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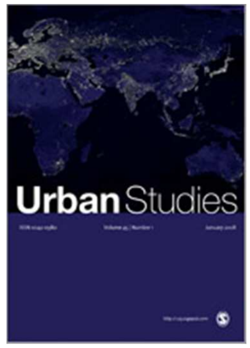
Article (Accepted version) (Refereed)

Original citation:
Waights, Sevrin (2018) *Does the law of one price hold for hedonic prices?* Urban Studies. ISSN 0042-0980



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Journal:	*Urban Studies*
Manuscript ID	CUS-358-17-04.R1
Manuscript Type:	Article
<b>Discipline: Please select a keyword from the following list that best describes the discipline used in your paper.:	Economics
World Region: Please select the region(s) that best reflect the focus of your paper. Names of individual countries, cities & economic groupings should appear in the title where appropriate.:	Europe
Major Topic: Please identify up to 5 topics that best identify the subject of your article.:	Transport, Neighbourhood, Economic Processes
You may add up to 2 further relevant keywords of your choosing below::	Spatial equilibrium, unit root tests

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Does the law of one price hold for hedonic prices?[*]

Abstract: Hedonic prices of locational attributes in urban land markets are determined by a process of spatial arbitrage that is similar to that which underpins the law of one price. If hedonic prices deviate from their spatial equilibrium values then individuals can benefit from changing locations. I examine whether the law holds for the hedonic price of rail access using a unique historical dataset for Berlin over the period 1890-1914, characterised by massive investment in the transport infrastructure. I estimate the hedonic price of rail access across multiple urban neighbourhoods and time periods to generate a panel dataset of hedonic price differences that I test for stationarity using a panel unit root test. Across multiple specifications I consistently fail to reject the null hypothesis of no unit root and accept the alternative hypothesis that the law holds. My estimates indicate a half-life for convergence to the law of one price that lies between 0.28 and 1.14 years. This result is consistent with spatial equilibrium.

Keywords: Spatial equilibrium, law of one price, hedonic prices, transport, unit root tests, panel data

Version: August 2017

JEL: R00 R12 R13 R31 N93

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[*] This data collection for this research was supported by a German Research Foundation (DFG) funded project on the urban structure of historical Berlin. I thank participants of the LSE Economic Geography cluster and the SERC Annual Conference, and especially Gabriel Ahlfeldt, Paul Cheshire, Steve Gibbons, Christian Hilber, Simona Iammarino, Kristoffer Moeller, Henry Overman, Rosa Sanchis-Guarner, Olmo Silva, Daniel Sturm and Felix Weinhardt for helpful comments and suggestions.

1 Introduction

The law of one price states that, in an efficient market, the price of an identical good or asset must be the same at all locations, otherwise there would be an opportunity for arbitrage. If a local supply (or demand) shock increases the price in one location, then rational agents will transport the good to the expensive location from the cheaper location to make a profit. This arbitrage will quickly eliminate the price difference. A similar argument unpins the assumption of spatial equilibrium in the determination of hedonic prices of the attributes of land (or housing): land prices must exactly compensate for differences in amenities across locations otherwise individuals would want to change location. A local shock to amenities (e.g. a new rail line) without a land price adjustment would imply the amenity (rail access) is 'too cheap' in the improved locations, i.e. that the hedonic price is below its spatial equilibrium value. Utility maximising households would demand land at the improved locations where rail access is cheaper. This pushes up the price of land until it fully compensates for the amenity improvement, i.e. until the spatial equilibrium hedonic prices of rail access are restored. This process is similar to LOP but where individuals move *themselves* to where non-tradable goods (attributes) are cheaper instead of transporting the goods.

This paper investigates the case of Berlin between 1890 and 1914, a period characterised by a series of massive infrastructure projects that represent a barrage of local shocks to the hedonic price of rail access across different neighbourhoods and time periods. Significant spatiotemporal variation in hedonic prices allow me to test if neighbourhood-specific shocks to hedonic prices are persistent or if price deviations from equilibrium are eliminated via spatial arbitrage. Put another way, this historical case provides an excellent scenario with which to examine if hedonic prices across urban locations are tied together in a long-run LOP relationship.

