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The impact of metro services on housing prices: a case study from Beijing

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Abstract Assessment of the impact of metro systems on housing prices is important for financing transport infrastructure via value capture. This paper provides evidence for this relationship, focusing particularly on the effects of metro services, and uses the large city of Beijing, China, as a case study. A spatial error model was applied to 2835 samples of online property sales data obtained in January 2016. Three transport service indicators associated with metro transfers and waiting times were explored: (1) metro headway, (2) access to different metro lines and (3) accessibility to employment opportunities. The results show that areas with more employment opportunities via public transit have higher housing prices than other areas. Shorter metro headways are positively related to housing prices near stations. Housing prices for neighborhoods having access to more than one metro line within 800 m-buffer area are higher than those without access to metro lines, controlling for number of accessible jobs within 30 min. This study sheds light on the importance of metro services on housing prices. It has implications for further research and for the planning policies of metro-dependent cities.

Keywords Transport service · Housing price · Spatial hedonic model · Metro · Beijing

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Introduction

In many cities around the world, 'transit cities' are being built to overcome the problems of car-dependent societies such as air pollution, traffic congestion and obesity (Cervero 2004). Metro lines are a mass passenger transport system that have the advantages of low emissions, low energy consumption, and high speed compared with other public transit modes. Metros can serve the whole population, allowing people to reach destinations such as places of employment, healthcare and education. Therefore, public transport is believed to improve transport equity (El-Geneidy et al. 2016). Metros can also be strong tools for directing the future development of whole cities. This can be achieved by transit-oriented development, whose main idea is to design high-density, mixed-use and walking-friendly urban areas near metro stations (Dittmar and Ohland 2012; Li and Zhao 2017).

However, methods for measuring the value of metro accessibility benefits is of key interest for metro investment, particularly in developing countries. Land or property value capture in relation to accessibility improvement of railways, including metro system, is believed to be a proper method of financing metro development (Mathur and Smith 2013; Medda 2012; Suzuki et al. 2015). Land value capture theory claims that the costs of metro investments can be recovered by capturing some of the capitalized benefits that result from the accessibility improvements brought by the metro system (Fensham and Gleeson 2003). According to this theory, the links between metro development and land values or housing prices are vital to capturing the increased property values brought by metro development. Many previous studies have examined the impacts of metro development on housing prices (Debrezion et al. 2007; Bowes and Ihlanfeldt 2001; Efthymiou and Antoniou 2013). Generally, prices of housing properties located near metro stations are higher than those further away.

Although many empirical studies have attempted to measure the monetary value of metro accessibility improvements (see "Literature review" section), several research gaps remain that need addressing. Firstly, existing studies have mainly focused on the effects of metro station proximity (Debrezion et al. 2007) and transit-oriented development (Duncan 2010) on surrounding housing prices. However, the effect of transport services, which can generate travel time differences at different stations and metro lines, are generally ignored. Secondly, previous studies have mainly relied on traditional hedonic models. Although these models are widely applied in housing studies, they fail to account for omitted variables and spatial autocorrelation. Econometric models, introduced to deal with spatial autocorrelation, have been used widely in housing studies. However, incorporating this method to explore the impact of metro lines on housing prices is a relatively recent trend (Armstrong and Rodríguez 2006), and empirical studies using spatial hedonic models to explore value capture related to metro accessibility remain scarce. Thirdly, existing discussions are mainly based on the Western context and may not be applicable to Asian cities characterized by high rates of metro usage and high-density development. Asian metropolitan areas are characterized by high dependence on public transit. Passengers in these metropolitan areas may be much more sensitive about the nuanced variations of public transit services than those in Western contexts.

In view of the above research gaps, this paper uses Beijing as an example and explores the impact of metro services (including job accessibility, access to different metro lines and metro headway) on housing prices. A spatial hedonic model is used to tackle the spatial autocorrelation problem. The remainder of this paper is structured as follows. The second section reviews the existing literature exploring the impacts of metro systems on housing prices, and demonstrates the research hypothesis and theoretical foundations. The third section presents our research methods. The fourth section presents the result of regression analysis. The fifth section discusses the analysis and draws conclusions.

Literature review

This study aims to explore the role of several metro service variables (metro headway, access to different metro lines, accessibility to job opportunities via metro) on housing prices. The first part of this section reviews the theoretical and practical rationales for investigating the role of metro services on housing prices. The second part reviews the other factors influencing housing values near metro stations which should be controlled for in the model. The third part reviews the existing empirical studies that have used spatial econometric hedonic models to explore the role of metro accessibility on housing prices. The final part reviews related studies conducted in China, especially Beijing. Table 1 summarizes the empirical findings regarding the factors influencing housing prices near rail/metro stations, as discussed below.

The role of metro services in housing prices: theoretical foundations and research hypotheses

The research uses location theory as its foundation. According to classical urban economic theory, every individual faces a trade-off between transportation and land rent costs under the same economic constraint (Alonso 1964; Muth 1969). This theory also applies to real estate studies in non-auto contexts to examine the impact of improvements of metro accessibility on housing prices (Giuliano 2004). Most previous studies pay excessive attention to the effects of metro station proximity on housing prices. However, travel time is also an important measure of metro accessibility. Improvements to a metro service that reduce passenger travel time can improve metro accessibility, and thus improve housing prices. However, empirical studies exploring this relationship are scarce.

To our knowledge, very few studies have investigated the role of transit services on housing prices. Debrezion et al. (2007) conducted a meta-analysis of 57 empirical studies focusing on the impact of railway accessibility on housing prices. They found that network connectivity and the local coverage of different railway lines could have various roles in housing value capture. Of all types of railway, commuter rail had the strongest influence on nearby housing prices. The magnitude of housing price value capture near light and heavy rail systems could be less significant. The different value capture effects of different types of railway lines can be explained mainly by differences in service frequencies, transfer times to destinations, and travel speeds. Debrezion et al. (2011) found that doubling the rail service frequency contributed to an increase of approximately 2.5% in housing prices. The study controlled for other factors and used data from the 1985–2001 Dutch housing market.

In this research, the basic assumption is that time spent commuting by metro is disliked, rather than enjoyed by passengers (Small and Verhoef 2007). According to the theory of *value of time* (VoT) in transportation economics, travel time can be capitalized as a monetary value, and people are willing to pay for the opportunity costs of travel based on their monetary constraints. In this sense, the choice of residential and employment location can be thought of as a three-way trade-off between after-tax income, housing expenditure, and travel time and cost. When it comes to public transit, previous studies found that waiting and transfer times are more distressing for metro passengers compared with in-

Table 1 Influences on housing prices near rail/metro stations identified in the literature

