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Metro systems: Construction, operation and impacts

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ABSTRACT

Metro systems have been in use for over 150 years, and new metro lines are still being constructed, either as new metro systems or as expansions of existing metro networks. In many cities the metro system is an essential form of transport to keep the cities functioning. This overview compares the findings of various international studies on metro construction and operation, and the impact that metro systems have on cities. The uncertainties inherent in underground construction, with sometimes uncertain hydro-geological conditions and impacts from nearby existing construction projects, are often apparent during metro construction, and have been widely studied. Similarly, passenger comfort and safety during operation is a topic that has received widespread attention, with the main focus on fire safety, as fire poses the most dangerous risk during operation. More recently, passenger comfort related to indoor air quality and aerodynamic effects has received increased attention. The vulnerability of the running stock and the metro network is a significant factor when determining the safety and efficiency of the metro system. Metro efficiency and reliability have a major impact on the transport, economic, environmental and social aspects of cities. Even though they are designed as separated own-right-of-way transport systems, metro systems strongly influence urban development and drive spatial changes in land use. The combination of metro systems with other urban functions provides great potential for the development of urban underground space and the development of more resilient and efficient urban areas. This in turn has an impact on housing prices and produces wider economic benefits beyond the city. Metro systems have also been shown to affect travel behaviour and have a positive impact on public health and environmental quality, by reducing pollution and emissions, despite the large concentration of passengers present in the metro, which brings its own problems. After an overview of the leading and more recent research topics in these areas, the key research gaps are discussed and recommendations for future research are made.

1. Introduction

The contribution of underground space utilisation to urban development has been confirmed by many studies. As a major form of underground space utilisation, the impacts of metro systems on social, economic and environmental development have attracted attention from researchers, practitioners, and decision-makers (Bobylev, 2016; Broere, 2016; Cui et al., 2021; Lin et al., 2022a, b; Peng et al., 2021; Qiao et al., 2022a, b, c; ITA Working Group on Costs-benefits of Underground Urban Public Transportation, 1987; ITA Working Group Number 13, 2004; Sterling, 1997; Sterling and Nelson, 2013). Metro systems (also referred to as subways or underground railways), as high-capacity urban rail systems that mainly operate in exclusive right-of-way corridors, play an important role in improving the efficiency of urban transport systems and people's mobility. It provides large numbers of people with an affordable, convenient, fast and reliable travel option for daily trips. Characterised by high speed, high capacity, and a high level of safety, metro systems have filled people's mobility needs in an economically and ecologically efficient way for more than a century and a half. Metro can bring benefits to many aspects of cities, helping to solve transport and environmental issues. The need to construct metro infrastructure with its own right-of-way corridors, and the difficulty in finding the required space in existing urban regions, more or less naturally means that most metro systems were and still are constructed underground in tunnels.

Considerable investment in metro systems in the past twenty years has resulted in an extremely rapid pace of metro construction and operation, with large numbers of passengers being transported by metro every day. Worldwide, there were about 168 million people transported by metro systems per day in 2017 (UITP, 2018). In major cities like Hong Kong and London, the share of trips made by metro in the total of daily trips made by public transport reached 35–41% (Transport Department,

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The Government of the Hong Kong SAR, 2020; Transport for London, 2020). Metro transport is often more reliable and faster than bus transport, with the result that a large proportion of long trips by public transport are metro trips, particularly in mega cities with high density and traffic congestion (Zhao and Li 2017). The development of metro systems has broad impacts on the environmental, economic and social development of cities. In the past two decades, with the rapid expansion of the systems, there also has been extensive research on metro construction, operational safety and the impacts of metro on urban developments. This paper presents a comprehensive overview of research on metro systems, with a focus on these aspects.

In contrast to conventional construction projects (e.g., residential and commercial buildings, industrial facilities, bridges, and highways), metro construction projects commonly have the characteristics of high cost, multiple stakeholders, and lengthy delivery times (Ding et al., 2013). As metro is primarily an underground transport system, its construction involves a high degree of technological complexity. Scores of construction methods have been developed, promoted, and utilised in different metro projects around the world (Cardu and Seccatore, 2016; Fang et al., 2012; Huang et al., 2018; Rehman et al., 2020; Tatiya, 2005). As most construction tasks in metro infrastructure are conducted below the ground (Wood, 2000; Zhou et al., 2022b), and underground construction is constrained by adjacent environments such as hydrogeological conditions and existing facilities, such as buildings, roads, pipelines, and existing metro systems, there is a high uncertainty inherent in these construction projects. This translates not only in larger construction and financial risks, but also increases the risk of fatal and non-fatal accidents on site. Therefore, metro construction is deemed to be far more hazardous than other types of construction projects (Sousa and Einstein, 2012; Zhang et al., 2021). Accidents resulting in fatalities and injuries have occurred frequently at construction sites throughout the history of metro development. Many deaths and injuries and considerable economic loss have resulted from these serious accidents (Ding et al., 2013; Zhou et al., 2019a).

The fact that metro systems are developed primarily in denser urban areas, after the initial urban development has been well established, creates its own boundary conditions and challenges. Metro construction almost always has to consider the existing urban framework and the design of metro stations and tunnels, as well as their construction, will be constrained by adjacent facilities, especially for projects in downtown areas (Wang and Chen, 2017; Zhou and Irizarry, 2016). During construction there will be a significant negative impact on adjacent facilities and environments, attracting extensive attention from both industry and academia (Berkelaar et al., 2007; Ding et al., 2012; Nishibayashi and Nagashima, 1998; Jiang et al., 2020). However, the long-term benefits of metro after construction has been completed were not considered for the period of metro construction.

Safety and comfort have also attracted much research interest since the rail transit system grew to be the most significant form of public transport in people's daily lives. Adequate procedures for fire prevention, personnel evacuation, aerodynamic safety and air quality can help prevent risk to the lives and health of passengers. An underground metro station fire can cause catastrophic damage in terms of fatalities and economic loss. Numerous accidents in the past provide stark illustrations of this. For instance, in October 1995, a disastrous fire in the subway of Baku Azerbaijan killed 289 passengers and injured 265 passengers (Hedefalk et al., 1998). Hundreds of people died in the most recent mass-casualty metro fire at Daegu's Jungangno Metro station (Li et al., 2022c). Metro stations concentrate a large number of people, and the consequences of uncontrolled fire are unimaginable. Once a fire occurs in a metro system, passengers should evacuate to the outside. Therefore, at metro stations, where unanticipated mishaps could result in injury and death, personnel evacuation is a crucial issue. Studies on metro evacuation have primarily concentrated on identifying the variables that affect evacuation and developing prediction modelling techniques. To increase evacuation effectiveness and safety, some recent studies concentrate on metro station evacuation optimisation.

Usually, the operating speed of most metro trains does not exceed 100 km/h. But with the emergence of high-speed urban rail transit, more and more metro trains are operating at speeds of over 100 km/h, and up to 160 km/h, as in cities such as Guangzhou, Chengdu, and Chongqing. This speed increase will also lead to more pronounced aerodynamic effects during metro operation. When trains pass through tunnels, a variety of aerodynamic issues arise, including pressure waves, complex slipstreams, aerodynamic drag, piston effects, micro-pressure waves near tunnel exits, several of which will result in passenger discomfort. In sharp contrast with the effects on high-speed rail lines, Liu et al. (2022a) found that metro systems produce more serious aerodynamic effects because of the blunt-head design of metro trains, while the doors on metro trains are not airtight. These metro system characteristics may aggravate passenger discomfort. Metro-train-induced aerodynamic problems (primarily piston wind and pressure waves) have received attention in recent years, as metro systems have evolved and running speeds have increased.

The expansion of large metropolitan metro networks has led to an exponential growth in the number of passengers using this efficient form of transport. Recent studies measured air quality to study characteristic exposure of users to particulate matter (PM) mass concentrations and chemical components in various transport modes (Martins et al., 2021). Compared with other types of transport, subways were found to have the greatest level of PMs. So, air quality in metro systems has become an area of focus that has attracted numerous researchers recently, and now also includes studies that model the spread of other hazardous materials or air-borne pathogens within these closed environments.

System reliability is a critical feature which is of great interest to logisticians, engineers, managers, and passengers (Lu et al., 2011). Metro reliability is highly valued by everyday users, as unreliability has adverse consequences, such as poor transfer connections, unpredictable waiting times, and potential penalties due to arriving at work late (Chakrabarti and Giuliano, 2015). Overcoming vulnerability is an essential attribute for the safe and productive operation of urban metro systems. There is significant interest among researchers in implementing vulnerability assessments of metro operation systems.

A well-functioning metro influences urban development in many ways, such as increasing housing and land prices, bringing about urban spatial changes, enhancing labour force mobility, reducing air pollution, improving public health, and promoting utilisation of underground space to enable intensive use of land. Metro transport fulfils the mobility needs of passengers, and enhances neighbourhood accessibility to many places, such as workplaces, homes and shopping destinations for a variety of activities, yielding beneficial social, economic and health outcomes (Ahn et al., 2020), and increases local job and population densities that help expand local retail markets. Amenities provided by public investment interact with amenities provided by the private sector, and together they form spatial structures in cities and positively affect quality of life (Zheng et al., 2016b). At the neighbourhood scale, metro accessibility is essential for maintaining urban spatial environments that are economically viable, functionally efficient, and socially equitable (Guan and Peiser, 2018).

This paper provides a comprehensive overview of metro systems from the perspectives of metro construction, operation as well as the impacts on urban development. After introducing the key concepts of metro systems, and the main factors associated with metro development, the paper provides an overview of key considerations in metro construction, operation and impacts. For each aspect, the overview explores the current research directions and key findings. The overview then discusses key research gaps and provides recommendations for future research. However, it is acknowledged that some topics and areas of metro related research, such as metro planning, design and architecture, vehicle scheduling, or passenger flow, have not been covered in this paper due to the scope of the journal, and the limited number of available studies on these specific topics.