I provide evidence on this question by developing and implementing a two-stage approach. In the first stage I use a unique historical panel dataset of land values and transport infrastructure for Berlin (1890-1914) where I estimate the hedonic price of rail access in city-neighbourhoods over time. I use these estimates to produce a panel dataset of hedonic price differences between neighbourhoods. In the second stage, I adopt a standard test in the LOP literature which is to examine the price differences for stationarity using a panel unit root test. In particular I employ a test which exhibits good properties for short panels (Blander & Dhaene, 2012). Across multiple specifications I consistently fail to reject the null hypothesis of no unit root and accept the alternative hypothesis that LOP holds. My estimates indicate a half-life for convergence to the law of one price that lies between 0.28 and 1.14 years. While this approach is not a direct test of spatial equilibrium, it does provides some reassurance that processes of spatial arbitrage in land markets determine prices.

By demonstrating mean reversion of hedonic prices that is consistent with spatial equilibrium, the results provide support for research that relies on this assumption, such as the intra-urban models of the Alonso-Mills-Muth type and the inter-urban models of the Rosen-Roback type.[1] Furthermore by investigating the processes by which hedonic prices are determined it also contributes to the literature on the determination of hedonic prices in equilibrium (e.g. Epple, 1987; Rosen, 1974). By estimating the hedonic price of rail access, the results also contribute to a literature which values transport innovations (e.g. Gibbons & Machin, 2005) and a literature that estimates the value of urban amenities and policies more generally using the hedonic method.[2] Finally, it contributes to the literature on the law of one price, in particular the more recent work that looks to test absolute/relative version of LOP with panel unit root tests and that which looks to test if LOP applies for heterogenous goods.[3] The structure of the paper is as follows. Section 2 provides a brief overview of the literature on LOP, highlighting the different versions of LOP and the typical empirical tests. In section 3, I develop the two-stage empirical approach. Section 4 outlines the data on historical Berlin. Section 5 gives the results of the hedonic price estimation and unit root tests, and section 6 concludes.

2 The Law of One Price

In this section I provide a brief outline the law of one price and its interpretations. In particular, I highlight that long-run LOP implies that price differences across locations will exhibit convergence. In the *absolute* version of LOP, the convergence will be to zero and under *Relative*-LOP the convergence is to a non-zero constant, i.e. there exists a fixed price difference between locations. Both versions imply that price differences between locations will be stationary which lends itself conveniently to empirical testing via a unit root test. This section provides just sufficient detail on the law for understanding the approach taken in this paper.

The strong, or short-run, version of LOP is the most literal translation of the law and requires instantaneous elimination of price differences between locations. This implies that prices must

[1] For intra-urban models see Alonso, 1964; Brueckner, 1987; Mills, 1969; Muth, 1969 and for systems of cities see Albouy, 2009; Roback, 1982.
[2] Some examples of the amenities literature are Black, 1999; Chay & Greenstone, 2005; Linden & Rockoff, 2008.
[3] These studies are reviewed in the next section on the law of one price.

be equal across locations at all times. The early empirical literature focussed on testing strong LOP by examining price differences of homogenous goods across countries (e.g. Frenkel, 1980; Isard, 1977; Krugman, 1978; Protopapadakis & Stoll, 1983; Richardson, 1978). This literature used regressions of the log of prices in a home country against the log of prices in a foreign country and the exchange rate. Generally, though, the law performed badly and the null hypothesis that the coefficient on foreign prices is equal to one (i.e. that LOP holds) was usually rejected. Confronted with this poor performance, the next wave of empirical literature examined whether LOP held in the long run (e.g. Frankel, 1986; Hakkio, 1984; Jenkins & Snaith, 2005; Rogers & Jenkins, 1993). This less-strict interpretation (the weak version of LOP) allows for price differences to exist, but states that they cannot persist in the long-run. Price differences are not necessarily eliminated immediately since there are transportation, information and transaction costs that may inhibit arbitrage (Engel & Rogers, 1994; Parsley & Wei, 1996, 2001). But large price differences are likely to be the subject of arbitrage, entailing convergence of price differences to an 'attractor equilibrium'. Therefore, this wave of literature focuses on testing for the existence of convergence through the application of unit root tests.[4] Most recently, tests of LOP have found strong support for price convergence using panel unit root tests on the price differences for homogenous goods across numerous countries (e.g. Blander & Dhaene, 2012; Funke & Koske, 2008; Goldberg & Verboven, 2004, 2005; Parsley & Wei, 1996).[5] The test provided by Blander and Dhaene (2012) is of particular relevance to this paper, since it is suitable for short panels. This is the test I will use in the empirical section.

