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Greenhouse gas emission analysis and measurement for urban rail transit: A review of research progress and prospects

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Abstract

Rail transit plays a key role in mitigating transportation system carbon emissions. Accurate measurement of urban rail transit carbon emission can help quantify the contribution of urban rail transit towards urban transportation carbon emission reduction. Since the whole life cycle of urban rail transit carbon emission measurement involves a wide range of aspects, a systematic framework model is required for analysis. This research reviews the existing studies on carbon emission of urban rail transit. First, the characteristics of urban rail transit carbon emission were determined and the complexity of carbon emission measurement was analyzed. Then, the urban rail transit carbon emission measurement models were compared and analyzed in terms of the selection of research boundaries, the types of greenhouse gas (GHG) emissions calculation, and the accuracy of the measurement. Following that, an intelligent station was introduced to analyze the practical application of digital collaboration technology and energy-saving and carbon-reducing system platforms for rail transit. Finally, the urgent problems and future research directions at this stage were discussed. This research presents the necessity of establishing a dynamic carbon emission factor library and the important development trend of system integration of carbon emission measurement and digital system technology.

Keywords: Urban rail transit, Life cycle assessment (LCA), Greenhouse gas emission, Digital collaboration technology, Carbon emission factors, Climate change, Measurement method

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Introduction

Environmental concerns are currently one of the key topics in global transportation policy. Urban rail transit is a type of environmentally friendly transportation that uses little energy and produces little pollution[1]. To reduce greenhouse gas (GHG) emissions and address the issue of global warming, there needs to be a vigorous development of urban rail transportation along with energy conservation[2] and emission reduction in transportation. GHG emissions have become an important part of environmental assessment in the transportation sector, and adequate urban rail transit carbon emission measurement studies can be used to accurately monitor and assess progress toward carbon reduction targets. The mechanism and laws governing the carbon emission of urban rail transit can also be revealed through analysis and prediction of the application effect of carbon emission reduction policies, allowing for the proposal of policies and measures aimed at reducing those emissions. Such comprehensive and in-depth research work can provide a theoretical basis for decision-makers and engineering organization managers to reasonably formulate urban transportation development policies and arrange construction tasks of engineering projects. The research on GHG emissions of urban rail transit involves many aspects, and different studies have different research objectives and other focuses. Therefore, it is necessary to summarize and organise the existing studies to clarify the current research progress and the future directions that need further efforts, in order to help researchers better carry out their research work.

There have been more studies on GHG emissions reduction for rail transit types other than urban rail transit, such as high-speed railways and intercity railroads, among which carbon emission analysis of new high-speed railways is the focus of research. For example, Lee et al.[3] conducted the first assessment of GHG emissions generated during the construction of high-speed rail infrastructure within Korea. According to some studies, it is possible to offset the majority of the emissions produced by new high-speed rail systems by reducing the need for road and airport construction and maintenance, as well as automobile manufacturing[4]. Moreover, the payback period of GHG emissions from the construction of high-speed rail facilities is influenced by the number of passengers using high-speed rail[5], and transportation mode shifts (high-speed rail diverting road and air traffic) also offset carbon emission from rail infrastructure construction and train manufacturing[6,7]. Due to the comprehensiveness of the life cycle assessment (LCA) methodology, it has been widely used earlier in the study of GHG emissions impacts of high-speed rail[8,9]. For example, Cheng et al.[10] assessed the carbon footprint of the Beijing-Tianjin intercity high-speed rail using the hybrid input-output life cycle method. Lin et al.[11] used the hybrid economic input-output and life cycle assessment (EIO-LCA) method to estimate the carbon footprint of the Beijing-Shanghai high-speed rail line. Some studies point out the need to introduce a life-cycle assessment approach to the measurement of GHG emissions from railroad systems and suggest that due to the long operational life of high-speed railways, their environmental assessment must be able to take into account long-term technological and energy structure changes[12,13]. The power production structure also has an important role in the life cycle environmental assessment of high-speed rail[14]. In addition, high-speed rail has a significant effect on reducing environmental pollution through the technology effect, configuration effect, and substitution effect[15]. Chen et al.[16] considered the spatial and temporal heterogeneity of carbon emission factors, analyzed the construction and operation data of the Beijing-Shanghai high-speed railway spanning several provinces and cities, and established a whole-life carbon emission model to calculate its carbon emission. Yang et al.[17] evaluated the energy saving and emission reduction effect based on the close value method, using the Beijing-Shanghai high-speed railway and Beijing-Shanghai freeway as calculation examples, which showed that the high-speed railway had the best energy saving and emission reduction effect compared with the other four transportation modes. The main differences in the research publications on the application of the LCA method to high-speed railways are the specific items related to the carbon emissions considered and the corresponding improvements and adaptations of the LCA method due to the different purposes of the research.

Research works such as carbon emission measurement of high-speed railways and intercity railroads have some inspirational value for urban rail transit, but because urban rail transit has its own characteristics, such as relatively low design speed, high departure frequency, many stops, high capacity, and small station spacing[18,19], there are clear differences from other rail transit types. The most important energy source in the operation phase of urban rail transit is electricity, and the use of electricity will bring GHG reduction potential when the generation method is renewable, but in countries or regions that rely heavily on coal-fired power generation, such as Australia[20], it may bring negative impacts, so the evaluation of the carbon reduction effect of urban rail transit is of great significance, and there are relatively few studies on urban rail transit carbon reduction measurement and analysis methods. Therefore, it is necessary to systematically study the carbon emission reduction potential of urban rail transit, the measurement method, and its accuracy. This research provides a comprehensive overview of the research work involving the analysis and measurement of GHG emissions of urban rail transit, assisting researchers in gaining a comprehensive understanding of the current status of research in this field and the problems that exist, with a view to providing directions and suggestions for further in-depth exploration in this field in the future.

The frame of this research is structured as follows. The next section discusses the carbon emission reduction potential of urban rail transit, the characteristics of urban rail transit carbon emission, and the complexity of its carbon emission measurement. Following that we present the measurement boundaries, calculation models, and discussions on the accuracy of carbon emission calculations for studies related to urban rail transit measurements. Next we provide analysis of the application of digital platform terminals in the field of energy consumption and emission sensing and control for urban rail transit, using a smart station as an example. Finally we provide an analysis of unresolved issues and future directions before concluding with a summary.

Carbon emission reduction potential, carbon emission characteristics, and measurement complexity of urban rail transit

The majority of the early research studies have debated and examined the potential of urban rail transit to reduce carbon emissions. In addition, we have summarized the characteristics of urban rail transit carbon emission through research and analysis. Based on these research results, this section analyses the complexity of urban rail transit carbon emission measurements.

