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How much do users value a network expansion? Evidence from the public transit system in Singapore

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ABSTRACT

We estimate the network effects of a public transit system by examining the impact of its expansion on housing prices. Our results show that a major expansion of Singapore's Mass Rapid Transit (MRT) system increased the price of apartments within 0.5 km of a pre-expansion station by 1.8% relative to apartments that were further away from a station. Evaluated at the mean housing price, the expansion increased the value of pre-connected apartments by at least S$455 million in aggregate, which is equivalent to 9% of the estimated S$5 billion cost of the expansion.

1. Introduction

With ever increasing connectivity, understanding the network economy has become important. While it has been well established theoretically that the value of a network increases with its size (Katz and Shapiro, 1985; Liebowitz and Margolis, 1994), empirical studies on this issue are still scant.[1] Moreover, to the best of our knowledge, there exists no empirical study that has examined network effects in the context of a public transit system, the focus of the present study.[2]

Public transit systems, particularly subways, provide many benefits such as faster travel between locations, reduced traffic congestion, and easier assess to workplaces and shops (Baum-Snow and Kahn, 2000; Anderson, 2014). A reduction in traffic congestion reduces auto emissions, hence improving air quality, and easier access to employment centers raises labor force participation, particularly for women (Black et al., 2014). Public transit systems have even been shown to reduce drunk driving (Jackson and Owens, 2011). However, these systems are very costly. Baum-Snow et al. (2005) document that the construction costs for subway lines in the US varied from 7 million USD per mile for the San Diego Orange Line to 330 million USD per mile for the Los Angeles Red Line. As such, accurate measures of the net benefits of public transportation are necessary to help guide policymakers considering such huge investments.

Traditionally, economists have attempted to measure the gross benefits of public transportation by comparing the values of housing near the location of new stations before and after construction (Dewees, 1976; Voith, 1991; McDonald and Osuji, 1995; Baum-Snow and Kahn, 2000; Bowes and Ihlanfeldt, 2001; McMillen and McDonald, 2004; Gibbons and Machin, 2005).[3] This approach is motivated by the simple logic that the benefits of public transportation are capitalized into the price of housing near new transit stations as people are willing to pay more for these now more desirable units. To the best of our knowledge, the gains from a network expansion to households that already have access to the existing system have not been examined. As a result, the benefits

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[1] Some papers in this literature include Saloner and Shepard (1995), which shows that the expansion of a network of automated teller machines benefits not only new users but also existing users, Gowrisankaran and Stavins (2004), which reaches a similar conclusion on the adoption of the automated clearing house electronic payment systems, and Gandal (1994) and Brynjolfsson and Kemerer (1996), which study the adoption of computer software.

[2] Kraus (1981) suggests that mild scale economies exist in urban highway travel.

[3] Differences in house values have also been used to evaluate the benefits of other public investments, such as environmental cleanup programs (Greenstone and Gallagher, 2008; Bajari et al., 2012).

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documented in previous studies could considerably underestimate the total benefits of a network expansion.

This paper aims to fill the gap by examining the impact of an expansion of a public transit system on the value of housing that was connected to the system prior to the expansion. (This housing will be referred to as "pre-connected" housing hereafter.) Finding a positive effect on the price of pre-connected housing would suggest that there exists economic returns to scale in public transit networks and that the benefits of public transportation systems have been underestimated in the existing literature. Moreover, by focusing on pre-connected housing in built-up areas in which amenities and the housing supply were stable, our approach provides a cleaner, albeit conservative,[4] identification of the direct benefit that public transportation provides, namely making travel between locations faster and easier. In contrast, the approach used in previous studies have difficulty establishing a causal link between changes in housing value and the accessibility to public transit system. As pointed out by Bowes and Ihlanfeldt (2001), changes in house prices could be due either to changes in connectivity, or to changes in the ambient environment around the new stations, such as the addition of new retail establishments and an increase in crime and noise. Local housing supply might also respond to an expansion of the transit system if property developers target these newly connected locations for new construction.

We consider a major expansion of the local commuter rail system in Singapore, the Mass Rapid Transit (MRT) system. The construction of the North East Line in 2003 increased the number of MRT lines from 2 to 3, the number of stations from 51 to 65, and increased total rail length from 89.4 km to 109.4 km, a jump of more than 20%. The expansion made it possible for people to ride the MRT to, among other places, two of the most popular retail and commercial areas in Singapore: HarbourFront, which contains a cruise ship terminal and VivoCity, Singapore's biggest mall, and China Town and China Square which contains 3.8% of all retail space and 5.1% of all office space in Singapore, reducing the round-trip travel time between these locations by about 20 min compared to taking the bus. Trips to these two MRT stations account for 1.5% of the 4 million daily trips made on public transportation in 2016, either by bus or by MRT.

To estimate the benefits of the expansion on pre-connected housing we use a difference-in-differences approach with rich transaction data of apartment sales provided by Singapore's public housing authority, the Housing Development Board (HDB). As we explain in detail below, while HDB allocates newly built public housing according to a set of rules and regulations, we use transaction data from the resales market, which is competitive, active, and relatively free of regulation.

Our results show that the addition of the North East Line raised the value of a pre-connected apartment by 1.5–2%, or from S$3654 to S$4872 when evaluated at the mean transaction price of S$243,604 (about US$180,000 dollars).[5] Assuming a 2.1% discount rate, the increase in price is equivalent to an annual utility stream of $111, worth 8.5 hours of traveling time for the median hourly wage in 2003 of $13. To get a sense of the size of this effect in aggregate, consider that in 2002 there were 415,060 housing units located in the mature "towns" we include in the analysis, and that pre-connected housing makes up between 20% and 40% of our sample, depending on the definition of connectivity. Assuming, for illustration, that 30% of units were affected, then our estimates imply that the expansion of the MRT added a total of at least S$455 million to the value of pre-connected housing, equivalent to 9% of the estimated S$5 billion cost of constructing the new line (Leong, 1996). Our findings suggest that the benefits realized by households living in pre-connected apartments constitutes a considerable fraction of the gains provided by mass transit systems and should be included in cost-benefit analyses evaluating these types of investments, which is not the current practice. Our results also show the importance of network externalities in public transportation networks.

The network expansion did not only improve the usefulness of existing stations, which raised the value of pre-connected apartments, but also connected previously unconnected apartments to the MRT network. As mentioned above, the benefits of the latter have been the focus of several previous studies. Our results serve as a complement to these studies.

We also estimate the North East Line's direct impact on newly connected apartments to get a sense of the importance of network externalities relative to the direct benefits. We find that the price of apartments that were located within 0.5 km of a newly opened station appreciated 2–3.2% more than those further away from a station, which is only slightly larger than the impact on pre-connected apartments. Nevertheless, since the number of affected apartments near the new stations were smaller than the number of pre-connected apartments, the total benefits from apartments along the newly constructed line is smaller than the indirect impact on pre-connected homes. This evidence suggests that ignoring the network effect will lead to a significant underestimation of the total benefits of the new line.

2. Institutional background and data

2.1. Background

Singapore is a city-state of 719 square km with a population of 5.5 million, of which 3.9 million are citizens or residents. More than 90% of households headed by a citizen or permanent resident own their own homes (Singapore Department of Statistics, 2015). Most of these homes are apartments in high-rise buildings developed by Singapore's public housing authority, the Housing and Development Board (HDB), established in 1960 shortly before independence. Nearly 90% of Singaporeans live in an HDB apartment. The remaining population live in apartment buildings or houses built by private developers.[6]

To keep costs low, early HDB apartments were designed to be simple, standardized, utilitarian, and capable of being built quickly. Apartments were either one, two, or three rooms, and came in three different models: "emergency," "standard," and "improved" (Housing and Development Board, 1985). Other models were introduced gradually over time, but overall the number of varieties remained very limited. For example, there are only 14 model varieties in the nearly 170,000 resale transactions during our sample period, 2000 to 2005. Standardization of units and limited variety means that HDB apartments are well-described by the number of rooms and the flat model, both observed in our dataset. Accordingly, unobservable differences in quality are much less than in other housing markets.

HDB apartment buildings are located in carefully planned satellite "towns" throughout Singapore. Each town has its own town center, commercial and retail space, and educational, health care, and recreational facilities. As the planning and development of the earliest established towns are completed, new HDB towns are developed incrementally to accommodate the ever increasing population in Singapore (Housing and Development Board, 1985).[7] The former towns,

[4] Because opening a new line will increase the supply of connected homes, it will reduce the price premium for these houses. If there is no network effect, the price differential between pre-connected and not connected houses should decrease after a network expansion.

[5] The median monthly salary in January 2000 was S$3173.

[6] According to the HDB Annual Report 2014/15, the total stock of HDB dwelling units in 2015 was 968,856.

[7] The population of Singapore has increased significantly since independence in 1965, with a population of 1,886,900, to a 2015 population of 5,535,002. During our sample period, population increased by 6% from 4,027,887 in 2000 to 4,265,762 in 2005 (Singapore Department of Statistics, 2015).

typically at least 20 years of age, are categorized by HDB as "mature."[8] The latter, still expanding towns are referred to as "non-mature."

We focus on resales of HDB apartments located in mature towns. The main reason for excluding new sales is that new HDB apartments are sold only to Singaporean citizens, under restrictive terms and conditions, and at heavily discounted prices.[9] In contrast, the resale market for HDB apartments, restricted to Singaporean citizens and permanent residents, is otherwise largely competitive.

The two main reasons for focusing on mature towns is the stability of the housing supply and of the quality of local amenities. There were 410,637 HDB apartments in mature towns in 2000 and 419,347 in 2005. Hence, our results are not affected by supply shocks. In comparison, the number of apartments in non-mature towns increased by 16.3%, from 352,610 in 2000 to 410,116 in 2005. (Housing & Development Board, various years).

