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Metro systems and urban development: Impacts and implications

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ABSTRACT

Many cities in the world have developed metro systems. Metro systems affect urban development in many ways, such as enhancing labour force mobility, increasing urban productivity and promoting urban underground space (UUS) utilisation to accommodate urban functions. This paper explores the relationship between metro systems and urban development, with particular focus on the comprehensive impacts of metro development on the economic, environmental and social development of cities. The contribution of metro systems to urban development has been confirmed by numerous studies in many cities in the world. The positive capitalisation of metro systems is reflected in property values in areas surrounding metro systems, although the impacts may vary spatially, temporally and geographically. In addition, metro systems impact on the natural and built environments by reducing air pollution and greenhouse gas emissions, encouraging new development and urban renewal, sharping urban development and land use, facilitating commercial growth and residential development, promoting the utilisation of UUS, and increasing mixed land use and urban density. However, there are mixed effects, both positive and negative, of metro systems on equality of transit opportunity, accessibility and connectivity, public health, travel behaviour, personal identity, travel experience and safety. This study sheds light on the impacts of metro systems on urban development, and provides important information for urban and transport planners and policy-makers wishing to develop metro systems to support sustainable urban development.

1. Introduction

Urbanisation is shaped by spatial and urban planning as well as by infrastructure investments by the public and private sectors. Economic activity and innovation are increasingly concentrated in cities, and cities evolve as central to the flow of transport, trade and information (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Critical transport infrastructure development requires significant investment and is used to promote urban development. Investment in inland transport infrastructure was 0.7% of the Gross Domestic Product (GDP) in the Organisation for Economic Co-operation and Development (OECD) countries, and China continued to achieve the highest inland transport infrastructure investment share of GDP (5.5%) in 2019 (International Transport Forum / OECD, 2021).

The ongoing rapid urbanisation process has resulted in increased concentration of urban populations. In big cities, particularly mega cities with population of more than 10 million, traffic congestion with considerable environmental, economic and social impacts has become a significant issue for urban planners and decision-makers. Many cities have adopted policies and strategies to encourage public transport to achieve transport mode shifts. Public transport, with its great capacity for transporting people efficiently and cheaply, can effectively address traffic congestion issues, increase labour force mobility and promote urban productivity in a comprehensive manner (Fouracre et al., 2003; da Silva et al., 2012). Moreover, with growing numbers of people moving into cities, the use of public transport contributes to air pollution reduction and climate change mitigation (United Nations, 2019).

Urban underground space (UUS), as a valuable resource and a new dimension of cities, has contributed to solving the problems of modern cities (Broere, 2016), developing liveable cities (Sterling, 1997), and supporting urban renewal (Cui et al., 2021). Metro, as a main form of public transport and urban underground space utilisation, has a history of more than 150 years since the world's oldest metro system, London's Metropolitan Railway from Paddington to Farringdon, was opened in 1863 (Cui and Nelson, 2019). Metro systems have been chosen by many world cities (particularly in a few Asian countries that have experienced

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massive growth during the last two decades) for addressing urban, transport and environmental issues (International Association of Public Transport, 2018; Lin et al., 2021a, 2021b). Metro systems not only are characterised by high capacity, high speed and a high level of safety but also can bring multiple benefits to the city. Therefore, metro systems, as an optimal option for addressing issues of environment, transport and urbanisation, have been adopted by many cities (ITA Working Group Number 13, 2004; ITA Working Group on Costs-benefits of Underground Urban Public Transportation, 1987). Cities have limited surface space for urban development, and metro has the advantage of more efficient use of space compared with other types of transport. For example, cars occupy 30–90 times more space than metro depending on the purposes for use (e.g. work, entertainment, or shopping) while buses occupy 3–12 times more space than metro depending on the nature of the service provided and the driving conditions (e.g. shared right-of-way or dedicated busway) (ITA Working Group Urban Problems - Underground Solutions, 2012). Since metro systems carry considerable numbers of passengers (over 4 million daily passengers in some of the busiest metros in the world), metro transport provides mobility for passengers and improves local accessibility to homes, workplaces, and shopping, entertainment and other destinations to conduct various activities, having economic, social, and public health impacts (Ahn et al., 2020) and increasing neighbourhood population and employment densities, with both contributing to a larger market for local retail businesses. Such significant public investment amenities interact with privately provided amenities (e.g., catering services), and together they can shape urban spatial structure and contribute to quality of life (Zheng et al., 2016b). At the neighbourhood scale, metro accessibility is believed to be a core component for maintaining a sustainable urban spatial environment that promotes functional efficiency, economic viability and social equity (Guan and Peiser, 2018).

Metro systems have widespread, profound and lasting effects on urban development. In fact, new metro investments were motivated by their economic, environmental and health benefits (Hirsch et al., 2018). The impact of metro development has long been an attractive topic for urban researchers, practitioners and decision-makers. A dramatic increase in the number of studies and publications on metro's impacts on urban development in various aspects has been seen in the last two decades. However, overwhelmingly, these studies focused on a single aspect of metro's effects. Usually, economists focused on the effects on land and property prices and value; urban planners were interested in the impacts on land use and density; transport researchers paid attention to improvements in traffic condition and changes in travel behaviour; and environmental scientists focused on the impacts on air pollution and greenhouse gas (GHG) emissions. This raises questions: what are metro's comprehensive impacts on urban development, especially economic, environmental and social development? What is the mechanism behind metro's comprehensive impacts on urban development? And to what extent do metro systems benefit urban development? The recent increase in publications on metro systems and urban development offers a good opportunity to analyse research findings from both developed and developing countries. Understanding the direction and magnitude of the impacts of metro systems is essential for planning sustainable urban futures (Ahmad et al., 2016).

This paper examines the wide-ranging effects of the provision of metro systems in urban areas. The paper aims to synthesise empirical evidence by exploring the impact of metro systems on economic, environmental and social development, to advance understanding of the comprehensive impacts of metro systems and provide important information to support decision-making on the development and expansion of metro systems in world cities. Considerable amounts of government funding have been spent on metro infrastructure with the goals of efficiently using the investments to maximise economic, environmental and social benefits. Therefore, a well-developed understanding of how metro systems can contribute to urban development has important and widespread significance for guiding decision-making regarding transport infrastructure investment and sustainable urban development.

2. Methodology

Metro, in this paper, refers to high-capacity urban rail systems, operating mainly in exclusive right-of-way underground tunnels. Metros provide high levels of service with regard to speed and service frequency (Fouracre et al., 2003). They are also known as subways or underground railways. This review draws on the authors' expertise in urban and transport studies and UUS research, with information sourced from publications via Google Scholar, ScienceDirect, Web of Science, and Scopus searches, using search terms that included four groups of key words: "metro" and terms that have similar concepts (including "subway", "underground" and "underground railway"); "development" and terms that have similar concepts (including "new metro" and "expansion"); "impact" and terms that have similar concepts (including "effect" and "influence"); and "urban development" and relevant terms (including "economic development", "environmental development" and "social development").

We focused on the relationship between metro systems and urban development at both macro and micro scales, covering both short-term and long-term impacts of metro systems. The review mainly focused on articles in the research fields of urban planning and urban studies. Only English articles were included. Only empirical studies on the impacts of metro systems on urban development were included. Metro's impacts on multiple aspects of urban development were considered, and these were categorised into three categories, namely, economic, environmental and social impacts. We also balanced the number of publications by considering the topics, research categories, and source countries and cities. We primarily focused on recent publications (i.e. published within the past two decades) and journal publications. A small number of non-recent publications, conference papers, and research reports were included to fill gaps in important topics. A total of 86 publications were included in this review. The existing literature focused on both developed and developing countries. A summary of the reviewed literature is shown in Table 1. The following sections discuss the review findings with regard to metro's comprehensive impacts on the economic, environmental and social development of cities.

3. Impacts on economic development

3.1. Metro proximity, metro accessibility, and land and property prices and value

Public transport development (e.g. metro) is widely believed to impact on property value as represented by sales price and rent (Saxe and Miller, 2016). According to traditional bid-rent theory, a metro station functions as an attraction and creates utility, in that people are willing to pay more for close proximity, and the rent displays a type of distance decay function (Ahn et al., 2020). With increased proximity to metro lines, the location attains greater accessibility (Zhu and Liu, 2004). Metro lines can significantly improve the accessibility of local areas and therefore impact on land and real estate value; this is the focus of research on metro's economic impacts. Studies on this topic have been conducted in both developed and developing economies (e.g. Australia, Brazil, Canada, China, Finland, India, Iran, Italy, Korea, Russia, Singapore, Spain, Turkey, and the United Arab Emirates). Many studies confirmed the positive effects of metro systems on land and property prices (e.g. Bajic, 1983; Diao et al., 2017; Dorantes et al., 2011; Guan and Peiser, 2018; Hiironen et al., 2015; Hsu, 2020). Some studies revealed a mix of positive and negative effects (e.g. Ahn et al., 2020; Seo and Nam, 2019). A few reported irrelevant relationships between metro accessibility and operation and property prices and value (e.g. Lee et al., 2020; Liou et al., 2016).