2. Construction of metro systems

2.1. Metro construction methods

There are multiple construction methods available for developing metro projects, such as the open-cut method, shield tunnelling method, new Austrian tunnelling method, shallow tunnelling method, and drill and blast method (Tatiya, 2005; Wood, 2000). The open-cut method, also named the cut-and-cover technique, is the traditional approach to metro construction (Nguyen et al., 2019) and was extensively employed in the early years of metro development. Excavation equipment is employed to dig a long trench where the metro tunnel is constructed and later covered by soil again. In early years brick-and-mortar tunnels were common, whereas concrete construction is almost exclusively used at present. A variant is top-down construction, where the (concrete) top deck is placed early on, before the full tunnel construction is completed, and once the deck is in place, activities on the surface are no longer influenced while underground construction tasks continue. The open-cut technique is usually adopted if excavation is possible and economical from the surface, and environmentally acceptable (Onsarigo and Adamtey, 2020). This method is advantageous because of its convenience, speed, safety, and cost-effectiveness, with minimal environmental impact. However, it can cause site congestion, pollution, noise and traffic disruption, and is weather-dependent.

As a highly mechanised construction technique, the shield tunnelling method is widely adopted for metro construction around the world (Huang et al., 2018; Koyama, 2003). This technique involves a shield in the front of which there is a rotating cutting head. Simultaneously, the shield acts as a temporary structure with the ability to support and stabilise the surrounding soil and structure (Maidl et al., 2013). Compared with other metro construction methods, shield tunnelling is safer with a high degree of efficiency. Nevertheless, tunnelling productivity using a shield is substantially dependent on adjacent geological conditions, hydrology, stratigraphic texture, existing structures, and other environmental factors (Maidl et al., 2013; Zhou et al., 2019a). In contrast to the method of open-cut excavation, shield tunnelling has far more limited impact because tunnelling works are conducted on the surface, and this method is widely adopted for constructing most running tunnels for new metro lines.

Another technique for metro construction is the New Austrian Tunnelling Method (NATM) (Karakuş and Fowell, 2004) or related sprayed-concrete-lining methods. It refers a combination of stepwise partial excavation, monitoring and control to optimise the use of wall and roof construction material according to the category of rock encountered during tunnelling (Guo et al., 2019). One significant principle of NATM is the utilisation of adjacent rocks to act as an integral part of the supporting structure system. This method is very appropriate for ground with a high degree of stability and a relatively low level of underground water pressure (Rehman et al., 2020; Shang et al., 2014). NATM, commonly used in underground projects like tunnels and urban subways, necessitates monitoring the dynamic deformation of surrounding rock and the stress state of support structures to ensure construction safety and quality. Rapid digitalisation using integrating technologies like big data, Internet of Things, and cloud computing, is likely to increase usage of this method.

Tunnelling in shallow ground conditions with soft soils is significantly different from that with solid and stable rock, despite the fact the construction methods deployed for the two hydro-geological conditions can be more or less the same (Cao et al., 2018; Fang et al., 2012). The stability of the soil is often lower and free-flowing water more present, requiring more direct mechanical support to keep the soil stable and the groundwater out. Therefore, the term, “shallow tunnelling method”, was assigned by China’s Ministry of Housing and Urban-Rural Development, to differentiate it from NATM (Fang et al., 2012), although many construction principles overlap and slight variations with different names do exist in other countries (Sadaghiani and Dadizadeh, 2010). This method incorporates the principles of the NATM and adopts multiple auxiliary techniques to activate the self-supporting capacity of the soil or rock. The shallow tunnelling method pays extensive attention to timely support for the avoidance of collapse events, and focuses on dynamic optimisation of the initial design through monitoring and feedback. This method has been primarily employed in China and Iran for metro construction in downtown areas with dense buildings or other structures.

Within hard rock conditions, drill and blast is a traditional alternative for constructing tunnels and caverns. This technique utilises explosives for blasting rock for tunnelling excavation (Gokhale et al., 2010). As the name suggests, the method of drill and blast is carried out by firstly developing a pattern of blasting and drilling holes into the rock. These holes are filled with a suitable quantity of explosives and detonated, bringing about the fracture of rock. When needed, the new tunnel surface is reinforced with steel or concrete construction. Lastly, these steps are repeated until the excavation goal is achieved (Cardu and Seccatore, 2016; Niu et al., 2022). This method is limited to hard rock, and as such often not suitable at shallow depth in urban areas due to soil conditions, although notable examples such as Helsinki exist where it has been extensively employed.

Table 1 compares the construction methods for metro systems, by description/feature, common usage scenarios, advantages, and disadvantages.

2.2. Construction safety

Metro construction projects, which are inherently more hazardous than general construction projects, are particularly susceptible to hydrogeological conditions due to their underground nature, increasing the level of uncertainty and safety risks. Studies on construction safety specifically for metro tunnels have focused on two perspectives. The first is an engineering technology perspective, which concentrates on stress or deformation analysis of the structural components and on soil displacements (Gendler and Ryzhova, 2020). Significant parameters are identified for continuous monitoring, with the objective of controlling risk and ensuring structural safety during metro construction whilst optimising the design (Sun et al., 2012; Vogiatzis et al., 2018). Some researchers conducted more detailed risk analysis and control analysis at specific metro tunnels or station projects, such as the Athens metro TBM tunnel (Costopoulos, 2004) and Porto metro (Sousa and Einstein, 2012) to explicitly determine the major risk factors. This research stream primarily elucidates individual or multiple engineering challenges in the metro construction process. Advancements in technology can have a direct influence on the constructability and overarching safety of metro projects. Furthermore, with the ongoing evolution of technologies such as artificial intelligence, digital twin, cloud computing, and the Internet of Things, it is expected that these technologies will be used to address intricate metro engineering issues.

The second perspective focuses on the identification and managing of safety risks using automated identification, analysis, evaluation, and control. Recently, the use of machine learning (ML) approaches has increased here. Based on multiple sources of information about monitoring parameters, visual inspections and design estimates at metro construction sites, a data fusion model was deployed for automatically assessing safety risks and providing site managers with early warnings by Ding and Zhou (2013) as an example. Using drawings from construction sites, Ding et al. (2012) proposed a model for determining safety risks in metro construction, and different recognition algorithms were adopted for setting technical parameters. Because safety information from various stakeholders can result in inconsistency, a model based on ontology (Xing et al., 2019) was developed for safety knowledge standardisation in metro construction. The model can provide guidance for risk identification. A variety of methods and theories (e.g., probability theory (Zhang et al., 2014), Bayesian network (Wang and Chen, 2017), and complex network (Zhou and Irizarry, 2016)) were adopted for the analysis of risks in metro construction. To obtain

Table 1
Comparison of common metro construction methods.

Method	Open-cut method	Shield tunnelling method	New Austrian tunnelling method	Shallow tunnelling method	Drill and blast method
Description / Feature	Downward excavation and then upward construction, followed by filling or restoration	Excavation and propulsion using shield machines	Focus on the self-supporting of rocks and the spatial constraint of excavation surfaces	Focus on support and reinforcement	Uses drilling and blasting
Common usage scenarios	Less densely built areas	Soft soil ground or ground with high water content	Relatively stable ground with low water pressure	Soft ground	Widely applicable
Advantages	Simple operation, guaranteed quality, fast progress, and low risk	Good concealment, fast progress, and relatively high safety	No or less ground interference and relatively small investment	No or less ground interference, relatively small investment, and flexible structure	Low-cost, simple equipment, and fast progress
Disadvantages	Considerable impact on the surrounding environment, underground pipelines, and traffic	High cost, poor adaptability, and complex operation	High labour demand and high risk	Slow progress, high labour demand, and low-level mechanization	Large disturbance to the stratum, poor quality of excavation, and low safety

adequate data for risk analysis, Ma et al. (2013) developed a data warehouse to store heterogeneous data about geotechnical instrumentation to enable better analysis of construction safety risks in metro projects. However, because of the unique characteristics of each metro project, hydrological and geological conditions may be totally different across various metro construction projects, and the applicability of a trained ML model from one project for the next project may be limited, and for some aspects even conditions within a single project may change to such an extent that the applicability within one project is limited (Erharter and Marcher, 2021).

Once the initial steps of risk identification and risk analysis are complete, risk evaluation in metro construction can be undertaken. A risk evaluation framework for metro construction was proposed through integration with credal networks, which was characterised as an expansion of Bayesian belief networks with an enhanced assessment method (Hou et al., 2021). This framework was validated through assessing safety risks at a Chinese metro construction site. An analytic network process and extension of cloud models were utilised to evaluate the resilience of safety management systems at metro construction sites by Guo et al. (2020). Safety competency of construction workers involves three factors: perceived safety, safety determination, and safety response competencies. Zhou and Guo (2020) measured the safety response competency of site workers in metro construction projects using item response theory.

Due to the high degree of uncertainty in working conditions, serious accidents can happen during metro construction, resulting in injuries, deaths, economic loss, cost overruns, scheduling delays, and negative impacts on surroundings. Therefore, the attention paid to safety risk control has been increasing in recent years. Because of the significance of design for safety, Zhou et al. (2013) employed a rule-based tool to automatically uncover unsafe conditions before construction commenced. A real-time early-warning system was devised for metro construction in the riverbed tunnel under the Yangtze River (Ding et al., 2013). And a study by Zhang et al. (2019) developed a new model for the optimisation of camera placement, to effectively monitor safety risks at the construction site of a metro station project. Compared with other categories of construction accidents, such as falls from heights and crane-related accidents, collapse accidents are much more hazardous and prone to cause more fatalities and serious injuries at metro construction workplaces. Zhou et al. (2022b) proposed an approach based on Bayesian network theory to investigate collapses and secondary accidents, in order to be able to systematically avoid metro construction collapse disasters, and to reduce the loss from resultant disasters. The construction of metro systems is a multifaceted issue of complex systems, involving the interplay of numerous factors, including geology, hydrology, construction parameters, technical equipment, and safety management. Current research predominantly concentrates on the static physical decomposition and amalgamation of safety risks associated with metro construction projects, with insufficient emphasis placed on the interrelations and coupling effects among causative factors.