Further, while mature towns tend to have better amenities, and, as a result, apartments in these towns tend to be more expensive, all major amenities have already been built by the beginning of our sample period, and, thus, focusing on mature towns means our results are unlikely to be driven by the addition of new amenities. In contrast, amenities of non-mature towns are expanding over time as their populations grow, with the addition of traditional Singaporean food centers (*hawker centres*), supermarkets, community facilities, etc., which positively affect housing prices over time. Even without the addition of new amenities it is still possible that the quality of amenities in mature towns improved over time via renovation. As long as the timing of renovations is not strongly correlated with the timing of the network expansion, these renovations should not affect our estimation results. We conduct a sensitivity analysis by excluding apartments near stations with a major shopping mall, a major amenity in Singapore susceptible to renovation.

The idea of constructing the MRT system in Singapore was first raised in 1967, though actual construction did not commence until October 1983. Initially, the MRT consisted of two segments, the North South Line and the East West Line, with 67 km of track and 42 stations, which were fully operational by July 1990. The North South Line was extended by an additional 16 km of track and 6 stations in February 1996. Between 1996 and 2003, only three more stations were opened, one in January 2001, one in October 2001, and one in February 2002.

The second major expansion of the MRT, and the one this paper focuses on, occurred in June 2003 with the opening of the North East Line and its 20 km of track and its initial 14 of 16 stations. Plans for the North East Line were approved by the government in January 1996 with a scheduled completion date at the end of 2002. In September 2002 it was announced that the opening would be delayed to as late as April 2003. After several more delays, the North East Line was finally opened in June 2003. Another station opened in January 2006, and the line was completed when the last station opened in June 2011. This expansion made it possible for people to ride the MRT to, among other places, two of the most popular retail and commercial areas: HarbourFront, which contains a cruise ship terminal and VivoCity, Singapore's biggest mall, and China Town and China Square. For individuals living in mature towns, traveling to these two locations by MRT rather than by bus saves them about 20 min per round trip.

In this paper, we focus on the impact of the 2003 North East Line opening on housing prices for several reasons: (1) The North East Line was a major expansion, increasing the number of MRT stations by 27% and the rail length by 22%; (2) There were no major additions to the MRT system within five and half years of the 2003 extension, which precludes any confounding effects of further expansions and allows the market to converge to a new equilibrium price; (3) Unlike later extensions, all 14 new stations of the North East Line were opened in the same month, which provides a well defined threshold for our before and after analysis.

Panel (a) of Fig. 1 maps the mature and non-mature HDB towns and the three MRT lines as of 2003. The East West Line and the North South Line have been in service since 1990, and the North East Line opened in June 2003. One can see that the mature HDB towns, that is, the oldest and completely developed towns, are nearest to the Central Business District (CBD). As the population of Singapore increases, towns are established further into the "suburbs" of Singapore. These towns are still being developed with amenities and new housing being added over time. Panel (b) maps the three MRT lines and all HDB buildings with at least 25 resale transactions in the sample period. The figure shows that the MRT lines were designed to connect HDB towns. As a result, most HDB apartments are located within 3 km of an MRT station. Panel (c) of Fig. 1 shows the location of HDB buildings in mature towns and within 1.5 km of an MRT station on either the East West Line or the North South Line. Resale transactions of apartments in these buildings are included in several specifications below.

2.2. Data

This study uses housing transaction data downloaded from the Singapore government's data portal: www.data.gov.sg. The data contains the universe of HDB resale transactions since January 1990 and includes transaction price, transaction date, street address including a 6 digit zip code, floor number in intervals, unit area, number of rooms, apartment model, and year of construction.

In our main analysis, we focus on transactions between the second quarter of 2000 and the third quarter of 2005, which covers a period of 3 years (12 quarters) before the expansion and 2 years (8 quarters) after the expansion. Our choice of sample period ends one quarter before the next MRT expansion occurred (one station) and several years before a larger expansion (six stations). Observations from the 12 quarters of the pre-expansion period help to identify whether the prices of pre-connected and unconnected apartments follow the same time trend before the expansion. The two years of observations from the post-expansion period allow us to check whether the price stabilized.

Using the Singapore government's map system, OneMap, we recorded the longitude and latitude of each HDB building that contains resale transactions. Then, for each building, we calculated the direct distance to the closest pre-expansion station. While the direct distance only serves as a lower bound for the actual walking distance, the difference between the actual walking distance and the direct distance is likely to be small as HDB communities are open, ungated communities that allow barrier-free passage.

Since we wish to abstract from the effect of being newly or better connected to the MRT system, we exclude transactions in any building in which the distance to the nearest MRT station decreased due to the expansion. Further, transactions in any buildings within 1.5 km of the new North East Line were also excluded. The reason for doing so is that people might value the ability to go directly to places on the route of the new line without switching trains even if they have to travel a bit longer to the new line than to the older ones.

Since we use data from mature towns, the expansion does not affect the distance from each building to the nearest MRT station in our sample. However, the distribution of the distance to the nearest MRT station of *transactions* could have changed if turnover in buildings close to an MRT station increased after the expansion. To get a sense of how the

[8] The mature towns at the time of the MRT expansion were Ang Mo Kio, Bedok, Bishan, Bukit Merah, Bukit Timah, Central, Clementi, Geylang, Kallang Whampoa, Marine Parade, Pasir Ris, Queenstown, Serangoon, Tampines, and Toa Payoh.

[9] Qualified individuals can only buy a second subsidized new apartment if they first pay a hefty levy, typically 20–25% of the resale price of their first subsidized apartment. Further, individuals can only own one HDB apartment at any point in time.

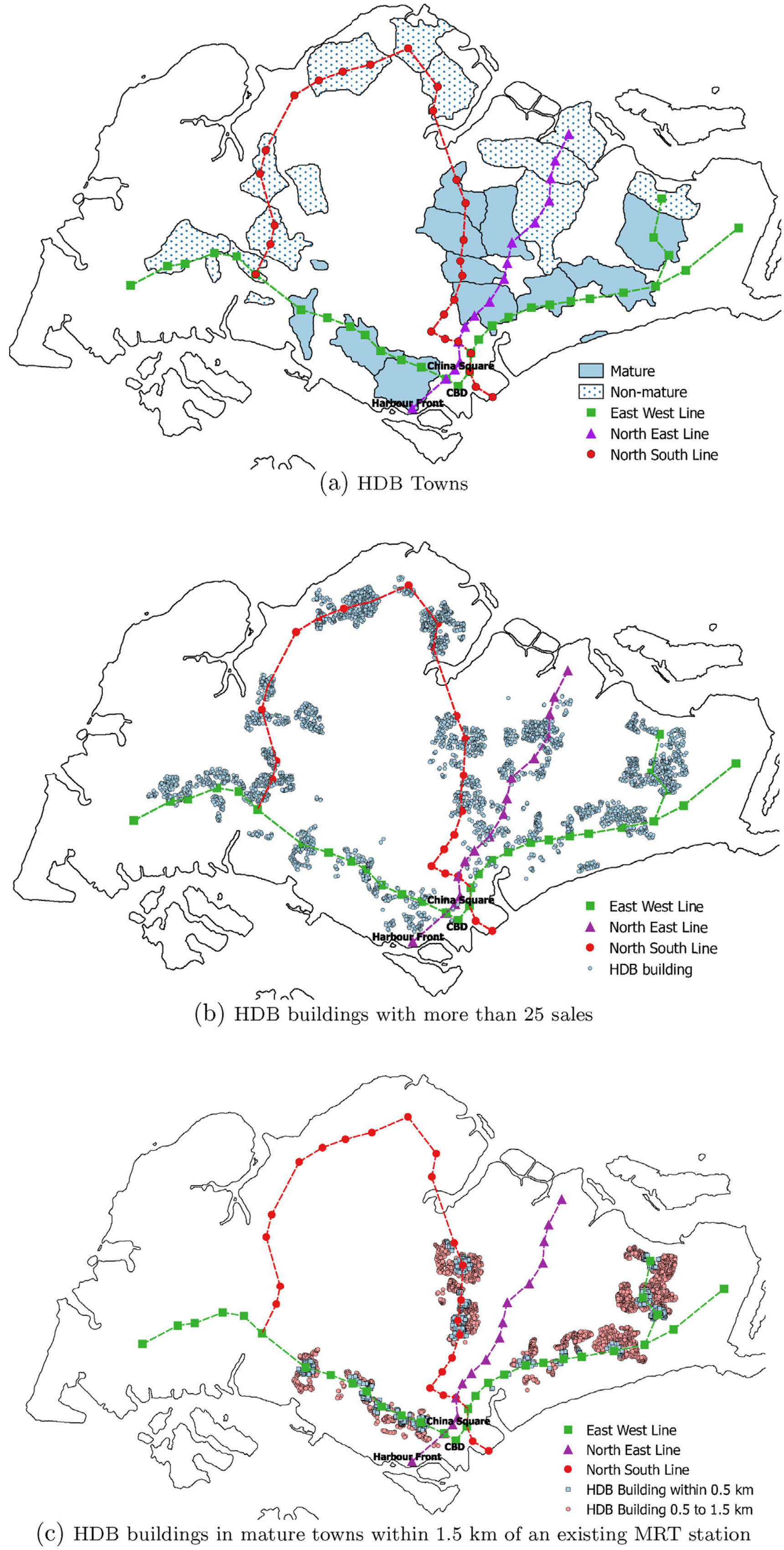
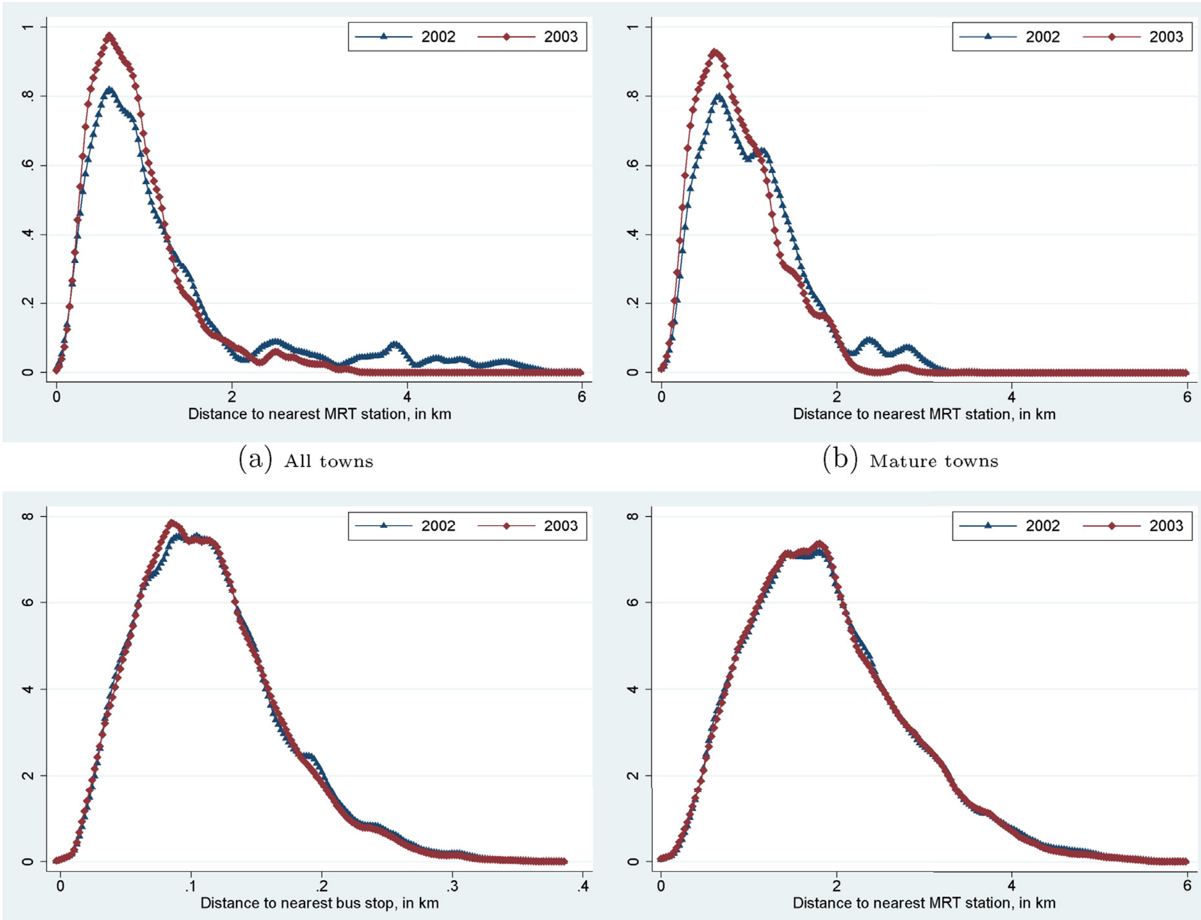