Carbon reduction potential ability/contribution of urban rail transit

The relative merits of urban rail transit versus other modes of public transportation have been debated[21,22]. It is widely believed that urban rail transit is energy-efficient and environmentally friendly, partly in consideration of the shift from other high-carbon-emitting modes of transportation to urban rail transit, while in practice, most of the shifted users originate from buses and nonmotorized users[23]. Additionally, even as urban rail transit mileage increases, car ownership will continue to rise[24]. However, the actual emission reduction effect of urban rail transit compared to other transportation modes (especially buses) needs to be further analyzed in depth based on specific spatial and temporal characteristics, especially when carbon emission from station energy and electricity are considered, the emission advantages of urban rail transit should be further quantified and evaluated[25]. First, the provision of new large-scale infrastructure is inherently GHG-emission-intensive, including underground systems such as tunnels and stations, whose GHG emissions are several orders of magnitude more intense than those of conventional above-ground systems, and thus require a comprehensive in-depth study[26]. Second, if there is less demand for space (e.g., less demand for urban rail in local cities) or less demand for time (e.g., during off-peak hours when public transportation is less effective[27]), resulting in a low passenger load factor, it is clearly not environmentally friendly, and increased use of private cars can reduce the carbon reduction of urban rail[28]. Meanwhile, the short-term environmental impacts of urban rail transit construction are undesirable[29]. Research conducted by Lee[30] shows that the carbon reduction effect of urban rail investments is highly effective in places with better public transport demand.

Rational development of urban rail transit is necessary, and many scholars have also conducted in-depth analytical studies for verification. The Sheppard subway line in Toronto, Canada, produced higher GHG per passenger kilometer than the buses it replaced for the first six years of operation, and the carbon reduction benefits of the line only became apparent after six years due to increased subway ridership and a rapid reduction in electricity emission factors, with calculations showing that after nine years of operation, the Sheppard subway line nearly compensated for the initial GHG emissions[31]. Research by Lederer et al.[32] using the Vienna metro line U2 as an example shows that the occupancy factor of the metro has the most significant effect on carbon emission reduction in urban rail transit, followed by other factors such as additional vehicles and changes in energy structure. A study by Andrade & D' Agosto[33] on the new L4 metro line in Rio de Janeiro shows that its operation has a positive impact on emissions even at a low occupancy factor (> 3.44%) or high electricity emission factor (below 1.14682 kg CO_2/PKM). However, the increasing use of alternative fuels in cars and buses could undermine the advantages of the rail system. Chen et al.[34] measured the carbon emission reduction results and sensitivity analysis of four typical urban rail lines (metro lines 6, 9, 10, and 15) in Beijing in 2014. Their findings revealed that urban rail transit carbon emissions were strongly correlated with the electricity carbon emission factor, the proportion of passengers' travel modes prior to the opening of urban rail lines (particularly the proportion of the minibus transportation mode); in addition, if the proportion of coal-source electricity is high, the emission factor will be higher, which in turn weakens the carbon emission reduction potential of urban rail transit. The study did not consider the mitigation effect of urban rail transit on road traffic congestion[35], which would further reduce carbon emission from road traffic that has not yet been transferred. The carbon reduction effect will be significantly increased if urban rail transit can convert car trips that aren't made on buses or bicycles. Rapidly growing metros have actually changed greening patterns such as bicycles and buses, and to reverse this trend, more restrictions on car use are needed, such as increased car congestion charges and park-and-ride lots (P+R) around suburban metro stations[34].

Yu et al.[36] estimated the carbon emission generated by the daily operation of the metro system and finally obtained the carbon emission generated per kilometer or per passenger trip, which provided a theoretical basis for the government to establish a citizen's carbon tax and carbon supplementation mechanism. Zhang et al.[37] used a backward analysis to analyze the proportional limits of coal and electricity consumption for urban rail transit in each of the 18 Chinese cities from 2015−2017. This research concluded two points: 1) Transportation demand is proportional to the carbon reduction potential of urban rail transit; 2) Compared to urban rail transit, the growth of surface public transportation is more beneficial to meeting carbon reduction targets for cities with high coal and energy usage. Promoting urban rail transit development to reduce energy consumption per unit travel distance per capita is a fundamental way to increase the emission reduction potential of urban rail transit.

In addition to the metro, light rail is also a common mode of urban rail transit. Compared to the metro, light rail has cheaper construction costs, a shorter construction cycle, and is better able to adapt to the transportation needs of small and medium-sized cities. A study of Metro's Orange Bus Rapid Transit and Gold Light Rail in Los Angeles showed that (Bus Rapid Transit) BRT outperformed light rail in terms of GHG emissions in the short term, while light rail may have greater potential to reduce life-cycle carbon emission in the long term[38]. Sadeghi[39] quantified the emission reduction potential of urban rail transit in Mashhad city based on considering the impact of fuel type and trip mode shift and analyzed the pollutant and GHG emissions trends of light rail operation phase in Mashhad city from 2011 to 2019, revealing that increasing the number of light rail trips and reducing the emission factor of power generation are the two main factors to improve the performance of light rail, and expanding the light rail system in Mashhad city will have a significant impact on emissions such as CO_2. Dimoula et al.[40] estimated GHG emissions for the construction and operation of major road and rail infrastructure in Greece and demonstrated that roads have a smaller environmental impact than railroads during the construction phase, while railroads are more environmentally friendly than roads during the operation phase. In addition to passenger transportation, the use of urban rail transit also has a positive effect on the reduction of carbon emission regarding freight transportation[41]. As a result, countries around the world are committed to developing urban rail transit, as shown in Table 1[42]. Urban rail transit has obvious advantages in reducing GHG emissions under certain conditions (reasonable electricity production structure, high efficiency of urban rail transit utilization, etc.).

Carbon emission characteristics of urban rail transit

Through our research and analysis, we conclude that the carbon emission of urban rail transit is characterized by multistage, influenced by nonoperational stages, and spatial and temporal heterogeneity, as follows.

Table 1. Total length of urban rail transit operation lines around the world in 2021.

Continent	Country/region	Metro mileage (km)	Light rail mileage (km)	Tram (km)	Total (km)
Asia	China	8206.48	422.51	563.63	9192.62
Europe	Germany	403.10	–	3537.49	3940.59
North America	The United States	1384.10	1316.01	353.32	3053.43
Europe	Russia	640.20	58.70	1369.20	2068.10
Europe	Ukraine	114.06	21.00	1209.60	1344.66
Europe	France	362.30	18.40	861.10	1241.80
Asia	Japan	791.20	108.80	220.45	1120.45
Europe	Poland	35.50	20.10	970.00	1025.60
Europe	Spain	510.00	146.12	340.79	996.91
Asia	Korea	837.44	88.31	–	925.75
Europe	The United Kingdom	450.50	99.50	229.60	779.60
Asia	India	709.49	–	28.00	737.49
Europe	Italy	221.70	27.70	361.30	610.70