Variables	City/Region, Country (study)	Method	Conclusions
Headway	Netherlands (Debrezion et al. 2011)	Nonspatial hedonic model	Doubling the rail service frequency contributed to an increase of approximately 2.5% in housing prices
Transfer station	Beijing, China (Dai et al. 2016)	Nonspatial hedonic model	Without considering other factors, the average housing prices near transfer stations were up to 3368.16 yuan/m^2 higher than near non-transfer stations
Job accessibility	Tyne and Wear, the UK (Du and Mulley 2012)	Geographically weighted regression (GWR)	Transport accessibility had divergent impacts on housing prices in different areas
	Taipei, China (Lin and Cheng 2016)	Nonspatial hedonic model	Job accessibility via public transit playsed a more important role in determining apartment rents than accessibility by automobiles in Taipei. Additionally, its role on low- and medium-rent apartments were positive, while its role on high-value apartments was negative
Metro/Rail proximity	California, US (Landis et al. 1995)	Nonspatial hedonic model	Single-family house premium related to the proximity to BART was US$2.39 per meter in Alameda County, US$1.96 per meter in Contra Costa County
	Washington, DC, US (John and Sirmans 1996)	Nonspatial hedonic model	Every 0.1 mile further from the metro station contributed to a 2.5% decrease in housing rent
	Oregon, US (Knaap et al. 2001)	Nonspatial hedonic model	Proximity to the stations planned by a light rail investment significantly increased the land price after the announcement of the plan
	New York, US (Hess and Almeida 2007)	Nonspatial hedonic model	Proximity to the metro station was associated with a US$2.31 per foot (straight-line distance) and US$0.99 per foot (network distance) increase in housing prices
	Chicago, US (McMillen and McDonald 2004)	Nonspatial hedonic model	Proximity to planned rapid transit stations on the downtown Chicago to Midway Airport line was positively associated with the prices of single-family houses
	Atlanta, US (Immergluck 2009)	Nonspatial hedonic model	The announcement of planning for Beltline in Atlanta increased housing property prices
	Atlanta, US (Bowes and Ihlanfeldt 2001)	Nonspatial hedonic model	Properties within 0.25 miles of a rail station sold for 19% less than those more than 3 miles away
	Tyne and Wear, UK (Du and Mulley 2006)	Geographically weighted regression	Geographically-weighted regression (GWR) results showed that the effects of metro proximity on land values varied between areas. In some areas, the relationship was positive; but in other areas, the relationship was negative or insignificant
	Seoul, Korea (Bae et al. 2003)	Nonspatial hedonic model	Proximity to the Line 5 metro stations in Seoul had a positive effect on property prices before the opening of the metro line

Table 1 continued

Variables	City/Region, Country (study)	Method	Conclusions
	Toronto, Canada (Haider and Miller 2000)	Spatial autoregressive (SAR) model, Nonspatial hedonic model	A spatial autoregressive model explained 83% of housing price variation, and was better than a standard hedonic model in terms of explanatory power
	Eastern Massachusetts, US (Armstrong and Rodríguez 2006)	Spatial autoregressive (SAR) model	Properties in municipalities with commuter rail stations were 9.6–10.1% higher in price compared with their counterparts. Properties within a 0.5 mile buffer of rail stations were 10.1% more expensive than those further away
	Santander, Spain (Ibeas et al. 2012)	Spatial autoregressive (SAR) model, Saptial error model (SER), Nonspatial hedonic model	A SEM model with a Queen-contiguity matrix provided the best fit to the data, and the results showed that proximity to rail stations had a negative effect on housing prices
	Athens, Greece (Efthymiou and Antoniou 2013)	Spatial autoregressive (SAR) model, Spatial error model (SER), Spatial Durbin model, Nonspatial hedonic model	The proximity to metro, tram and suburban railway stations had positive impacts on the values and rents of nearby properties
	Lisbon, Portugal (Martínez and Viegas 2009)	Spatial autoregressive (SAR) model, Nonspatial hedonic model	This study compared the roles of local versus system-wide accessibility on housing values. The results showed that local accessibility could better explain housing price variations, and that proximity to metro and rail lines had significant impacts on housing values. However, the SAR model showed no significant fit to the data compared with an OLS model based on the Akaike Information Criterion (AIC)
	Beijing, China (Liang et al. 2007)	Nonspatial hedonic model	The value of houses within 2 km of metro stations near Line 13 in Beijing was 267 yuan higher per square meter compared with houses beyond this distance
	Beijing, China (Feng et al. 2011)	Nonspatial hedonic model with Box-Cox transformation	Proximity to metro stations along Line 5 in Beijing had a significant, positive effect on housing prices, but there was no effect on houses located more than 2 km from metro stations
	Beijing, China (Gu and Guo 2008)	Nonspatial hedonic model	In the suburban area, every 1 km nearer to metro stations along the Batong Line contributed 1.8% to housing prices; however, in the downtown area, proximity to metro stations along this line had no effect on housing value premiums

Table 1 continued

Variables	City/Region, Country (study)	Method	Conclusions
	Beijing, China (Gu and Zheng 2010)	Nonspatial hedonic model	In the downtown area, proximity to metro stations along Line 13 had no significant role on housing price increases. However, in the suburban area, houses within 1 km of the metro stations along this line were 20% more expensive than houses beyond this scope
	Beijing, China (Sun et al. 2015a, b)	Nonspatial hedonic model, Repeat-sales model	Rent-distance elasticity in this study was − 0.02, lower than that of traditional hedonic models
Housing type and neighborhood design	Phoenix, US (Atkinson-Palombo 2010)	Nonspatial hedonic model	The light-rail system added a 6% premium to single-family houses and 20% to condos for walk-and-ride neighborhoods. For park-and-ride neighborhoods, the light rail added no significant premium to single-family houses, and reduced the value of condos
	San Diego, US (Duncan 2008)	Nonspatial hedonic model	The capitalization of light rail proximity on condominiums exceeded 10%, while the capitalization on single-family houses was less than 10%
	New York, US (Hess and Almeida 2007)	Nonspatial hedonic model	Proximity to the light rail system had a positive effect on high-income neighborhoods, and a negative effect on low-income neighborhoods
	Atlanta, US (Bowes and Ihlanfeldt 2001)	Nonspatial hedonic model	Proximity to light rail transit had a negative effect on the property values of high-income neighborhoods within 0.25 mile of stations, especially when the stations were downtown and had carparks
	Miami, US (Gatzlaff and Smith 1993)	Nonspatial hedonic model, Repeat-sales model	Proximity to light rail stations had a weaker effect on high-value houses experiencing growth than on those declining in value
	Atlanta, US (Nelson 1992)	Nonspatial hedonic model	Proximity to heavy-rail stations had a positive effect on low-income neighborhoods, and a negative effect on high-income neighborhoods
Transit-oriented development	San Diego, US (Duncan 2010)	Nonspatial hedonic model	Condos near a walking-friendly rail station had more value than ones further away; while condos near a park-and-ride station were worth less than ones further away
	Fourteen cities, US (Kahn, 2007)	Difference in difference	From 1970 to 2000, communities with improved access to "Walk and Ride" stations experienced greater gentrification than those in proximity to "Park and Ride" stations
	Atlanta, US (Bowes and Ihlanfeldt 2001)	Nonspatial hedonic model	Parking lots near railway stations had positive effects on the prices of houses located 0.25–3 miles from metro stations

vehicle time (St-Louis et al. 2014; Tyrinopoulos and Antoniou 2008; Iseki and Taylor 2009). This paper focuses on public transit and explores the role of metro travel time on housing prices. Public transit service quality can be evaluated using various factors such as accessibility, punctuality, fares, information availability, convenience, and the built environment of transit stops (Lai and Chen 2011; Hu and Jen 2006; Fan et al. 2016; Iseki and Taylor 2009, 2010). In this study, the destination accessibility and convenience of the metro network are mainly explored for the following reasons: (1) most previous studies exploring the role of public transit on housing prices report that housing premiums are mainly the product of public transit proximity. However, accessibility measurements are via public transit are rarely included in these studies; (2) the unavailability of data, especially real-time data, prevents us from further exploring other service indexes, such as punctuality and information availability for passengers; (3) among these variables, previous studies have shown that the amenities around stops only have a marginal influence on passenger ridership, although they can affect passenger satisfaction. Therefore, the built environment of stops was not investigated in this study. (4) Transit fares are also not a focus of this study, because transit fares in Beijing are relatively low compared with residential property values. The Beijing metro system adopts a distance-based fare system. One-way travel within six kilometers costs three yuan (approximately US$0.45), and within 32 km it is six yuan (approximately US$0.90). Therefore, passengers focus more on travel time than travel expenditure. In this sense, four hypotheses are proposed based on the existing literature.