A metro construction project involves a series of high-risk, complicated activities, with frequent accident occurrences, including collapses, object strikes, mechanical injuries, fires, electric shocks, water surges, explosions, and toxic gas ingestion. During the process of metro construction, many safety hazards may exist due to uncertain environmental features, the complexity of technology and equipment, the failure of organizational safety management, unsafe behaviours of workers, and the long project duration. All these safety risk factors can potentially lead to metro accidents and have a negative impact on the overall safety performance of metro projects. The common safety hazards suggested in the literature (Deng et al., 2023; Yu et al., 2014; Zhou et al., 2022c) to increase the possibility of accident occurrence in metro construction projects are displayed in Fig. 1.

2.3. *Cost and schedule*

A metro construction project can be split in three components: the stations boxes, the running tunnels, and the electrical and technical installations for the metro line. The entire construction process involves multiple disciplines, such as civil engineering, electrical engineering, telecommunications, and railway construction. Despite its overall great benefits for the metro user and city, the direct construction expenses for metro are still significant (Wang et al., 2016a; Zhang et al., 2020c). Metro projects are often deemed the largest investment that a city has ever made, and the upfront investment in metro construction is 20 to 30 times greater than for bus rapid-transport systems (Benardos et al., 2021). The cost components of a typical metro construction include civil engineering costs for metro stations, tunnels, tracks, vehicle bases, traffic, signalling, power supply systems, electromechanical machines, installation, loan interest, vehicles, and human resources (Ding and Xu, 2017). The entire metro project contains almost all the high-technology fields of modern civil engineering and electromechanical equipment engineering.

Most metro construction projects take place underground and in the urban hinterland. Planning and design of lines must take many aspects into account, such as underground hydrological and geological conditions, surrounding environments on the ground, and type of construction technique. Simultaneously, the construction process should also consider the arrangement of underground pipelines, building subsidence, environmental pollution, and other aspects, making construction management and planning very difficult. Geological uncertainties and complicated construction methods for underground tunnel projects can lead to cost overruns (Maruvanchery et al., 2020). A common situation is the adjustment of the design and construction plan due to unexpected circumstances (e.g., waterlogging, ground subsidence, natural disasters, structural defects, accidents, and technical difficulties), thus causing

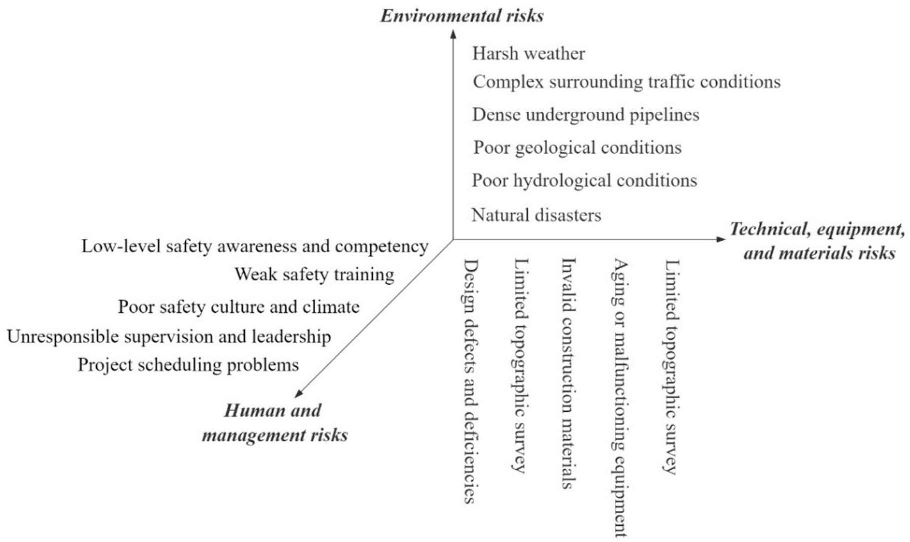

Fig. 1. Common safety hazards of metro construction.

increased cost. Researchers are actively exploring the effective control and prediction of metro construction costs, for example in a cost-benefit analysis for the expansion project of Athens metro (Benardos et al., 2021), or an estimation of delay costs in the metro project of Chennai (Mittal et al., 2019). As the design of metro alignment has a significant impact on construction costs, especially where the depth of station boxes is concerned, some researchers explored multi-criteria vertical location assessments to optimise the deployment of metro systems (Wang et al., 2022d), and measured the influence of designing a symmetrical vertical sinusoidal alignment on construction costs using artificial neural networks (Pineda-Jaramillo et al., 2020). Traditional cost analysis is still undertaken at the design stage, making accurate estimation and analysis of construction costs impossible, and negatively impacting cost control and overall project management. However, ongoing digitalisation and information technology efforts are expected to improve this situation.

One can distinguish three major stages, namely land acquisition and demolition, project bidding, and construction management on site, that require schedule management in metro construction projects (Ding and Xu, 2017; Zhang et al., 2020b; Zhou et al., 2011). Demolition disputes and complicated bidding procedures may significantly delay the start of the metro construction process. Guaranteeing required investment, selecting the proper construction entities, and obtaining technologies and materials are other factors that may cause delays in construction projects (Ding and Xu, 2017). The construction process involves many entities and cross-discipline professions to act together, which makes the process prone to information-transfer and coordination issues, thus causing scheduling delays in construction. In addition, many different types of accidents can happen during the underground construction; these include for instance structural collapses, seepage and sudden water inflow, poor ventilation, gas leakage, falls from height, impacts of personnel by heavy objects, pipe ruptures, and fires (Zhang et al., 2020b). Such events will not only incur additional costs and possible injuries or loss of life, they will also give rise to delays in metro construction. In the context of these situations, traditional schedule management tools based on the critical path method are often less applicable. Therefore, a schedule management approach for metro construction was deployed using linear planning (Zhou et al., 2011). Recently, the application of information technologies, such as smart sensors, building information modelling, machine learning, and digital twins, have helped construction schedule management to be dynamic and intelligent (Duan et al., 2022; Shi and Ouyang, 2017; Wu et al., 2022a). As metro construction projects involve multiple participants and many professions, the mutual collaboration of all parties and professions is an important prerequisite for the smooth progress of construction. Developments in computer-aided tools and the popularisation of information communication and sharing technologies help to optimise the metro construction process, identify schedule deviations, and improve schedule planning.

In summary, research on the cost of metro construction mainly includes two aspects, i.e., huge direct construction costs and serious cost overruns, while research on scheduling mainly focuses on two stages, i.e., early planning and construction management. As the cost and scheduling of metro construction are contradictory elements, with the two elements influencing and constraining each other, scheduling is the critical factor affecting cost. Adjustment or delay in schedules will inevitably lead to cost overruns, and extending the schedule time will also increase the cost of metro projects. To ensure reasonable cost, it is necessary to manage and track the scheduling of metro projects over time, and strictly control increases in scheduling cost. Therefore, there is a need to balance the relationship and influence between the two elements to promote the smooth progress of metro construction projects. The synergy of intelligent algorithms and information technology can effectively solve the issues of cost overruns and schedule delays in metro construction, and is an effective tool for studying cost and scheduling in metro construction.

2.4. *Impact on adjacent structures and environment*

Most metro construction projects take place underground and in the urban hinterland, having significant impacts on adjacent facilities and environments, such as roads (Nishibayashi and Nagashima, 1998), buildings (Zhang et al., 2021), bridges (Ding et al., 2011), pipelines (Jiang et al., 2020), and existing metro tunnels and stations (Berkelaar et al., 2007). Consequently, the planning and design of metro lines must take many aspects into account, such as type of construction technique, underground hydrological and geological conditions, and the surrounding environments on the ground.

Nishibayashi and Nagashima (1998) investigated the impact of Tokyo metro station construction on the surrounding roads, and it was found that longitudinal excavation of the foundation pit for this station brought about a large degree of road subsidence. The vibration resulting from the blasting pattern of excavation in metro construction can generate adverse influences on surrounding buildings. Zhang et al. (2021) carried out in situ tests for monitoring the strain on civil air defence tunnels in the vicinity, to develop safety risk responses for the impact of blasting excavation of a metro tunnel. Ding et al. (2011) paid attention to safety controls for Xunlimen station in Wuhan metro line 2, as it was constructed very close to a light-rail bridge. Finite difference software in the field of geotechnical engineering was adopted to simulate excavation of a foundation pit and its effect on the light-rail bridge. Increasingly detailed material models and inverse analysis are employed by various authors, e.g., Schoen et al. (2022) to model the construction interaction processes on the environment. To ensure the reliability and safety of surrounding pressure gas pipelines during the process of blasting excavations for foundation pits in metro construction, a mathematical approach was used to demonstrate the degree of attenuation around the peak particle velocity of ground soils on the surface (Jiang et al., 2020). Berkelaar et al. (2007) concentrated on the safety risks associated with expansion and upgrading of a metro station in Rotterdam. Because construction tasks were being conducted within one metre of an existing station, a monitoring system was deployed for real-time monitoring of any structural deformation at this station. The additional negative impact of the metro construction process requires monitoring the state of adjacent buildings, and soil forces and displacement. It is also necessary to identify the causal factors of metro construction safety risks to the surrounding environment, and to propose corresponding safety risk prevention or reduction methods.

In summary, the construction environment of metro projects is usually located in densely populated and built-up areas, and the vibrations generated during metro construction are the main cause of damage to the surrounding building structures and environment. To solve these issues, scholars normally use simulation software and mathematical methods to simulate and calculate the degree of impact on the surroundings during metro construction, to help prevent the occurrence of hazards during the construction process.