Multistage

In order to more effectively and rationally mitigate the environmental impact of transportation, decision-makers need to consider the full life cycle of energy use and carbon emission. Carbon emission from urban rail transit involves materials production, construction and building (material transportation, site construction), operation and maintenance, and scrapping and dismantling, while more than 90% of carbon emissions (not considering the scrapping and dismantling stages) are generated in the operation stage[43]. These phases can be categorized as operational (both train operations and station operations) and nonoperational[44]. Therefore, a comprehensive measurement of urban rail transit carbon emission requires consideration of emissions at all stages of the full life cycle. LCA aims to provide a near-complete accounting of the impact of a product throughout its life cycle[45]. LCA consists of four steps: goal and boundary definition, inventory analysis, impact assessment, and interpretation[46]. Life cycle inventories are needed first, and Horvath[47] provide a life cycle inventory of air emissions associated with the transportation of goods by rail and other modes in the United States. Chester et al.[48] created inventories that calculate life-cycle energy and emissions for multiple modes of transportation (including cars, buses, and trains) for metropolitan areas in the United States. This inventory includes both operational and nonoperational components of vehicles. Trevisan & Bordignon[49] extracted research hotspots from the literature on the level of GHG emissions, such as carbon dioxide from aviation, road, and rail transportation as well as discovered that emissions from infrastructure development, which have a significant impact on total emission levels, are frequently overlooked.

Highly influenced by the nonoperational phase

Compared to road and aviation, the energy consumption and GHG emissions of railroads are more influenced by the nonoperational phase[50], such as the energy use in station construction and the operation of infrastructure other than train traction. This is especially true in some cities where excessive ornamentation is used to build urban rail stations, which significantly raises energy use for regular station operations. The construction and operation of railroad-affiliated infrastructure and train manufacturing can increase total railroad exhaust emissions by a factor of 5−17 and total air emissions by a factor of 3−9[51]. Additionally, using more hydropower and other renewable energy sources during the operational phase compared to coal power may result in significant reductions in GHG emissions.

Spatio-temporal heterogeneity

Different regions have different transportation system structures, electricity production structures, and other factors, resulting in large differences in urban rail transit carbon emission in different regions. For instance, a study found that the eastern provinces of China were the source of more than half of the 335 million tons of carbon dioxide equivalent of total GHG produced by urban passenger transportation in China[52]. In addition, the carbon emission factor is very high in northern China because almost all electricity relies on fossil fuel production. In contrast, the southern region mostly comes from hydropower or nuclear power, so the carbon reduction effect of urban rail transit is higher[34]. Moreover, even if the regions are the same, changes in electricity emission factors and efficiency gains in technological processes can make carbon emission vary over time from a macro perspective. From a microscopic perspective, the carbon intensity of urban rail transit is also significantly different between peak and off-peak periods[53]. In addition, the wide heterogeneity of different urban rail projects in terms of type (subway, light rail, tram, etc.), location (including ground conditions and elevation), design (including stations and the proportion of elevated and tunneled sections of the line required), and soil properties can also lead to large differences in assessing GHG[54].

Complexity of urban rail transit carbon emission measurement

Combining the characteristics of carbon emission of urban rail transit, we analyzed the complexity of carbon emission measurement of urban rail transit with the difficulty of tracing the power production structure, the uncertainty of new urban rail transit, the large scope involved in the whole life cycle evaluation, and the complexity of quantifying the carbon emission effect under the interaction with other transportation modes through further in-depth study.

Difficulty of power production structure traceability

Most of the energy consumed in the whole life cycle of urban rail transit is electricity, so its GHG emissions are indirect. And the electricity production structure has an important influence on the carbon emission of urban rail transit. The measurement of carbon emission of urban rail transit involves the exploration of the terminal emission of electricity production. Further research on the terminal emission of electricity production will generate a large workload, and the factors that need to be considered include the proportion of electricity sources, whether other countries and regions are involved, and even the spatial and temporal heterogeneity of electricity emission factors (a dynamic electricity carbon emission factor library is lacking), etc. The losses during power transmission should be analyzed accordingly[55]. Therefore, existing studies are less likely to analyze this in depth. However, it is necessary to consider the end emissions of power production, and in order to avoid the workload being too large, the relevant research in the power industry should be connected with the urban rail transit industry to ensure the credibility of the carbon emission measurement of urban rail transit.

Uncertainty of new urban rail transit

In building capital-intensive urban rail transit, there is a need to fully account for all long-term costs and benefits[56]. For new metro and other urban rail transit projects, to measure their carbon emission reduction benefits, it is necessary to predict the future traffic mode conversion and traffic volume, etc. This includes the redistribution of passenger flows in the existing public transport system, the possibility of replacing walking and cycling, and the state of induced demand for new transport[26]. A study of the Los Angeles Light Rail in the United States showed that at least 35% of the volume of traffic needs to be diverted from automobiles to repay GHG emissions during construction and operation, so modeling predictions of changes in passenger volumes are critical[38]. Even if the proportion of chosen public transport modes increases relatively, the positive stimulating effect of new urban rail transit on transport demand may instead increase rather than decrease GHG emissions[57], and consideration of this aspect is necessary, but there are fewer relevant studies. Future research may focus on the implementation strategy of transportation demand management (TDM) and carbon emission reduction in urban rail transit. In addition, the proportion of tunnel sections constructed has important implications for assessing the environmental impact of new rail infrastructure and should be given due consideration[58]. For projects that have been completed or are under construction, data such as changes in traffic volume before and after construction need to be collected for reference to future construction project forecasts. The impact of new urban transit-induced travel on GHG emissions also needs to be quantitatively assessed, not only for new transportation demand[59] but also for modal shift projections.

Whole life cycle evaluation covers a large scope

The essential elements that should be taken into account in a thorough evaluation of the GHG impacts of railroad infrastructure projects are outlined in Fig. 1, which covers the many components of measuring the carbon emissions of urban rail transit. This includes a detailed analysis of the scrapping and dismantling phase, such as recycling rates and other indicators. In particular, it is difficult to establish a unified evaluation model because of the differences in the characteristics of different urban rail transit projects, the focus of the research objectives, and the type and level of detail of the data obtained.

Key factors to consider include transportation mode shift and ridership, temporal and spatial heterogeneity, and urban form and land use. Meanwhile, the different methods of determining carbon emission factors for different energy types are also key indicators that affect carbon emissions. Among them, for urban rail transit, the main energy supply comes from electricity, and the electricity production structure has an important influence on the carbon emission factor of electricity, which is generally determined according to the geographical region where the research project is located.