As the assumption states, people's residential and employment location choices are determined jointly by job opportunities, transport costs, and housing prices. Thus, Hypothesis 1 relates to the influence of job accessibility via metro on housing prices. Several studies have explored the property premiums resulting from job accessibility. For example, Osland and Thorsen (2008) found that labor-market accessibility explained variations in housing prices in Norway. Some scholars have found that job accessibility has different patterns of impacts on property values in different areas. Adair et al. (2000) found that job accessibility could only explain a small proportion of housing price variation in Belfast, Ireland, with a greater effect evident in low-income areas. Du and Mulley (2012) explored the role of metro accessibility in Tyne and Wear, UK and found it had divergent impacts on the housing prices in different areas. In Taipei, Taiwan, Lin and Cheng (2016) found that public transit job accessibility had a more important influence on apartment rents than automobile accessibility. Additionally, its influence on low- and medium-rent apartments was positive, while its role on high-rent apartments was negative. Overall, this information informed the production of Hypothesis 1.

Hypothesis 1 Houses near metro stations that facilitate job accessibility will have higher prices than houses in areas with poor job accessibility by metro.

Public transit waiting time is an important component of travel time, and is often regarded negatively by passengers (Fan et al. 2016). Additionally, waiting time is often regarded as more distressing than in-transit time, and is perceived to be longer than it actually is (Wardman 2004). Therefore, one hypothesis of this study is that housing properties near metro stations with shorter waiting times should have higher prices than others. It is difficult to retrieve real waiting times, so in this study, peak-hour headway was used as a proxy for waiting time. One caveat is that the real waiting time for an individual could be much longer than the headway, because of in metro station congestion. The hypothesis is:

Hypothesis 2 Houses near metro stations with short service headways will have higher prices than houses near stations with long headways.

Additionally, transfers through different transit routes add additional time. Even if transfer time can be neglected in some cases, passengers perceive transfers negatively. This negative effect is called “transfer penalty” (Horowitz 1981; Horowitz and Zlosel 1981). The most direct way to assess the impact of the “transfer penalty” effect on housing prices is by investigating the effect of variations in transfer time on housing prices. However, this data is unavailable to us. Therefore, a proxy variable—whether the house could access more than one metro line within a buffer threshold—was used to estimate the potential transfer time of a metro passenger. Houses having access to more than one lines in a given buffer could reach more destinations without needing to transfer between lines. In this sense, passengers having access to different metro lines may have shorter travel times than those near regular stations. Therefore, the number of metro lines a neighborhood could access in a given buffer adds an extra premium to housing prices, controlling for other variables. A recent study in Beijing (Dai et al. 2016) explored the influence of transfer station presence on housing prices by using this proxy variable. Their study found that, without considering other factors, average housing prices near transfer stations were up to 3368.16 yuan/m^2 higher than for those near non-transfer stations. However, one serious drawback of this study was that it did not consider differences in metro service factors between transfer and non-transfer stations, such as headway and job accessibility. Additionally, this measurement is difficult to disentangle the positive and negative effects of transfer stations. It is also unable to evaluate the access benefits of the neighborhood having access to different metro lines by accessing to different metro stations within walking distance. Without considering these factors, it is at risk of overestimating the role of transfer stations on housing prices, and masking the roles of other metro service factors. This information led to the formation of Hypothesis 3:

Hypothesis 3 Houses which could access to more different metro lines within a buffer threshold have higher values than houses which could access to one or no lines within the buffer.

Other factors

In order to explore the influences of metro headway and accessibility to employment centers on housing prices, other transport modes, land use, and neighborhood attributes influencing housing prices should also be taken into account.

Metro station proximity is a variable that needs to be considered. Previous studies have reported mixed findings about the impact of metro station proximity on housing prices. Many researchers have found that the proximity of housing to metro stations positively affected their value. This has been reported in cities in North America (Landis et al. 1995; John and Sirmans 1996; Knaap et al. 2001; Hess and Almeida 2007; McMillen and McDonald 2004; Immergluck 2009), the UK (Du and Mulley 2006), and Korea (Bae et al. 2003). However, some researchers came to the opposite conclusion. They claimed that metro station proximity had no effect, or even negative effects on housing prices, controlling for other factors (Landis et al. 1995; Bowes and Ihlanfeldt 2001). The possible reason might be that the negative externalities of metro stations, such as crime, congestion, and air and noise pollution, exceeded the benefits of accessibility and business vibrancy that the metro stations brought (Bowes and Ihlanfeldt 2001). Similarly, proximity to bus stations is also considered to be an important influence on housing prices, though its role is still arguable (Stokenberga 2014).

Moreover, housing type and neighborhood design also have important bearings on housing prices near metro stations (Atkinson-Palombo 2010). Several studies found that the impact of metro accessibility improvements affected nearby condominiums and apartments more so than single houses and townhouses (Atkinson-Palombo 2010; Cervero 2004; Duncan 2008). Moreover, while few studies found that metro accessibility improvements improved affluent neighborhoods (Hess and Almeida 2007; Bowes and Ihlanfeldt 2001), many researchers believe that it leads to higher capitalization in low-income neighborhoods because residents there have a higher propensity to use public transport (Gatzlaff and Smith 1993; Nelson 1992).

In relation to neighborhood design, new urbanism neighborhoods that were walking friendly and had well-designed amenities were claimed to be beneficial to increasing housing prices (Song and Knaap 2003). A recent study conducted in the city of Phoenix, USA, provided evidence that walking-friendly neighborhood designs promoted housing prices more so than car-oriented designs, after controlling for metro station proximity and other variables. This was because the car-oriented neighborhoods had higher negative externalities such as noise, air pollution, and traffic congestion (Atkinson-Palombo 2010).

Transit-oriented development (TOD) of metro stations also increases housing prices, after controlling for metro accessibility. In recent years, several studies revealed the impact of TOD on housing prices. Duncan (2010) believed that people were willing to pay for a pedestrian-friendly environment that encouraged people to drive less. His study illustrated that, within a quarter mile of metro stations, increases in business area, four-way crossings, and the flatness of the roads, contributed to housing prices significantly. The prices of transit-oriented condominiums with better walking environments were significantly higher than others. Similarly, Kahn (2007) found car-oriented metro stations had negative impacts on surrounding housing prices, while pedestrian-oriented ones increased them, after controlling for other variables. However, few studies have found that parking facilities near metro stations enhance housing prices. A study by Bowes and Ihlanfeldt (2001) found that locating parking sites near metro stations had positive effects on the prices of houses located between 0.25 and 3 miles from metro stations.

Spatial hedonic models and related studies

Hedonic modeling is widely used in housing studies to examine housing value capture. It was developed by Rosen (1974), who claims that the observed price of a specific property can be revealed by a set of implicit characteristics. A main assumption of the model is that differences in property prices can be expressed by customers' willingness to pay for a bundle of attributes that influence the property value. Housing attributes, neighborhood attributes, the location, and the built environment of the neighborhood, constitute a bundle of characteristics that influence property prices.