China Square
CBD
Harbour Front
Mature
Non-mature
East West Line
North East Line
North South Line
(a) HDB Towns
China Square
CBD
Harbour Front
East West Line
North East Line
North South Line
HDB building
(b) HDB buildings with more than 25 sales
China Square
CBD
Harbour Front
East West Line
North East Line
North South Line
HDB Building within 0.5 km
HDB Building 0.5 to 1.5 km
(c) HDB buildings in mature towns within 1.5 km of an existing MRT station

Fig. 1. Maps.



(a) All towns (b) Mature towns (c) All towns (d) Mature towns

Fig. 2. Distance to MRT stations and to bus stops of resale apartments.

2003 expansion affected this distribution, we compared the distribution of the distance to the nearest station of all resale transactions in 2002, before the expansion, and in 2003, after the expansion, and in all towns and in mature towns only. Panels (a) and (b) of Fig. 2 plot the kernel density estimates. We can see from panel (a) that the MRT expansion decreased the density at the right tail, as expected. While a considerable proportion of transacted units were at least 3 km from a MRT station in 2002, almost all transacted units were within 3 km of a MRT station in 2003. This change could be driven by both the expansion and to changes in the demand for units close to an MRT station. Panels (b) shows the change for mature towns was smaller indicating that the decrease in distance for the largest distances occurred in the non-mature towns. This is expected as new stations were constructed in the newest towns. Nevertheless, the density also decreased at the right tail even among mature towns, suggesting the expansion indeed made units closer to MRT stations more attractive at the given price. The expansion of the MRT network might also affect the price premium for apartments close to a bus stop as public buses are a close substitute for the MRT. Panels (c) and (d) plot the kernel density estimates for distance to the nearest bus stop. In contrast to the distance-to-MRT-stations graphs, there was little difference in distance to the nearest bus stop before or after the MRT expansion or between mature and non-mature towns.

Table 1 reports descriptive statistics. Our full sample consists of 72,889 transactions within 2 km of a pre-expansion MRT station. Of these transacted apartments, 21% were within 0.5 km of a pre-expansion station, 43% within 0.75 km, 62% within 1 km, and 89% within 1.5 km. The average distance to the nearest MRT station was 0.89 km. The proximity to an MRT station is used to define an apartment's connection status. We consider an apartment as connected to the MRT system if it is within walking distance. Given the year-long hot and humid tropical climate of Singapore, people are rarely willing to walk a long distance. According to the 2004 Household Interview Travel Survey conducted by the Land Transport Authority, the median walking distance to the MRT was 0.19 km and 82% of those who walked to the MRT station walked 0.5 km or less. We use these values as a guide to define "pre-connected" apartments in our main specification as those within 0.5 km of a pre-expansion station. These apartments are compared to "unconnected" apartments within 0.5 and 1.0 km of a station. To check whether our results are sensitive to the definition of pre-connected and unconnected apartments, we use different radiuses, including defining pre-connected apartments as units within 0.75 km of a station and unconnected apartments as units up to 1.5 and to 2 km away from a station. We also use continuous distance in one specification and include multiple treatment rings in another specification as further robustness checks.

The average distance to the Central Business District (CBD) was about 10 km (the Raffles Place MRT station in the CBD is used as the reference point). The average apartment price in January 2000 Singapore dollars was S$243,604 (US$180,000), with the lowest price around S$53,000 (US$39,000) and the highest a little over S$700,000 (US$514,000). Average age was about 18 years, implying that, under the 99 year lease attached to HDB apartments, there were 81 lease years

Table 1
Summary statistics.

Variables	Mean	St Dev	Min	Max
Price in January 2000 S$	243,604	100,817	53,027	728,637
Price per m^2 in January 2000 S$	2584	454	819	4924
Proportion of apartments within 0.5 km	0.21	0.41	0.00	1.00
Proportion of apartments within 0.75 km	0.43	0.50	0.00	1.00
Proportion of apartments within 1.0 km	0.62	0.49	0.00	1.00
Proportion of apartments within 1.5 km	0.89	0.32	0.00	1.00
Post-expansion period	0.36	0.48	0.00	1.00
Distance to MRT in km	0.89	0.44	0.07	2.00
Distance to CBD in km	9.95	3.16	2.53	15.95
Age in years	18.45	8.52	0.00	38.00
Unit area in m^2	91.93	26.62	38.00	243.00
6th floor or lower	0.46	0.50	0.00	1.00
3 rooms or fewer	0.44	0.50	0.00	1.00
Observations	72,889			

Table 2
Housing characteristic means by connectedness and period.

Variables	Pre-expansion			Post-expansion			
	Pre-connected (1)	Unconnected (2)	(2)–(1) (3)	Pre-connected (4)	Unconnected (5)	(5)–(4) (6)	(6)–(3) (7)
Price per m^2 in January 2000 S$	2675.27	2545.68	129.59	2741.15	2574.50	166.65	37.06
Distance to CBD in km	8.80	9.77	−0.97	8.48	9.50	−1.02	−0.05
Age in years	20.14	18.66	1.48	23.77	21.96	1.81	0.33
Unit area in m^2	86.68	90.16	−3.48	83.13	86.68	−3.55	−0.07
6th floor or lower	0.48	0.45	0.03	0.45	0.44	0.01	−0.02
3 rooms or fewer	0.54	0.46	0.08	0.59	0.52	0.07	−0.01
Observations	9618	18,643		5917	11,022		

Note: Pre-connected includes HDB apartments within 0.5 km of a pre-expansion MRT station in mature towns. Unconnected includes HDB apartments between 0.5 and 1 km of a pre-expansion MRT station in mature towns.

remaining at the time of transaction.[10] The fraction of units on the 6th floor or lower is 46%, and the fraction of units with 3 rooms or fewer is 44%. (In the regression analysis below, we use a finer categorization of these variables.)

Table 2 reports several key housing characteristics by connection status and transaction period. The mean price per square meter of pre-connected apartments in the pre-expansion period was S$129.59 higher than that of unconnected apartments. Post expansion, this difference increased to S$166.65. In other words, an apartment close to a pre-expansion MRT station appreciated S$37.06 per square meter relative to an apartment farther away, or 1.4% of the average price per square meter of the sample, S$2584. We will see below that this estimate is very similar to regression estimates of the impact of the expansion when including a full set of controls.

One sees in Table 2 that there was relatively little difference between the observed characteristics of pre-connected and unconnected apartments, and the changes in the differences in characteristics from the pre-expansion to the post-expansion period were small both economically and statistically. This indicates that there is no selection on observables, which suggests that selection on unobservables is likely to be negligible. The mean difference between pre-connected and unconnected apartments in distance to the CBD was about 1 km before and after expansion. Pre-connected apartments were 1.5 years older than unconnected apartments in the pre-expansion period; this increased to 1.8 years after expansion. The difference between pre-connected and unconnected apartments in average unit size was about 3.5 square meters, both before and after expansion. The difference in the fraction of units on the 6th floor or lower across periods, 0.03 and 0.01, and the change over time, −0.02, was very small. Similarly, the difference in the fraction of units with 3 rooms or fewer was small and very similar over time: 0.08 in the pre-expansion period, 0.07 after, and the difference over time was −0.01.