3. Operational aspects of metro systems

3.1. Fire safety

Of all operational risks, fire and the associated smoke form the largest risk factor for any underground construction, and metro systems form no exception. To ensure a safe environment for evacuation, smoke must be exhausted from metro tunnel fires. Currently, natural ventilation and mechanical ventilation are both widely used in metro tunnels. Comparisons of tunnel ventilation methods in the event of fire are provided in Table 2. Considering natural ventilation, the critical length of roof openings has been researched (He et al., 2018a). Previous research indicates that longitudinal ventilation is the most commonly used fire ventilation method in metro tunnels (Fan et al., 2013). The use of transverse ventilation or semi-transverse ventilation is also an option for metro tunnels. To meet the ventilation system requirements, it is necessary to install smoke exhaust ducts and air supply ducts for the transverse ventilation system, as well as smoke exhaust ducts or air supply ducts for the semi-transverse ventilation system. Compared with transverse ventilation and semi-transverse ventilation, longitudinal ventilation has the advantages of simplicity, good ventilation effect and cost savings, and is adopted in most metro tunnels. In the study of longitudinal ventilation tunnel fire, the length of smoke back-layering, critical velocity and temperature distribution are the main concerns. When ventilation velocity does not reach critical velocity, the distance between the upstream smoke front and the fire source is defined as the back-layering length. The study of critical velocity and back-layering length began with Thomas (1968). Since then, a large number of researchers have conducted much research in this field (Hu et al., 2008; Li et al., 2010; Weng et al., 2016; Weng et al., 2015; Zhao et al., 2018b). The influence of factors such as tunnel shape, size, and slope has been studied. Due to the large blocking ratio and long blocking distance of metro tunnels, metro trains can significantly affect the critical velocity and back-layering length (Zhang et al., 2020a; Zhang et al., 2016b; Zhu et al., 2017; Cong et al., 2022). For this reason, the influence of metro trains on critical velocity (Wang et al., 2022a) and back-layering length (Wang et al., 2022c) has been studied. The effects of ambient pressure have also been studied (Wu et al., 2018). Studying the temperature distribution under the ceiling of a subway tunnel with longitudinal ventilation is helpful for predicting the spread of fire, guiding the installation and distribution of alarm devices, and facilitating the safe evacuation of personnel (Zhao et al., 2018a). In terms of maximum temperature, the most widely used empirical model of maximum temperature was proposed by Kurioka et al. (2003). Based on the research, a section coefficient was proposed to describe the shape parameter of the metro tunnel section (Liu et al., 2016), and the revised prediction model of the maximum temperature under the metro tunnel ceiling was introduced. The influence of fire source location on the maximum temperature rise below the ceiling through numerical and theoretical aspects was studied (Cong et al., 2020). In terms of vertical distribution of temperature, the exponential decay regularity of temperature was found (Hu et al., 2005). An empirical model for temperature distribution upstream of the fire source was developed by comparing and analysing the temperature attenuation on both sides of the fire source (Zhao et al., 2018a). While the temperature distribution downstream of the fire source has been researched, the temperature distribution upstream of the fire source is starting to gain attention. It is also important to study situations where the fire occurs in the middle of the train, with some passengers evacuating to the upstream area.

Table 2
Comparison of tunnel ventilation methods in the event of fire.

Ventilation method	Natural ventilation system	Mechanical ventilation system		
	Natural ventilation	Longitudinal ventilation	semi-transverse ventilation	transverse ventilation
Driving force	Wind pressure and hot pressure	Fan	Fan	Fan
Method	Smoke flows freely	Smoke exhaust along longitudinal direction and air supply along longitudinal direction	Smoke exhaust along transverse section and air supply along longitudinal direction, or air supply along transverse section and smoke exhaust along longitudinal direction	Smoke exhaust along transverse section and air supply along transverse direction
Advantages	No equipment, No investment	Low project investment Better smoke-control effect.	Medium project investment Better smoke-control effect	High project investment Best smoke-control effect
Disadvantages	Restricted by ambient wind, and not suitable for long tunnels	Ventilation fan, no ventilation duct The loss of ventilation resistance may be large in long tunnels, not suitable for extra-long tunnels	Ventilation fan, needs smoke exhaust or air supply duct Occupies tunnel space height, increases the cost of tunnel construction	Ventilation fan, needs smoke exhaust and air supply ducts Occupies tunnel space height, increases the cost of tunnel construction

The influence of piston wind, induced by metro vehicles running in relatively tight tunnels, on the features of smoke flow in metro stations was studied using numerical simulation (Zhong et al., 2015). A natural ventilation pattern with shafts for fire smoke control in conventional metro stations was proposed (Wu et al., 2017). Smoke motion and temperature dispersion under various smoke control methods were analysed by a full-scale experiment (Liu et al., 2020a). The critical velocity that prevents smoke from spreading from the platform to the lobby floor through the staircase during a platform fire was investigated (Liu et al., 2021). In addition, the optimal smoke curtain depth required to prevent the spread of smoke from the platform floor to the lobby floor was studied (Liu et al., 2022b).

Far fewer studies, such as Shi et al. (2020), focus on the potential for fires to develop and the heat released from metro carriages, although the great potential for increased fires safety by reducing the potential heat release rate has been demonstrated for instance in the Paris Metro (Marchais, 2007).

Fire is a great risk to metro systems, especially when metro stations and tunnels are located underground. Fire is even more dangerous if the metro tunnel is a narrow and enclosed underground space, making it very difficult for passengers to evacuate, and for fire crews to conduct rescue operations, making fire the highest risk for tunnel operation. To protect people, fire smoke control systems for metro tunnels have been a research focus. In-depth research into maximal smoke temperature, temperature distribution, smoke back-layering length, and critical velocity have been carried out, and a number of prediction models have been proposed, but the effects of further combined factors are still being studied.

3.2. Personnel evacuation

Apart from the development and spread of smoke and fire, the impact of fires in metro systems is also governed by the amount of people in the metro system and their ability to evacuate safely in case of incidents. As with all underground facilities, the need to flee upwards to safety creates specific conditions that make that emergencies in metros deserve special attention. Some previous studies indicated that the mental reactions of passengers on stairways might affect evacuation in metro stations in emergencies, especially in the case of fire (Cai et al., 2022; Hong and Xu, 2011; Li et al., 2022b; Qin et al., 2020). Some researchers have noticed the impact of other parameters on evacuation, such as exit configurations (Fridolf et al., 2014), and personality types (Chen et al., 2021c). Similarly, many researchers focus on prediction modelling methods of evacuation. Wang et al. (2012) compared the inconsistency in the evacuation load of existing rail station evacuation test strategies domestically and internationally, and established an evacuation simulation model based on field investigation. Zhang et al. (2016a) developed a route choice planning method based on systematic simulation-based multi-attribute decisions. Some researchers used underground metro stations to analyse the impact of worst-case scenarios of exit choice on evacuation time by using the Pathfinder software package (Kallianiotis et al., 2018). The fractional effective dose calculated by Fire Dynamic Simulation has been suggested as a method to determine the available safe egress time for fire emergencies in metro tunnels (Papakonstantinou et al., 2021).

According to the solution strategy research of service facility problem, an evacuation partition optimisation algorithm was proposed. (Mei and Xie, 2018). Some new simulation methods to evaluate and optimise subway station evacuation, such as LightGBM, NSGA-III (Guo and Zhang, 2022a), RF and NSGA-III (Guo and Zhang, 2022b), were proposed. A leader-led passenger evacuation optimisation model in subway stations and a modified maximum-coverage model were established (Zhou et al., 2019b). To optimise evacuation efficiency, an adaptive train door control strategy was proposed (Shen et al., 2022). The influencing factors of congestion (Wu et al., 2022b) and proposed corresponding optimisation methods (Zhou et al., 2022a) were studied.

In recent years, some new scenarios and technologies have also been developed. The evacuation strategy of deep buried subways based on the characteristics of fire smoke diffusion in the model of a deep buried subway was studied (Cai et al., 2016). The characteristics of passenger mobility during fire evacuation was simulated (Wang and Song, 2020). Some researchers used Cellular Automata (Zhang et al., 2018), and BIM tool (Tang et al., 2021b) to simulate evacuation. In addition, recently a strategy for passenger evacuation while maintaining safe distances in the context of COVID spreading was proposed (Yang et al., 2022).

As metro stations are crowded places, evacuation plans present huge challenges in an emergency, especially at peak times. To satisfy safety evacuation requirements, many researchers take metro stations as examples for designing evacuation plans, and optimise the evacuation plans by simulation. However, different metro stations exhibit different flow patterns for people, and obtaining accurate passenger flow information as the input boundary condition is still a problem. Especially during the design phase, it is very difficult to estimate the future development of passenger flow. New technologies, such as virtual reality technology and video analysis, are increasingly used in evacuation research.

3.3. Impact of aerodynamic effects

As the operation speed of metro trains increases, the problem of the aerodynamics effect has attracted increasing attention. The air tightness of metro trains cannot attain the same air tightness as high-speed trains, because of the door design. Hence, the aerodynamic effect of metro trains cannot be ignored. When a metro train travels in a very long and narrow metro tunnel, the positive pressure generated at the front of the train helps discharge harmful air outside the tunnel, and the negative pressure induced at the rear of the train drags fresh air inside, by generating a piston wind (Pan, 2013). The challenges associated with aerodynamic effects on trains travelling through tunnels are depicted in Fig. 2. The piston wind influences the driving behaviour of the metro, the ventilation systems, passenger comfort in the metro train. In terms of piston wind characteristics, the non-constant flow law of subway trains using a moving model experimental device was studied, the pressure time history and air velocity curve were analysed, and a simplified calculation method to predict spatial distribution of air flow and piston wind speed was proposed (Kim and Kim, 2007; Wang et al., 2009). To calculate piston wind speed, based on the Bernoulli equation, a theoretical model considering the factors affecting ventilation rates was developed (Zhang et al., 2017a). A numerical simulation study based on a dynamic grid technique for piston wind in metro stations was carried out (Xue et al., 2014). The characteristics and influencing factors of the piston effect of multi-train tracking were discussed (Liu et al., 2020b; Wang et al., 2020). On the utilisation of piston wind, Huang et al. (2012b) used computational fluid dynamics simulation to explore piston wind in tunnels with natural ventilation ducts. The ventilation performance of natural ventilation ducts in subway tunnels was evaluated (Huang et al., 2012a). The effects of train-induced piston wind on the environment and performance of jet fans were also addressed by other researchers (Zarnaghsh et al., 2019).