Existing studies usually use ordinary least squares regression (OLS) and its extended forms (semi-log and double-log) to estimate the coefficients of specific attributes. Spatial autocorrelation, which suggests that the attributes of a property are spatially related to those of properties nearby, could lead to biased OLS regression estimates and, therefore, should be incorporated into the regression model. Moreover, traditional hedonic models are incapable of exploring the impact of one variable on housing prices at different locations. Spatial econometric models can be used to analyze spatial dependence and spatial heterogeneity (Anselin 2010). Spatial dependence views the correlations of different variables or unobserved variations in various areas are derived from the spatial orderings. When spatial dependence exists in dependent variable, spatial autoregressive (SAR) model should be used. When dependence exists in the error term, spatial error model (SEM) should be used. When dependence exists in both the dependent variable and the error term, spatial Durbin model (SDM) should be used (Anselin 2010; Elhorst 2010). Spatial heterogeneity means that observed and unobserved spatial variations remain. Previous studies have typically explored variations in metro accessibility across different, segmented locations in a city using geographical weighted regression (Kim and Zhang 2005). Many economic cases have been made in support of SDM, claiming that the SDM can estimate the unbiased parameters without information for true data generating process, and provided clearer analysis for spillovers effect for the concerned variables. However, SEM can provide fuller expression of spatial dependence than SDM and accurately capture the potential shocks to a broader range of unspecified variables rather than just to the dependent variables (Glass et al. 2012). Moreover, the estimators from SEM, revealing the whole direct effects, can be more easily interpreted in the usual way, while those in the SDM or SAR can only be interpreted as direct and indirect spillover effect.

Spatial econometric techniques have been adopted in recent studies to overcome the problems of spatial autocorrelation and omitted variable problem, and to better evaluate the value capture effect of metro accessibility (Armstrong and Rodríguez 2006; Shin et al. 2007). Haider and Miller (2000) employed a spatial autoregressive (SAR) model to explore the effects of public transit proximity on housing price. The results showed that the models outperformed the traditional hedonic model and explained 83 percent of housing price variation. However, proximity to public transit was found to be a weak determinant of housing price. Armstrong and Rodríguez (2006) developed a SAR model to investigate the value capitalization of railways in eastern Massachusetts. The analysis demonstrated that the values of houses located in municipalities with rail lines were significantly higher than those that were not. Additionally, properties within a half-mile buffer of rail stations had higher values than those further away. Ibeas and his colleagues explored the impact of rail accessibility value capture in Santander, Spain. They found that a spatial error model (SEM) had the highest goodness-of-fit to the data. Properties close to rail stations had lower values (Ibeas et al. 2012). Efthymiou and Antoniou (2013) employed SAR, SEM, and geographically-weighted regression models to investigate the impact of proximity to transportation infrastructure on housing prices in Athens, Greece. They found that metro and suburban railway proximity had positive effects on housing prices and rents. Most previous studies have found that spatial econometric models outperformed traditional hedonic ones. One exception is Martínez and Viegas (2009), who found that spatial econometric models gave similar results to those of traditional hedonic models. This study is notable, and two reasons may explain this seemingly surprising result. One possible reason is that the absence of housing value data in the whole study area made it difficult to formulate an accurate spatial econometric model. The other reason is that the authors incorporated detailed local and system-wide accessibility in the model, and the inclusion of these variables may have captured some spatial variation.

Related studies in China

Many empirical studies have been conducted to estimate the value capitalization of metro accessibility on housing and land prices (Zheng et al. 2014). Most empirical studies in Beijing suggested that metro station proximity had positive effects on residential housing prices (Liang et al. 2007; Feng et al. 2011). Another study showed that apartments near the

Bus Rapid Transit system (BRT) in Beijing also experienced faster growth in value over time (Deng and Nelson 2010). Few studies have payed attention to spatial variations in metro accessibility in Chinese cities. For example, Gu and Guo (2008) found that the impact of metro station proximity on housing prices was more significant in suburban areas, taking Batong Line as an example. Gu and Zheng (2010) suggested that the values of properties within 1 km of a metro station were 20 percent higher than those further away, while those located in urban areas showed no price variation according to metro station proximity. Sun et al. (2015b) estimated the rental value capture of metro station proximity in Beijing using repeat-rentals models. The results showed that from 2005 to 2011, the distance-rent elasticity of properties was − 0.02, which was much lower than that of cross-sectional hedonic estimations.

While these existing studies do provide useful background information, several research gaps remain. Firstly, these studies mainly explored the effect of metro station proximity on housing prices, while generally ignored the effect of transport service quality (frequency, reliability, speed, etc.). Secondly, these studies have rarely considered the effects of metro-determined accessibility to employment jobs. Thirdly, previous studies have rarely used spatial hedonic models and, therefore, their results may have been biased by spatial autocorrelation.

Research design

Method

This research applies spatial error model (SEM) to overcome autocorrelation problems. Autocorrelation may occur on the dependent variable, the error term (Anselin 1993), or both (LeSage and Pace 2009). As cited above, SEM has advantage over SDM when we expect to achieve a fuller representation of spatial dependence, and also capture the potential shocks to a broader range of unspecified variables rather than just to the dependent variables (Glass et al. 2012). SEM is used in this study rather than the alternative SDM for the following reasons: first, based on the practical criteria provided in Glass et al. (2012), we found that the spatial autocorrelation coefficient is larger and more significant than coefficient on the spatial autoregressive variables; Additionally, we are more interested in obtaining the fuller direct effect of metro service on housing price effect rather than its spillover effect over all the variables. Moreover, to overcome autocorrelation problems which may occur on the dependent variable, the error term (Anselin 1993) or both (LeSage and Pace 2009), we used the diagnosis of two types of autocorrelation provided by LeSage and Pace (2009). The results show a spatial auto-regression process in the error term but not in the dependent variable is most suitable for this study. So, the spatial error model is used in this paper as the estimation method. The SEM formula can be stated as:

$$\mathrm{Y} = \mathrm{X}\beta + (\lambda \mathrm{W})\mu + \varepsilon$$

where ε is the error term assumed to be unrelated to the other variables, and the spatial auto-regression coefficient λ is applied to spatial error term μ by the spatial weight matrix, W. Term X denotes various housing, neighborhood location, built environment and metro attributes, and β is the coefficient of those attributes. The selection of a spatial weight matrix is an important issue in specifying the model, because it is an essential determinant of its accuracy. A spatial weight matrix is a positive matrix where non-zero elements reflect the variables assumed to be interacting with each other (Kim et al. 2003). The typically-used matrix is based on the geographical relationships of observations. In our analysis, considering that the housing transaction samples are highly clustered and have a wide spatial coverage, we used the K-nearest neighbor method to control for potential spatial error. This method assumes that k of the nearest observations of the unit have spatial dependence. Observations beyond this scope are spatially independent from the unit. We also checked the robustness of our results by choosing various k values from $k = 5$ to $k = 15$. There were no significant changes in our results, and all coefficients for metro services, housing characteristics and interaction terms were consistent across the models with different weight matrixes, implying that our results are robust and insensitive to the value of k used in the weight matrix. Analyses using a spatial weight matrix where $k = 15$ fitted the data best in terms of the maximum likelihood value. The calculation process follows LeSage (1999) and was performed with Matlab (2014a) software. All data were transformed to deviations from the means, which was suggested by LeSage (1999). They argued that otherwise, the numerical hessian approach might lead to a negative variance, due to the difficulty of determining accurate gradients during the computation process. Standardized transformation and scaling manipulation would be the most efficient approach to solve the negative variance problem.

City context

Beijing is the capital of China and is one of the biggest cities in the country. It has a population of 21 million in an area of 41,000 km^2 as of 2014 (Wang et al. 2015). As the first Chinese city to construct metro systems, Beijing has had a metro planning system since 1953. At the end of December, 2015, Beijing had 18 metro lines (including one line to the airport) and 334 metro stations covering eleven municipal areas. The total length of the metro lines was 554 km (Huang 2014a). Figure 1 shows the travel mode share and average travel distance per trip for different travel modes in 2015, Beijing. As the figure shows, there were more than 4.53 million trips by metro in the Beijing Metropolitan Area and thus, metro was the second-most important travel mode for residents' daily needs. In terms of travel distance, the average travel distance via metro per trip was 13.3 km. This suggests that the metro system has significantly improved people's activity space and thus, metro accessibility from home to employment and other amenities may be important influences on choices of residential and employment locations. Therefore, exploring the role of metro services on housing prices is very important for both metro investment and land use planning in Beijing.