Table 3 contains demographic summary statistics by connectedness, computed from the Land Transport Authority of Singapore's 2004 Household Interview Travel Survey, which contains a limited number of demographic variables. Although we cannot compare values before and after the expansion as we did in Table 2, we can still get a glimpse of whether pre-connected and unconnected households differed significantly by household size and household income. Here, we define households within 0.5 km of a pre-existing MRT station as connected and those from 0.5 to 1 km as not connected. We see that household size and income were fairly similar. Pre-connected households averaged 3.8 household members and 3.6 household members 6 years old or older while unconnected households averaged 4 and 3.7, respectively. The distribution of household income proportions are very similar. 46% of pre-connected households earned a monthly income less than S$3000, 37% earned between S$3000 and S$6000, and 17% earned above S$6000, practically identical to the 47%, 36%, and 17%, respectively, for the unconnected households.

3. Empirical model

In this section, we discuss our estimation approach and contrast it with previous studies. In particular, to recover the marginal willingness to pay for an apartment located d km from the nearest station of a transit system, previous studies estimate:

$$\ln p_i = X_i\beta + d_i\gamma + \epsilon_i, \tag{1}$$

[10] As a former British colony, Singapore follows the British leasehold system in which land is either freehold, i.e., owned in perpetuity, or leased from a freeholder for a fixed number of years. HDB apartments are sold with a 99 year lease at the end of which the ownership of the apartment reverts to HDB. For further details on the leasehold system in Singapore, readers may refer to Fesselmeyer et al. (2018).

Table 3
Demographic means by connectedness, 2004.

Variables	Pre-connected (1)	Unconnected (2)	(2)–(1) (3)
Number of persons in household	3.78	3.97	−0.19
Number of persons 6 years old or older in household	3.55	3.71	−0.16
Proportion of households with monthly income less than S$3000	0.46	0.47	−0.01
Proportion of households with monthly income between S$3000 and S$6000	0.37	0.36	0.01
Proportion of households with monthly income greater than S$6000	0.17	0.17	0.00
Observations	557	1011	

Source: Authors' calculations using the 2004 Household Interview Travel Survey conducted by the Land Transport Authority of Singapore. Pre-connected includes households in HDB apartments within 0.5 km of a pre-expansion MRT station in mature towns. Unconnected includes households in HDB apartments between 0.5 and 1 km of a pre-expansion MRT station in mature towns.

where p_i is the price per unit area of unit i and X_i is a vector of observed characteristics, such as unit size, floor number, and local amenities, such as quality of local schools. The major challenge in identifying the impact of d_i on price is that the locations of stations are not randomly determined, that is, $cov(d_i, \epsilon_i) \neq 0$. For instance, stations are typically constructed in high density areas in which housing is more expensive. Moreover, a new station often is accompanied by new shops and offices. As a result, the OLS estimate, $\widehat{\gamma}$, can be driven either by accessibility to the transit system or by the shopping and jobs around the station. The simultaneity in station openings and shops and offices makes it hard, if not impossible, to identify the direct impact of public transportation on housing prices by measuring how price changed after a station opened.

In this paper, we identify the impact of public transportation on housing prices via the improvement in network coverage caused by the expansion of the transit system. Presumably, the expansion had limited impact on amenities in areas surrounding existing stations. Moreover, focusing on mature, built up towns further helps minimize the likelihood that new shops and offices were built around these already connected stations. Nevertheless, an important amenity such as local shopping malls could have been improved in response to the potential increase in traffic volume drawn by the network expansion, which might affect the price premium of apartments closer to existing MRT stations. In our sensitivity analysis, we exclude apartments surrounding stations with major shopping malls. The results are not sensitive to the exclusion. This is likely because owners of these shopping malls cannot time the completion the renovation and the opening of the new MRT line due to the uncertainty in the duration of their renovations and of the construction of the new MRT line.

In addition to changes in amenities, changes in the supply of apartments closer to MRT stations, a critique raised by Molloy and Shan (2013) in the literature measuring the impact of gasoline prices on house prices, could be another concern. Again, by focusing on mature towns help us to address this issue. As discussed in Section 2, the housing stock in mature towns hardly changed during our sample period. Given the widely held view that location is one of the predominant factors in housing choice, the estimated price premium for pre-connected apartments in mature towns is unlikely to be affected by the increase in the overall supply of apartments close to MRT stations. Moreover, because an increase in supply will depress the price premium, the increase in the price premium of pre-connected apartments would have been even higher than our estimate if the supply of connected apartments had not increased citywide.

To illustrate our identification strategy, we assume that there are only two types of apartments: pre-connected and unconnected. If the value of pre-connected apartments depends on the network coverage, the expansion of the network will raise the valuation of the former but not the latter. Therefore, the latter can be used as the control group while the former is the treatment group, where the treatment is the opening of the North East Line. In particular, let the price per square meter of apartment i in period t be

$$\ln p_{it} = \beta_0 + X_{it}'\beta_1 + \sum_j \delta_j T_{ijt} + \gamma S_i + \phi S_i \times E_{it} + \epsilon_{it}, \quad (2)$$

where X_{it} are observable apartment characteristics, $S_i = 1$ if apartment i is connected to the MRT system and 0 otherwise, T_{ijt} is a time dummy that equals one if the transaction was made in period j and 0 otherwise, and $E_{it} = 1$ if the transaction was in the post expansion period and 0 otherwise. Because we focus on apartments whose distance to a station (both pre- and post-expansion) was not affected by the expansion, the variable S does not have a time subscript. The effect of the expansion is the difference-in-differences coefficient, ϕ.[11]

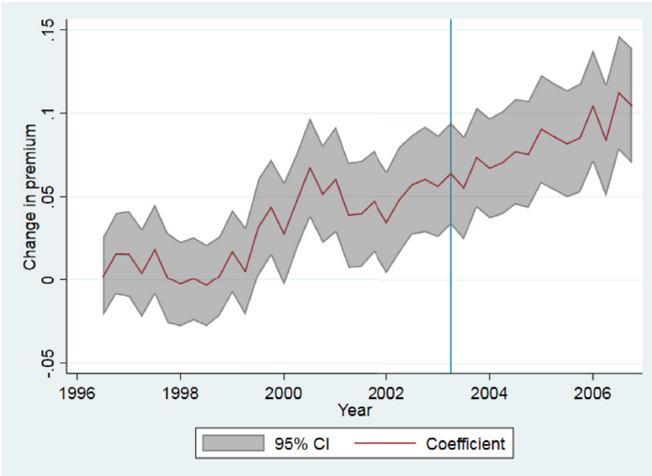
Given the findings of the large body of literature on announcement effects (Waud, 1970; Jud and Winkler, 2006; Grimes and Young, 2013), simply estimating the pre- and post-expansion difference might be too arbitrary. As people foresee that the pre-connected apartments will become more attractive because of the new MRT line and apartments are very long-lived assets whose price depends on the discounted sum of future utilities, prices should start to appreciate even before the opening. In our sensitivity analysis, we replace the interaction between S and E with a series of interactions between S and T. By doing so, the price differences between the pre-connected and unconnected apartments can change freely over time. We indeed find that the price premium of pre-connected apartments started to appreciated before the opening of the new line. This suggests that ϕ could underestimate the "true" price appreciation introduced by the new line.

To identify the impact of the MRT expansion on prices, we need two key assumptions to be satisfied: (1) the valuation of the pre-connected and unconnected apartments would follow the same time trend if there was no expansion, and (2) changes in unobserved quality are not correlated with an apartment's connection status.

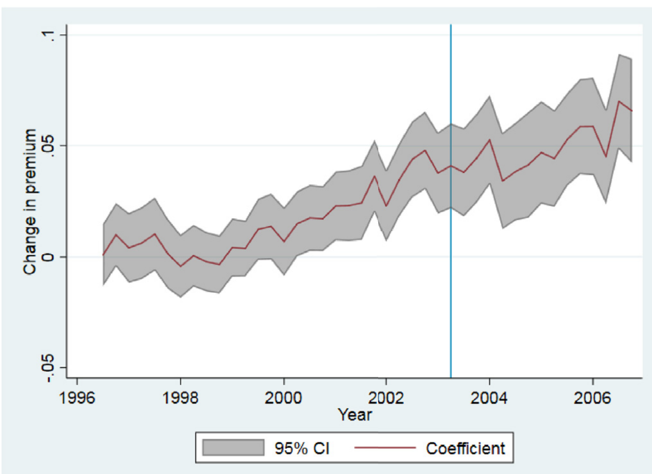
Although the first assumption is not testable since the counterfactual of no expansion is not observable, examining trends before the expansion can be informative. Fig. 3 graphs the price premium of pre-connected apartments over time. The pre-connected apartments are those located within 0.5 km of a station, while the unconnected apartments are located between 0.5 and 1.0 km of a station. These somewhat arbitrary choices are checked for robustness in our empirical analysis below. The baseline quarter is 1996Q3, the quarter after plans for the North East Line were announced.

Panel (a) of Fig. 3 shows that the pre-connection premium is constant from 1996 to the end of 1999, suggesting that the treatment and control rings share a similar trend. At the end of 1999, the premium begins to increase, perhaps because buyers anticipate the opening of the

[11] We note that any post-expansion change in the price differential, ϕ, could be caused by either an increase in the price of pre-connected apartments or a decline in the price of unconnected apartments. We thank a referee for alerting us to this.



(a) Without control variables



(b) With control variables

Fig. 3. Change in premium of pre-connected apartments over time (relative to 1996Q1 base), with and without control variables. The blue line indicates the opening quarter of the North East Line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

North East Line, indicated by the blue line, and the benefits of the network expansion were capitalized into the price of pre-connected apartments. In any case, these are "raw" price premiums for which we have not controlled for characteristics of the apartment. Later, we discuss panel (b), which contains the changing price premium when controlling for a full set of hedonic characteristics.