The complexity of quantifying the carbon reduction effect under the interaction with other transportation modes

Urban rail transit belongs to the integrated transportation system, and it is difficult to quantify the carbon reduction effect under the interaction between urban rail transit and other transportation modes. Most studies solely segregate urban rail transit from the integrated transportation system to analyze carbon emissions, and the studies on how other transportation modes interact only look at the obviously biased mode shift study of traffic volume. For example, for new BRT and LRT (light rail transit) lines in Los Angeles, Chester et al.[60] conducted near-term and long-term life-cycle impact assessments involving two different frameworks (attributional and consequential) based on passenger transit mode shifts. For the analysis of transportation mode shift, it is necessary to take into account the impact of GHG emissions in the first mile before passengers go to the station to board the train and the last mile from the station to the destination for urban rail transit, but in practice, it is often difficult to include this factor in the study due to the lack of data, which is an aspect that needs further improvement in future studies. Such studies tend to ignore the carbon emission reduction effect generated by the interaction of different transportation modes. The integrated transportation mode based on multimodal transportation is the future development trend. Accordingly, how to measure the carbon emission reduction effect under the interaction between urban rail transportation and other transportation modes is a complex systemic issue, which requires the establishment of different scenarios for comparative analysis.

Calculation model of urban rail transit carbon emission research

This section summarizes the research boundaries that need to be determined first for urban rail transit carbon emission studies and the main existing carbon emission calculation models. Based on the above work, this research further discusses the accuracy of carbon emission calculation in terms of the applicability of carbon emission factors, the selection of measurement stages, and the accuracy of data.

Research boundaries

For urban rail transit carbon emission measurement, there are two main types of research boundaries. One type is for a specific stage of the life cycle of the urban rail transit system, while the other type is for the whole process of the life cycle.

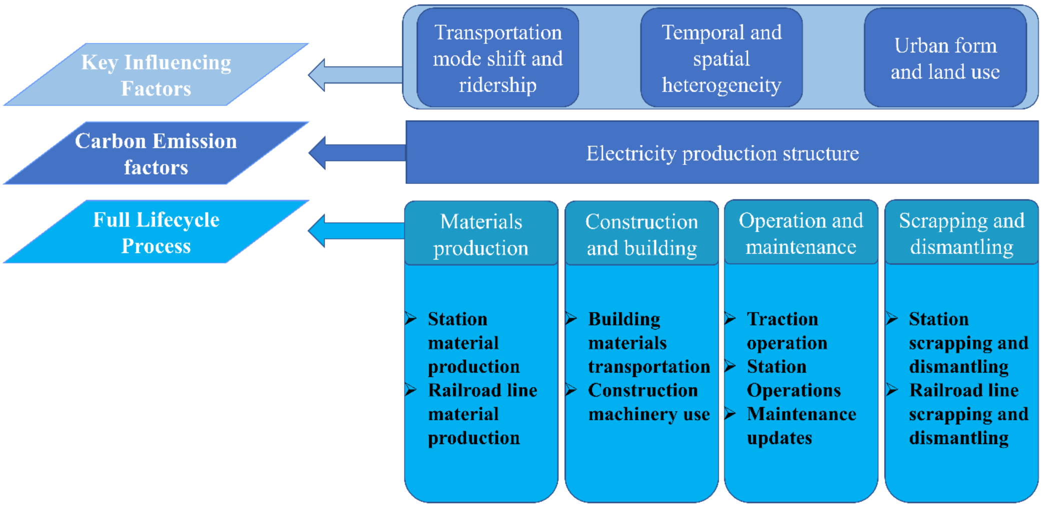

Fig. 1 Key elements of the net GHG impact of urban rail transit systems.

Based on these two types of research boundaries, various scholars have established different emission measurement models accordingly. When determining the carbon emission research boundary, the urban rail transit system is similar to other railroad systems, and its life cycle stages are shown in Fig. 2, including four stages: materials production, construction and building, operation and maintenance, and scrapping and dismantling. Some scholars also point out that the whole life cycle stage also includes the design stage of urban rail transit[61], but most studies using the LCA method to measure the carbon emission of urban rail transit do not take carbon emission in this stage into account. This is because the carbon emission in this stage is negligible in comparison to other stages. Olugbenga et al.[54] reviewed 57 case studies from 22 publications investigating the state of research quantifying implicit GHG emissions in rail (including rail, intercity rail, light rail, commuter rail, heavy rail, freight, and metro) infrastructure and based on this, proposed a model for estimating the gas impacts of rail infrastructure sketch model. The study compared the boundaries, functional units, methods, and data identified across the literature. The results show that most studies use engineering-based LCA for attribution analysis, and the study highlights the need for standardization of specific GHG reporting for rail infrastructure.

Stage-specific measurements

The GHG emissions measurements for specific phases are mainly focused on the construction and building phase and the operation and maintenance phase, and the construction and building phase includes both station construction and building and line construction and building. For station construction carbon emission, Liu et al.[62] proposed a quote-based carbon emission model for metro station construction and established a carbon emission database for each subproject. In further research work, artificial neural network (ANN) models were used to predict GHG emissions during the construction of the planned lines, and the payback period of each station was evaluated based on the training data of the in-service lines of the Fuzhou Metro[63]. A process-based quantitative model for the construction of subway stations using assembled structures was developed to study the mitigation potential of GHG emissions from prefabricated structures in metro stations, and the results showed that the construction of prefabricated sections per unit length produced 12.59% less GHG emissions than cast-in-place sections[64]. For carbon emission from line construction, Liu et al.[65] conducted a comparative evaluation of the environmental impacts of two excavation methods (open-excavation and underground-excavation) in metro construction. Zhang et al.[66] assessed the comprehensive environmental impact of CO_2 emissions from excavated soil and rock landfills and recycling during the construction and building phase of a metro, using the SLCA (streamlined life cycle assessment) method associated with the disposal phase of excavated soil and rock. Furthermore, Zhang et al.[67] conducted a global warming trend analysis of different recycling and landfill scenarios of excavated soil and rock for metro construction using an LCA model based on field investigations. Makarchuk & Saxe[68] studied the GHG emissions generated during the construction and reconstruction of the 510 Spadina streetcar route in Toronto and calculated that the total emissions from construction and reconstruction activities were 27.4 kilotons of CO_2 equivalent (kt CO_2e) over a 28-year period.

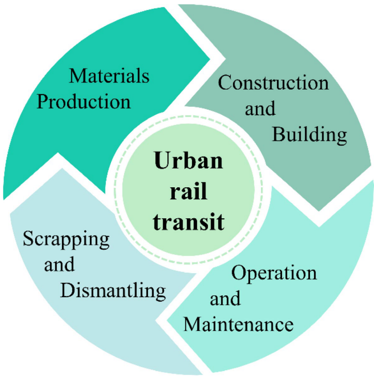

Fig. 2 Urban rail transit life cycle process.