Although Beijing is a metro-dependent metropolitan area, metro services still await improvement. Two problems facing some metro stations and lines in Beijing are long waiting times and transfer times, especially in peak periods. Metro headways are important determinants of the passenger capacity of metro lines, especially in peak hours. Some suburban metro stations serving nearby residential clusters face heavy passenger pressure in peak hours, and the relatively long headways are an important factor. For example, since the opening of Stage 2 of Line 6, many residents living along the suburban corridors of Line 6 have started commuting by metro (Huang 2014b). However, the headway of 4 min is too long and increases passenger pressure in this line. Metro companies in Beijing has attempted to improve the metro service by shortening service intervals. For example, Line 1 has shortened its minimum intervals to 2 min in peak times so that the line can transfer 4.2 percent more passengers daily (Liu 2015). Changping Line shortened its peak time

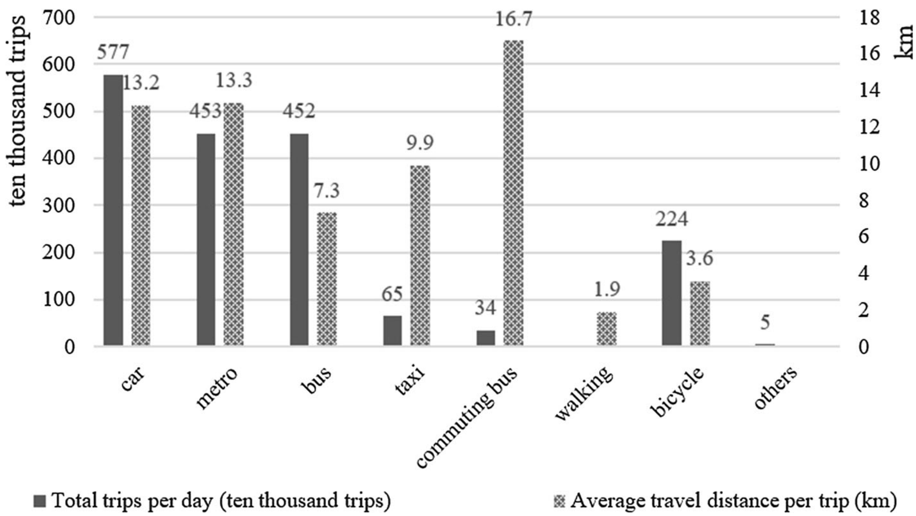

Fig. 1 Travel mode share and average travel distance per trip for different travel modes, 2015. *Note*: Waking trip distance is not covered in the original data source. *Source*: Beijing Transportation Institute (2016)

headway from 6.5 to 6 min, and the transportation ability of the line increased 6.3% (Yin 2016). These facts show that although the headways of Beijing metro lines are short and have nuanced differences, the high travel demands of the system make passengers sensitive about the frequency of metro services.

Another problem of the Beijing metro service is the long waiting time and inconvenience involved in making transfers between lines at certain stations. Several reasons are responsible for this phenomenon. One is the larger number of passengers that transfer stations serve. Another reason is that the transfer passages between lines are often too long. For example, some transfer stations in Beijing require passengers to walk more than 300 steps, which takes 5 min, to transfer between lines during regular hours (Zhang 2015). In peak periods, it takes passengers much longer, due to congestion.

The metro system in Beijing facilitates the regional accessibility of the whole city, especially suburban areas. Meanwhile, the Beijing metro plays an important part in orienting the future development of the city and creating new city centers. In view of the whole city, various city subcenters play an important role in mitigating the population and employment pressures of economic downtowns to some extent. Various metro lines linking these employment centers with residential clusters have significantly improved citizens' accessibility to jobs. Suburban lines have also connected existing city centers and residential sites with emerging suburban 'new towns'. These metro-oriented suburban employment centers speed the process of urbanization in suburban and fringe areas in Beijing. Nevertheless, they have not become sub-centers of the city, mainly due to lags in infrastructure construction, such as in Tongzhou New Town (Fang et al. 2014; Zhao et al. 2011).

Data

The housing data used in this paper was obtained through a web spider tool. All of the second-hand housing transactions in Beijing listed on the Anjuke website (http://bj.anjuke.

com/), the first online housing broker in China, were collected in January 2016. However, because these housing prices were reported prices rather than actual sale prices, not all of them are accurate. In order to avoid the negative effects of extreme observations and obtain a reliable dataset, we selected the medium number of housing price for a property in the same neighborhood, and only retained the observations that were posted online in a single neighborhood. We compared their values with nearby houses and their prices posted in the previous months. As the population density of Ecological Conservation District (202 persons/km^2) was far lower than the other three districts, and had a small sample of housing properties, the samples located in this area were dropped. After performing quality control on the data, 2835 houses from different neighborhoods in Beijing were retained for analysis. Although this sample was small compared with the scale of the real estate market in Beijing, these samples were from different neighborhoods, and their property values were reliable and representative of Beijing. According to the market share of Anjuke and the spatial distribution of property sales shown in Fig. 2. We compared the average property values with those from various website resources, and found that property sales analyzed in this study could be considered approximately representative of the whole city. Apart from housing prices, we also considered housing attributes (including housing size, storey, orientation, built year, decoration, number of rooms) and neighborhood attributes (total number of households in the neighborhoods and the ratio of green space to built space in the neighborhood).

Built environment variables were obtained from the Baidu Points of Interest (POI) online map (http://map.baidu.com). Straight-line distances from every neighborhood to amenities, and the density of bus stops near neighborhoods were calculated in ArcGIS 10.5. Each neighborhood's proximity to freeways and density of bus stops were included in the model to control for the roles of automobiles and buses. Job density and residential density were calculated at the sub-district level rather than neighborhood level. This is because sub-districts are the minimum level officially used to collect residential population and employment data in China.

Job accessibility data came from the Beijing Job Accessibility Map, calculated by Global Transit Innovations at the University of Minnesota, Twin Cities (Sun et al. 2015a). Accessibility was measured as the total number of job opportunities from each sub-district that could be reached within 30, 45 and 60 min by public transit (metro and bus) during the morning peak hours. Other accessibility measurements were not included in this dataset, because individual travel data of the whole city was not available. Data from Beijing Transportation Institute (2016) showed that the average travel time on metro and bus per trip during the morning peak hours were 62.3, 60.5 min respectively. Extremely long hours were mainly due to the long waiting and transfer time during the peak hours. Thus, these three thresholds could all be considered as reasonable metro travel time, and will be included in different models in the analysis. Travel time in this dataset included in-vehicle time, access and egress time, and waiting time, which were calculated using the Baidu Direction API. Although accessibility was measured based on the whole public transit system, including the metro and bus systems, the calculation tool would select the quickest route, which was highly dependent on the metro system. Additionally, as shown in Fig. 1, the metro was an essential part of the public transit system, and its share rate was slightly higher than that of the bus system. Therefore, this dataset was a good reflection of job accessibility via metro for every sub-district in Beijing. However, a caveat of this study is that in suburban areas, passengers rely more on buses than the metro because of the inferior coverage of metro lines. Thus, the analytic results might exaggerate the role of job accessibility via metro in the suburban area. Figure 3 shows the example