As discussed above, weak-LOP suggests that prices differences between locations will not persist in the long-run and will, therefore, exhibit stationarity. Stationary series, however, do not necessarily converge to a mean of zero. The literature on Relative-LOP provides some reasons why there may exist a persistent and constant price difference between locations. For example, Goldberg and Verboven (2005) suggest differences in trade policies, local distribution costs, or elasticities of demand may lead to the possibility of constant price difference between locations. For example with local distribution costs, the price differences should converge to a constant that is equal to the difference in distribution costs between the locations. Therefore, Absolute-LOP is defined as a stationary price series that converges to a mean of zero and Relative-LOP is convergence to a non-zero constant.

[4] The methods of co-integration and error-correction have also been used in the LOP literature but are less common. See Froot and Rogoff (1996) for a detailed comparison of the different methods

[5] There is also a literature that tries to test for price convergence for heterogeneous goods e.g. Spreen, Kilmer, & Pitta, 2007.

Before going on to the next section, it worth considering for a moment which of these versions of LOP is likely to be relevant to the context of hedonic prices in an urban context. Whilst short-run LOP has not received great support in cross-country tests, it is possible that it there are fewer frictional costs to arbitrage in an intra-city context. Information should flow fairly quickly over such short distances. Transportation, in terms of individuals moving between urban locations, on the other hand, represents an entirely different cost structure to the cross country transportation of goods and it is difficult to suppose which is more or less costly. Finally, there may be transaction costs in the form of rental contracts, zoning restrictions and regulation. Overall, it seems plausible that either the short-run or the long-run version may hold for hedonic prices.

3 Empirical Analysis: testing for mean reversion in hedonic price differences

3.1 The first stage: estimating the hedonic price of rail access

Stage one of my empirical strategy is estimate hedonic prices of rail access that vary across neighbourhoods and time as follows:

$$\ln LV_{int} = \alpha_{nt} + \beta_{nt} \ln SDENS_{int} + \delta_{\mathrm{nt}} X'_{int} + \varepsilon_{int} \tag{1}$$

where $\ln LV_{int}$ represents logged land values for land plot *i*, neighbourhood *n* and time period *t*, $\ln SDENS_{int}$ is a logged station density measure that captures rail access, X_{int} are the control variables, and α_{nt} are individual neighbourhood-year effect. The land values, station density measure, control variables and neighbourhood definition are described in more detail in the data section below. The scale-invariant log-log form delivers elasticities and is standard in the literature (e.g. Ahlfeldt, Nitsch, & Wendland 2016).

The coefficients β_{nt} are neighbourhood-year varying estimates of the hedonic price of rail access. They are estimated by creating neighbourhood-year indicator variables and interacting them with the rail access variable. The resulting rail access estimates are an $N \times T$ matrix of hedonic prices where N is the number of neighbourhoods and $T = 6$ is the number of time periods. A similar approach is taken for the vector of control variable estimates δ_{nt} – although these won't be used for testing for convergence since they are not time-varying themselves. Finally, α_{mt} is intended to capture both neighbourhood level time-varying unobservables.

Identification of the neighbourhood-year specific hedonic prices of rail access in equation (1) assumes that the unobserved determinants of land value are uncorrelated with station density. The variables in X_{int} control for some of the major sources of correlation between station density and land values. Firstly, land values may be high in more central locations since agglomeration economies increase productivity in those locations. Therefore, I control for both the effect on land values of distance to the central business district (CBD) and distance to the city's important secondary centre (Kurfürstendamm). I include distance to the CBD as a polynomial to capture a potential non-linear relationship. Secondly, amenities that positively impact on land values may be clustered in locations where rail access is greater. For example, Berlin has a river running through its centre and a large park in between its central and secondary business districts. Therefore, I control for distance to the nearest greenspace and distance to the nearest water body. Finally, disamenities may also be correlated with rail access and impact on land values. Most obviously there may be a direct dis-amenity value from the transport infrastructure itself. Ahlfeldt, Nitsch, & Wendland (2016) highlight the importance of train noise as a disamenity associated with rail lines running through the city. Given that the majority of rail lines in the period ran overground, I control for distance to the track and the squared distance to track.[6] These control variables are described in the data section.