The operation and maintenance phases are other important carbon emission measurement phases besides the construction phase, which involves a long process cycle and correspondingly rich research content. Krezo et al.[69] systematically estimated GHG emissions during railroad construction and maintenance, which indicated that extending the service life of railroad infrastructure assets through maintenance is beneficial for reducing GHG emissions. Saxe et al.[70,71] studied the net GHG emissions of the Jubilee Line Extension in London, UK, assessing GHG emissions associated with construction, operation, passenger volumes, and changes in urban density. This research also analyzed the changes in passenger travel behavior and its impact on GHG emissions and calculated the GHG emissions reduction from 2000 to 2011 to be 338 kt CO_2e. Krezo et al.[72] pioneered the study of the CO_2 impact of resurfacing during ballasted track bed maintenance in the railroad maintenance phase. Andrade & D'Agosto[33] presented and applied a procedure to calculate the reduction of energy use and emissions of the new metro line 4 in Rio de Janeiro by attracting users of other transport modes between 2016 and 2040 based on the projected demand of local traffic conditions and energy structure. The results of this research show that the new metro line 4 in Rio de Janeiro will reduce net CO_2 emissions by 55,449 t per year, 44.53 g per passenger kilometer, and reduce the energy to 0.76 MJ per passenger kilometer. Chen et al.[34] established an urban rail transit carbon emission calculation model based on transportation mode shift by comparing the travel mode, distance, and corresponding energy consumption of residents before and after the opening of urban rail transit based on a large amount of transit smart card data. Tuchschmid et al.[73] developed a methodology and calculation tool to determine the carbon footprint and environmental impact of rail infrastructure. Wei & Chen[74] proposed a life-cycle approach to quantify the energy and carbon footprint of urban transportation infrastructure (roads, metros, etc.) over time. Hanson et al.[75] proposed a methodology to assess GHG emissions associated with the construction of commuter rail projects. This method focuses on material-related upstream emissions, specifically tracks, catenaries, station platforms, parking facilities, as well as bridges and tunnels. Liu & Wang[76] used an improved weighting method considering the mileage traveled to assess the carbon emission of urban cars and metros, and their part of calculating the carbon emission of metros was based on the amount of energy consumed at the operating terminal of the train phase with a carbon emission factor. Lee & Suzuki[77] evaluated several scenarios based on GIS estimates of car and metro travel times to analyze the effect of CO_2 reduction. Since the phase of analysis is specific and involves a short process, the measurement of urban rail transit carbon emission for a specific phase facilitates in-depth analysis of a specific problem. However, its drawback is also obvious, as the measurement of specific stages often does not consider enough mechanism of interaction of each stage, which makes it difficult to thoroughly and comprehensively analyze the overall carbon emission level of the urban rail transit system.

Whole LCA

Compared with the carbon emission measurement of urban rail transit for a specific stage, the whole LCA is beneficial to consider the carbon emission reduction effect caused by the interaction of each stage. In addition, the whole life cycle process must be considered for analyzing the carbon emission recycling period of urban rail transit construction and operation. Therefore, the introduction of the whole LCA method can comprehensively assess the carbon emission level of urban rail transit and is also a research method that has been more frequently adopted in recent years. Figure 3 depicts the system boundary for the detailed GHG emissions calculation of the urban rail transit system.

Lederer et al.[32] used the life cycle inventory assessment (LCIA) method to calculate the cumulative energy demand and GHG emissions of Vienna's subway line U2 under the conditions of implementation of different measures (high full load factor, changes in the electricity production structure, and energy efficiency due to technological progress). Andrade et al.[78] evaluated the energy used, emissions generated, and emissions decreased over the 60-year life cycle (infrastructure construction, train manufacturing, maintenance, infrastructure operation, and train operation) of the new lines of the Rio de Janeiro metro network. The results of this research show that the CO_2 emissions per passenger per kilometer are 13.90 g over the full life cycle, while nonoperational emissions will be compensated 14 years after the start of the system. Kimball et al.[79] evaluated the impact of transit-oriented development along the Phoenix light rail system on reducing the total life-cycle environment. For the heavy metro trains that will operate in the Rome metropolitan area, Del Pero et al.[80] performed an LCA prediction analysis. Isler et al.[81] studied the life-cycle costs of different rail improvement strategies and showed that promoting new optimized routes can provide economic benefits in terms of reduced fuel consumption for companies operating urban rail transit and society due to reduced GHG emissions. Li & Zhu[82] proposed a method to quantify carbon emissions from monorail transit using the LCA method. Gulcimen et al.[83] conducted a life cycle sustainability assessment of a light rail transit system in Kayseri, Turkey, using the PhD version of SimaPro 8.4.1 software based on ISO 14040 and 14044.

Carbon emission calculation model

To obtain a uniform metric, we usually convert other types of GHG (methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), etc., and sometimes CO is included in the calculation) into CO_2e for GHG carbon emission measurement[84]. There are two main types of carbon emission calculations for urban rail transit, one is based on the end-use energy consumption and carbon emission factors, and the other is the measurement of CO_2 emission factors based on travel distance and travel mode[23]. While calculations based on end-use energy consumption and associated carbon emission factors are more suitable for data on urban rail transit, the first type of carbon emission measuring method is more direct and accurate but complete fuel consumption statistics are not readily available[85].

Calculation based on end-use energy consumption and carbon emission factors

Most studies based on end-use energy consumption and carbon emission factors have measured carbon emission for the operational phase, such as calculating GHG emissions by multiplying the electric energy consumption of urban rail transit systems by the carbon emission factor of electricity[86]. Chen & Wang[87] developed a comprehensive urban transportation carbon emission calculation model including urban rail transit and set up three low-carbon scenarios to analyze the carbon emission reductions compared to the baseline scenario. Hu et al.[88] developed a model for calculating the energy

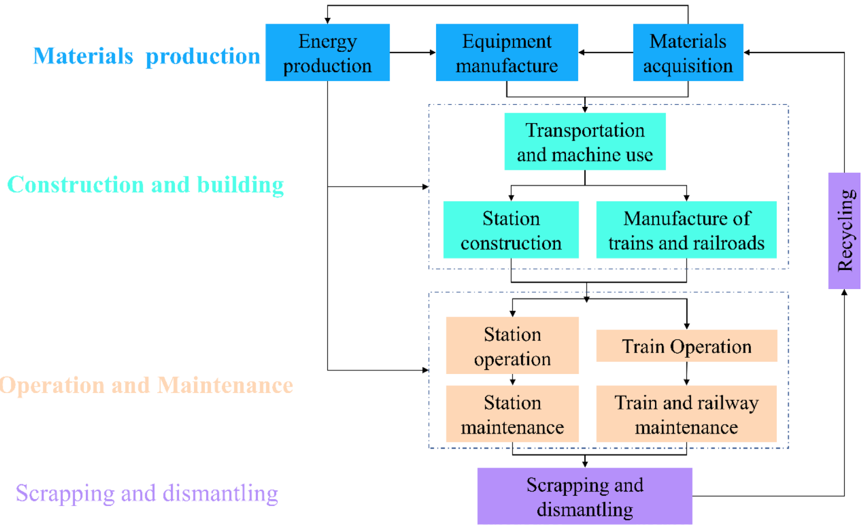

Fig. 3 Research boundary of life cycle carbon emission measurement for urban rail transit.

consumption and GHG emissions of urban rail transit, dividing the energy consumption into two parts: trains and stations. Inside the model, the carbon emission calculation only takes into account the impact of carbon emissions from thermal power generation, even though other power generation actually also generates a certain percentage of emissions. Kudo & Nakamura[89] developed a simulator to quantitatively evaluate the carbon emission reduction effect generated by transportation mode shifts, and the calculation involved carbon emission factors using data recommended by the Ministry of the Environment of the Japanese government. Mallia et al.[90] incorporated GHG observations from light rail platforms into the inverse modeling framework to provide additional constraints on urban GHG emissions estimates. Wang et al.[25] developed a carbon emission estimation model for typical urban passenger transport (including private cars, urban rail transit, cabs, and buses) in developing countries.