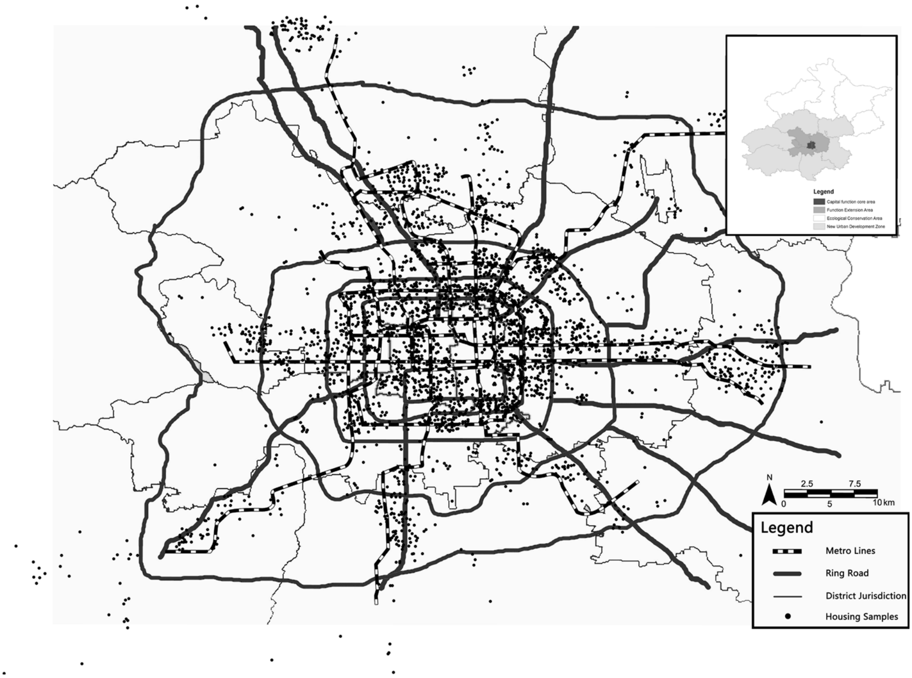

Fig. 2 Study area and distribution of housing samples. *Source*: The authors

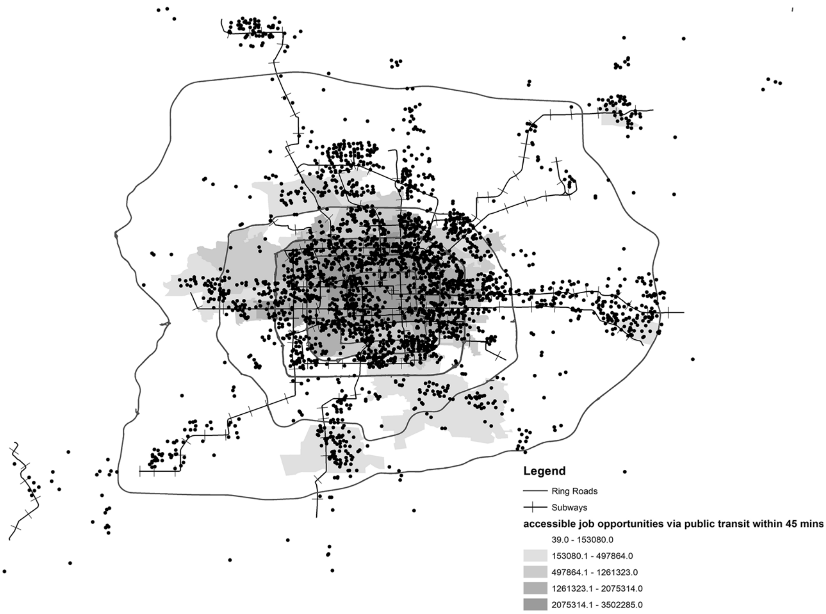

Fig. 3 Number of job opportunities accessible within 45 min by public transit for sampled residential areas. *Source*: The authors

figure of combining housing samples and jobs accessible via public transit within 45-min threshold. As the figure shows, job accessibility via metro was unevenly distributed among the neighborhoods. For neighborhoods in the peripheral areas, job accessibility was extremely low. In contrast, in the downtown and inner suburban areas, such as the northwestern area, job accessibility was extremely high. Headway and access to different metro lines were measured according to the attributes of the metro station nearest to each property. Headway was derived from the peak-time headway of every metro line in Beijing. Practices in Beijing show that even marginal decreases in headway can contribute significantly to improvements in passenger capacity. For example, Line 1 shortened its minimum intervals to 2 min in peak times so that the line can transfer 4.2% more passengers daily (Liu 2015). Changping Line shortened its peak time headway from 6.5 to 6 min, and the transportation ability of the line increased 6.3% (Yin 2016). These facts show that although the headways of Beijing metro lines are short and have nuanced differences, the high travel demands of the system make passengers sensitive about the frequency of metro services. It is true to some extent that headway is largely determined by the travel demands of metro passengers. That is to say, the business of a metro station is negatively related to metro headway. However, in Beijing, to a large extent, there is a mismatch between headway and travel demand. One possible reason is that the old lines, such as Batong Line, have failed to forecast the soaring travel demand, and have been unable to improve their service frequency. Meanwhile, newly-built metro lines have shorter headways due to technological innovations. Another reason is that, in many lines, it is difficult to shorten the existing headway because other metro lines connected to them may face various problems, such as electricity provision and signal control (Huang 2013). *Access to different metro lines* is measured by the number of different metro lines a neighborhood could access within 0.5 mile from the neighborhood. A 0.5-mile buffer was used because it was usually considered as an acceptable distance walking from home/workplace to metro station (O'Sullivan and Morrall 1996). Neighborhoods having a transfer station within the station buffer is also considered to access to multiple metro lines. This variable is a categorical variable, categorizing the neighborhoods into ones with no access to metro lines, having access to only one metro line and more than one metro lines within the buffer area. Variable measurements and descriptive statistics are shown in Table 2.

Analysis

Table 3 shows the regression results of metro service on housing price. Model 1 is a regression model without inclusion of metro service variables. Model 2 to Model 4 shows the regression results with accessible job opportunities via public transit within 30, 45 and 60 min respectively. The results show that the incorporation of metro services in Model 2 to Model 4 significantly changed the results compared to Model 1. After including the metro service variables, the role of many variables on housing prices, such as the distance to the city center, job density at the sub-district level, and other house attributes like size, and the number of bedrooms and living rooms, declined. The results demonstrated that, as expected according to the hypotheses, all the metro service variables, including job access via public transit, metro service frequency, and presence of transfer stations, all had positive effects on property values. However, the impacts of these variables might have

Table 2 Variable measurements and descriptive statistics

Variable	Measurement	Unit	Mean (n)	SE (%)	Min	Max
Pr	House price	10 thousand RMB	471.206	470.292	43	8000
House attributes						
Size	House floor area	Square meters	101.16	57.38661	11	700
Floor	Floor on which the house is located	Count	6.934	5.543	1	36
Tfloor	Number of floors in building where the house is located	Count	12.684	7.62	1	60
or_NS	= 1 if the house has windows to the south and north, otherwise = 0	Dummy	1510	53.26		
or_NoS	= 1 if the house has windows to the south or north, otherwise = 0	Dummy	1018	35.91		
or_O	= 1 if the house neither has windows to the south or north, otherwise = 0	Dummy	307	10.83		
Y_2010	= 1 if the house is built after 2010, otherwise = 0	Dummy	301	10.62		
Y_2001	= 1 if the house is built between 2001 and 2010, otherwise = 0	Dummy	1526	53.83		
Y_1991	= 1 if the house is built between 1991 and 2000, otherwise = 0	Dummy	688	24.27		
Y_90	= 1 if the house is built before or during 1990, otherwise = 0	Dummy	320	11.29		
Dec	= 1 if the house is decorated	Dummy	1650	58.2		
Dec	= 0 if the house is not decorated	Dummy	1185	41.8		
Bath	Number of the bathrooms in the house	Count	1.32	0.585	0	6
Bedr	Number of bedrooms in the house	Count	2.304	0.823	1	9
Liv	Number of living rooms in the house	Count	1.34	0.54	0	4
Neighborhood attributes						
Hhs	Households in the neighborhood	Thousand households	1.712	2.903	0.048	51.264
Ratg	Ratio of green to non-green space		0.33	0.087	0.1	0.8
Neighborhood built environment						
dis_mall	Distance to the nearest shopping mall	Kilometers	1.106	1.002	0.012	10.922
dis_sch	Distance to the nearest key primary or middle school	Kilometers	2.003	2.126	0.024	17.626
dis_hos	Distance to the nearest top-class hospitals	Kilometers	3.484	3.529	0	23.402
dis_park	Distance to the nearest park or square	Kilometers	0.705	0.59	0.013	7.219
dis_metro	Distance to the nearest metro station	Kilometers	1.136	1.553	0.019	25.325
Bus	Number of bus lines within 500 m from the neighborhood	Count	21.49	17.75	0	167
Free	Distance to the nearest ring road	Kilometers	1.731	1.907	0.001	21.867
dis_cen	Distance to the Tian'anmen Square	Kilometers	12.83	8.72	0.238	49.453