The second assumption implies

$$\left[E(\epsilon_{it}|E_{it}=1,S_i=1,T_{it})-E(\epsilon_{it}|E_{it}=0,S_i=1,T_{it})\right]$$
$$=\left[E(\epsilon_{it}|E_{it}=1,S_i=0,T_{it})-E(\epsilon_{it}|E_{it}=0,S_i=0,T_{it})\right]. \quad (3)$$

While it is possible that HDB might adjust the quality of their new projects after the expansion to cater to buyers with a higher valuation of the distance to a MRT station, distance does not change once the construction has completed. Since the stock of HDB apartments hardly changed during our sample period, with apartments already built years before the expansion, changes in building quality should not be an issue. However, even though Equation (3) might hold for the entire housing stock, it might not be valid among resale units as these apartments were self-selected. For instance, households with stronger preferences for connected apartments might also have stronger preferences for other housing characteristics. If the preference for the observed and unobserved characteristics are correlated, and the preference for these characteristics are indeed correlated with the preference for an apartment's connection status, then the estimate of ϕ in Equation (2) should be sensitive to whether we control for the observed characteristics, X. We find, in fact, that our estimate is *not* affected by the inclusion of X. The robustness of our results suggest that even if the expansion of the MRT indeed changed the composition of resale apartments, which does not seem to be the case given the analysis in Table 2, these changes were likely to be similar for the pre-connected and unconnected units.

4. Estimation results

Table 4 reports the estimation results using the natural log of deflated price per square meter as the dependent variable. For columns (1) to (5), we define a treatment ring of "pre-connected" apartments and a control ring of "unconnected" apartments, with the categorization depending on the distance to the nearest pre-expansion MRT station. For example, in column (1), the treatment ring includes all apartments within 0.5 km of a pre-expansion MRT station, and the control ring includes all apartments from 0.5 to 1.0 km of a pre-expansion station. Because the price premium is likely to be correlated with distance to the nearest MRT station, our estimates can be interpreted as an average treatment effect. Since some apartments located in the control ring could also benefit from the network expansion, our estimate provides a lower bound for the network effect.

In the first regression in column (1), we control only for an apartment's connection status, a post-expansion dummy, and their interaction. The coefficient on the interaction is 0.018 (SE = 0.008), suggesting that the expansion increased the price premium of pre-connected apartments by 1.8%. If the only difference between the pre-connected and unconnected apartments, on average, is their connection status, then adding other housing characteristics should not affect our estimate. To check whether this is indeed the case, we control for a set of housing characteristics that are commonly included in hedonic regressions. Specifically, in columns (2) to (5), we include a quadratic function of distance to the CBD, of age, and of the size of the apartment, number of rooms fixed effects, flat model fixed effects, floor bin fixed effects, 2-digit zip code fixed effects, and transaction quarter fixed effects.[12] Adding these controls raised the R^2 from 0.024 to 0.673 (column (2)), indicating that these characteristics have considerable explanatory power. The coefficient on the interaction term did not change, 0.018, while the standard error of the estimate shrunk by a quarter to 0.06. The similarity between these two estimates suggest that pre-connected and unconnected apartments are indeed comparable, which is consistent with the homogeneity of HDB apartments in general.

To check whether our results are sensitive to how we define the treatment and control rings, we expand the control ring to 0.5–1.5 km in column (3), the treatment ring to 0–0.75 km in column (4), and the treatment and control ring to 0–0.75 km and 0.75–2.0 km, respectively, in column (5).[13] Overall, the results are similar across the different ring definitions, and the direction of any differences in the estimates is consistent with the explanation that the impact of the MRT expansion decreases in the distance to a pre-expansion MRT station. That is, apartments further from a pre-expansion MRT station benefited less from the expansion than closer apartments.

[12] Each building in Singapore is assigned a unique 6 digit zip code. In our main specifications, we control for location by grouping buildings by the first two digits of the building's zip code, which introduces 53 location fixed effects. In a robustness check, we control for location more finely by grouping buildings by the first four digits, which introduces 465 location fixed effects.

[13] Note that we choose ring sizes that correspond closely to the 25th (0.51 km), 50th (0.76 km), and 75th (1.01 km) percentiles of distance of apartments to a pre-expansion station for all apartments within 1.5 km of a pre-expansion station.

Table 4
Dependent variable: Log deflated price per m².

Treatment ring:	0 to 0.5 km	0 to 0.5 km	0 to 0.5 km	0 to 0.75 km	0 to 0.75 km	Continuous
Control ring:	0.5–1 km	0.5–1 km	0.5–1.5 km	0.75–1.5 km	0.75–2 km	distance (km)
	(1)	(2)	(3)	(4)	(5)	(6)
Pre-connected	0.044***	0.039***	0.056***	0.059***	0.060***	
	(0.010)	(0.004)	(0.004)	(0.003)	(0.003)	
Pre-connected × Post expansion	0.018**	0.018***	0.019***	0.015***	0.020***	
	(0.008)	(0.006)	(0.005)	(0.005)	(0.004)	
Distance to MRT in km						−0.085***
						(0.004)
Distance to MRT × Post expansion						−0.034***
						(0.005)
Distance to CBD in km		−0.100***	−0.072***	−0.072***	−0.063***	−0.063***
		(0.013)	(0.010)	(0.010)	(0.009)	(0.009)
Distance to CBD, squared		0.004***	0.003***	0.003***	0.002***	0.002***
		(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Age in years		−0.027***	−0.021***	−0.024***	−0.022***	−0.024***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age, squared		0.001***	0.000***	0.000***	0.000***	0.001***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Apartment model fixed effects	No	Yes	Yes	Yes	Yes	Yes
Number of rooms fixed effects	No	Yes	Yes	Yes	Yes	Yes
Floor bin fixed effects	No	Yes	Yes	Yes	Yes	Yes
Unit area quadratic	No	Yes	Yes	Yes	Yes	Yes
2-digit zip code fixed effects	No	Yes	Yes	Yes	Yes	Yes
Post-expansion dummy variable	Yes	NA	NA	NA	NA	NA
Transaction quarter fixed effects	No	Yes	Yes	Yes	Yes	Yes
R^2	0.024	0.673	0.638	0.643	0.652	0.659
Observations	45,200	45,200	64,649	64,649	72,889	72,889

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. The dependent variable is the logarithm of the apartment's transaction price divided by the size of the unit (in January 2000 S$ per m²). Standard errors, in parentheses, are clustered by zip code. Columns differ by the radius of the inner ring and outer ring around each MRT station.

Expanding the control ring in column (3) increases the impact of the estimate to 0.019 (SE = 0.005) as the average impact within the larger control ring decreases relative to the treatment group, increasing the estimate. The evidence supports our conjecture that our estimate is likely to provide a lower bound for the impact of network expansion on housing price. Enlarging the treatment ring in column (4) shifts apartments from 0.5 to 0.75 km, whose benefit from the expansion is less than apartments nearer the MRT, into the newly defined treatment group, which reduces the average impact within it. But the benefit of these same apartments is greater than the benefit of those farther away from an MRT station, which decreases the average impact in the new control group as well. The decrease in the estimate to 0.015 implies that the former effect dominates. The point estimate increases to 0.020 in column (5), where the control ring is between 0.75 and 2.0 km, because of the addition of apartments 1.5–2 km from a MRT station, which were not likely affected much by the expansion. In column (6), we replace discrete rings with continuous distance in km to the nearest pre-expansion MRT station. We limit this subsample to include apartments within 2 km of a pre-expansion station. The coefficient on the interaction between the post-expansion dummy and the distance to the nearest MRT station is −0.034 (SE = 0.005), i.e., the value of apartments located at 0.25 km from the nearest station increased by 1.7% relative to similar apartments located 0.75 km from the nearest MRT station, which is nearly identical to the estimate in column (2).

As a further robustness check of the ring size, we estimated the regression with multiple rings. These rings contain apartments located 0–0.5 km, 0.5–0.75 km, and 0.75–1.0 km from a pre-expansion station. The omitted ring contains apartments locate 1.0–1.5 km from a pre-expansion station. Results are reported in Table 5.

The results are as expected: the closer the apartment is to a station the higher the price. For example, an apartment within the first ring sold for 8.8% more than an apartment in the baseline ring. The premium within the second ring is 5.8% and within the third ring, 2.8%. Moreover, apartments in the first ring, closest to a pre-expansion station, appreciated after the network expansion by 2.2% and the effect is statistically significant. The estimates of the expansion effect for the second and third rings are economically small and not statistically different than zero, suggesting that the apartments closest to a pre-expansion station particularly benefited from the expansion.

Table 5 also contain a placebo test of the pre-trends in column 2. We restrict our sample to the third quarter of 1996, one quarter after a North South Line expansion, to the last quarter of 1999 and use the period after the second quarter of 1998 as the placebo treatment period. The coefficient estimate on the interaction term between the placebo treatment dummy and pre-connected apartment dummy is 0.003 with a standard error of 0.003. This result supports the common pre-trend hypothesis. We reach a similar conclusion if we use either the first quarter or the third quarter of 1998 as the starting point for the placebo treatment period.

Table A.1 in the Appendix repeats the analysis of Table 4 using finer location fixed effects by grouping buildings by the first 4 digits of the zip code. The estimates are very similar to those in Table 4. Table A.2 replaces the dependent variable with deflated price per square meter in levels. The results remain very robust: the price of a pre-connected apartment is estimated to have increased between S$28 and S$42 per square meter due to the MRT expansion and all results are significant at the 1–10% level. Using continuous distance, we find that an apartment near a pre-expansion station appreciated by about S$74 after the expansion relative to an apartment 1 km away.

One implicit assumption of Equation (2) is that the expansion only affected prices from the time that the North East Line opened. However, given the findings of a large literature on announcement effects mentioned in the previous section, price may have begun adjusting before the North East Line opened. To check whether this is the case, we expand our sample to the third quarter of 1996, one quarter after the 1996 North South Line expansion and a quarter after plans for the North East Line were announced, ending in the year of the next MRT expansion in 2006, and re-estimate a more flexible specification of Equation (2):

Table 5
Multiple rings by distance and a placebo test. Dependent variable: Log deflated price per m^2.