When a metro train suddenly enters a narrow tunnel, a compression wave travelling at the speed of a sonic wave will be generated (Zhang et al., 2017b), and as the rear of the train also drives into the tunnel, an expansion wave travelling at the speed of sonic wave will also be induced. This generates additional pressure changes on top of the piston wind effect, and primarily impacts passenger comfort in the metro trains. The aerodynamic behaviour of metro trains running at different speeds in a tunnel was studied (Yang et al., 2021). The effects of three tunnel cross-sectional shapes (circular, rectangular, and horseshoe) on the transient pressure evolution were discussed by Huang et al., 2020. The impacts of shaft position and train speed on pressure waves were investigated through small-scale experiments and numerical simulations (Meng et al., 2019). The aerodynamic drag of a high-speed subway train passing through a tunnel at 120 km/h based on numerical simulations

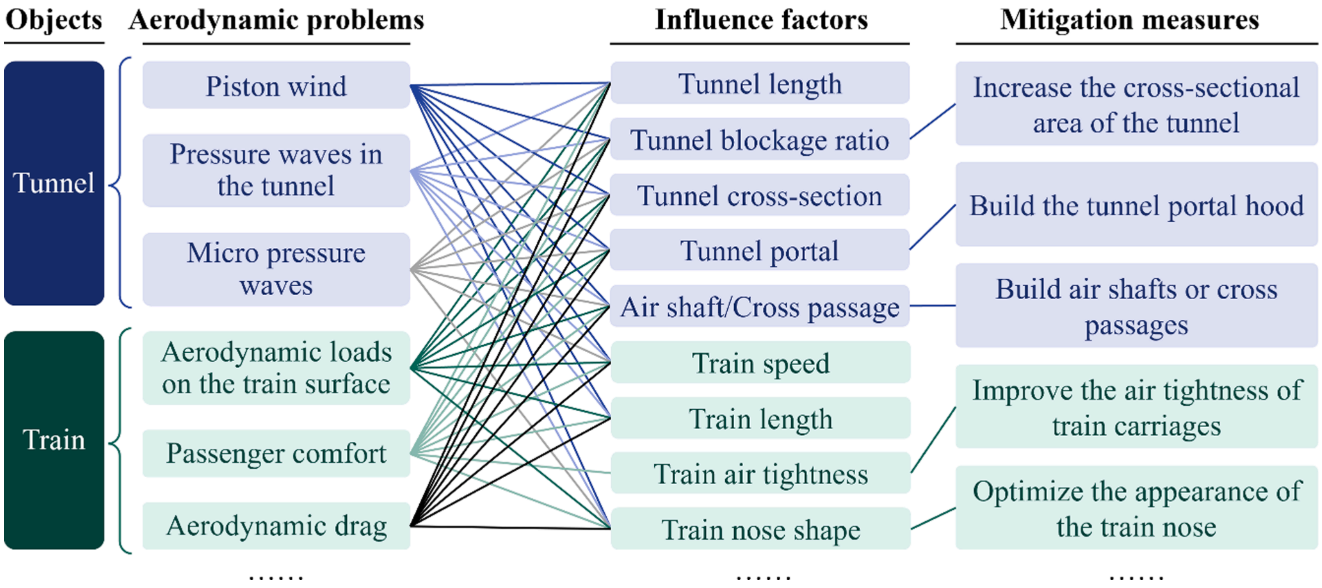

Fig. 2. Challenges associated with aerodynamic effects on trains travelling through tunnels.

was studied (Liu et al., 2020c). The tunnel aerodynamic performance of metro trains with different length configurations was also studied (Guo et al., 2022). Ambient pressure mainly affects the peak value of pressure waves (Liu et al., 2022a). Aerodynamic pressures induced by the operation of single and double trains in very long tunnels were studied by numerical simulations (Wang et al., 2022b).

In addition, the study by Xiong et al. (2020) showed that ventilation shaft, operation mode and train speed were critical factors that led to rapid changes in the internal and external pressures of metro trains. The effects of train speed, train operation mode, and number of air shafts on internal and external pressure, as well as passenger comfort on trains, were analysed (Li et al., 2022a). The pressure load on screen doors at metro stations was also an important part of the research on metro pressure waves. The mechanism of pressure variation and spatial–temporal variation characteristics of platform screen doors (PSD) was investigated by numerical simulation (Yang et al., 2009). Zeng et al. (2021) also paid attention to the effect of the transient pressure induced by metro trains on the PSD at metro stations.

According to the traditional concept, aerodynamic effects will not affect the safety of subway operation, because the operation speed of the metro train will not exceed 100 km/h, and will not cause operational accidents. With the extension of metro to the outskirts of the city, the distance between metro stations has increased, resulting in increased speed of metro trains. If train speeds exceed 100 km/h, reaching up to 160 km/h, then aerodynamic effects cannot be ignored. If metro trains enter tunnels from open space, this causes serious aerodynamic problems. Previous research has begun to pay attention to this issue, but most research has been conducted on high-speed trains, which have big differences in blockage ratio, train tightness, and locomotive shape compared to metro trains. Thus, research on the impact of aerodynamic effects should consider these issues carefully.

3.4. *Indoor air quality*

Both indoor and outdoor environments are increasingly polluted, and this can be hazardous to people's health. Studies in underground rail lines and metro stations indicated that CO_2 levels and PM concentrations have the biggest effects on indoor air quality (Moreno et al., 2015; Reche et al., 2017; Shakya et al., 2020; Yu et al., 2021). The pollutant concentration in the platform area was relatively high (Moreno et al., 2015). The distribution profile of viable airborne bacterium concentrations was measured in metro stations, with important implications for linking station ventilation systems to health hazards (Hwang and Park, 2014). Deposited granulometric and magnetic particles from various metro station locations were measured to examine the transmission of deposited particles (Cui et al., 2016). Researchers used the $PM_{2.5}$ to PM_{10} ratio to determine the proportional share of $PM_{2.5}$ in metro environmental management systems (He et al., 2018b). The amount of PM was shown to be related to preventable significant deterioration and a significant factor in the stations' overall pollution levels (Zhao et al., 2017). The in-cabin concentrations of $PM_{2.5}$ and CO_2 were investigated to access the rate of passenger exposure to pollution under various conditions (Xu et al., 2016). The difference in PM concentration distribution in temporal and spatial terms between inside and outside stations was analysed (Liu et al., 2017). The PM concentration at ground-level station platforms was not significantly different from that of the outdoor environment (Guo et al., 2014). If there were open windows, pollution levels inside the carriages were very high (Cartenì et al., 2015). Air quality on underground railway station platforms was influenced by station design and the piston wind effect, and this may have an impact on both energy use and passenger health (Moreno et al., 2014). Some researchers have focused on PM concentrations in tunnels (Qiao et al., 2015). The results showed that tunnel PM concentration was related to types of platforms, train frequency, rush hours and ventilation systems. Lee et al. (2017) took the train schedule, the peak period and the air quality changes outside into consideration, proposing a new gain-scheduled ventilation control strategy. According to research by Leng and Wen (2021), the key issues in metros are warm/cold variations, piston wind coupled with other wind environments, and identification of pollution sources. $PM_{2.5}$ mass and elemental concentrations were assessed in both summer and winter at metro stations (Ji et al., 2021). Most researchers focused on certain ventilation types at metro stations, but did not consider how pollutants were affected by the coupling effect between piston airflow and metro ventilation systems, and the need to obtain a suitable ventilation control strategy coupled with seasonal factors to make systems more efficient and energy-saving (Reche et al., 2017). The seasonal model was superior at forecasting PM and nitrogen amounts at train stations (Kim et al., 2012). A methodology was developed to identity indoor concentrations of CO_2, PM and TVOCs by Assimakopoulos et al. (2013).

To travel by metro train, passengers enter or leave metro stations. Although the stay time at metro stations is short, indoor air quality in these areas has attracted the attention of many researchers. They have researched the characteristics of pollutant concentration distribution using short-term experimental tests or simulations, and have obtained some meaningful results. Because the metro station is a crowded place, some of the research uses CO_2 as an important indicator to measure air quality. As CO_2 concentration sensors have been installed in many metro stations, the long-term tracking of CO_2 concentrations based on passenger flow can be used in research, providing improved results, which can be used to drive the operation of the fresh air system and reduce the energy consumption of fresh air systems.

3.5. Reliability and vulnerability

The reliability of a metro system is commonly associated with the ability to guarantee passengers' travel time on a given route. Reliability is highly valued by metro passengers, because low reliability can bring about unfavourable results, such as inconsistent transfer connections, unpredictable waiting times, and potential penalties due to arriving later than expected (Chakrabarti and Giuliano, 2015). Metro systems in most cities are composed of multiple stations belonging to different, physically separate, lines that are inter-connected with each other in metro networks as an integral part of urban transport (Alkheder et al., 2020; Li et al., 2012; Lu et al., 2011). Therefore, some researchers investigated the reliability of metro infrastructure from the perspective of complex systems. Mathematical studies of the characteristics of small world have attracted extensive interest, and the characteristics of small world can be identified for various types of networks. Boston metro system was taken as an example for the introduction of the efficiency measure, which provided a more general mathematical definition of small worlds (Latora and Marchiori, 2002). Metro network reliability was addressed by using the measurement of connectivity in a complex network. Two measures of network connection probability and relative rate of connectivity were adopted for reliability assessment (Chen et al., 2009). Zhang et al. (2015) explored the connectivity reliability of Beijing's metro network, and topological parameters (e.g., degree, degree distribution, shortest path, and diameter) were computed for evaluating network complexity.