Based on the features of urban rail transit in Beijing, Hu et al.[91] created a model for calculating energy consumption and carbon emissions for urban rail transit. They then calculated the carbon emissions for train operation and station operation. Li et al.[85] developed a composite calculation model based on the characteristics of different transportation modes, in which for carbon emission of urban rail transit, the calculation is still based on the energy consumption of terminals and the carbon emission factor of electricity. Dong et al.[92] quantified the carbon emission of urban public transport systems (including buses and metro) in Shenzhen using the LCA approach, where the energy consumption of buses and metro was calculated based on different energy types (including diesel, hybrid energy, electricity, etc.). Ha et al.[93] studied GHG emissions calculations based on transportation mode shift and demonstrated the positive environmental impacts of tram line extension. Other scholars have also considered the carbon emission reductions resulting from transportation mode shifts due to the introduction of the metro, where carbon emission reductions from other transportation mode shifts are calculated using a method based on travel distance and transportation mode[94−96]. Kaewunruen et al.[97] introduced the first digital twin technology to assist in the assessment of urban rail transit life cycle carbon emission, and despite the limitations of poor model data interoperability, the study is still prospective. Wang et al.[98] studied the development of a bi-objective timetable optimization model to reduce passenger time and carbon emission based on train operation and passenger demand data, which divided the train operation process into tractive phase, coasting phase, and braking phase, where the carbon emission was calculated based on energy consumption. The GHG emissions benefits of private cars are inferior to the worst rail service category even when they are fully loaded, according to Logan et al.[99] who estimated GHG emissions per passenger km for rail trains (both electric and hydrogen train types) and private cars and examined the emission levels of four different rail service categories under four different generation scenarios in the UK from 2017 to 2050.

Calculation of carbon emission factors based on travel distance and transportation mode

The determination of carbon emission factors for various modes of transportation (not just urban rail transit; for urban rail transit alone, different modes of transportation such as metro, light rail, and tram are also distinguished) is necessary when calculating CO_2 emission factors based on travel distance and mode of transportation, where the travel distance is primarily influenced by land use patterns[23]. Zhang et al.[100] constructed two travel scenarios (scenarios with and without urban rail transit) from the perspective of passenger travel demand by considering the scale of travel demand attracted by different transportation modes in the city. The carbon emission per capita for each mode of transportation in this research area was obtained from the study and multiplied by the total number of passengers on the target routes to calculate the carbon emission from transportation trips. Shen et al.[101] developed a general calculating software that can calculate the energy consumption and GHG emissions of urban road and urban rail transit with input parameters such as the number of vehicles, passenger volume, and average travel distance. Aggarwal & Jain[102] studied the carbon emission of five types of transport modes based on the same model of calculating the distance traveled and its carbon emission factors for that mode of transport.

Table 2 summarizes and analyzes some of the research work on urban rail transit GHG emissions analysis and measurement in the literature.

Discussion of the accuracy of carbon emission calculation

Applicability of carbon emission factors

Most of the urban rail transit carbon emission lifecycle analysis is based on the system-wide average emission factors, and the match with the actual measured cases needs to be examined. Hanson et al.[75] studied the data for the materials and dimensions used for New Jersey Transit's five commuter lines based on guidance from existing engineering, with emission factors for each component sourced from existing upstream emission databases and analyzed the applicability of the data to derive GHG projections with greater accuracy of the calculations. For predicting the carbon emission intensity of a new metro in the future, the carbon emission reduction from the relief of road traffic congestion due to transportation mode shift should also be considered[34]. New urban rail infrastructure is a large infrastructure project whose construction will inevitably result in a reduction in urban tree cover, reducing the city's carbon sequestration potential. For example, the construction of the Kochi metro in India resulted in a 14.51 ha reduction in tree cover within 60 m of the metro centerline[103], so this influence should not be ignored when estimating carbon emission from urban rail transit.

Selection of measurement phases

The LCA method has become more widely used to assess infrastructure products, but it is also important to understand the research limitations of uncertainty in LCA. The transportation sector is also lagging in adopting uncertainty analysis for the application of standards, analysis of spatial and temporal differences, and industry characteristics, which call attention to their variability[104]. Whole life cycle evaluation of the actual transportation mode shift, mode share, and associated impacts on urban form is necessary. Saxe et al.[26,31,45,59,70,71,104] from 2015 to 2020 have conducted continuous and in-depth research work on urban rail transit carbon emission measurement, and this series of research work also reflects the trend and importance of introducing the whole life cycle of the urban rail transit carbon emission measurement research. The effects

Table 2. GHG emissions measurement model of urban rail transit in literature.

Country/ region	City	Type of urban rail transit	Research boundary	Summary	Reference
China	Beijing	Comprehensive	Operation and maintenance	No carbon emission by default for power generation methods other than thermal power	[88]
China	Hefei	Metro	LCA	The digital twin system was introduced to assist in LCA; there are limitations in data interoperability between different models of the system	[97]
India	Delhi	Metro	Operation and maintenance	The impact of transport mode shift due to the introduction of the metro on carbon emission is considered	[95]
China	Baoji	Comprehensive	Operation and maintenance	Developed a passenger demand-based carbon emission model	[100]
Austria	Vienna	Metro	LCA	Ignoring carbon emission from maintenance, dismantling, and recycling phases	[32]
Brazil	Rio de Janeiro	Metro	LCA	The GHG emissions compensation period of the urban rail transit system was analyzed	[78]
United States	Los Angeles	Light Rail	LCA	Two different LCA frameworks are used	[60]
United States	Phoenix	Light Rail	LCA	Developed an integrated transportation and land use LCA framework	[79]
China	Beijing	Metro	Construction and building	A quota-based GHG emissions quantification model for metro station construction is proposed	[62]
Canada	Toronto	Streetcar	Operation and maintenance	Study of GHG emissions from the construction and reconstruction of the Spadina streetcar route	[68]
United Kingdom	London	Metro	Operation and maintenance	Analyzed the impact of changes in passenger travel behavior on GHG emissions from metro	[70]
United States	New Jersey	Commuter rail	Construction and building	Different material inputs were evaluated during the construction of the railroad project	[75]
Italy	Rome	Metro	LCA	The use of data sourced from metro operators reduces the uncertainty of the results	[80]
Turkey	Kayseri	Light Rail	LCA	Integrating environmental, economic, and social factors with the LCA approach	[83]

of policies related to urban rail transit, such as parking policies and TOD (transit oriented development) development patterns, on the carbon reduction benefits of urban rail transit also deserve further analysis and research[105].