Despite inclusion of these control variables, the estimates may be biased by unobserved factors that impact on both rail access and land values. A major source of these is reverse causality. It could be that the high land values represents economic development that *leads to* rail access rather than the other way around. However, the historical context provides an advantage in that, while it is difficult to collect as comprehensive a dataset of controls as for modern cases, there is a greater likelihood that transport developments represent execution of a 'grand plan'. This means that transport is more likely to be relatively exogenous compared with modern, more incremental improvement that are likely to be responding to demand. Ahlfeldt, Moeller & Wendland (2014) examine exactly this possibility using a method that allows for bi-directional causality between land values and rail access for the same historical period in Berlin. Whilst they find that causality runs in both directions, they confirm that the impact of land values on rail access is significantly smaller in magnitude. They estimate that the impact of rail access on land values is nearly double the size of the impact in the reverse direction. They suggest that this is likely because rail access over the period was the result of complex planning and politics. Overall, the evidence suggests that, although rail improvements is this context were not completely exogenous, the larger part of their effects result from exogenous variation.

[6] I do not use wages as a control variable since these are assumed to be a city level factor available to all residents. This is a common simplification in within-city analysis in urban economics.

Given the nature of my study, a certain degree of endogeneity may be considered acceptable. This is partly because the historical period makes it difficult to create as comprehensive a dataset of controls as might be available using modern data.[7] But the main reason is that my study does not aim to evaluate the magnitude of the impact of rail access on land values, per se, but to examine whether the LOP holds for the hedonic price of rail access. This means that estimating the hedonic price is only a means and not the ends of the analysis. If there is a bias in the hedonic price, it only becomes a problem to the extent that it invalidates the unit root test in the second stage. Such a bias could result in a false positive in the unit root test if the bias is itself mean-reverting and represents a major proportion of the estimates. However, this seems unlikely given the evidence discussed above that suggests the endogenous part of the relationship is a smaller effect than the exogenous part, and given that there seems to be no particular theoretical reason why the bias would be mean-reverting. Therefore, if the actual hedonic price differences were in fact not mean-reverting, then they would be unlikely to become mean-reverting simply due to a bias in the estimation.

Following the conventional approach from the LOP literature I generate price differences from a reference location i.e. $q_{nt} = e^{\beta_{nt}} - e^{\beta_{ref,t}}$. Since the hedonic prices are in elasticity form, the exponential gives the effect of station density on logged land values. This is equivalent to the logged hedonic prices and, therefore, consistent with the standard in the literature of testing for a unit root in logged price differentials. In order to demonstrate robustness with respect to choice of base neighbourhoods, I will conduct the multiple unit roots test, changing the reference neighbourhood each time until all neighbourhoods have served as the reference.

3.2 The second stage: panel unit root test

In the second stage of I proceed to test the estimated matrix of hedonic prices for compliance with LOP. To do this I test the matrix of estimated price differences q_{nt} stationarity using the unit root test described by Blander and Dhaene (2012):

$$q_{nt} = \alpha_n + \varphi q_{nt-1} + \rho \Delta q_{nt-1} + \varepsilon_{nt} \tag{2}$$

where the null hypothesis is $\varphi = 1$, that the price differences have a unit root and that LOP does not hold. A rejection of this null hypothesis implies that q_{nt} exhibits convergence and that LOP holds. If the constant terms α_n are zero then absolute LOP holds and if they are positive and

[7] The decision to focus on the historical context is motivated by the need to have a barrage of shocks in order to test the process of interest. Furthermore, as discussed, the given the greater likelihood of exogeneity in the historical context it does hold some advantage over modern cases.

significant then relative LOP holds. This test also incorporates a single lagged difference (with parameter ρ) and is hence the panel equivalent of an ADF(1) test. This allows for AR(1) error terms. The Blander-Dhaene test exhibits strong properties for short panels and is therefore suitable for a dataset with only 6 time periods. The authors also note that results using panel unit root tests are sensitive to the choice of reference location when calculating price differences. Therefore I will conduct the analysis using every location as a reference location once.