Different from the method based upon complex network theory, Liu et al. (2018) deployed a path-finding algorithm based upon schedules for metro network systems to determine the schedule-based shortest path for every pair of beginning and end of journeys. Pievatolo et al. (2003) investigated the actual reliability of metro train door opening systems prior to the expiration of warranty, where both total distance travelled and operational life time were analysed for every individual failure. A Monte Carlo algorithm was adopted for calculating the reliability of metro network systems according to their practical security, safety security, and unavailability by Ji et al. (2018). Given that traditional reliability analysis based on static process reasoning is not able to represent the dynamic impacts from surrounding environments, Liu et al. (2020c) developed a binary discrete time-varying Bayesian copula model to accurately assess the structural reliability of metro tunnels in operation.

In contrast to reliability, vulnerability is a systematic feature that describes the severity of consequences resulting from the occurrence of an individual dangerous incident (Eusgeld et al., 2011). Research on the vulnerability of metro systems was focused on factors such as network structure (Cai et al., 2017; Derrible and Kennedy, 2010), physical components (Deng et al., 2015), station location (Zhao et al., 2020), micro-environmental health (Qi et al., 2017), and social vulnerability (Napieralski et al., 2022). To deal with evolutional dynamics with a long-term view and the uncertainties in vulnerability in metro operation, a hybrid approach was proposed on the basis of the integration of system dynamics with Monte Carlo simulation (Chen et al., 2021b). In consideration of transferring between urban metro systems and high-speed rail systems between cities, Hong et al. (2020) took the two types of transport systems for time-varied accessibility and vulnerability analyses. Zhang et al. (2020c) incorporated two measures of passenger flow and path distance into a double-weighted model for determining the vulnerability of Shanghai's metro system. A link-weighted adjacency matrix was constructed, and node-weighted network efficiency was estimated through integrating path distance with ridership between every two metro stations.

Fig. 3 illustrates a series of sequential changes (i.e., disturbance, exposure, sensitivity, adaptability, and outcome) that may occur in a metro operation system in the context of a sudden dangerous event. The metro operation system can be stable, secure, and reliable, if the system is not exposed or sensitive to disturbance, or possesses high-level adaptability and resistance capabilities. Overall, the reliability and vulnerability of a metro system are two key elements of its operation; the former relates to passenger travel time and transfer convenience, while vulnerability is concerned with the chain reaction following a hazardous event. Existing studies were limited by data access and computational resource constraints. In addition, the complexity of the metro system, such as the interaction between stations and the uncertainty of passenger behaviour, is sometimes ignored, and this may have a significant impact on the reliability and vulnerability of the metro system.

4. Impacts of metro systems

4.1. Land use and urban underground space utilisation

A study by Jothimani and Yamamura (1995) revealed that the development of metro systems led to an expansion of urban areas. Lin et al. (2006) found that opening of new metro lines weakened residential activities while enhancing employment and recreation activities in the new city centre. Sonnenschein et al. (2022) examined multiple cities and indicated that in most cities, metro expansion significantly increased the density and multifunctionality of local amenities, particularly social amenities, e.g., arts, restaurants and entertainment. Generally, metro development facilitated urbanisation, residential and commercial development, population growth in station areas in the outer suburbs, and densification in station areas, leading to urban decentralisation and commercial suburbanisation (Calvo et al., 2013; Gonzalez-Navarro and Turner, 2018; Jun et al., 2015; King, 2011; Lee et al., 2021; Tan et al., 2019; Zhu and Diao, 2016). However, it is still not clear whether metro development causes residential and commercial development and population growth. The metro system did grow most in areas with commercial growth (King, 2011), and commercial activities were attached to the metro system (Lee et al., 2021). However, whether metro expansion occurred before residential development is a question yet to be determined.

Metro development facilitates urban underground space (UUS) utilisation in metro station areas, providing opportunities for creating UUS that consists of different land uses and accommodates multiple urban functions (e.g. transport, commerce, offices, and public spaces). Metro systems carry a considerable number of people, transport them to different areas across the city, and generate high pedestrian flows and high demand for services in station areas. Therefore, UUS in station areas has been shaped to meet the high demand. UUS has been developed in tower basements in various forms, including underground shopping malls and streets, underground concourses and atriums, and underground car parks, linked by underground walking corridors, forming multi-functional UUS (Barker, 1986; Belanger, 2007; Dong et al., 2021; Sijpkes and Brown, 1997; Terranova, 2009; Wallace and Ng, 2016). Not only the public sector, but also the private sector has played an important role in creating underground networks in station areas. Private sector developments have linked commercial and retail properties to the UUS network surrounding metro stations, offering hubs of activity and vitality, and shopping opportunities in the underground network (Wallace & Ng, 2016).

Metro station areas with different environmental characteristics impact UUS utilisation. Peng et al. (2019) revealed that passenger flow rate, land price, and spatial distribution of land use were correlated with UUS utilisation in metro station areas. Xu and Chen (2022) examined the

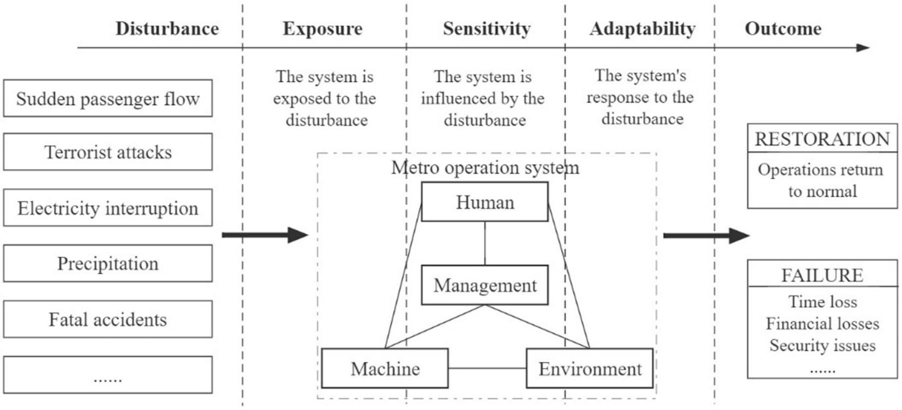

Fig. 3. Vulnerability analysis of metro operation systems.

relationship between spatial vitality and environment factors of UUS in metro station areas. They found that spatial vitality was correlated with accessibility (degree of integration), visibility (degree of visual integration), spatial scale (length, shape, and proportion), catering business distribution, traffic environment (traffic transfer and getting around), and the physiological environment (wind speed and temperature). The effects of these influencing factors varied according to the different types of UUS (UUS as a whole, the ground public space, or the underground shopping malls) and during different time periods in the day.

Metro systems, as major transport infrastructure that is developed under the ground, shape land development, both on the ground and under the ground, around station areas in the city centre and in the suburbs. Current studies have proven that metro development is associated with residential and commercial development and population growth. Therefore, metro development can be used as a strategy to achieve city planning and development goals. Metro-led UUS utilisation can promote the development of the three-dimensional city, increase urban density, combat urban sprawl, provide an opportunity to upgrade public transport systems, and attract investment from the private sector to create quality public space with the public sector. Despite the important roles that metro systems can potentially play in affecting urban land use, metro station areas with different environmental characteristics influence UUS utilisation. This is an area that requires more research to advance our understanding of metro's impacts.

4.2. *Property price and economic impacts*

Locations with closer proximity to metro systems have greater accessibility (Zhu and Liu, 2004). People choose to pay more for living closer to a metro station to take advantage of metro travel (Ahn et al., 2020). Generally, metro systems and stations increase housing prices (Diao et al., 2017; Im and Hong, 2018; Kholodilin and Maksimova, 2019; Sharma and Newman, 2018; Tian et al., 2020).

However, there are both spatial and temporal differences in metro systems' and stations' impacts on housing prices. Focusing on spatial variability, metro's impacts were smaller in the CBD area than in the areas distant from the CBD (Sun et al., 2016; Tang et al., 2021a). The impacts varied (positively or negatively) with different distances between the housing locations and metro stations (e.g., short distance, medium distance and long distance) (Mohammad et al., 2017), between affluent neighbourhoods and poor neighbourhoods (Forouhar, 2016), and between areas with good metro accessibility to job centres and other areas (Li et al., 2019a).

The impact of metro systems and stations on housing prices also varies at different time periods of metro system development (e.g., planning, construction and operation). During metro construction, positive (Bae et al., 2003; Chen et al., 2019), negative (Lee et al., 2020) and mixed (Tian et al., 2020) impacts were reported in different places in the world. During metro operation, generally, positive impacts were seen (Celik and Yankaya, 2006; Wang et al., 2016b). While a close link between metro operation and property prices was not seen, the likely growth in property prices might have occurred during the phases prior to the metro opening (Lee et al., 2020).

Metro station areas with different built environments impact economic activities in different ways. Zhao and Li (2018) found mixed land use was positively related to the number of passengers' shopping trips in metro station areas. The scale of non-residential developments, distance from a metro station to the CBD, and housing prices were positively and significantly associated with the number of passengers' dining and entertainment trips in metro station areas. Xue et al. (2012) stressed the successful metro station plus metro mall development mode in Hong Kong. They found that this mode ensured high metro patronage that can be taken advantage of by shopping malls affiliated with metro stations. In shopping malls affiliated with metro stations, the number of customers and their sum expenditure were significantly higher than malls in ordinary streets (Xue et al., 2012).

Metro systems have wider economic benefits in facilitating business investment and sectoral changes (Beyazit, 2015), firm establishment (Du and Zheng, 2020), restaurant openings (Zheng et al., 2016a), and mobility and labour productivity in the city, region and country (Haddad et al., 2015).