Although the impacts of metro development on land and property prices and value may vary in different locations, the existing literature

Table 1
Reviewed literature on metro systems and urban development.

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
Australia	Sydney	Chen et al. (2019)	Economic	Housing value	The impact of a new metro line on residential property value	Data from CoreLogic, the largest provider of property information and analytics in Australia; Google Maps; the Australian Government, Australian Bureau of Statistics context information on community profiles, extracted from the 2016 Census data	Hedonic price model
Brazil	São Paulo	Haddad et al. (2015)	Economic	Wider economic impacts	The higher-order economic impacts of the metro system	Data from the Origin Destination Survey for the São Paulo Metropolitan Region	A spatial computable general equilibrium model integrated to a transportation model
Brazil	São Paulo	da Silva et al. (2012)	Environmental	Air quality	Metro's short-term effect on air quality	Particulate matter (PM_{10}) concentration data collected using automatic stations of the São Paulo environmental state agency (CETESB) air quality monitoring system network; and data for mortality due to cardio-respiratory diseases for the elderly (age 65 and over) obtained from the municipal program	Statistical models
Canada	Montreal	Chapleau et al. (1987)	Social	Travel behaviour	The impact of metro extension on travel behaviour	Data from large-scale regional origin–destination surveys carried out by the Montreal Urban Community Transit Corporation (the local transit operator)	MADITUC (a Model for the Disaggregate Analysis of Trips on a Transit Network)
Canada	Montreal	Sijpkes and Brown (1997)	Environmental	UUS utilisation	Montreal's underground city's 35 years of development	N/A	Case study research
Canada	Toronto	Bajic (1983)	Economic	Housing prices	The impact of a new metro line on housing prices	Homeowners' survey data	Modal choice model; and hedonic price models
Canada	Toronto	Barker (1986)	Environmental	UUS utilisation	Toronto's underground pedestrian network	N/A	Case study research
Canada	Toronto	Belanger (2007)	Environmental	UUS utilisation	Toronto's underground pedestrian network	N/A	Case study research
Canada	Toronto	Saxe et al. (2017)	Environmental	GHG emissions	The impact of a new metro line on GHG emissions	GHG emissions from construction were estimated from available construction data and correlations with the literature; the operational GHG was calculated from operational energy requirements provided by the operating transit authority and published GHG-	Quasi-experimental analysis

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						energy intensity conversation factors; impacts of changes in ridership behaviour were assessed through an analysis of ridership counts and on-board surveys; longitudinal changes in mode share were assessed using transit survey data; the relationship between new metro and changes in residential density was investigated by comparing the change in accessibility provided by the case study metro lines and the subsequent observed changes in residential density, and by a quasi-experimental analysis of the changes in residential density compared to controls. GHG emissions' impact on changes in residential density was calculated from the relationship between residential density and energy expenditure reported in the 2006 Canadian long form census.	
China	Beijing	Du and Zheng (2020)	Economic	New firm formation	The accessibility to business clusters and low-cost rental housing through the metro network on new firm formation	Data on new business formation and agglomeration economies obtained from annual firm registration records in the registry database of the State Administration for Industry and Commerce, which is the official agency for firm registration in China; Baidu Application Programming Interface; the rental transaction records on 5i5j.com; Beijing land transaction data; location information from Fangtianxia (https://www.fang.com https://www.fang.com); and satellite images	Matched differences-in-differences (DID) estimation
China	Beijing	Li and Zhao (2017)	Social	Travel behaviour	Car ownership and car use in neighbourhoods near metro stations	Survey data from a travel survey conducted by the Center for Urban Planning and	Multinomial logistic model; and negative binomial regression

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
China	Beijing	Li et al. (2019a)	Economic	Housing prices	The impact of metro services on housing prices	Transport Research at Peking University Second-hand housing transactions from Anjuke website (https://bj.anjuke.com/), the first online housing broker in China	Spatial error model
China	Beijing	Li et al. (2019b)	Environmental	Air quality	The impact of metro expansion on air quality 2008–2016	The first dataset contains daily air quality readings from 27 monitors in Beijing; the second dataset records the opening dates and the locations of subway lines; and the third dataset contains daily weather variables.	DID framework
China	Beijing	Sun et al. (2015)	Economic	Housing value	The capitalisation of metro proximity in home value	A large longitudinal dataset of transactions in the rental housing market of Beijing from the rental units brokered by WoAiWoJia (https://www.5i5j.com); and all auctioned residential land parcels by year obtained from the China Real Estate Index System	A cross-sectional hedonic model; and a repeat-rentals model
China	Beijing	Wu and Hong (2017)	Social	Travel behaviour	The potential effect of metro system expansion on commuting behaviour	Questionnaire survey data	Bayesian multilevel binary logistic models
China	Beijing	Yang et al. (2018)	Social	Traffic congestion	The effect of metro expansions on vehicle congestion	Daily data on subway ridership, bus ridership, and traffic congestion obtained from Beijing Daily Transport Operation Monitoring, released by the Transport Operation Control Center of Beijing	A regression-discontinuity framework
China	Beijing	Zhang et al. (2017)	Social	Car ownership	The impact of metro proximity on automobility	Data from the Housing, Transportation and Energy Consumption Survey of Beijing Households conducted by the Institute of Real Estate Studies at Tsinghua University; and historical travel time data from GAODE Map	Heckman two-step method
China	Beijing	Zheng et al. (2016a)	Economic	Wider economic impacts and housing value	The impact of metro on restaurant activities and rental housing prices	Restaurant information from dianping.com (the Chinese version of Yelp); and housing data provided by WoAiWoJia, one of the major real estate brokers in China	Negative binomial regression; and a hedonic home rent model
China	Beijing	Zheng et al. (2016b)	Environmental	Commercial land use	The effects of new metro stations on		DID strategy; two-way fixed-effects model; and negative binomial regression technique

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
					catering openings, diversity and consumer demand in neighbourhoods near a metro station	City wide catering establishment data from dianping.com	
China	Beijing and Hangzhou	Zhang et al. (2019)	Economic	Housing prices	The relationship between urban structure, metro system and housing prices	The dataset for Beijing and Hangzhou was collected from https://www.fang.com/, the largest and most famous online information platform that provides detailed sales and transaction information of new and second-hand apartments; and Baidu Place API	The Getis–Ord local statistic using the hot-spot analysis tool; hedonic price model; and constrained clustering
China	Changsha	Tang et al. (2021)	Economic	Housing value	The land value-added benefit brought by a metro line	The topographic map and GIS data on property and other related infrastructure provided by Changsha Real Estate Management Center; line map and station GIS data of Changsha Metro Line 2 provided by China Railway Siyuan Survey and Design Group Co., Ltd; and other relevant data	Generalized transportation cost model analysis; and spatial econometric model analysis
China	Changsha	Zheng et al. (2019)	Environmental	Air quality	Metro's medium-term effect on local air quality	Data on air quality from the National Environmental Protection Agency; and weather data from the National Oceanic and Atmospheric Administration	DID method
China	Chengdu	Xiao et al. (2021)	Social	Obesity	The impact of metro development on obesity	Survey data	DID model
China	Hangzhou	Tian et al. (2020)	Economic	Housing prices	The property price premium due to the opening of a metro line	Residential property transaction data from the Hangzhou Real Estate Administration	Hedonic models in a DID framework
China	Hong Kong SAR	Wallace and Ng (2016)	Environmental	UUS utilisation	Development and application of underground space use	N/A	Case study research
China	Nanchang	Sun et al. (2020)	Social	Travel behaviour	The impact of a new metro line on travel behaviour changes	Survey data	DID method
China	Nanjing	Fu and Gu (2018)	Social	Travel behaviour	The operation of a new metro line impacts on passenger flow and travel time	Smart card data	Spatial and temporal analysis
China	Multiple cities	Gu et al. (2021)	Social	Traffic congestion	The impact of a metro line on alleviating road congestion	Traffic speed data from China's leading provider of digital map services, which collects and processes real-time traffic information	DID