Table 2 continued

Variable	Measurement	Unit	Mean (n)	SE (%)	Min	Max
Popden	Population density of the sub-district level, 2010	Thousand people/ km^2	14.498	9.799	0.213	39.526
Jobden	Density of job opportunities of the sub-district level, 2013	Thousand people/ km^2	11.44	14.35	0	79.995
Suburb	= 1 if the house was located outside the 4th Ring Road, otherwise = 0		1219	43		
Urban	= 1 if the housing was located within the 4th Ring Road, otherwise = 0		1616	57		
Metro service						
Access_30	The number of job opportunities which could be accessed by public transit within 30 min at the sub-district level	10 thousand jobs	240.112	227.928	0	119.698
Access_45	The number of job opportunities which could be accessed by public transit within 45 min at the sub-district level	10 thousand jobs	101	929.305	0	350.228
Access_60	The number of job opportunities which could be accessed by public transit within 60 min at the sub-district level	10 thousand jobs	242.056	187.086	0	594.651
Fre	Number of metro services per hour at the station nearest to the house	Count	20.671	8.28	7.059	30
Line_0	= 1 if there is no accessible metro line within 800 m from the neighborhood		1338	47.2		
Line_1	= 1 if there is only one accessible metro line within 800 m from the neighborhood		1000	35.27		
Line_M	= 1 if there are more than one accessible metro line within 800 m from the neighborhood	Dummy	497	17.53		

nuanced differences considering number of job opportunities within different time thresholds.

Accessibility to jobs via *public transit* had a significant and positive influence on housing prices. One standard deviation of this variable within 30, 45 and 60 min caused a 7.7% ($P < 0.01$), 11.7% ($P < 0.01$) and 12.6% ($P < 0.01$) change in housing price. The results show that the more job opportunities employees can reach by taking public transit (mainly the metro), the more they are willing to pay for a house. This supports Hypothesis 1, and reveals that job accessibility via public transit adds a premium to housing prices. Variations in Model 2 to Model 4 also shows that the number of job opportunities via public transit within different thresholds have different importance on housing price, but the significance is robust over different models. Number of job opportunities within 60-min

Table 3 Regression results without interactions for all samples

Variable	Model 1 (without metro service)		Model 2 (with metro service, 30-min accessibility)		Model 3 (with metro service, 45-min accessibility)		Model 4 (with metro service, 60-min accessibility)	
	Coefficient	Asymptote-t	Coefficient	Asymptote-t	Coefficient	Asymptote-t	Coefficient	Asymptote-t
cons_								
Lambda								
House attributes								
Size	0.445***	29.914	0.293***	29.884	0.290***	29.878	0.292***	30.049
Floor	− 0.019*	− 1.869	− 0.014**	− 2.048	− 0.014*	− 2.070	− 0.014*	− 2.047
Tfloor	0.081***	6.765	0.055***	6.985	0.056***	7.263	0.055***	7.096
or_NS	0.091***	3.315	0.072***	5.063	0.081***	5.717	0.079***	5.547
or_NoS	0.004	0.141	0.015	1.064	0.022	1.541	0.019	1.330
Y_2010	0.161***	4.126	0.113***	5.214	0.118***	5.490	0.116***	5.402
Y_2001	0.109***	3.666	0.088***	5.828	0.096***	6.479	0.094***	6.332
Y_1991	0.009	0.303	0.016	1.043	0.021	1.378	0.018	1.231
Dec	0.104***	6.403	0.065***	6.387	0.063***	6.307	0.062***	6.171
Bath	0.047***	3.766	0.033***	4.011	0.033***	4.028	0.033***	4.043
Bedr	0.167***	14.368	0.106***	13.888	0.107***	14.155	0.105***	13.923
Liv	0.094***	9.167	0.061***	9.038	0.061***	9.188	0.061***	8.986
Neighborhood attributes								
Hhs	− 0.006	− 0.829	− 0.003	− 0.636	− 0.003	− 0.509	− 0.003	− 0.538
Ratg	0.011	1.435	0.007	1.435	0.009*	1.724	0.009*	1.722
Neighborhood built environment								
dis_mall	0.004	0.294	0.006	0.783	0.005	0.621	0.005	0.716
dis_sch	− 0.050***	− 3.361	− 0.041***	− 4.009	− 0.035***	− 3.433	− 0.034***	− 3.287
dis_hos	− 0.041***	− 2.579	− 0.021**	− 1.999	− 0.021**	− 2.011	− 0.016	− 1.545
dis_park	− 0.024**	− 2.195	− 0.016**	− 2.243	− 0.014**	− 2.003	− 0.014**	− 2.028
dis_metro	− 0.035**	− 2.556	− 0.020**	− 2.207	− 0.028***	− 3.059	− 0.029***	− 3.195

Table 3 continued

Variable	Model 1 (without metro service)		Model 2 (with metro service, 30-min accessibility)		Model 3 (with metro service, 45-min accessibility)		Model 4 (with metro service, 60-min accessibility)	
	Coefficient	Asymptote-t	Coefficient	Asymptote-t	Coefficient	Asymptote-t	Coefficient	Asymptote-t
Bus	0.002	0.157	− 0.005	− 0.736	− 0.005	− 0.757	− 0.004	− 0.656
Free	− 0.02	− 1.366	− 0.020**	− 1.993	− 0.020*	− 1.958	− 0.016	− 1.617
dis_cen	− 0.307***	− 14.965	− 0.177***	− 11.940	− 0.151***	− 10.006	− 0.143***	− 9.258
Popden	0.040***	2.976	0.001	0.155	− 0.014	− 1.511	− 0.023**	− 2.389
Jobden	0.092***	7.491	0.022**	2.443	0.026***	3.080	0.035***	4.043
Metro service								
Access_30			0.077***	7.825				
Access_45					0.117***	10.777		
Access_60							0.126***	10.092
Fre			0.021**	2.491	0.023***	2.729	0.022***	2.634
Line_1			0.008	0.676	0.004	0.319	0.002	0.189
Line_M			0.027*	1.830	0.021	1.422	0.023	1.526
N	2835		2835		2835		2835	
− 2LL	1149.658		1358.8997		1411.4364		1399.136	
R^2	0.8309		0.8376		0.8376		0.8394	

*** $P < 0.01$; ** $P < 0.05$; * $P < 0.1$

threshold has the greatest impact on housing price, controlling for the other factors. This result suggests that the residents have higher willingness to pay for housing price considering the number of job opportunities within higher travel time threshold. It should be noted that the lower time threshold may overestimate the role of access to job opportunities via bus, but the 60-min would consider the role of metro to a larger extent. Therefore, the metro service significantly improves people's job search scope. Another reason for this result is that the job opportunities are concentrated in Beijing, and the houses near these workplaces have obvious premiums than the other areas of Beijing. In face of the financial pressure of housing price, the residents, especially the metro dependents are willing to live in the suburban areas where is further from the workplace but has convenient metro service.