	(1)	(2)
Pre-connected ring (0–0.5 km)	0.088***	0.041***
	(0.004)	
Pre-connected ring (0.5–0.75 km)	0.058***	
	(0.004)	
Pre-connected ring (0.75–1.0 km)	0.028***	
	(0.004)	
Pre-connected (0–0.5 km) × Post expansion	0.022***	
	(0.007)	
Pre-connected (0.5–0.75 km) × Post expansion	0.008	
	(0.007)	
Pre-connected (0.75–1.0 km) × Post expansion	0.003	
	(0.006)	
Pre-connected × Post expansion placebo		0.003
		(0.003)
Distance to CBD in km	−0.070***	−0.011***
	(0.010)	(0.002)
Distance to CBD, squared	0.002***	−0.000
	(0.000)	(0.000)
Age in years	−0.024***	−0.008***
	(0.001)	(0.001)
Age, squared	0.000***	0.000***
	(0.000)	(0.000)
Apartment model fixed effects	Yes	Yes
Number of rooms fixed effects	Yes	Yes
Floor bin fixed effects	Yes	Yes
Unit area quadratic	Yes	Yes
2-digit zip code fixed effects	Yes	Yes
Post-expansion dummy variable	N/A	N/A
Transaction quarter fixed effects	Yes	Yes
R^2	0.652	0.833
Observations	64,649	68,286

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. The dependent variable is the logarithm of the apartment's transaction price divided by the size of the unit (in January 2000 S\$ per m^2). Standard errors, in parentheses, are clustered by zip code. The omitted ring in column (1) contains apartments located between 1 and 1.5 km from a pre-expansion station. Column (2) is a placebo test for an expansion in 1998Q1 for sample period 1996Q3 to 1999Q4.

$$\ln p_{it} = \beta_0 + X_{it}'\beta_1 + \sum_{j=1996Q4}^{2006Q4} \delta_j T_{ijt} + \gamma S_i + \sum_{j=1996Q4}^{2006Q4} \phi_j S_i \times T_{ijt} + \epsilon_{it}, \tag{4}$$

where γ is the pre-connected price premium, the price differential between the treatment and control group, in the third quarter of 1996, seven years before the expansion. Each coefficient ϕ_j can be interpreted as the impact of the network expansion on the price premium in each quarter, up to the end of 2006.

Panel (b) of Fig. 3 plots $\widehat{\phi}_j$ and their 95% confidence intervals. The blue line indicates the second quarter of 2003, the opening quarter of the North East Line. Supporting the common trend assumption, $\widehat{\phi}_j$ is not statistically significant from 1996 to the beginning of 2000. That is, the pre-connected premium did not change between 1996 and 2000. The pre-connection price premium then begins to increase steadily, suggesting that the benefits of the network expansion are being capitalized as the opening date approaches. After the opening, the growth of the price premium seizes and remains constant for several more years, up to the next small expansion in 2006 (followed by a major expansion in 2009, the opening of a new MRT line).

To get a better sense of the magnitude of the estimated price effect, note that the 1.8% estimate in column (2) of Table 4 implies an increase of S\$4385 at the average price in the sample. We can use a simple discounting model to convert this figure into an annual benefit.

Consider a model in which the transaction price of an apartment is equal to the sum of discounted annual utility over the lifetime of the apartment, T years. Let u be the constant, annual utility in real dollars provided by an apartment near a pre-expansion MRT station before the expansion, and r be the real discount rate. Then, the price of this unit is determined by:

$$p = \left(1 + \sum_{t=2}^{T} \left(\frac{1}{1+r}\right)^{t-1}\right) u. \tag{5}$$

Let the utility derived from a similar unit transacted after the expansion be u' and let its price be p'. Then, the difference in prices can be written as:

$$p' - p = \left(1 + \sum_{t=2}^{T} \left(\frac{1}{1+r}\right)^{t-1}\right) \left(u' - u\right). \tag{6}$$

We have estimated $p' - p$ to be S\$4385. To determine a reasonable value for T, consider, as mentioned previously, that HDB apartments are sold with 99-year leases, at the end of which they return to HDB. Since the average age in the sample is around 18 years, the average remaining lease years is about 81 years, which we will take to be the value of T. Finally, for r we use the 2.1% estimated by Fesselmeyer et al. (2018) with Singapore housing data. Using these values, from equation (6), we estimate $u' - u$ to be S\$111 per year. That is, in real terms, we estimate that the annual utility of living in a already connected apartment increased by S\$111 due to the expansion of the MRT network, worth 8.5 hours of traveling time when evaluated at the median hourly wage of \$13 in 2003. The opening of the new line reduced a round trip via public transportation from most pre-connected apartments to either HarbourFront or China Town, two places with a high concentration of shopping and office spaces, by about 20 min. Thus, as long as a household make 25.5 person-round-trips per year to either of these two locations, the savings in time costs would be large enough to compensate for the increase in price.

5. Heterogeneous effects

In the next subsections, we consider whether the valuation of the MRT expansion differs by subsample. In particular, we measure whether the effect of the MRT expansion on price differs by car ownership rates, by distance to the nearest bus stop, by family size (proxied by flat size), and by income (proxied by floor). We find that our estimated effects vary in reasonable ways, providing further robustness to our primary results. We also consider a robustness test for the impact of improving amenities and several other regressions that test whether the effect of the expansion differed by location.

5.1. Car ownership

Due mostly to government regulation that aims to push commuters to use public transportation, owning and operating a car in Singapore is very expensive and the overall ownership rate, particularly among HDB households, is low.[14] As such, one would expect the value of the MRT expansion to differ across households with and without cars as, presumably, MRT use is significantly less common among households that own cars. Hence, as a means of transportation, car owners should value the expansion less than those that do not own cars. And due to large transaction costs, these households are unlikely to sell their apartments to enjoy the appreciation due to the expansion, at least initially.[15] Ideally, this would be tested using household level data on car ownership and housing prices, but this data is unavailable. Instead, we test for heterogeneous effects by estimating whether areas with low car ownership rates valued the expansion more than in areas with high car ownership rates.[16]

To do so we divided our sample into two subsamples. The low car ownership sample contains all transactions of apartments in two-digit zip code locations with car ownership rates below the median rate of 0.3. The second subsample contains the remaining transactions in two-digit zip code locations with car ownership rates of 0.3 or greater. As in all the subsections below, we estimated our preferred model, with a treatment ring to 0.5 km and a control ring from 0.5 to 1 km, and a complete set of control variables, on each subsample. The results are reported in Table 6, panel (a).

Column (1) contains the results for the subsample below the median car ownership rate, and column (2) above. The coefficient estimate on the treatment ring-post expansion interaction is 0.015 and significant at the 5% level (p-value = 0.024) for the subsample with low car ownership rates. The estimate for the high car ownership group is less than half the size, 0.006, and not statistically different than zero. In words, households near a pre-expansion MRT station in areas with low car ownership rates value the expansion of the MRT network. Those households near a pre-expansion MRT stations in areas with high car ownership rates did not value the expansion any differently than households located further away. These results provide evidence that the MRT expansion was valued by the households most likely to benefit from it, namely those households that were least likely to own cars and that were living in apartments near a pre-expansion MRT station.

The difference in the valuation of pre-connected apartments between households with and without cars might bias our estimates if the cost of car ownership changed simultaneously with the network expansion. For instance, a sudden rise in the cost of car ownership could reduce car ownership, raising the price premium of pre-connected apartments. Fig. 4 plots the quarterly mean price for a Certificate of Entitlement (COE), which provides the right to own a car for 10 years, for cars with an engine 1600cc or smaller. The figure shows that the COE price generally follows a downward trend, except a sudden big drop 8 quarters before the expansion and a subsequent rebound. The dip was mostly driven by an extremely low price of S$101 in June 2001. The price bounced back to S$26,239 the following month.[17] Because households living in unconnected apartments benefited more from car ownership, they might have had a higher probability of purchasing a car as the COE price declined, which would bias our estimate downward.

5.2. Bus network

In this subsection we explore the possibility that households away from an MRT station but near a bus stop valued the MRT expansion more than households not near a bus stop or MRT station.

Consider that households who travel mostly by public transportation gain the most from the MRT expansion by substituting the MRT for buses. Households not within walking distance of an MRT station but living close to a bus stop might find it more attractive after the expansion to take a short bus ride to the nearest MRT station first, and then ride the MRT to their destination. In contrast, the expansion likely had little impact on the traveling mode of households who are not very close to a bus stop or an MRT station, and accordingly these households valued the expansion very little.

Using this rationale, we divided apartments in the control ring into two groups according to their distance to the nearest bus stop. One group consists of apartments within 100 m of a bus stop; the second group is farther than 100 m. We do not divide the treatment groups because households close to an MRT station are less likely be affected by the distance to bus stops as they should generally prefer the MRT to buses as long as their traveling destinations are close to an MRT station.

The results including transactions of apartments near an MRT station or a bus stop are in column (3) of Table 6, panel (a). The results including those close to an MRT station and those not close to an MRT station or a bus stop are in column (4). The estimate of the value of the MRT expansion in column (4) is bigger and statistically significant when we limit the control group to transactions of households that find it particularly costly to reach the MRT on foot or by bus and are least likely to use the MRT network; their valuation of the expansion must be very small. The subsample that limits the control group to transaction of apartments near a bus stop results in a smaller and noisier estimate in column (3), possibly because some households in the control group take the bus to the MRT network.

[14] Singapore policy discourages car use in several ways. To own a car one must have a Certificate of Entitlement (COE), which provides the right to own a car for 10 years. COEs are limited by a quota and allocated by auction. The average COE auctioned for about S$31,000 in 2002, the year before the expansion, and S$25,000 in 2004, the year after. In addition, car owners have to pay an Additional Registration Fee that is between 100% and 180% of the car's open market value and Excise Duty of 20% of the car's open market value. In total, a new, mid-sized sedan such as a Toyota Camry can cost well over S$100,000. See Ho et al. (2018) for further details on the COE system and Singapore car policies.

[15] All buyers need to pay a stamp duty that varies from 1 to 3% of the market value of the property.