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						from user-generated data	
China	Multiple cities	Liu and Li (2020)	Social	Travel behaviour	The impact of metro on urban passenger transport modes	List of cities with a subway development plan from the National Development and Reform Commission website; data on subway opening date, subway length, and number of lines from the China Urban Rail Transit Association; and economic data from the China City Statistical Yearbook	DID method
China	Multiple cities	Lu et al. (2018)	Environmental	Air quality	The impact of metro openings on reducing $PM_{2.5}$ concentrations	The opening dates of new subway lines collected primarily from the China Metro website and official websites of subway operating companies in sample cities; air quality data published daily and hourly by the Ministry of Environmental Protection; daily weather data collected from 2345 weather websites; and historical visibility data from the website https://www.wunderground.com	Regression discontinuity design
China	Multiple cities	Wei (2019)	Environmental	Air quality	The impact of metro on Air Quality Index and four pollutants, namely $PM_{2.5}$, SO_2, NO_2 and CO	Data from Air Quality Monitoring and Analysis Platform of China; Ministry of Housing and Urban-Rural Development of the People's Republic of China; Municipal Bureau of Statistics; and China Statistical Yearbook compiled by the National Bureau of Statistics of China	Fixed-effects model
China	Multiple cities	Xiao et al. (2020)	Environmental	Air quality	The impact of metro on air pollution	Air pollution data from the website https://www.tianqihoubao.com/aqi/; subway data from the website https://www.urbanrail.net/ and Wikipedia; socioeconomic data from the China City Statistical Yearbook and the China Urban Construction Statistical Yearbook; and meteorological data from https://www.tianqihoubao.com/lishi/	Spatial difference-in-differences (SDID) method
China	Shanghai	Dong et al. (2021)	Environmental	UUS utilisation	Metro-led underground space use	Metro line data from online map; indices of space syntax of	Technique for order preference by similarity to an ideal solution (TOPSIS) method

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						metro-led underground space (MUS) processed and calculated by Depthmap; statistics of online map; shapefile of MUS extracted from online map with manual correction; site investigation; point of interest data acquired from the application programming interface provided by Amap (one of the most prominent digital map suppliers in China); and underground point of interest data extracted by python code	
China	Shanghai	Guan and Peiser (2018)	Economic	Housing prices	The impact of metro development and urban form on housing prices	Price data collected from online real estate open source platforms (https://www.fang.com); accessibility attributes calculated using time-distance analysis (time to centers and distance to stations) and counted using ArcGIS analysis (bus, high-rise office, and commercial); location of the high-rise office and commercial buildings collected by the authors; and urban form attributes acquired from both online real estate platforms and spatial analysis conducted by the authors	Analysis of variance; pairwise correlation analysis; principle component analysis; and ordinary least square hedonic regression analysis
China	Shanghai	Li et al. (2018)	Social	Happiness	The impact of metro proximity on happiness	Survey data	Ordered logit regression
China	Shanghai	Wang et al. (2016)	Economic	Rental prices	Rent premium for transit proximity	Data from the largest rental advertising websites in China (https://www.haozu123.com and https://www.fang.com) run by Leixury Real Estate Market Research and Consulting Co.,Ltd	Spatial quantile hedonic regression method
China	Shenyang	Liu et al. (2021)	Social	Equity of accessibility	The impact of metro expansion on inequity of healthcare accessibility	Population-demand data extracted from the Shenyang Statistical Yearbook provided by the Shenyang Bureau of Statistics in 2019; healthcare services data mainly collected from an online medical service website called 99	A two-step floating catchment area method

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						Hospital Library (https://yyk.99.com.cn/); and data on public transport connections between various origins and destinations derived from the AutoNavi Open Platform (https://lbs. amap.com) by implementing Python-based web crawling technology, supplemented by material from the Shenyang Metro website (https://www.symtc.com/)	
China	Tianjin	Sun et al. (2016)	Economic	Housing value	The impact of metro lines on residential property value	Property price data from the actual transaction data listed on the Tianjin "Housing Search" website	Hedonic pricing model
China	Wuhan	Tan et al. (2019)	Economic & environmental	Land use and housing prices	The effect of new metro stations on local land use and housing prices	Data from Baidu Maps; station name, opening date, line number, and transfer station indicator based on Baidu Baike, Wikipedia, and the official Wuhan metro website (https://www.whrt.gov.cn/); second-hand housing transaction data from Lianjia (https://bj.lianjia.com); and population data from the Resource and Environment Data Cloud Platform	The traditional hedonic price model; and the DID model
China	Xi'an	Huang et al. (2017)	Social	Transport	The impact of metro on the ownership of autos, bikes, e-bikes, and motorcycles	Questionnaire survey data	Ordered probit models; and binary probit model
China	Xi'an	Yin et al. (2021)	Social	Life satisfaction	Metro and life satisfaction	Questionnaire survey data	Structural equation modeling
Finland	Helsinki	Hiironen et al. (2015)	Economic	Housing value	The impact of a new metro line on property value	Data from the Finnish realtors' own price register on apartment prices published online (https://www.asuntojen.hintatiedot.fi); and the travelling time to CBD defined by using the official route calculator (https://www.reittiopas.fi) that analyses travelling time (minutes) with the chosen transportation	Hedonic price models
India	Bengaluru	Sharma and Newman (2018)	Economic	Land value	Metro influence on land value uplift	Data from a real estate company (M/s LJ Hookers)	The panel data hedonic price model; and a cross-sectional data hedonic price model
India	Delhi	Ahmad et al. (2016)	Environmental	Land use	The impact of metro on land cover change	Decadal urban population data; remote sensing data;	Descriptive statistics

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						satellite images; and census data	
India	Delhi	Gopal and Shin (2019)	Social	The lives and travel experiences of women	The impact of metro on the lives and travel experiences of women	Data from participant observation and in-depth interviews	The notion of empowerment as a theoretical framework; and content analysis
Iran	Tehran	Bagheri (2019)	Social	Travel behaviour and gendered identities	The impact of metro on women's spatial mobility, the construction of self, and social production of space	Data from 46 semi-structured interviews with women who were using subway Line 1	Qualitative analysis
Iran	Tehran	Forouhar (2016)	Economic	Housing value	The impact of metro rail stations on residential property value	The individual sales transaction records of real estate agencies; the Tenement Management Information System of Iran; the Real Estate Market Information System of the Ministry of Housing and Urban Development of Iran and Tehran Municipality; and data from semi-structured interviews with local residents around metro stations	A pre/post methodology; DID model; and qualitative impact assessment
Italy	Naples	Gallo (2018)	Economic	Housing value	The effect of metro systems on real estate value	Census data obtained from the Italian National Institute of Statistics; real estate values obtained from the Real Estate Market Observatory, which is a database provided by the Italian Revenue Agency about real estate values in all Italian cities; and data on the transit supply system collected directly from the operators	Hedonic model
Japan	Osaka	Peng et al. (2019)	Environmental	UUS utilisation	Factors in the development of UUS surrounding metro stations	Data from site investigations; and data provided by local departments, such as the Osaka Urban Planning Bureau	Linear regression analyses
Japan	Sapporo	Jothimani and Yamamura (1995)	Environmental	Land use and ecosystems	The impact of metro on spatial changes in urban land use and ecosystems	INFO/TABLES database	ARC/INFO GIS spatial analysis
Japan	Tokyo	Zacharias et al. (2011)	Environmental	UUS utilisation	Metro station complexes	N/A	Case study research
Korea	Busan, Daegu, Daejeon and Gwangju	Ahn et al. (2020)	Economic	Housing prices	Economic impacts of metro accessibility	Housing transaction data published by the Ministry of Land, Infrastructure and Transport; Statistics Korea; the National Spatial Data Infrastructure Portal; and the Korea Transport Data Base	A hedonic price model; and a spatial lag model