Accuracy of data

The data applied in the calculation is also one of the important influencing factors that affect whether the results of the model calculations are reliable. The data sources used in many studies include statistics from the transportation sector, and whether the statistics of such data are comprehensive and detailed is something that needs to be determined. For example, Liu et al.[106] reassessed the energy use of transportation in China in 2009 and found that the national transportation system's oil consumption was 57% of the national oil consumption, much higher than the 38% in the statistics. The main reason for this phenomenon is the difference between the Chinese energy statistics system and international standards. Moreover, as the majority of computational models include nondynamic limits on carbon emission components and are static, this restriction may allow for some room for improvement in the precision of carbon emission measurements[107].

Application of carbon emission measurement model for urban rail transit

The research on carbon emission measurement of urban rail transit eventually needs to be implemented into actual production, but there are few examples of the overall application of digital platform terminals in the field of sensing and controlling the energy emissions of urban rail transit systems. The combination of urban and digital system technology is the inevitable trend of future smart city development, and the design of system integration technology solutions and the establishment of terminal visualization platforms are the development trends of future urban rail transit carbon emission measurement models in actual production and life application. Therefore, this section will take an intelligent station design as a case for illustration, and the intelligent control platform display interface of this station is arranged as shown in Fig. 4. The mechanism of this station's intelligent control platform is to quantify the energy consumption (mainly electrical energy) of the rail transit system, followed by the measurement of the GHG emissions, to achieve the monitoring and carbon reduction management of the GHG emissions for the rail transit system.

The case station establishes a building equipment monitoring and energy management system, connecting it to the passenger station, passenger service and production control platform, remote centralized meter reading system, and automatic fire alarm system. The system also extends down to the central air conditioning energy-saving control system, intelligent lighting control system, electromechanical equipment monitoring system, various sensor collection gateways, and energy data collection host. By interacting, interlocking, analyzing, and strategizing with the data, the system can monitor the operation status of various types of mechanical and electrical equipment in the station and execute refined energy-saving control. The system comprehensively follows the three intelligent management objectives of safety, comfort, and energy saving. Through the scientific perception of environmental data, precise collection, and combination of passenger information, the main energy consumption equipment is extended from the control mode of self-closed loop within the respective system to a large closed-loop control related to the whole environment.

The passenger service and production control platform system of the case station provides technical support for im-

Fig. 4 Case station intelligent control platform display interface.

proving passenger management capability, passenger service quality, and equipment operation quality by establishing a passenger service and production control platform and realizing data sharing, business linkage among the passenger ticket system, passenger service system, building equipment monitoring and energy management system and comprehensive video monitoring system of the station. Figure 5 illustrates the architecture of the case station building equipment monitoring and energy management system. The interface of the case station building equipment monitoring and energy management system is shown in Fig. 6.

Building Automation Systems-Building Energy Management Systems (BAS-EMS) integrates a central air conditioning system, intelligent lighting system, electromechanical equipment monitoring system, environmental data collection system, energy management system, and other intelligent subsystems to form a comprehensive system with the functions of information gathering, resource sharing, and optimal control. The system allows for flexible control by integrating passenger information to optimize the control of related energy-consuming equipment. Intelligent lighting subsystem sets a single light control and dimming function in the public areas for the first time and can realize control according to the density of human flow, train arrival and departure information, improve lighting comfort, and enhance the level of intelligence and energy-saving effect through precise adjustment and control. The central air conditioning subsystem can realize system linkage control, which upgrades the innovative step-by-step control from the end air conditioner to the heat and cold source host without coordination mechanism to linkage calculation and parallel control, reducing the operating energy consumption. The electromechanical equipment monitoring system mainly consists of redundant access layer switches, redundant PLCs, IBP disks and various I/O modules, as well as other equipment to realize the status acquisition and control of electromechanical equipment, including escalators, on-site water supply and drainage equipment, air supply and exhaust equipment, and other similar items.

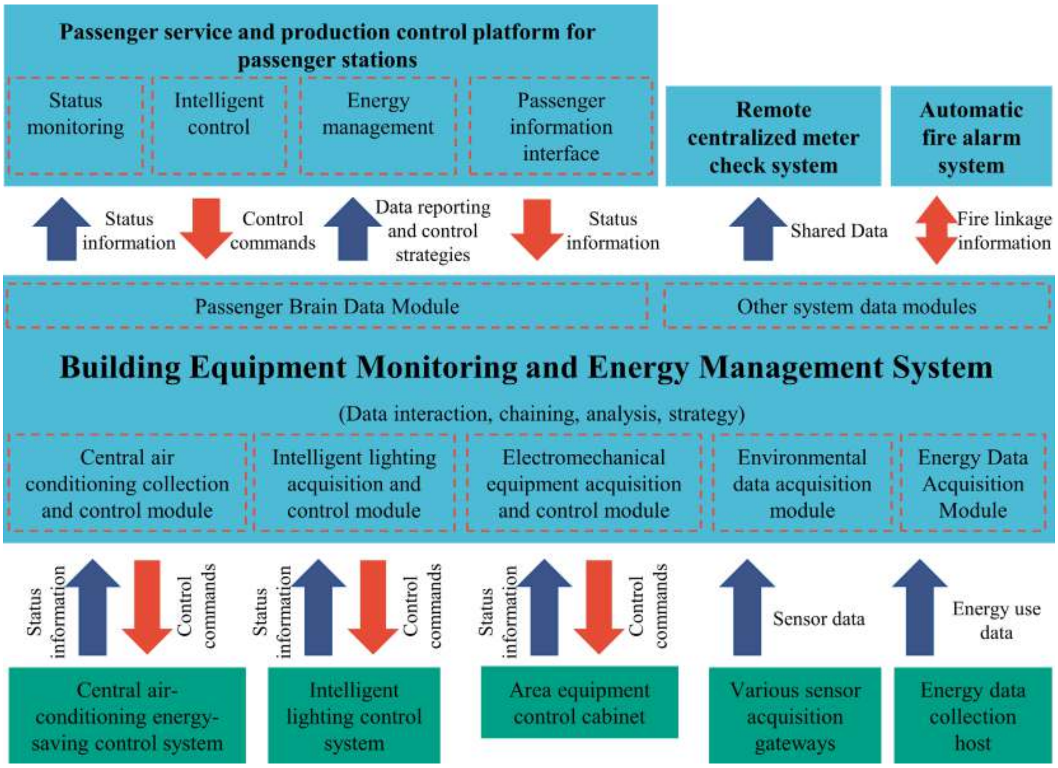

Fig. 5 Architecture of building equipment monitoring and energy management system of the case station.