The economic impacts of metro development, particularly its impact on increasing housing prices, is a mainstream topic of metro research. The topic has attracted a great number of international studies in the past decade, reflecting the rapid development of metro in world cities, and increasing research interest in metro's economic impacts. With this abundant research, there is a well-developed understanding of the impacts of metro on housing prices spatially and temporally. Unsurprisingly, metro systems also have wider economic benefits in other sectors, and economic impacts on broader areas beyond station areas, and these could be further examined by future research.

4.3. *Travel behaviour and public health*

Metro systems also impact travel behaviour of a city's population. Metro development affects urban passenger transport modes, travel duration and car ownership, as it replaces bikes, e-bikes, and bus trips with metro trips (Deng & Zhao, 2022), reducing the number of trips by bus and the number of cars and taxis on the road (Liu and Li, 2020), decreasing the number of commuting trips by bus and active transport modes (Wu and Hong, 2017), slowing the growth of car trips (Deng & Zhao, 2022), and decreasing the average travel duration of trips by active transport modes (Sun et al., 2020). Metro operation impacts the ownership and use of cars and bicycles, thereby decreasing car ownership (Huang and Chao, 2014; Huang et al., 2017), reducing car use (Zhang et al., 2017c; Zhu and Diao, 2016), decreasing e-bike ownership

(Huang et al., 2017), and increasing bicycle ownership (Huang et al., 2017). But in contrast, a few studies did not find significant change in trips made by car or e-bike (Sun et al., 2020) or car ownership (Zhu and Diao, 2016) because of metro development.

Differences in the built environment in metro station areas in various urban and social contexts may partially explain the different impacts of metro on people's travel behaviour. Chen et al. (2022) found that population density had a negative relationship with mode share of metro for commuting trips, street intersection was positively associated with mode share of metro by commuting trips, and street intersection and office-oriented urban function had a positive relationship with metro ridership. Huang et al. (2022) revealed that during morning rush hours, public transport accessibility and employment density were positively correlated with alighting ridership. Crowley et al. (2009) revealed that a convenient walking distance to a metro service was strongly correlated with metro use throughout the day in a relatively low-density urban setting. Deng and Zhao (2022) indicated that the impacts varied in different metro catchment areas. New metro development resulted in increased metro trips and activity space for people living in all three studied ranges (0–1 km, 1–2 km and 2–3 km) although the impacts on activity space were more significant for those in the 1–2 km and 2–3 km ranges than for those in the 0–1 km range. For total trip frequency and distance, new metro development only increased these factors for those living in the 0–1 km range. Lee et al. (2013) found that in the CBD and fringe areas, density primarily affected metro ridership, whereas in subcentral areas, diversity generally influenced metro ridership. And additional bus lines in metro station areas increased metro ridership.

Metro operation also contributes to public health. Living near a metro station decreases overweight and obesity (Oreskovic et al., 2009; Rundle et al., 2007; Xiao et al., 2021). Metro development, accompanied by a reduced number of motorised vehicles, resulted in improved air quality and reduced mortality rates attributed to cardiovascular and cerebrovascular diseases (Chen et al., 2021a). During specific time periods, e.g. during an influenza epidemic, metro systems may have negative impacts on public health. In such cases, metro transport helps spread disease due to the large number of people using metro to travel for long distances and across large areas, and the interactions among them facilitate disease transmission (Cooley et al., 2011).

Metro, as an important part of urban public transport systems, impacts people's travel behaviour and therefore their physical activities and public health. The impact of metro use on changing people's travel behaviour has long been a key topic of transport research. Existing research focuses on the impact on transport modes, the number of trips by transport modes other than metro, travel duration, and vehicle ownership, as well as the role of the built environment in metro station areas in affecting metro's impact on travel behaviour. Metro's impact on public health is a topic that has attracted increasing attention in health research. Understanding metro's impacts beyond the traditional transport area and into other related areas, e.g. public health, provides compelling justification for metro development.

4.4. Air quality and greenhouse gas emissions

The increased use of metro systems reduces air pollution and greenhouse gas (GHG) emissions in cities. A variety of reasons contribute to the reduction. Metro expansion and improved metro coverage may lead some commuters to shift mode from car to metro (Li et al., 2019b; Saxe et al., 2017), therefore reducing road transport (Lu et al., 2018) and traffic congestion (Li et al., 2019b; Xiao et al., 2020; Zheng et al., 2019). Metro development can also result in energy savings due to increased residential density (Saxe et al., 2017), and use of cleaner energy (Lu et al., 2018).

Metro systems have different effects on changing the levels of various air pollutants of cities, and the changes are not consistent throughout the world. Some studies found metro development and expansion decreased the level of $PM_{2.5}$ concentrations found in the urban environment (Lu et al., 2018; Xiao et al., 2020; Zheng et al., 2021), PM_{10} (da Silva et al., 2012; Xiao et al., 2020), or CO (Wei, 2019; Zheng et al., 2019, 2021), while other studies found no apparent impact on SO_2, NO_2, and CO (Xiao et al., 2020), $PM_{2.5}$ (Wei, 2019; Zheng et al., 2019), PM_{10} (Zheng et al., 2019) or O_3 (Xiao et al., 2020; Zheng et al., 2019). Wei (2019) found that subway operation accompanied by vehicle fuel standards reduced the level of $PM_{2.5}$ concentrations.

Li et al. (2019b) found that an increase in metro network density reduced air pollution. Xiao et al. (2020) indicated that the number of metro stations and metro mileage were negatively associated with levels of $PM_{2.5}$ and PM_{10}. Lu et al. (2018) revealed that population scale and city tier affected the impact of metro expansion on $PM_{2.5}$ reduction. Li et al. (2022b) found that the impact of new metro lines on mitigating air pollution (through switching commuting demand to less polluting transport options) varied during different time periods, and the impact was more significant during rush hours than non-rush hours. This implies that metro cities can improve air quality by increasing the number of metro trips and therefore reducing car trips, particularly during rush hours.

Focusing on GHG emissions, the development of metro systems reduced CO_2 emissions (Ikeshita et al., 2013; Saxe et al., 2017). Metro transit proximity impacts on ride-hailing trips and GHG emissions. Gao et al. (2022) found that one kilometre reduction between metro station and pick-up location reduced the vehicle kilometres travelled during ride-hailing trips by 0.315 km, and this reduced CO_2 emission by 0.063 kg; one kilometre closer to metro from drop-off location reduced the vehicle kilometres travelled during ride-hailing trips by 0.273 km, and this reduced CO_2 emission by 0.055 kg.

The combined health benefits and reduced mortality due to metro's positive impacts on air quality were tremendous (see Gendron-Carrier et al., 2020; Li et al., 2019b). Zheng et al. (2021) discovered that in the areas that were no more than 2 km from a metro station, metro expansions resulted in a 3.93% extra reduction in the air pollution level compared to areas further away. They predicted the health benefits due to air improvement attributable to metro expansion, and found the total number of averted premature deaths per year was between 300,000 and 443,000 for a city like Nanjing with a population of over 13 million.

Metro development impacts on the air environment, and a considerable number of studies have been conducted on this topic in recent years, reflecting increasing attention to and acknowledgement of metro's benefits in reducing urban air pollution and GHG emissions. Case studies have been conducted in local areas, at the city level, and nationwide. Compared with metro's impacts on land use, economy, and transport, all of which have been examined for a long time, its impact on air pollution and GHG emissions is a relatively new topic that is likely to receive increasing interest from environmental scientists and researchers in coming years. Fig. 4 shows the impacts of metro systems on land use, property price, economies, travel behaviour, public health and air quality.

5. Discussion

The total number and combined length of metro systems worldwide have expanded at an increasing pace, thanks to massive investment in metro development in the past two decades, allowing metro to become the typical transport mode for large numbers of people.

Metro systems play a very important strategic role in urban transportation and social development, and the construction of metro systems is a complex and prolonged process. Various types of construction methods, such as the cut-and-cover, shield tunnelling, NATM, shallow tunnelling, and drill-and-blast methods, are commonly adopted for developing metro projects. Shield tunnelling and cut-and-cover are still used for most running tunnels and station boxes, and the other construction techniques are used where geotechnical and environmental circumstances dictate their use. Each of the above-mentioned construction methods has advantages and disadvantages, and the method

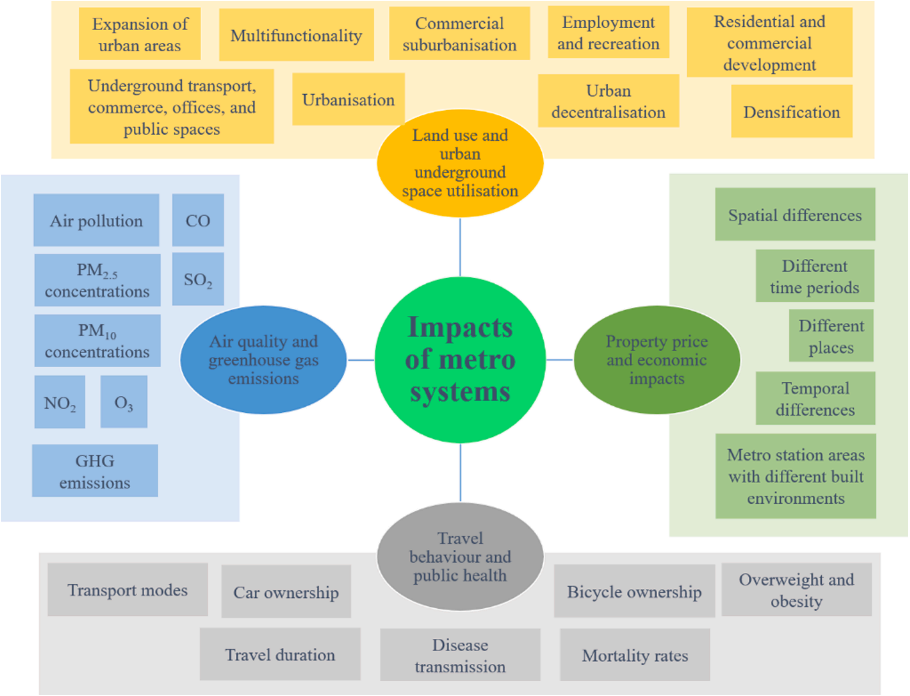

Fig. 4. Impacts of metro systems on land use, property price, economies, travel behaviour, public health and air quality.

employed should take account of geological conditions, scheduling requirements, cost, and other factors.