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
Korea	Daegu	Im and Hong (2018)	Economic	Housing prices	The impact of a new metro line on housing value	Apartment sales price data provided by Kookmin bank and housing statistics of Daegu city	Hedonic models in DID framework
Korea	Daejeon	Kim and Byun (2021)	Economic	Land prices	The impact of a newly built metro line on land prices	Land price data officially assessed by the government of South Korea	Geographically and Temporally Weighted Regression method
Korea	Gwangju	Song et al. (2018)	Social	Transit equity	The impact of metro expansion on transit equity	Road and bus network data acquired from two public websites: the Korea Transport Database (KTD) and the Gwangju City Bus Information System; subway network data integrated based on data from the coordinates of stations provided by the KTD and Gwangju Metropolitan City; subway station information for the statistical analysis collected from the Gwangju Metropolitan Transit Corporation (Gwangju Metro, https://www.gwangjusubway.co.kr); and demographic and socio-economic data obtained from Statistics Korea	A set of statistical models based on a logistic regression
Korea	Seoul	Bae et al. (2003)	Economic	Housing value	The impact of the construction of a new metro line on nearby residential property values	Housing price data from the Budongsan Bank (Real Estate Bank); housing characteristic data from the website (https://www.allapt.co.kr); network distances to Line 5, the CBD, the major subcentres, the Greenbelt and the Han River estimated using the 1999 geographic information system (GIS) maps derived from the network data file for Seoul; population and employment density data from the City of Seoul's database; and School District data provided by the Department of Education in Seoul (Gyoyuk Chong)	A hedonic pricing model
Korea	Seoul	Jun et al. (2015)	Environmental	Density and diversity	Land use characteristics of metro catchment areas	The 'jipgyegu' dataset for the Seoul metropolitan area obtained from the Korea Statistical Office	GIS spatial analysis; and a multinomial logit model
Korea	Seoul	Kim and Song (2015)	Environmental	Accessibility and reliability	The impact of evolution of a	Station information from a public	Linear regression model

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
					metro system on accessibility and reliability	website, Korea Transport Database (https://www.ktdb.go.kr)	
Korea	Seoul	Lee et al. (2021)	Environmental	Population and activities	Accessibility of the metro system impacts on spatiotemporal distributions of population	The rail network GIS database provided by the Ministry of Land, Infrastructure and Transport; the ridership data provided by the Seoul Metropolitan Government; and population data provided by the Seoul Metropolitan Government	Linear regression analysis
Korea	Seoul	Seo and Nam (2019)	Economic	Housing prices	The effect of metro accessibility on apartment prices	Real transaction price data published by the Ministry of Land, Infrastructure, and Transportation	Conventional hedonic price model; spatial autoregressive combined model; and geographically weighted regression
Russia	Multiple cities	Kholodilin and Maksimova (2019)	Economic	Rental prices	The impact of metro proximity on rental prices	Data from the advertisement website Avito, which has a real estate section with more than 6 million ads on long-term residential renting	Traditional hedonic methodology
Singapore	Singapore	Diao et al. (2017)	Economic	Housing prices	The impact of the opening of a new metro line on housing prices	Non-landed private housing transaction data obtained from the "Realis" system of the Urban Redevelopment Authority	DID approach
Singapore	Singapore	Li et al. (2019c)	Social	Equality of public transit connectivity	Equality of metro connectivity of individual buildings	Land-use data sets collected from OpenStreetMap (OSM 2017) and the Internet which are publicly available; public transportation data sets provided by Singapore Land Transport Authority (LTA) DataMall (2017); dynamic bus arrival time at bus stops through web API provided by LTA DataMall; and house transaction data set from the Housing and Development Board website	Graph-based transportation analysis; and house price prediction models
Singapore	Singapore	Zhu and Diao (2016)	Environmental & Social	Density and mobility	The impact of metro on the density and mobility	New sale transactions of private housing units recorded in the REALIS database produced by the Urban Redevelopment Authority of Singapore; information on land use type and density constraints for land parcels from the Master Plan of Singapore; and two sets of household interview travel survey data collected	OLS regression model

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						by the Land Transport Authority	
Singapore	Singapore	Zhu and Liu (2004)	Social	Accessibility	The impact of metro on accessibility to the CBD, the working population, and industrial and commercial opportunities	Most of the spatial data in the GIS database derived from digital land base data provided by the Singapore Land Authority under the Ministry of Law; and population, land use and other socio-economic data at the level of the Development Guide Plans obtained from the Census 1990 (SDS, 1994), the Census 2000 (SDS, 2001), Housing and Development Board Annual Reports (HDB) (https://www.hdb.gov.sg/), the published profile of HDB residents (HDB, 2000), and the Development Guide Plans (https://www.ura.gov.sg/dgp_reports/)	An integrated GIS approach to accessibility analysis
Spain	Madrid	Calvo et al. (2013)	Environmental	Land use	The impact of metro on population settlement and land use	Data on population and land use obtained from census sections provided by the Institute of Statistics of the Community of Madrid from the Annual Census	The method proposed by Gutiérrez (1997) and Chakraborty and Armstrong (1997)
Spain	Madrid	Dorantes et al. (2011)	Economic	Housing prices	The effect of proximity to metro stations on housing prices	Cross sectional data from the real estate web page https://www.idealista.com (Spain's largest real estate website)	Hedonic models; and spatial analysis
Taiwan	Taipei	Chen et al. (2021)	Environmental & Social	Air quality and public health	Metro and occurrence of respiratory and cardiovascular illnesses attributed to air contaminants	Mortality data collected from Taiwan's Ministry of Health and Welfare and Ministry of Interior Affairs; and air quality data obtained from Taiwan's Environmental Protection Administration	Robust generalized Poisson regression models
Taiwan	Taipei	Hsu (2020)	Economic	Value of metro proximity	People's willingness-to-pay for a house in the metro areas	Questionnaire survey data	Contingent valuation method; and a Tobit regression model
Taiwan	Taipei	Huang and Chao (2014)	Social	Car ownership	The impact of metro on household car ownership	Data from Taiwan's Family Income and Expenditure Survey conducted by the Taiwanese government	DID strategy integrated with Poisson, generalized Poisson, and zero-inflated Poisson regression models
Taiwan	Taipei	Lee et al. (2020)	Economic	Housing prices	The impact of construction and operation of metro on neighbourhood housing prices	Housing transaction data obtained from the reports on Taiwan real estate transactions	DID method that incorporated the spatial lag model and spatial error model

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Table 1 (*continued*)

Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
						published by the Department of Land Administration of the Ministry of the Interior and GigaHouse	
Taiwan	Taipei	Lin and Yang (2019)	Environmental	Commercial land use	The impact of newly launched metro stations on commercial gentrification	Image records of Google Maps Street View	Logit models
Taiwan	Taipei	Liou et al. (2016)	Economic	Housing prices	The impact of distance to metro on house prices	Data from the database, Real Estate Transaction Price Inquiry System, managed and provided by the Department of Land Administration, Ministry of the Interior	Hedonic price model
Thailand	Bangkok	Ikeshita et al. (2013)	Environmental	GHG emissions	The impact of metro expansion on the reduction of CO_2	Network data and public transport line data	Demand forecasting model
Turkey	Istanbul	Beyazit (2015)	Economic	Wider economic impacts	Wider economic impacts of metro	Census data provided by the Turkish Statistical Institute; three Transport Master Plan reports; commercial data gathered from the Istanbul Chamber of Commerce; and residential and office value data from district municipalities	Ex-post analysis; descriptive analysis; and chi-square analysis
Turkey	Izmir	Celik and Yankaya (2006)	Economic	Housing value	The impact of metro on the residential property values	Data from a survey of all real estate agencies	Hedonic price model
UAE	Dubai	Mohammad et al. (2017)	Economic	Property value	The effect of metro on the value of residential and commercial properties	Two datasets provided by the Dubai Real Estate Regulatory Authority for sale transaction records of residential and commercial properties	DID; and hedonic pricing methods
UK	London	Levinson (2008)	Environmental	Land use and density	The impact of metro on population growth, and residential and commercial development	Population data obtained from the Vision of Britain website; employment data from the City of London Workforce Info Census 2001 and 2006; and transport network data obtained from existing publications	Regression models
US	Dallas	Terranova (2009)	Environmental	UUS utilisation	Underground Dallas as a systematic solution to the declining downtown	N/A	Case study research
US	Massachusetts (state)	Oreskovic et al. (2009)	Social	Obesity	Effect of the built environment on obesity	Data from a large integrated health care system (Partners HealthCare)	Bivariate and multilevel analyses
US	New York	Cooley et al. (2011)	Social	Public health	The impact of metro travel on the spread of an	Historical data from the 1957–1958 influenza pandemics	A Susceptible–Exposed–Infected–Recovered disease model framework