Region	Temperature (℃)	Humidity (%)	Wind speed(m/s)
Waiting hall A	25	40	0.15
Waiting hall A	25	40	0.15
Waiting hall A	25	40	0.2
Waiting hall A	26	40	0.14
Waiting hall A	27	40	0.12

2020-01-01 12:11:00

Location : First floor waiting hall

Operation : Hot and cold water valve opening (80%), outlet 001 stall (high grade)

2020-0

Location : First floor waiting hall

Operation : Hot and cold water valve opening (80%), outlet 001 stall (high grade)

2020-01-03 12:11:00

Description: The first floor waiting hall, Doremon DC001 malfunctioned

2020-01-01 10:11:00

Description: The first floor waiting hall, Doremon DC001 malfunctioned

Fig. 6 Interface of building equipment monitoring and energy management system of the case station.

The case station terminal collection and fresh air system adds $PM_{2.5}$ and CO concentration collection and linkage control to optimize air quality and enhance personnel comfort. By further optimizing the selection of collection points, the system sets up multifunctional sensors to detect environmental parameters such as temperature, humidity, CO_2 concentration, CO concentration, $PM_{2.5}$, and illumination, and carries out data auditing and abnormal data processing, thus realizing a series of automatic processing such as alarming and timely detection of station environmental problems and providing a basis for energy-saving linkage analysis. At the same time, the system is equipped with independent learning and self-improvement functions. The feedback value will be automatically fed back to this system to form a closed loop after the energy saving operation program is executed for the execution effect. The system will automatically judge the effectiveness of the implementation of this push program and self-learning, and constantly and dynamically improve the algorithm optimization model to ensure the continuous improvement of the system effect.

Unresolved issues and discussions

(1) Different components of urban rail transit, such as stations, trains, and other auxiliary facilities, have different life cycles. Further research is needed on how to reasonably integrate each component to measure the whole life cycle of the urban rail transit system. In particular, the issues such as the traceability of carbon emission inventories for each element in the construction phase, as well as the experiments on carbon emission measurement for civil engineering under mechanical shift and quota conditions, and the determination of carbon emission factors in the operation and maintenance phase (different regions, times, and different power production structures, etc.) are urgent subjects to be addressed.

(2) Most of the existing urban rail transit carbon emission studies focus on the micro level, while the macro carbon emission evaluation system has not been established, and the corresponding principles and methods are of relatively low application. For the evaluation of carbon reduction, several researchers[108,109] used the improved close value method, but more engineering theoretical methodologies require careful consideration. The measurement of carbon emission of urban rail transit is a system engineering, therefore, considering the evaluation of carbon emission reduction effect of urban rail transit system based on improved system engineering decision theory can be a direction for further discussion.

(3) There is a need for more research on the impact of modern control technologies on carbon emission in urban rail

transit systems[98,110], yet there are few pertinent studies available. In addition, there is less research on the application of the combination of urban rail transit carbon emission and digital system technology, and the design of the system integration technology scheme and the establishment of terminal visualization platforms are in urgent need of further in-depth research. For example, research on the integrated technology of digital carbon reduction management system of urban rail transportation for the whole process of 'sense-predict-induce'. For the station part, the construction of a comprehensive transportation hub/station carbon emission holographic sensing simulation and technology platform should be considered. Similarly, research on the optimization of energy saving and emission reduction in urban rail transit train scheduling schemes needs to be further enriched[111].

(4) Further research is needed to quantify the GHG emissions reduction effects of urban rail transit based on modal shift to mitigate traffic congestion, especially for the assessment of traffic peak periods[27]. Among the further research directions: research on the internalization of external costs of urban rail transit and carbon trading policies should be added; consideration of the impact of MaaS (Mobility as a Service) on the carbon emission effect of urban rail transit should also be added, and research on the carbon footprint calculation and incentive scheme optimization of urban rail transit passenger trips under the Mass mechanism should be conducted.

(5) For the measurement of urban rail transit, there are differences in the level of granularity of calculations by different scholars. Clearly, it is not possible or necessary to analyze every detailed aspect involved. Therefore, it is worth exploring whether the analysis of energy use in urban rail transit systems needs further refinement in the future[86]. On the one hand, too many detailed considerations will make the workload extremely large, and on the other hand, the impact of minor aspects on the overall carbon emission measurement can be ignored. What level of refinement we need to attain in the research we need to perform, then, is the crucial question, and the research needs to answer this. Conversely, when analyzed from a more macroscopic perspective, for example, the impact of urban rail transit systems on land use and urban development along their routes (e.g., commercial growth, residential development, and population density) can also contribute to GHG emissions to some degree[112−115], which is difficult to analyze quantitatively, but in-depth studies are necessary.

Conclusions

This research reviews the research progress in the field of carbon emission measurement of urban rail transit and provides a comprehensive overview of the existing studies. Current research has been more mature in terms of analysis of carbon emission reduction potential of urban rail transit, definition of research boundaries, measurement methods, and model construction. Due to the difficulty in tracing the structure of electricity production, the unpredictability of new urban rail, the length of the whole life cycle, and the complexity of interactions with other modes of transportation in the context of multimodal transportation, this research highlights the complexity of measuring carbon emissions from urban rail transit. In such a complex context, how to ensure the accuracy of carbon emission measurements, including the determination of carbon emission factors, the selection of measurement stages, and the accuracy and validity of data, are factors that should be considered in future research. In particular, this research analyzes the application of digital platform terminals in the field of energy consumption and emission sensing and control of urban rail transit, using a smart station as an example. There is a certain level of research system and progress in this field, but there are some unresolved issues. For example, the application of the whole LCA method has been more systematic and mature, but the research on realizing the real-time synchronous detection of the digital twin system for urban rail transit carbon emission measurement is not sufficient and still in the initial stages. The carbon emission measurement of the urban rail transit system involves many aspects, and there are problems such as the lack of accuracy and perfection of the data required for the measurement and the ambiguity of the definition of carbon emission, which hinder the realization of its simultaneous and accurate measurement.

Therefore, future research efforts should focus on:

(1) To guarantee the perfection of data detection and collection required for carbon emission analysis of urban rail transit systems and to improve the quality of data.

(2) Establishing a database of regional dynamic carbon emission factors and improving the carbon emission measurement model of urban rail transit system considering the spatial and temporal heterogeneity of carbon emission factors.

(3) Building a digital twin system to track the GHG emissions of urban rail transit system throughout its life cycle operations, combining data from various life cycle stages into a single model, and realizing the digitalization and visualization of urban rail transit greenhouse gas emission measurements[97].

(4) In determining the research boundaries, most of the existing studies are based on separating urban rail transit from the urban transportation system. Therefore, the research involving the measurement of carbon emission of urban rail transit in the integrated transportation system of multimodal transport types needs to be further improved[116].

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Conflict of interest

Yang Yang is the Editorial Board member of Journal *Digital Transportation and Safety*. He was blinded from reviewing or making decisions on the manuscript. The article was subject to the journal's standard procedures, with peer-review handled independently of this Editorial Board member and his research groups.

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