage intensity, infrastructure characteristics, and geographical differences on safety risks. The concentration of incidents in metro networks in

Europe and Asia is particularly associated with the high passenger traffic, infrastructure deficiencies, insufficient maintenance practices, and regional differences in safety standards in these areas. The intense use of metro networks in developed countries and their complex structures emerge as additional factors increasing risks. The size of metro systems and their reliance on technology necessitate regular maintenance and high safety standards, and neglecting these requirements contributes to the frequency of accidents.

3. Fire Prevention and Safety Systems in Metro Networks:

From an occupational health and safety (OHS) perspective, these findings highlight the importance of implementing comprehensive safety measures in metro lines with intensive usage and advanced infrastructure. In particular, the high passenger capacity of metro systems in developed countries necessitates more detailed risk analyses and the application of preventive measures based on these analyses. Comprehensive risk analyses, considering regional differences, play a critical role in developing effective measures, continuously improving OHS standards, reducing accidents, and making public transportation safer. In this context, based on statistics from metro fire incidents, the necessary precautions and measures in terms of occupational health and safety have been examined in the literature. Fire safety in metro systems has been evaluated under five key headings aimed at ensuring passenger safety and enhancing operational efficiency.

3.1. Engineering Controls:

Engineering controls used to ensure fire safety in metro systems are closely related to the selection and application of fire-resistant materials. For instance, the use of materials like ceramic insulation, aerogel insulation, and intumescent fire-resistant coatings, instead of traditional materials in the flooring systems of rail vehicles, effectively raises safety standards. These materials not only provide fire protection but also enhance passenger safety and the sustainability of the infrastructure. The alignment of fire-resistant material applications with international safety standards (e.g., NFPA 130) is a critical step in strengthening both the safety and resilience of metro systems. (Liu, 2020)

3.2. Ventilation Systems:

The control of smoke and toxic gases produced during a fire in metro systems can be achieved through an effective ventilation system. Critical components of smoke evacuation systems, such as jet fans and ceiling exhaust systems, are activated quickly and efficiently during a fire, facilitating passenger evacuation and preventing the fire from spreading (Wong et al., 2019). Additionally, innovative technologies like stratified ventilation show significant potential for improving air quality within metro cars. These technologies not only enhance fire safety but also contribute to passenger safety during emergencies such as pandemics. The proper design and optimization of ventilation system timing play a fundamental role in improving the safety of metro systems (Mao et al., 2022).

3.3. Administrative Controls:

Administrative controls aim to enhance the effectiveness of fire response processes. Regular review of emergency response plans in metro systems enables faster and more efficient solutions for potential fire scenarios. Additionally, regular staff training and fire drills help reduce errors stemming from human factors during emergencies, thereby ensuring passenger safety (Zhang et al., 2022). Simulation-based studies for emergency scenarios facilitate the more efficient use of resources and minimize fire response times, reducing economic losses and fatalities.

3.4. Fire Detection and Suppression Systems:

The early detection of metro fires is critically important for effective intervention. Fire detection systems, utilizing sensors and automation technologies, can swiftly detect smoke, heat, and flames, triggering alarm systems (Yang et al., 2021). These early warning mechanisms provide valuable time for controlling the fire, while suppression systems play a vital role in preventing its spread. Advanced suppression systems not only physically control the fire but also enable the safe evacuation of passengers. The integration of intelligent systems has opened new horizons in fire safety, allowing for predictive maintenance processes based on data analysis. Artificial intelligence-based systems process real-time data from sensors to foresee risky situations and automatically activate emergency plans. This capability ensures rapid and accurate critical decision-making without requiring human intervention.

When evaluated under these headings, fire safety in metro systems can be achieved through a combination of engineering and administrative approaches, alongside the integration of smart technologies. Technological advancements, intelligent systems, and proactive safety protocols not only enhance passenger safety but also support the long-term sustainability of public transportation systems. Smart fire detection and suppression systems play a vital role not only in immediate interventions but also in optimizing infrastructure management by improving the overall safety performance of systems.

3.5. Innovative Training:

Simulation and gamification represent innovative approaches to fire safety training in metro systems. Simulation technologies realistically model emergency scenarios, enabling both personnel and passengers to learn how to respond during a fire (Kırtaş & Altundağ, 2020). The use of gamification elements in this process increases participants' interest in the training, making the learning process more effective and sustainable. Virtual reality (VR)-based simulations, in particular, provide an opportunity to safely experience risks during a fire, aiding in the development of decision-making and reflexes under stress (Uluç, 2022). Integrating such technologies into training programs not only optimizes fire response processes but also strengthens the overall safety culture within public transportation systems (Qui et al., 2020).

Based on the findings, it is critically important to implement necessary measures for fire prevention and safety systems in metro networks within the framework of occupational health and safety. To minimize fire risks and enhance passenger safety, it is essential to integrate engineering and administrative controls with advanced fire detection and suppression systems. Studies in the literature demonstrate that these measures form a functional safety network for early detection and effective intervention of fires. In this context, the need for improving fire prevention and safety strategies in metro systems is clearly highlighted.

4. Conclusion:

In light of the findings presented in this study, it is evident that fire safety in metro systems is not merely a technical challenge but also a critical occupational health and safety (OHS) concern. The analysis of 52 metro fire incidents highlights the multifaceted nature of fire risks driven by electrical faults, human errors, aging infrastructure, and environmental factors. These risks are exacerbated in older metro systems that lack modern safety protocols. The study underscores the necessity of integrating advanced engineering solutions, administrative controls, and comprehensive safety systems to mitigate fire hazards. Effective fire prevention strategies, such as the use of fire-resistant materials, robust ventilation systems, and advanced detection technologies, play an indispensable role in reducing the impact of fires. Administrative controls, including stringent personnel training and emergency response planning, complement these technical measures by ensuring coordinated and effective interventions during fire incidents.

Moreover, geographical analysis emphasizes the need for tailored fire safety strategies that address regional infrastructure and operational challenges. This highlights the importance of developing localized risk assessments and region-specific safety protocols.

The contribution of this study lies in its holistic approach to understanding metro fire dynamics and its emphasis on protecting both passengers and employees. By advocating for a proactive stance in improving metro system safety standards, the study ensures that both existing and future metro networks are equipped to manage fire risks effectively. By prioritizing occupational health considerations within fire management strategies, stakeholders can achieve a safer and more resilient urban transportation system.

This research provides policymakers, safety experts, and metro operators with a foundation to enhance their approaches to fire safety and establish a global standard that aligns with the evolving demands of urban transportation networks.

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