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Country/ Region	City	Author (Year)	Impact Category	Research Area	Topic	Main Data	Research Method
					influenza epidemic	and from New York City travel surveys	
US	New York	King (2011)	Environmental	Land use	The impact of metro growth on land use	New York City Primary Land Use Tax Output data (parcel-level data) for Manhattan, Queens, Brooklyn, and the Bronx, combined with datasets of subway stations and lines	Spearman's rank correlation tests; and Granger causality models
US	New York	Rundle et al. (2007)	Social	Obesity	Built environment (including metro stops) and obesity	Existing survey data for the New York Cancer Project	Cross-sectional multilevel analyses
US	San Francisco	Wang (2017)	Social	Crimes	The impact of metro on public security	Crime data from data.sfgov.org	Spatial analysis; and multiple regression analysis
Worldwide	Multiple cities	Gendron-Carrier et al. (2018)	Environmental	Air quality	The impact of metro openings on urban air pollution	Air pollution data based on remotely sensed measures of suspended particulates; and subways data from primary data collection	An econometric framework; regression analysis; back of the envelope cost estimates
Worldwide	Multiple cities	Gonzalez-Navarro and Turner (2018)	Environmental & Social	City population and city spatial configuration	The extent of a city's metro network impacts on city population and city spatial configuration	Population data from the UN World Cities Data; subways data and ridership data from primary data collection; and description of urban spatial structure from satellite lights at night data	Regression analysis

generally supports the positive capitalisation of metro as shown by property price. Metro accessibility is an influencing factor behind residents' housing location selection; that is, to have better access to metro, residents may choose to live in metro station precincts. Existing studies examined the likely metro premium, through investigating sale or rental transaction data from local, state or national authorities (e.g. Ahn et al., 2020; Diao et al., 2017; Gallo, 2018; Lee et al., 2020; Liou et al., 2016; Mohammad et al., 2017; Seo and Nam, 2019; Tian et al., 2020), sale or rental transaction data from real estate websites (e.g. Dorantes et al., 2011; Guan and Peiser, 2018; Hiironen et al., 2015; Kholodilin and Maksimova, 2019; Li et al., 2019a; Sun et al., 2015; Tan et al., 2019; Tang et al., 2021; Zhang et al., 2019), real estate data from the private sector such as banks and real estate companies (e.g. Im and Hong, 2018; Sharma and Newman, 2018), and survey data (e.g. Bajic, 1983; Celik and Yankaya, 2006; Hsu, 2020). With regard to research method, hedonic price models have been widely applied in empirical studies on the impact of metro development on property value (e.g. Ahn et al., 2020; Bae et al., 2003; Bajic, 1983; Celik and Yankaya, 2006; Chen et al., 2019; Gallo, 2018; Hiironen et al., 2015; Im and Hong, 2018; Mohammad et al., 2017; Sharma and Newman, 2018; Sun et al., 2016; Tan et al., 2019; Tian et al., 2020). While the overwhelming majority of studies investigated metro development impacts on property prices and value, a small number of studies examined metro development impacts on land prices; an example of the latter is Kim and Byun's (2021) analysis of estimated land price data obtained from local authorities.

There are temporal differences in the effect of metro development on property prices and value related to the different periods over which the metro system is developed, with existing literature reporting mixed findings. Before the opening of Seoul's new Line 5, proximity to the metro stations of Line 5 had a statistically significant and negative impact on residential property values (Bae et al., 2003). In Hangzhou, China, the increased value effects of metro opening were negative for cheap residential properties in the early stage for a short time (e.g. 3 months) and then became positive. The enthusiasm of buyers of cheap properties came later, compared with buyers of expensive properties (Tian et al., 2020). Residential property prices in Sydney increased by 0.037% on average for every 1% increase in proximity to the nearest metro station during the construction stage of the Northwest Metro (Chen et al., 2019). Other studies found that metro construction reduced housing prices (e.g. in Taipei by about 7.9%) due to disrupted urban traffic conditions, air pollution, and noise (Lee et al., 2020). Generally, the operation of metro systems positively affected property value and rental prices. In Shanghai, rental prices increased by about 0.4% for every 100 m reduction in distance from the nearest metro transport (Wang et al., 2016). In Izmir, Turkey, property prices decreased by about 1.3% for every additional 100 m distance from subway stations (Celik and Yankaya, 2006). Subway lines that have already been built had a more significant impact on surrounding housing prices than lines that were being planned in Tianjin, China (Sun et al., 2016). In some cases, a significant relationship between operated metro and housing prices was not found, and it is likely that the increase in housing prices may occur during metro planning, announcement, and construction phases (Lee et al., 2020). In Daejeon, Korea, through examining commercial and residential uses, it was shown that the land value effect (geographically) is greater on commercial land than on residential land. Comparatively, the scale of the land value effect is wider on commercial land, while the temporal effect on land value lasts longer on residential land (Kim and Byun, 2021).

When metro systems are in operation, for most socioeconomic classes, subway accessibility positively impacted housing location choices (Seo and Nam, 2019). Direct savings in commuting costs were capitalised into housing value (Bajic, 1983). People were willing to pay higher

prices (e.g. 5.9–7.9% more in Taipei) for a house on the peripheries of metro stations than for a house in other areas (Hsu, 2020). High-priced residential properties could obtain more significant value effects from metro development than cheap properties (Tian et al., 2020). New metro stations significantly increased housing prices (e.g. a 7–14% increase for second-hand properties within 1600 m in Wuhan, China; a 2.3% increase for properties within 1000 m in Hangzhou, China; a 15% increase for residential apartments within 400 m and 11% within 800 m in Helsinki, Finland; a 1.6% increase for properties within 400 m in Singapore; and a 96.3 USD increase per square metre for homes within 500 m in Daegu, Korea) (Diao et al., 2017; Gallo, 2018; Hiironen et al., 2015; Im and Hong, 2018; Tan et al., 2019; Tian et al., 2020). A subway station within a radius of 3 km increased the rent by 0.36% in Russia's seven cities with metro systems (Kholodilin and Maksimova, 2019). In the city of Bengaluru in India, property price increased 4.5% across the whole city (Sharma and Newman, 2018). The significant impact of the metro system on total real estate value was 8.5% in Naples, Italy (Gallo, 2018). Shorter service headway and access to multiple metro lines were associated with higher housing prices (Li et al., 2019a). Metro lines with frequent services (6 trains/h or more) significantly impacted on real estate value, and metro lines with less frequent services were not found to have such impacts in Naples, Italy (Gallo, 2018).

The impacts of metro development on property value vary spatially. The impacts were greater in marginal zones of the city than in the city's CBD in Tianjin, China (Sun et al., 2016). This is consistent with a study in Changsha, China that found a dumbbell-shaped impact along the metro line with a distance-dependent pattern at each metro station, with a smaller impact of the stations near the CBD and an increased impact of the stations as the distance from the CBD increased (Tang et al., 2021). Similarly, a study on Dubai's metro in the United Arab Emirates (UAE) found that metro's impacts on property values varied according to the distance between the properties and metro station. For residential properties located close to metro stations (e.g. 301–500 m), a negative impact (-6%) of the metro on sale values was found; for residential properties located 701–900 m of a metro station, the peak positive impact (+13%) was found; for residential properties located further (e.g. 901–1100 m), a 10% increase in sale prices was found; and no significant impact was found for residential properties located even further away. Regarding the metro effect on commercial property values, the effect (25–76%) was significant across all distance ranges and reached its peak (76%) for properties located 701–900 m from a metro station (Mohammad et al., 2017). In Tehran (Iran), overall, in affluent neighbourhoods in the northern areas, the impact of metro stations on residential property value was negative, while in poor neighbourhoods close to the southern stations, the impact was positive and high (Forouhar, 2016). The capitalisation of metro proximity in housing values was weaker where land supply was more elastic (Sun et al., 2015). Areas with better metro-facilitated accessibility to employment centres had higher housing prices than other areas (Li et al., 2019a).

Existing studies also explored other factors that might influence the impact of metro accessibility on land and property prices and value. First, research revealed the prevalence of trade-off between metro accessibility and size of housing. In Seoul, Korea, the influence of metro accessibility on house location choice varied for households with different levels of income. For high-income households, housing locations further away from metro stations were preferred for a more attractive living environment; for those with low income, low-cost housing and greater metro accessibility were preferred (Seo and Nam, 2019). Second, the local contexts of individual cities influence the economic benefits of subway accessibility. In Gwangju, Korea, the low modal share of the Gwangju subway network, delayed construction, and lack of effective integration of the network into urban planning and development plans to enable it to serve many new trip-generating sites precented the potential benefits from being widely and fully realised (Ahn et al., 2020). Third, urban structure can affect the relationship between metro accessibility and housing prices. In a monocentric city, the larger the urban core, the greater the improvement in metro commuting efficiency and the metro premium on housing units; in a polycentric city with a small urban core, the metro premium on housing units was negative in the core region and positive in the outside area (Zhang et al., 2019). Fourth, whether there are existing metro lines can influence the impacts of the new metro lines on housing prices. In Daegu, Korea, the metro premium from improved accessibility mainly appeared for housing located within 500 m from the new metro line and beyond 5 km from the nearest station of the existing metro lines. For housing close to both existing metro lines and the new line, such a metro premium from improved accessibility did not appear. This means that the metro premium from improved accessibility only benefited housing that had limited benefits from existing metro lines (Im and Hong, 2018).