Shorter metro headways were associated with higher housing prices after other variables are taken into account. The significance of this variable is also robust over Model 2 to Model 4. One standard deviation of metro lines passing the metro stations per hour increased 2.1% ($P < 0.05$), 2.3% ($P < 0.01$) and 2.2% ($P < 0.01$) of the housing price for models incorporating job accessibility within 30, 45 and 60 min respectively. This result confirms Hypothesis 2. It should be noted that peak-hour headway is not exactly the same as waiting time, but it could be an important determinant of it in Beijing. Because of technological limitations and the complexity of Beijing's metro networks, it is difficult for some metro lines to enhance their service frequency. Thus, residents living near these lines could wait longer compared with residents living near lines with shorter headways, and it could be even worse when many residents live near these lines. In contrast, if the metro line is newly built and opened, then it is likely that the headway is short, and residents nearby need not wait long to use the metro in peak hours. Shorter metro headway means shorter waiting times at stations when travel demands are equal, and the results confirmed that residents would pay more for houses that are close to metro stations with short headways.

The variable *access to different metro lines* was not robust over Model 2 to Model 4. This variable was sensitive to the incorporation of number of job opportunities within different travel time thresholds. Only for the model incorporating the number of job opportunities within 30 min via public transit, neighborhoods having access to more than one metro line was 2.7% ($P < 0.1$) more expensive than the ones without access to metro lines within 800 m-radius buffer. However, for the other models incorporating higher travel time thresholds, access to different metro lines had no significant. This result partly confirmed Hypothesis 3. This study further advanced the study of Dai et al. (2016), who argued that housing prices near metro transfer stations added an extra premium on housing prices in Beijing. Transfer station is not a pure variable to measure metro service, because it has both positive effects, such as better connectivity to different destinations and thus, shorter waiting and transfer times for metro passengers, and also negative aspects, such as noise and crowds on housing price. Only incorporating transfer station as a dummy variable is unable to disentangle various aspects of transfer station. Moreover, transfer station itself could not capture the flexibility of neighborhood residents to take different metro lines within walking distance. This study replaced transfer station with a more nuanced measurement, *access to different metro lines*, and controlled for other service variables, such as headway and job accessibility via public transit. The results revealed that access to different metro lines, indicating more travel choices and maybe less transfer and waiting time, may have extra benefits on housing price within lower travel time thresholds, but the number of available jobs may play a dominant role in housing price, making the effect of *access to different metro lines* insignificant.

It is notable that after controlling for metro service variables, metro station proximity also increased housing prices. One standard deviation closer to metro station contributed a 2.2% ($P < 0.05$), 2.8% ($P < 0.01$) and 2.9% ($P < 0.01$) in Model 2 to Model 4 respectively. It revealed that when other metro service variables were held equal, metro station proximity causes a housing price gradient. This result was consistent with recent studies in the whole city of Beijing (Qin and Han 2013; Sun et al. 2015b).

Discussions and conclusions

The metro service is an important determinant of people's residential and employment location decisions. According to location theory, metro-dependents have a three-way trade off between housing prices, transport costs and employment opportunities. This paper mainly discusses the role of headway, access to different metro lines and metro-facilitated accessibility to employment centers on housing prices in Beijing. Using a spatial error model, we found that better job accessibility via public transit added a premium to housing prices in Beijing. Shorter service headway had a positive effect on housing prices. Access to different metro lines had an extra premium on housing price controlling for job accessibility within 30 min, although the significance was marginal.

It should be admitted that there are several caveats for this study. Firstly, since the study was cross-sectional, it is unable determine the causal relationship between metro services and housing prices. Exploring the causal relationship between two variables requires longitudinal data, including housing prices before and after metro development. Additionally, an important variable—crowdedness, or the maximum number of passengers a station can serve—was omitted. Omission of this variable may significantly underestimate or overestimate the roles of headway and transfers for different metro stations. In this sense, the study was unable to estimate the separate contributions of waiting time and transfer time on housing prices. Thirdly, this study was mainly based on housing prices in Beijing. According to previous studies, the impact of metro proximity and other related attributes acted differently on housing prices and rental prices (Efthymiou and Antoniou 2013). Nevertheless, this study failed to explore the impact of metro services on rental prices due to a lack of data. Finally, this research could not rule out the deficiencies of hedonic models as stated preference models. Hedonic models are unable to include passengers' evaluations and preferences of metro services, so more solid evidence about the relationships between metro services and housing prices should be examined and combined with stated preference data.

This paper has several policy implications and theoretical implications for future research. Firstly, it adds to the existing literature about the impact of metro services on housing prices. The results showed that longer waiting and transfer times can reduce willingness to pay for housing near metro stations. Besides, better accessibility to job opportunities can also bring about property value premiums (Lin and Cheng 2016). Future researchers should give attention to this relationship. The effect of housing value capture for other aspects of metro services should also be included in future research once relevant data are available, such as the punctuality, queuing times, crowdedness, and comfortableness of metro services (Fan et al. 2016). Besides, travel by other modes, such as automobile and Bus Rapid Transit, to jobs and other non-work destinations, should also be considered.

Secondly, this paper provided evidence that housing price premiums are brought by shortening of metro service headways. This result supports the policy of shortening metro service intervals for all metro lines in Beijing. It also applies to other transit-dependent metropolitan areas. Additionally, the study also found that access to different metro lines had an extra premium on housing price in Beijing incorporating job accessibility via public transit within 30 min. This further developed the findings by Dai et al. (2016). However, for models incorporating the number of job opportunities within higher travel time thresholds, access to more than one metro line had no significant effect on housing price. This result suggests that compared with job accessibility via public transit and headway, access to more than one metro line is a marginal factor on housing price, and could be more periphery, especially when controlling for accessible job opportunities via public transit within a larger time scope.

This study also has important implications for spatial planning in Beijing. Job accessibility via public transit adds a premium to housing prices. The accessibility index incorporates job location distribution and all components of travel time (in-vehicle, waiting and transfer) and thus, this result has policy implications for both transportation and land use planning. Many suburban metro stations face overloading in peak hours (Deng 2014). Passengers face long waiting times, and things get even more unpleasant in poor weather. Longer waiting times reduce passenger satisfaction with metro travel. Since metro station areas are mainly dominated by residential land, regional job opportunities are rare, or job positions are not well matched to the socioeconomic status of residents (Zhao et al. 2010). Therefore, it is important to create more suburban job centers along metro corridors through transit-oriented development.

Finally, this study provides important insights for future metro investment in Beijing. Although Beijing endeavors to improve metro services for passengers, especially those living in suburban areas, the government pays little attention to the value capture issue in metro investment. As a result of large amounts of investment in the metro system and relatively low fare, the system runs at a financial loss. Local governments need to subside the subway company of Beijing accordingly (Huang 2014c). This study suggests ways that transit-oriented cities like Beijing could finance the metro system. Transport service improvements can improve housing prices, especially in suburban areas. Land value capitalization brought by accessibility improvements could require a betterment tax to subsidize the metro system. This could cover the costs of metro investment and incite the metro company to provide better services, as per the successful experiences of Hong Kong and Singapore (Medda 2012; Chi-Man Hui et al. 2004). However, capitalization assessment and the design of financial mechanisms will require more solid evidence from future studies.

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