As most construction tasks in metro projects take place underground, they are more susceptible to the impacts of hydrological and geological conditions. Additionally, safety hazards may arise due to technical equipment complexity, organizational safety management failure, unsafe behaviour, and long project duration. Construction safety is a key issue involving many aspects, such as structural safety, safety information flow, data analysis, organizational management, and behavioural psychology. Despite extensive attention to metro construction safety management, both from an engineering technology perspective, and from a risk management and probabilistic perspective, there are no complete accident records from metro construction sites for use in accident case analysis. This failure is a contributing factor to accident recurrence.

Cost overruns and delays are among the most common problems in metro construction project management. Compared with other types of construction projects, the construction costs of metro projects are often greater. The actual cost of a metro system is often higher than estimated at the design stage due to a variety of factors, such as geological uncertainties, complex construction methods, and accidents. In addition, organizational management factors play a crucial role in construction cost overruns. According to the results of this review, many cost-control and prediction methods, such as cost-benefit analysis, econometric models, machine learning, and deep learning, are being explored. Construction schedule management is also of great concern as the metro construction process involves many subjects and interdisciplinary professions working together, and this process is prone to information transfer and coordination problems, thus causing construction schedule delays and triggering chain reactions.

Different strategies for controlling fires in metro tunnels during emergencies have been researched, with most attention on various forms of ventilation. Longitudinal ventilation has been proven to be the most efficient method. A variety of different forecasting models, including maximum temperature, temperature distribution under the tunnel ceiling, back-layering length, and critical velocity for longitudinal ventilated tunnels, have been proposed and revised. Additionally, the formation mechanism and influencing factors of aerodynamic effects, such as piston wind and pressure waves when high-speed metro trains pass through tunnels, have been studied under different conditions.

The safety of metro systems during fires and other emergencies depends not only on fire control and ventilation, but also on ability to escape. To assist in preventing stampedes among crowds of passengers in emergency situations, evacuation strategies for people in metro systems during emergencies have been researched, bottlenecks in personnel evacuation have been identified, and optimal methods have been discussed. The characteristics of passenger mobility, and new scenarios created by the BIM tool have been researched. New technologies, such as virtual reality technology and video analysis, have also been developed.

Metro stations are closed underground facilities with high occupancy rates during operational hours. While the indoor environment mainly relies on air conditioning systems to maintain comfortable temperatures and humidity, air quality should not be ignored. Increased fresh air supply can improve air quality, meaning that the ventilation load and the air conditioning load will also need to be increased. Achieving a balance between air quality and energy consumption has aroused researchers' attention, and many strategies for improving air quality have been proposed and discussed. Air quality is influenced by station design, train scheduling, peak periods, outside-air-quality changes, ventilation control strategies, and piston wind effects. Most studies have focused on specific ventilation methods at metro stations.

In addition, metro system reliability has been investigated from different perspectives. The reliability and vulnerability of metro systems is affected by many factors, such as network structure, physical components, station location, micro-environmental health, and social vulnerability. Metro operation problems have been identified and discussed, with most research focused on current metro systems. Research methods used include numerical simulation, small-scale model experimental tests, and restricted full-scale model experimental tests, but there is limited full-scale testing after metro system operation commences.

Metro development has a clear impact on urban development. Metro systems promote land development and urban spatial changes in land use by facilitating urbanisation, population growth around metro stations in outer suburbs, utilisation of UUS, densification in station areas, residential and commercial development, urban decentralisation, and commercial suburbanisation. Although previous studies have revealed the impacts of metro development on land use, it is yet to be confirmed whether metro development occurred before residential and commercial development and population growth.

Metro systems also impact travel behaviour, resulting in changes in transport modes used, often reduced travel duration and sometimes but not always reduction in car ownership. These changes in travel behaviour indicate ways in which metro operation has improved public health, since these changes are accompanied by reduced numbers of motorised vehicles, improved air quality, and reduced mortality rates. The positive impacts of metro development can be used to promote the use of public transport, and decrease the use of car transport, thus supporting sustainable transport development.

The development of metro systems also reduces air pollution and GHG emissions in urban areas due to a variety of reasons, e.g., mode shift from car to metro, reductions in road transport and traffic congestion, energy savings due to increased residential density, and use of cleaner energy. However, the closed nature of many metro systems and stations means that pollutants, specifically particulate matter, are trapped, and the indoor environment in station boxes may be of lower quality than that of the surface environment. There has been an increase in the number of studies on the impacts of metro development on land use, travel behaviour, air pollution, and GHG emissions in recent years, providing evidence to support decision-making in relation to metro infrastructure development and expansion.

The impact of metro development on housing prices has long been a research focus in transport economy research. Generally, the development of metro systems has positive impacts on housing prices, and wider economic benefits beyond the city. The impact of construction activities can be severe in the short term, but generally the long-term benefits during operation outweigh the negative impacts during the relatively short construction period.

Based on the above discussion of metro construction, management and impacts, the following recommendations for practical implementation and future research are provided:

- During the construction process, multiple methods are often adopted in combination to achieve the best effect. With the widespread use of artificial intelligence, Internet of Things, big data and other technologies, these information technologies can be utilised more in future metro construction processes.
- A specific database that gathers data about metro construction accidents from different data sources would be extremely helpful for researchers and practitioners, enabling them to retrieve valuable information for systematic learning of lessons from past accidents and prevention of similar accidents in the future.
- With the increasing complexity and coupling of the internal elements and external environments of metro construction projects, traditional safety theories, methods and models focusing on linear causality may no longer be applicable. The present overview calls for a more proactive philosophy (e.g., resilience engineering, high-reliability organization), and a system perspective for future research in metro construction safety.
- With the progress and development of Construction 4.0, the application of technologies such as big data, Internet, blockchain, computer-aided management and BIM may help to effectively manage and control many aspects of the metro construction process, including scheduling and cost.
- Given the trend of metro systems towards increased travel speed of metro trains in relatively narrow tunnels, the control of aerodynamic effects to improve passenger comfort requires further attention. As aerodynamic conditions in high-speed metro systems influence passenger comfort, safety control strategies require ongoing attention.
- To reduce the energy consumption of indoor environmental control systems, there is a need for in-depth studies on how pollutants are affected by the coupling effect between piston airflow and metro ventilation systems.
- With ongoing technological development in metro systems, the current reliability issues will eventually be mitigated, but at the same time new problems will be identified, providing new areas for research, with continued attention on reliability and vulnerability.
- Metro's impacts on land use and UUS utilisation, travel behaviour, public health, housing prices, the wider economy, air pollution, and GHG emissions have been mostly examined at a small scale (e.g. in station areas) and have adopted a short-term perspective (e.g. during a short time period). Considering the longer-term impacts of metro development, and incorporating broader urban development goals, including sustainability and resilience, require more research attention.
- With more and more metro systems being developed, it is increasingly important to adopt an inclusive perspective regarding the impacts and consequences of such development. Like many forms of urban underground development, metro construction affects underground conditions, e.g., by altering water, soil and rock environments, and these changes generally are irreversible. Whether these changes, and the changes in urban mobility, health, and economic, environmental, and social dimensions are a net benefit has been little examined, and this issue will require more studies in the future.

6. Conclusion

This comprehensive overview of the metro system, comparing the findings of various international studies on metro construction and operation, and the impact of metro systems on cities, is significant as it advances understanding of metro systems as important urban transport infrastructure. The following conclusions and future research directions are provided.

First, the development of metro construction was reviewed, with a particular focus on major methods for metro construction, construction safety risk in metro projects, cost and scheduling of metro projects, and metro construction impacts on adjacent structures or environments. Despite the extensive attention paid to subway construction safety management, a complete accident record from metro construction sites does not exist for use in accident case analysis, a method which is recognised as one of the most effective methods for preventing accident occurrence. Such a specific database is necessary for gathering information on metro construction accidents from different data sources. It is helpful for researchers and practitioners to retrieve this valuable information, in order to systematically learn lessons from past accidents and avoid similar accidents in the future.

Second, to ensure operational safety, various aspects such as fire safety control, passenger and personnel evacuation methods, impacts of aerodynamic effects, and indoor air quality in the context of the safety of metro systems during daily operation have been reviewed. With the rapid development of rail transit technology, metro systems are constantly being updated, tunnel types are becoming more and more diverse, metro stations are being buried deeper and deeper, more and more multi-line transfer stations are being constructed, and transport hubs that connect metro systems with high-speed train connections or airports are being put into operation. Fire safety control strategies and evacuation methods for use in normal scenarios will not necessarily be suitable for more complex metro tunnels and stations, and are likely to become important research topics in the future. As trains are running faster than before, the impact of aerodynamic effects, and the influence of aerodynamic effects on passenger comfort and indoor environment cannot be ignored. The combined impact of aerodynamic effects and ambient wind is another potential research subject in the future.

Third, the impacts of metro development have been reviewed, in particular its influence on land use, urban underground space utilisation, property prices, urban economies, travel behaviour, public health, air quality, and greenhouse gas emissions. Such impacts of metro development have been investigated by researchers in various contexts in recent years, with most studies confirming the long-term benefits of metro development. Nevertheless, the net benefits to society and the environment from metro development, taking into consideration these impacts and other irreversible changes on underground conditions, e.g. by altering water, soil and rock environments, have only been narrowly examined. Therefore, this topic requires future research to advance our understanding of the overall cost-benefits of metro development, and to support decision-making.

CRediT authorship contribution statement

Dong Lin: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Zhipeng Zhou:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Miaocheng Weng:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Wout Broere:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Jianqiang Cui:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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