3.2. *Wider economic impacts*

Metro development has wider economic benefits, e.g. changed job density, thus affecting the productivity and efficiency of the labour market. The metro system in Istanbul generated wider economic impacts, especially in terms of business investment and sectoral changes. In Istanbul, Turkey, the metro system started the transformation of its catchment areas from industry- and manufacturing-related businesses to service-related businesses. The agglomeration of finance and business services created agglomeration economies. In addition, facilitating capital accumulation and attracting large investments in the metro corridor, therefore forcing small companies in industrial and manufacturing sectors to leave the areas along the corridor and allowing large companies and service-related businesses to locate in these areas, resulted in the gentrification of these areas. Despite this, the metro network's effects on population, job and business growth in the neighbourhoods of its stations were negligible. This may be because of the lack of a supportive relationship between the metro corridor development plans and metro investment (Beyazit, 2015).

Du and Zheng (2020) examined metro's effects on the establishment of firms in Beijing. With a 1% improvement in accessibility to agglomeration through the metro network, the number of new skill-intensive establishments increased by 0.44%; with a 1% improvement in accessibility of affordable rental housing through the metro network, the number of skill-intensive firms increased by 0.74%. New openings of nearby restaurants due to metro development in Beijing were examined by Zheng et al. (2016a) who found a positive contribution of metro development to the number of new restaurants and the diversity of neighbourhood restaurants. Such impacts on restaurant activities following metro development allowed a 20–40% increase in housing value, thus supporting the "multiplier effect" of metro development on neighbourhood retail amenities, and subsequently, on local home prices.

The economic impacts of metro development have been confirmed at the local level (e.g. areas along the metro corridors) and the city level. Some studies found that the positive economic impacts of metro infrastructure went beyond the city boundary. Haddad et al. (2015) examined the economic impacts of existing metro infrastructure of São Paulo in Brazil and found enhanced mobility and labour productivity, with 32% improvement in the city of São Paulo, 11% in other municipalities in the metropolitan area, 12% in the State of São Paulo and 45% in the rest of the country.

4. Impacts on environmental development

Metro systems influence both natural and built environments. Studies have been conducted in both developed and developing countries (e.g. Brazil, Canada, China, India, Iran, Japan, Korea, Singapore, Spain, Thailand, UK and US). Many studies applied statistical analyses (Ahmad et al., 2016; Gendron-Carrier et al., 2020; Gonzalez-Navarro and Turner, 2018; Huang et al., 2017; King, 2011; Lee et al., 2021; Levinson, 2008; Li and Zhao, 2017; Lin and Yang, 2019; Peng et al., 2019; da Silva et al., 2012; Wu and Hong 2017; Zhu and Diao, 2016),

particularly the difference-in-differences technique (Gu et al., 2021; Huang and Chao, 2014; Li et al., 2019b; Liu and Li, 2020; Sun et al., 2020; Xiao et al., 2020; Zheng et al., 2016b; Zheng et al., 2019). The existing literature explores metro's effects on land use and density, property development, urban renewal, UUS utilisation, car dependence, traffic congestion, air quality and GHG emissions. The following sections discuss the built environment and the natural environment, respectively.

4.1. Built environment

Metro development influences land development/redevelopment and spatial changes in urban land use. An early study in the 1990 s in Sapporo, Japan indicated that metro development resulted in an increase in built-up areas. There was an increase in commercial land use along the metro corridor, an increase in recreational/sports land use buffering the metro systems, and an impressive growth of areas of artificial parks because of metro development (Jothimani and Yamamura, 1995). However, In Delhi, India, metro lines and stations did not promote an increase in built-up areas along the metro corridors or around stations; instead, it brought about land use change in peripheral districts (Ahmad et al., 2016).

The development of metro systems facilitates commercial growth, residential development and population growth surrounding metro stations. In Madrid, Spain, significantly more active urbanisation and residential development was found in areas influenced by metro expansion than in other similar areas without metro influence. Residential developments and population growth around new metro stations were found to be greater in the outer city areas than in the city centre and satellite towns, particularly in the new suburbs that rapidly grew along with the metro development. In the vicinity of new metro stations in outer city areas and in satellite towns, as distance from the station increased, population density decreased, particularly in the new urban area developments encouraged by new metro stations (Calvo et al., 2013). A study on Wuhan, China confirmed that the operation of new metro lines had greater effect in revitalising the areas close to suburban stations than areas close to central stations. However, population growth was more significant in the areas close to central stations than in areas close to suburban stations prior to the opening of a new metro line (Tan et al., 2019). To what extent a city's subway network impacts on city population and city spatial configuration was examined by an analysis of the 632 largest cities (with and without metro systems) in the world. It found that larger cities were more likely to develop metro systems. However, metro's economic effect on urban population growth was insignificant. Metro played a role in urban decentralisation, but its influence was not as great as that of highways (Gonzalez-Navarro and Turner, 2018).

The question of whether metro extension leads to population growth and residential and commercial development, or vice versa, is yet to be confirmed. A study in New York City revealed that the metro network developed most extensively in areas with growth in commercial development. However, there was no evidence to suggest there was metro growth prior to residential development citywide. Rather, new metro stations were built in the areas already well-served by the metro system and metro growth followed residential and commercial development. With metro routes and stations being built in areas with established ridership demand, the metro network played a role in facilitating decentralisation (King, 2011). A study in Seoul on the impacts of the metro system on populations and their urban activities found that among different activities (commercial, residential, entertainment and work), only commercial activities closely accompanied with the metro network. In the process of commercial suburbanisation that separated residential activities from commercial activities in the urban core area, residents relocated from the urban core area to the suburban areas. The process is closely related to metro development in Seoul (Lee et al., 2021). In the suburbs of London, construction of new metro stations during the 19th and 20th centuries increased suburban populations, while additional population density contributed to more metro developments. Comparatively, in central London, the additional accessibility provided by metro led to commercial development and associated depopulation (Levinson, 2008). In Beijing, new metro stations increased the number, diversity and demand of neighbourhood catering services. Statistically significant impacts were found consistently within 800 m from stations, with higher influence in the area closer to a new station. The growth of new neighbourhood catering services in the metro station areas in the urban fringe was more significant compared with those in the inner city (Zheng et al., 2016b).

In Singapore, new metro lines had the effect of densification of upper- and upper-middle-class households in the catchment areas of metro stations. This is because upper- and upper-middle-class people can afford private housing, and housing developers built more smaller housing units in the station area as a response to the market and the restrictions of the Master Plan on the density and intensity of residential development (Zhu and Diao, 2016). Built environments in Seoul's subway catchment areas followed transit-oriented development (TOD) principles in terms of density and diversity. Population and employment densities in the catchment areas decreased outwards from stations, and the catchment areas had high levels of mixed land use (Jun et al., 2015).

The development of metro systems has promoted the utilisation of UUS around metro stations and the formation of multi-functional UUS that comprises multiple land uses and urban functions. As a travel mode for a considerable number of people, metro transport generated large pedestrian flows and created unprecedented demand for services in the vicinity of subway stations. To meet the demand for these services, UUS around metro stations was encouraged to accommodate consumption and leisure facilities to enhance passengers' travel experiences. Accordingly, underground walkways linked metro stations, basements of towers, underground commercial spaces (such as shopping malls, underground shopping streets and underground retail stores), underground car parks and underground public spaces (such as concourses and atriums), forming multi-functional UUS. Many cities have developed multi-functional UUS as a result of metro development, such as in Toronto (Barker, 1986; Belanger, 2007) and Montreal (Sijpkes and Brown, 1997) in Canada; in Tokyo (Zacharias et al., 2011) in Japan; in Hong Kong SAR (Wallace and Ng, 2016) and Shanghai (Dong et al., 2021) in China; and in Dallas (Terranova, 2009) in the US. It was found that the development of UUS near metro stations was great when the land was used for commercial, office, and recreational uses (Peng et al., 2019).

4.2. Natural environment

Metro operation contributes to a reduction of air pollution and GHG emissions due to various considerations, such as mode shift from cars (Saxe et al., 2017), reduced energy consumption (Ikeshita et al., 2013; Xiao et al., 2020), the offset in road transport (Lu et al., 2018), use of cleaner energy (Lu et al., 2018), mitigation of traffic congestion and improvement of air quality (Ikeshita et al., 2013; Li et al., 2019b; Zheng et al., 2019), and increased residential density and subsequent energy savings in the station areas (Saxe et al., 2017).