[16] Car ownership rates were computed using data from the 2004 Household Interview Travel Survey.

[17] While such a big swing in the COE price is unusual, it has occurred other times. For example, the lowest COE price ever was only S$2 in November 2008. In comparison, the price was S$10,989 and S$6200 in October and December 2008, respectively.

Table 6
Dependent variable: Log deflated price per m^2.

(a)

	Car ownership <0.3 (1)	Car ownership ≥0.3 (2)	Bus stop ≤0.1 km (3)	Bus stop >0.1 km (4)	Room number ≤3 (5)	Room number >3 (6)	Floor ≤6 (7)	Floor ≥7 (8)
Pre-connected	0.033***	0.054***	0.044***	0.038***	0.042***	0.053***	0.030***	0.042***
	(0.005)	(0.008)	(0.005)	(0.005)	(0.005)	(0.003)	(0.005)	(0.004)
Pre-connected × Post expansion	0.015**	0.006	0.011	0.020***	0.004	0.012***	0.024***	0.015***
	(0.007)	(0.008)	(0.007)	(0.006)	(0.006)	(0.004)	(0.009)	(0.005)
Distance to CBD in km	−0.097***	−0.148***	−0.125***	−0.092***	−0.113***	−0.059***	−0.105***	−0.098***
	(0.014)	(0.022)	(0.016)	(0.015)	(0.017)	(0.010)	(0.014)	(0.013)
Distance to CBD, squared	0.004***	0.007***	0.005***	0.003***	0.005***	0.002***	0.004***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
Age in years	−0.025***	−0.052***	−0.026***	−0.029***	−0.019***	−0.023***	−0.027***	−0.027***
	(0.001)	(0.003)	(0.001)	(0.001)	(0.003)	(0.001)	(0.001)	(0.001)
Age, squared	0.000***	0.001***	0.001***	0.001***	0.000***	0.000***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Apartment model fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of rooms fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Floor number fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Unit area quadratic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2-digit zip code fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transaction quarter fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.657	0.756	0.682	0.688	0.547	0.808	0.601	0.687
Observations	30,930	14,270	26,468	34,267	22,921	22,279	8794	36,406

(b)

	No major mall within 0.2 km (1)	Distance to CBD <10 km (2)	Distance to CBD ≥10 km (3)	Entire sample (4)	Entire sample (5)
Pre-connected	0.046***	0.046***	0.033***	0.042***	0.039***
	(0.006)	(0.006)	(0.005)	(0.004)	(0.004)
Pre-connected × Post expansion	0.021***	0.017**	0.006	0.012**	0.014*
	(0.007)	(0.008)	(0.006)	(0.005)	(0.007)
Distance to HarbourFront < 12 km				−0.007	
				(0.011)	
Distance to HarbourFront < 12 km × Post expansion				0.033***	
				(0.005)	
EW × Pre-connected × Post					0.005
					(0.008)
Distance to CBD in km	−0.127***	−0.127***	−0.067*	−0.099***	−0.099***
	(0.021)	(0.021)	(0.039)	(0.013)	(0.013)
Distance to CBD, squared	0.006***	0.006***	0.002	0.004***	0.004***
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Age in years	−0.024***	−0.028***	−0.031***	−0.026***	−0.027***
	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
Age, squared	0.000***	0.001***	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Apartment model fixed effects	Yes	Yes	Yes	Yes	Yes
Number of rooms fixed effects	Yes	Yes	Yes	Yes	Yes
Floor number fixed effects	Yes	Yes	Yes	Yes	Yes
Unit area quadratic	Yes	Yes	Yes	Yes	Yes
2-digit zip code fixed effects	Yes	Yes	Yes	Yes	Yes
Transaction quarter fixed effects	Yes	Yes	Yes	Yes	Yes
R^2	0.652	0.720	0.609	0.675	0.673
Observations	29,342	25,599	19,601	45,200	45,200

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors, in parentheses, are clustered by zip code. The dependent variable is the property's transaction price divided by the size of the unit (in January 2000 S$ per m^2). The treatment group in columns (3) and (4) consists of apartments within 0.5 km of an MRT station regardless of their distances to bus stops. The control group in columns (3) and (4) consist of apartments within 0.5–1 km of an MRT station and within 100 m of a bus stop (column (3)) or not (column (4)).
Notes: ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors, in parentheses, are clustered by zip code. The dependent variable is the property's transaction price divided by the size of the unit (in January 2000 S$ per m^2).

5.3. Household size

In this subsection, we consider whether family size affects the valuation of the MRT expansion. We expect larger families to value an expansion more as more family members can enjoy the benefits. Since we do not observe family size directly, we proxy family size by the number of rooms in the apartment because, in general, a larger family requires more living space.[18] In particular, we split the sample into two

[18] According to the 2000 Census of Population, the mean number of household members in apartments with 3 rooms or fewer was 2.97 and 4.03 in apartments with more than 3 rooms (Singapore Department of Statistics, 2001). Further, according to the General Housing Survey of 2005, 64% of students age 5 or older that did not walk to school used public transportation (Singapore Department of Statistics, 2005), which is important since larger families are more likely to have young children.

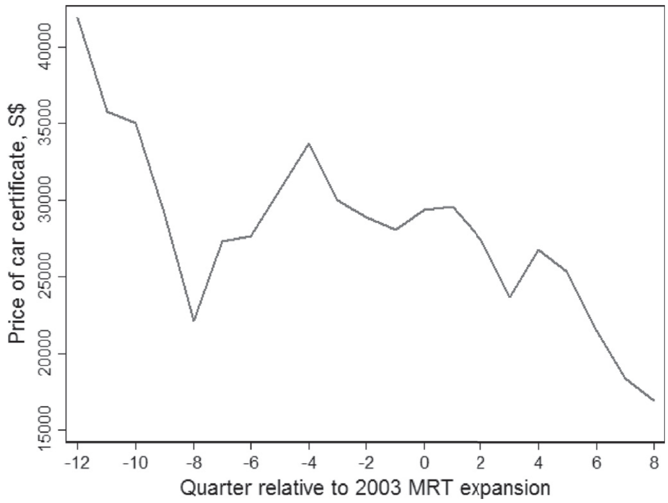


Fig. 4. The price of the certificate of entitlement for cars with 1600cc (or smaller) engines.

subsamples based on the median number of rooms (3), and run separate regressions.

The results of the regression using the subsample of small apartments of three rooms or fewer are reported in column (5) of Table 6, panel (a), and those using the subsample of large apartments of four rooms or more are in column (6). The effect of the MRT expansion estimated using small apartments is close to zero and not statistically significant. The effect for large apartments is over twice as big and statistically significant at the 1% level. This difference suggests that larger families value the MRT expansion more than smaller families do.

5.4. Income

We now consider how income affects the valuation of the MRT expansion. With the high cost of owning and operating a car in Singapore, car ownership is strongly correlated with income. Hence, we expect low income families to value the MRT expansion more than high income families.[19] Since we do not observe income we proxy for it using floor number. Because of the tropical climate, to avoid bugs and to enjoy the breeze Singaporeans prefer living on high floors, and these units cost much more than units on lower floors. For example, the highest apartments, on the 28th to 30th floors, sold for 56% more than apartments on the 3rd floor or lower. Presumably then people living on higher floors have higher incomes. We split the sample into two subsamples based on the median floor, and run separate regressions.

The results of a regression using the subsample of apartments on the 6th floor or lower is contained in column (7) of Table 6, panel (a), and those using the subsample of apartments on the 7th floor or higher are in column (8). The effect of the MRT expansion on the low floor apartments subsample is significantly larger than on the high floor apartments subsample, 2.4%–1.5%, with both estimates being statistically significant. That is, lower income families value the increased access via the MRT twice as much as higher income families.

5.5. Change in amenities

As mentioned previously, even though mature towns were fully developed by the beginning of our sample period, one may be concerned that our results are affected by improvements in local amenities, and, in particular, shopping malls, an important amenity in Singapore that may be improved by renovation. Since many Singaporeans spend a considerable amount of time in shopping malls, improving the quality of existing shopping malls could increase the value of neighboring housing. As a further robustness check, we estimated the effect of the MRT expansion on a subsample of transactions of apartments at least 200 m from a major shopping mall. Column (1) of Table 6, panel (b) shows that the resulting estimate of 2.1% is very similar to the full sample estimate, providing evidence that improving amenities are likely not an important factor behind our results. This does not necessarily imply that there were no major renovations or that these renovations do not affect housing price. Rather, owners of these shopping malls likely cannot synchronize the completion of renovations with the opening of the new MRT line.

5.6. Geographic location

In this section, we consider how the network expansion may have differed across locations. Firstly, we divide the sample into two subsamples based on the median distance to the CBD, 10 km. Column (2) of Table 6, panel (b) shows that the subsample of apartments near a pre-expansion station and less than 10 km from the CBD appreciated by 1.7% after the expansion.[20] Pre-connected apartments farther than 10 km did not show any appreciation (column (3)). Further, in column (4) of Table 6, panel (b) we allowed the expansion effect on apartments nearest to HarbourFront, a major destination on the new North East Line, to differ from apartments farther away. We do so by interacting a dummy that equals 1 if distance to HarbourFront is less than the median, 12 km, and 0 otherwise, with a post-expansion indicator. The greater price appreciation for pre-connected apartments closer to the CBD or HarbourFront could be due to the fact that the reduction in traveling time, particularly in percentage terms, is higher for people living relatively close to the CBD or HarbourFront. In addition, individuals who need to go to the CBD or HarbourFront more frequently are also more likely to live close to these destinations, and hence benefit more from the expansion.