The impact of metro development on different air pollutants varies, and research findings are inconsistent. An investigation of 160 prefecture-level cities in China found that metro development reduced the concentrations of $PM_{2.5}$ and PM_{10} but there was no apparently impact on SO_2, NO_2, CO and O_3 (Xiao et al., 2020). Metro operation decreased CO in 16 major cities in China, but metro alone did not affect $PM_{2.5}$ concentrations (Wei, 2019). da Silva et al. (2012) investigated metro's short-term effect on air quality in São Paulo, Brazil and found the disruption of metro operation services increased PM_{10} concentrations. After a year's operation of the first metro line in Changsha, China, CO pollution in areas close to the metro line was significantly decreased. However, no apparent effect was found for PM_{10}, $PM_{2.5}$ or O_3 (Zheng

et al., 2019). New metro openings in 58 worldwide cities were investigated, and generally, it was found that particulate concentrations did not change following metro openings. For cities with initially high levels of air pollution, metro opening decreased particulate concentrations by 4% in the area close to city centres. The longer the distance to a city centre, the lower the effect of metro openings on reducing particulate concentrations (Gendron-Carrier et al., 2020). A study of 37 new metro lines in 29 Chinese cities found that metro operation decreased $PM_{2.5}$ concentrations by an average of 18 ug/m^3 (Lu et al., 2018). The reasons for inconsistent research findings need to be further explored in the future, e.g. via including or excluding the influence of some factors of city development.

For world cities with initially high levels of air pollution, a new metro opening brought a 1 billion USD external mortality benefit per year due to decreased mortality because of reduced air pollution (Gendron-Carrier et al., 2020). It was estimated that the total health benefit from reduced mortality and morbidity of 20 years' operation of 14 new subway lines in Beijing accounted for 1.0–3.1 billion USD (1.4–4.4% of the total construction and operating cost) (Li et al., 2019b). It was suggested that the impact of metro development on air quality should consider air pollution's spatial spill-over effect to avoid overestimation of metro's impact (Xiao et al., 2020). With regard to the influence on GHG emissions, metro extensions decreased CO_2 emissions in Bangkok (Ikeshita et al., 2013). After nine years' operation of a metro line in Toronto, Canada, it was found that metro transport nearly paid back the initial GHG emissions in the optimistic scenario (Saxe et al., 2017).

Metro systems with different scales have various effects on air pollution. Examination of 160 Chinese cities revealed that metro mileage and numbers of metro lines and stations were negatively related to levels of the Air Quality Index and $PM_{2.5}$. Metro mileage and number of metro stations were negatively and non-significantly associated with PM_{10} (Xiao et al., 2020). An increase in subway density improved air quality (Li et al., 2019b). In addition, local contexts affect the influence of metro systems. In Chinese cities, central heating in winter, population scale, and city tier can influence new metro lines' effects on $PM_{2.5}$ emission reduction (Lu et al., 2018).

Metro development impacts on ecosystems. Metro development in Sapporo, Japan led to major ecosystem changes of agricultural fallow/marshy areas into other urban uses: orchards/vegetable farms (greater than 95%), marshes (90%), open spaces (60%) and forested areas (30%) were lost and changed to transport, residential, recreational and other urban uses (Jothimani and Yamamura, 1995). Metro development and operation also impact on ground vibration (Qu et al., 2021), groundwater (Chae et al., 2008; Ho, 2016), noise (Wang et al., 2017), and excavated soil and rock (Zhang et al., 2020). Due to the nature of these studies in the areas of engineering and construction technology, the details of these studies are not discussed here.

5. Impacts on social development

Public transport is a transport mode used by people without access to private, motorised transport. Enhancing transit services (e.g. through providing quality metro services) can have significant social impacts (Fouracre et al., 2003). This review discusses the social impacts of metro development primarily on equality of transit opportunity, accessibility and connectivity, public health, personal identity, travel experience and safety. Existing studies analysed data from single or multiple sources including Internet websites (Kim and Song, 2015; Li et al., 2019c; Liu et al., 2021; Song et al., 2018), local authorities and organisations (Chen et al., 2021; Song et al., 2018; Zhu and Liu, 2004), and surveys and interviews (Gopal and Shin, 2019; Xiao et al., 2021; Yin et al., 2021). They employed various research methods, primarily statistical analysis (Chen et al., 2021; Kim and Song, 2015; Song et al., 2018; Xiao et al., 2021; Yin et al., 2021) and spatial analysis (Wang, 2017; Zhu and Liu, 2004).

Metro development can decrease the social and spatial exclusion of disadvantaged groups. A study on Gwangju, Korea found that metro expansion resulted in consistently improved transit equality. The first linear metro line did not benefit groups that relied on transit. However, when an additional circular metro line was operated, travel by women and young people appeared to be significantly and positively associated with the increased transit supply. This indicated that with a fairer distribution of metro transit resources, disadvantaged groups, e.g. groups reliant on transit, may have benefited more (Song et al., 2018). Metro systems are developed to improve accessibility for travellers to get to key trip destinations of working, living, entertaining and other social activities. Zhu and Liu (2004) found that a new metro line had a heterogeneous effect on accessibility to different destinations for different areas of Singapore. This is consistent with a study conducted by Liu et al. (2021) who found that the impact of metro expansion on healthcare accessibility for different areas of a city was heterogeneous. In Shenyang, China, metro expansion, by itself, had limited impact on addressing inequity in healthcare accessibility. People living in *peri*-urban areas had low accessibility to healthcare services due to low metro coverage (Liu et al., 2021). The different spatial patterns and pace of improvements in accessibility and reliability following metro expansion over time were also confirmed in Seoul. Compared with a consistent increase in accessibility from the city core to urban periphery, reliability was quickly improved and then stabilised in the middle stage of the history of metro development (Kim and Song, 2015). Metro services in Singapore significantly improved public transit connectivity of individual buildings. However, on a city scale, they failed to enhance equality of public transit connectivity: on one hand, they reduced the difference between central and peripheral regions; on the other hand, they increased the difference among buildings due to different levels of accessibility to metro stations (Li et al., 2019c).

Metro operation may benefit public health. In Taipei, the extension of the metro system together with a reduction in the number of motorised vehicles resulted in a significant decrease in air pollutant levels and consequently an improvement in ambient air quality. Considering the relationship between air pollution and mortality, the development of metro benefited public health, as evidenced by lower mortality rates (Chen et al., 2021). Metro transport may have a negative impact on public health during special time periods. Due to numerous passengers using metro transport to travel across cities and the interactions among metro passengers, metro transport may help spread an influenza epidemic. An investigation found that if influenza that was featured the 1957–1958 pandemic would occur in New York City, metro transport would be responsible for 4% of transmissions (Cooley et al., 2011). Living close to a metro station may reduce obesity. Proximity to a greater density of subway stations had an inverse association with children's overweight and obesity in Massachusetts, US (Oreskovic et al., 2009). A study in Chengdu, China found although a mean body mass index (BMI) increase of 1.0 kg/m^2 over 10 years was reported by survey respondents, those who lived within 400 m distance from the nearest metro station had a significantly reduced BMI increase (by 0.545 kg/m^2) compared with those living more than 400 m distance from the nearest metro station. Those who lived within 800 m distance from the nearest metro station had a significantly reduced BMI increase (by 0.434 kg/m^2) compared with those living more than 800 m distance from the nearest metro station (Xiao et al., 2021). The density of metro stops was significantly inversely related to BMI after adjustment for individual- and neighbourhood-level sociodemographic characteristics (Rundle et al., 2007).

Metro that was developed in developing countries' cities (e.g. Tehran in Iran) enhanced women's mobility, providing them with access to greater spatial urban areas and offering good access to educational, professional and recreational opportunities, particularly for those who did not have private car access (Bagheri, 2019). A study in 43 Chinese cities found that a new metro line attracted 4.1% of former bus passengers annually, equivalent to the passengers of 10 or more bus lines (Liu and Li, 2020). An early study in Montreal, Canada found that metro

extension increased transit ridership, significantly decreased travel time and reduced the number of transfers required of transit passengers. This effect was significant within 1.6 km from the metro line and showed a temporary effect shortly after metro extension, prior to a reduction of mode share for public transit (Chapleau et al., 1987). An international study of the 632 largest cities in the world indicated that a 10% increase in metro expansion was related to about a 6% increase in metro ridership but had no effect on bus ridership (Gonzalez-Navarro and Turner, 2018). The operation of a new metro line in Nanjing, China increased passenger flow across the whole metro network and decreased crowding at some metro stations due to the flow of passengers to the new line (Fu and Gu, 2018).

Metro development changed travel behaviour, e.g. decreasing bus, taxi and car trips (Liu and Li, 2020), reducing commuting trips by walking, cycling and bus (Wu and Hong, 2017), and reducing the average travel time for walking and cycling trips (Sun et al., 2020). However, there was no change in car and e-bike trips (Sun et al., 2020). Metro affects car and bike ownership. A study in Taipei found that metro operation dramatically decreased the level of household car ownership (Huang and Chao, 2014). Metro operation in Xi'an, China had a negative association with car ownership and e-bike ownership, and was positively associated with bike ownership (Huang et al., 2017). Households living close to new metro stations had lower dependence on cars in Singapore and Beijing (Zhang et al., 2017; Zhu and Diao, 2016). Mixed land use and improved accessibility of amenities in metro station areas reduced car dependence (Li and Zhao, 2017). Proximity to metro stations with shorter travel time to the city centre or the nearest sub-centre reduced car ownership significantly (Zhang et al., 2017). Relocation to metro neighbourhoods reduced the level of car and e-bike ownership in Xi'an, China (Huang et al., 2017). Households with high dependence on metro transport had lower car ownership rates in Taipei (Huang and Chao, 2014). However, metro development in Singapore did not noticeably change the household demographic characteristics (e.g. household size, car ownership rate, and number of workers) of those who lived close to metro stations compared with those who lived further from the stations (Zhu and Diao, 2016).

An examination of 45 new metro lines in 25 Chinese cities found a positive effect of metro development on alleviating road congestion. In the first year after the metro openings, road speed in rush hours increased by around 4% on nearby roads (Gu et al., 2021). In Beijing, traffic congestion reduced dramatically following the opening of new lines. The opening of each metro line reduced delay times by 15% on average in the short term across the entire city (Yang et al., 2018).

The impact of Delhi Metro on the lives and travel experiences of women was examined by Gopal and Shin (2019). They found that women had generally empowering and positive travel experiences with metro, due to their relative sense of safety in metro produced by the metro's safety measures. Women's gendered identities were constantly changed through the improved mobility that was enhanced by metro development in Tehran, Iran (Bagheri, 2019). Proximity to a subway station was found to robustly promote happiness of individuals in Shanghai (Li et al., 2018). Metro transport had an association with life satisfaction. By linking to quality transit service, walkability, accessibility, and travel satisfaction, metro transport in Xi'an, China was positively related to life satisfaction. Metro development was a more influential instrument for wellbeing enhancement in cities in developing countries than in developed countries (Yin et al., 2021).

However, metro was also found to be closely related to crimes in San Francisco. At the macro level, the overall distribution of crimes in the whole city was consistent with the metro service alignment. At the meso level, metro stations had a significant correlation with most types of crimes. On the micro level, the neighbourhoods surrounding metro stations tended to have crime clusters (Wang, 2017).

6. Discussion and conclusion

Cross-sectional, longitudinal and before-and-after studies have been conducted to explore the association between metro development and economic, environmental and social outcomes. Studies have been conducted in both developing and developed countries with very different urban contexts in urban form, density and transit systems (Zhu and Diao, 2016). An increasing number of studies from Asian countries indicate that rapid growth in metro development and operation has contributed to the majority of new metro systems in the last two decades in the world (UITP, 2018).

Metro systems have been viewed as an ecologically and economically efficient option for transporting large numbers of passengers in mega cities. However, heavy initial investments are needed for metro projects, and considerable financial uncertainties need to be addressed in the areas of planning, project management and operational management. It is essential for the financial success of a metro project to have capital funding support from the public sector and participation and contribution from the private sector in its execution and operation (Fouracre et al., 2003). A key finding from the review is metro's positive economic impact on property prices and value. The metro premium was confirmed by numerous studies in different cities in the world, and land value uplift due to travel time savings provided by metro systems can be capitalised into the land close to metro systems (Saxe and Miller, 2016). Land value capture can be introduced to pay for the development of the metro infrastructure that created the value, using taxation mechanisms and/or public–private partnerships based on the land value uplift associated with metro development (Saxe and Miller, 2016), to solve the problem of fund shortage. This is an area that attracts policy-makers' interests, and reliable estimations of value capture benefits successful financing of metro projects. In fact, to what extent new metro development impacts on property value is important to the projection of local fiscal revenue, particularly in counties with rapid development of metro infrastructure (Sun et al., 2015). Therefore, more empirical studies on metro's economic impacts from countries with rapid development of metro infrastructure would be important and helpful for decision-makings related to infrastructure development and financing.

The review indicates metro's effects in promoting residential developments and population growth around new metro stations, increasing housing density in the station area, promoting utilisation of UUS to accommodate multiple land uses and urban functions, increasing transit ridership and decreasing car dependence (Belanger, 2007; Calvo et al., 2013; Gonzalez-Navarro and Turner, 2018; Huang and Chao, 2014; Zhu and Diao, 2016). In addition, this review also indicates that metro development accelerates suburbanisation and decentralisation (Gonzalez-Navarro and Turner, 2018; Lee et al., 2021). It is well-known that transport planning and land use planning can be integrated to achieve better planning outcomes. Land use patterns of the metro station area are closely related to metro ridership (Jun et al., 2015). Proactive planning may be needed to allow decentralised growth to take place in the form of subcentres, i.e. TOD, to combat outer development and urban sprawl (Suzuki et al., 2013). The impact of metro development, particularly around metro stations in this review, as mentioned above, is compatible with TOD principles and objectives (Hsu, 2020). Therefore, when developing metro systems, TOD strategies need to be considered by planners and decision-makers, if possible, to form optimal land use patterns, particularly around metro stations, to promote sustainable development.

Although the development of metro infrastructure requires significant initial investment, metro systems have economic impacts on property value and a wider economic effect at the city, regional and national levels. In addition, metro development has confirmed environmental and social values. Some studies have estimated some environmental values of metro development. For example, the Sheppard metro line in Toronto, Canada, after nine years' operation, had almost paid back its initial GHG emissions in the optimistic case, due to modal

shift from cars, and increases of residential density and energy use efficiency in the metro station areas (Saxe et al., 2017). Nowadays, many countries are confronted with environmental problems. Air pollution is believed to be a serious problem in urban areas, particularly for developing countries that are facing growing numbers of cars, limited road capacity and few transit investments (da Silva et al., 2012). This review highlighted metro's effects on improving air quality since metro systems effectively increased public transport use and reduced private car use. For developing economies that often need to develop their economies at the price of environmental deterioration, metro systems may be an attractive option for infrastructure development, to effectively address traffic congestion and improve transport efficiency for economic development, at the same time protecting the environment. Undoubtedly, UUS development is irreversible, and UUS utilisation (e.g. metro) affects underground environments such as water, soil and rock. These impacts, both positive and negative, need to be evaluated and considered. Cost-benefit analysis of metro's effects that comprehensively considers their economic, environmental and social values would not only be essential for sustainable transport analyses (da Silva et al., 2012), but also be supportive for decision-making about infrastructure investment and economic, environmental and social development.

From this review, it can be seen that research on metro systems' effects on urban development has been conducted in many areas. The contribution of metro systems to urban development has been confirmed by numerous studies in many cities in the world. The review found that many studies examined metro's effect on land and property prices and value. Although the impacts of metro development on land and property prices and value may vary spatially, temporally and geographically, the existing literature generally supports the positive capitalisation of metro in property value. In addition, many studies investigated metro's effect on land use, density, population and UUS utilisation. The studies generally support the effects of metro development on encouraging new developments and urban renewal, shaping urban development and land use, facilitating commercial growth and residential development surrounding metro stations, promoting utilisation of UUS for multiple urban functions, changing people's travel behaviour and therefore reducing car dependence and alleviating traffic congestion, increasing mixed land use and urban density, and encouraging TOD development. Studies of metro's effects on the natural environment focused on reducing air pollution and GHG emissions, and generally, reported positive influences. Moreover, equality of transit opportunity, accessibility and connectivity, public health, travel behaviour, personal identity, travel experience and safety were the foci of research on the social impacts of metro development, with researchers reporting mixed findings of positive and negative effects. The effects of metro systems on urban development are demonstrated through property value, land use, travel behaviour, air pollution, and public health. This review mainly focused on articles in the research fields of urban planning and urban studies. A separate review of other areas associated with metro's effect on urban development e.g. engineering and construction technology, would provide additional information to support decision-making for metro infrastructure investment and development.

CRediT authorship contribution statement

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

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