Lastly, as seen in Fig. 1c, the pre-connected apartments along the North South Line are very close to the new line while the pre-connected apartments along the East West Line are a bit further away. Hence, households that reside along the North South Line might benefit less from the expansion if people mostly use the new line as a means to travel to the north region covered by the new line. However, if the benefits from the expansion are mainly from improved accessibility to the two main hubs, China Town and HarbourFront, then the benefits from the expansion should be comparable for households living along the North South Line and the East West Line. To test this, we include the triple interaction among the connection status, post-expansion status, and along the East West Line into the regression and report the results in column (5) of Table 6, panel (b). The coefficient on the interaction between the connection status and post-expansion status declines slightly to 0.014 with a standard error of 0.007. The coefficient on the East West Line interaction term is 0.005 with a standard error of 0.008, which is not statistically significant even at the 10% level. This suggests

[19] According to the 2005 General Household Survey, 59.6% of resident workers earning less than S$2000 per month used public transportation and 4.8% primarily used cars to travel to and from work. In contrast, 38.9% of those earning more than S$8000 per month used public transportation and 43% used cars (Singapore Department of Statistics, 2005).

[20] The newly opened Chinatown station is only 1.2 km away from the center of the CBD.

that the increase in the price premium of pre-connected apartments is likely driven by the improved accessibility to the two main commercial hubs, even if people might put some value on the improved accessibility to the city peripheries.

6. Conclusion

In this paper, we measure the impact on housing prices of the opening of the North East Line, a major expansion of Singapore's commuter rail system that added 14 stations and increased rail length by over 20%. In contrast to the approach of the existing literature which focuses on housing whose proximity to the transit network is affected by an expansion, we measure the change in housing prices in areas that were already connected, which provides cleaner identification of the benefits of the expansion. We also contribute to the literature on network effects by measuring the benefit of a network expansion to early adopters of the network in a context that has not been considered before.

We find that the North East Line increased the prices of already connected apartments by 1.5%–2.0%, suggesting that public transit networks enjoy economic returns to scale. According to the 2001/2002 HDB Annual Report, there were 415,060 housing units located in Singapore's mature towns in 2002. Using our transaction data, we find that the mean value of these apartments is S$243,604 (about US$180,000 dollars), and about 30% of them were within 0.5 km of an existing MRT station. Consequently, the expansion increased the value of pre-connected HDB apartments by at least S$455 million, which is equivalent to 9% of the estimated S$5 billion cost of the expansion, indicating that the magnitude of the network effect is substantial in comparison to construction cost, which is consistent with the findings of Gowrisankaran and Stavins (2004). The presence of such a sizable network effect indicates that the benefits to households living in already connected apartments should be included in cost-benefit analyses evaluating investments in public transit systems.

Further, as discussed in Appendix A.1, we estimated the direct price effect of the North East Line on apartments to be between 2 and 3.2%. Given that there were approximately 35,000 apartments within 0.5 km of a new station, significantly fewer than pre-connected apartments, with a mean value of S$210,316 in our transaction data, and applying a price effect of 3%, the aggregate effect of the opening of the North East Line on newly connected apartments was about S$221 million, or about 4.4% of the cost of the total expansion, again, suggesting that ignoring the network effect will lead to a significant underestimation of the total benefits of the new line.

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A.1. New connections to the MRT system

As a comparison, we estimated the impact of being newly connected to the MRT network along the North East Line on price, the direct effect of the North East Line. The regressions we estimate have a similar specification to the regressions of the network effect. As reported in Table A.3, we find that the direct price effect of the North East Line to be between 2 and 3.2%, depending on the definitions of the treatment and control rings. That is, an apartment near a new station increased in value between 2 and 3.2% after the station opened. This direct effect is somewhat larger than the estimated network effect, as one might expect. Note, however, that these estimates should be taken in the context of the concerns raised in the introduction with regards to the difficulty cleanly identifying the direct effect of new public transportation on prices.

Table A.1
Dependent variable: Log deflated price per m^2.

Treatment ring: Control ring:	0 to 0.5 km 0.5–1 km (1)	0 to 0.5 km 0.5–1 km (2)	0 to 0.5 km 0.5–1.5 km (3)	0 to 0.75 km 0.75–1.5 km (4)	0 to 0.75 km 0.75–2 km (5)	Continuous distance (km) (6)
Pre-connected	0.044***	0.028***	0.027***	0.032***	0.030***	
	(0.010)	(0.004)	(0.004)	(0.004)	(0.004)	
Pre-connected × Post expansion	0.018**	0.018***	0.019***	0.014***	0.019***	
	(0.008)	(0.005)	(0.005)	(0.005)	(0.004)	
Distance to MRT in km						−0.062***
						(0.005)
Distance to MRT × Post expansion						−0.031***
						(0.005)
Distance to CBD in km		−0.091***	−0.062***	−0.075***	−0.078***	−0.082***
		(0.018)	(0.017)	(0.017)	(0.016)	(0.016)
Distance to CBD, squared		0.005***	0.003***	0.003***	0.003***	0.004***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age in years		−0.032***	−0.033***	−0.034***	−0.032***	−0.032***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age, squared		0.001***	0.001***	0.001***	0.001***	0.001***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Apartment model fixed effects	No	Yes	Yes	Yes	Yes	Yes
Number of rooms fixed effects	No	Yes	Yes	Yes	Yes	Yes
Floor bin fixed effects	No	Yes	Yes	Yes	Yes	Yes
Unit area quadratic	No	Yes	Yes	Yes	Yes	Yes
4-digit zip code fixed effects	No	Yes	Yes	Yes	Yes	Yes
Post expansion dummy variable	Yes	NA	NA	NA	NA	NA
Transaction quarter fixed effects	No	Yes	Yes	Yes	Yes	Yes
R^2	0.024	0.702	0.683	0.683	0.689	0.693
Observations	45,200	45,200	64,649	64,649	72,889	72,889

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors, in parentheses, are clustered by zip code. The dependent variable is the property's transaction price divided by the size of the unit (in January 2000 S$ per m^2). Columns differ by the radius of the inner ring and outer ring around each MRT station.

Table A.2
Dependent variable: Deflated price per m^2.

Treatment ring: Control ring:	0 to 0.5 km 0.5–1 km (1)	0 to 0.5 km 0.5–1 km (2)	0 to 0.5 km 0.5–1.5 km (3)	0 to 0.75 km 0.75–1.5 km (4)	0 to 0.75 km 0.75–2 km (5)	Continuous distance (km) (6)
Pre-connected	129.59***	107.75***	156.05***	161.28***	165.68***	
	(27.99)	(10.92)	(10.94)	(8.50)	(8.44)	
Pre-connected × Post expansion	37.06*	34.36**	37.63***	28.41**	41.96***	
	(22.38)	(13.89)	(13.47)	(11.60)	(11.27)	
Distance to MRT in km						−238.98***
						(9.48)
Distance to MRT × Post expansion						−73.80***
						(12.90)
Distance to CBD in km		−276.35***	−201.15***	−201.72***	−178.10***	−178.05***
		(34.18)	(28.29)	(27.89)	(24.29)	(23.24)
Distance to CBD, squared		11.02***	7.14***	7.22***	5.84***	5.92***
		(1.62)	(1.19)	(1.18)	(1.00)	(0.94)
Age in years		−78.63***	−59.31***	−65.80***	−60.64***	−65.99***
		(3.45)	(2.48)	(2.37)	(2.07)	(2.12)
Age, squared		1.59***	1.18***	1.34***	1.22***	1.33***
		(0.09)	(0.07)	(0.07)	(0.06)	(0.06)
Apartment model fixed effects	No	Yes	Yes	Yes	Yes	Yes
Number of rooms fixed effects	No	Yes	Yes	Yes	Yes	Yes
Floor bin fixed effects	No	Yes	Yes	Yes	Yes	Yes
Unit area quadratic	No	Yes	Yes	Yes	Yes	Yes
2-digit zip code fixed effects	No	Yes	Yes	Yes	Yes	Yes
Post expansion dummy variable	Yes	NA	NA	NA	NA	NA
Transaction quarter fixed effects	No	Yes	Yes	Yes	Yes	Yes
R^2	0.023	0.705	0.664	0.669	0.675	0.684
Observations	45,200	45,200	64,649	64,649	72,889	72,889

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. The dependent variable is the the apartment's transaction price divided by the size of the unit (in January 2000 S$ per m^2). Standard errors, in parentheses, are clustered by zip code. Columns differ by the radius of the inner ring and outer ring around each MRT station.

Table A.3
Direct price effect of new connection to MRT network

Treatment ring: Control ring:	0 to 0.5 km 0.5–1 km (1)	0 to 0.5 km 0.5–1.5 km (2)	0 to 0.75 km 0.75–1.5 km (3)	0 to 0.75 km 0.75–2 km (4)
Near new station location	0.013**	0.013*	0.001	0.011
	(0.007)	(0.007)	(0.010)	(0.010)
Near new station location × Post expansion	0.020*	0.026**	0.027***	0.032***
	(0.011)	(0.011)	(0.011)	(0.012)
Distance to CBD in km	−0.221***	−0.243**	−0.281***	−0.099
	(0.081)	(0.100)	(0.097)	(0.074)
Distance to CBD, squared	0.016***	0.016***	0.018***	0.006
	(0.005)	(0.006)	(0.006)	(0.004)
Age in years	−0.024***	−0.023***	−0.023***	−0.026***
	(0.004)	(0.004)	(0.004)	(0.003)
Age, squared	0.001***	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Apartment model fixed effects	Yes	Yes	Yes	Yes
Number of rooms fixed effects	Yes	Yes	Yes	Yes
Floor bin fixed effects	Yes	Yes	Yes	Yes
Unit area quadratic	Yes	Yes	Yes	Yes
Station fixed effects	Yes	Yes	Yes	Yes
Post-expansion dummy variable	N/A	N/A	N/A	N/A
Transaction year and quarter fixed effects	Yes	Yes	Yes	Yes
R^2	0.683	0.648	0.645	0.630
Observations	3972	4352	4352	5815

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. The dependent variable is the logarithm of the apartment's transaction price divided by the size of the unit (in January 2000 S$ per m^2). Standard errors, in parentheses, are clustered by zip code. Columns differ by the radius of the inner ring and outer ring around each North East Line station.

Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.regsciurbeco.2018.04.010.

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