4 Data: historical Berlin

Local shocks to amenities are a source of possible violations of spatial equilibrium. Therefore in order to test for the existence of potential adjustment processes it is helpful to examine a period in with many local shocks. I use a unique dataset that covers historical Berlin between 1890 and 1914. This is a period characterised by significant change, including a population growth (almost doubled between 1880 and 1912), large transport infrastructure projects and large changes in the structure of land use. These dynamic factors mean that the utility of land at different locations will be subject to an almost continual battery of 'shocks' requiring constant adjustment in land values in order to maintain spatial equilibrium. This makes it a very appropriate case study with which to examine the existence and speed of convergence.

4.1 Land values

Land values are the dependent variable in the first stage of the analysis and allow for the estimation of the hedonic prices of rail access. Land values are given at the plot level for Berlin for 6 time periods (approximately every 5 years) between 1890 and 1914. This land value dataset was produced by the renowned technician Gustav Müller under the imperial valuation law or *Reichsbewertungsgesetz* of the German Reich. This law includes the strict direction to use capital values for assessing the pure value of land plots based on the fair market price. Müller's values adjust for all structural building and garden characteristics as well as plot specificities such as soil properties, courtyards and whether it is a corner lot. The data were produced in order to serve as official guides to private and public investors into Berlin's real estate market.

The Berlin land values dataset can be compared to the *Olcott's Blue Book of Land Values for Chicago* which is well known in the field of urban economics and has helped Chicago to become a unique laboratory for testing theories of urban economics (McDonald & McMillen, 1990; McMillen, 1996). The Berlin data, like the Olcott values, are available as highly detailed maps.

Figure 1: Section of land values (1914)

They have also contributed to historical Berlin becoming somewhat of a laboratory of its own. Previous research has used these data to estimate the changing land gradient (Ahlfeldt & Wendland, 2011), valuing transport innovations (Ahlfeldt, Nitsch, & Wendland, 2016; Ahlfeldt & Wendland, 2009) and exploring the role of agglomeration economies (Ahlfeldt & Wendland, 2013). Due to the rapid growth of the city over this period and restructuring of the patterns of land use, the land values are originally an unbalanced panel. From this I took the maximum possible balanced panel resulting in a dataset of 31,790 observations per time period that covers approx. 75 km^2 of land area and 1,758 city blocks. Figure 1 shows these land values for a small section of Berlin in 1914.

4.2 Quasi-Neighbourhoods

In order to estimate the hedonic price over time in each neighbourhood in the city I define a set of arbitrary grid-neighbourhoods called quasi-neighbourhoods. The reason I define arbitrary grids rather than using administrative unit is so that I can flexibly vary neighbourhood size (an therefore number) in order to vary the width of the resulting panel of hedonic price differences. A wider panel (more neighbourhoods) will increase the power of the panel unit root tests on these price differences. However, a wider panel requires reducing the size of neighbourhoods used to estimate the hedonic price of rail access leading to less precise estimates. In order to demonstrate robustness in the face of this trade-off, I define quasi-neighbourhoods of different sizes. First I define an 8×16 grid to create 128 grids cells in abstract space. These grid cells are laid over the land value sample as illustrated in Figure 2. In the first neighbourhood definition, these grid cells are divided between two areas by a vertical line as illustrated in Figure 2 by the thick line labelled '2'. In this two-neighbourhood definition, the 64 grid cells to the west of the dividing line make up Neighbourhood 1 and the 64 to the east are Neighbourhood 2. In order to generate the four-neighbourhood definition, I draw an additional (horizontal) line, marked by '4' in Figure 2. The resulting definitions are shown in Figure 3(a) and Figure 3(b). This procedure is repeated for 8, 16, 32 and 64 neighbourhoods. It is apparent however, that some of the neighbourhoods in some of these definitions will have very few observations or even none within their boundaries. This is problematic for the estimation of hedonic prices within these zones and the following solution is implemented. If the number of observations in one neighbourhood is less than a third of the mean number of observation across all neighbourhoods, then it is merged with an adjacent neighbourhood. An example of this is illustrated in Figure 5 where the first and second neighbourhoods have been merged into Neighbourhood 1. Therefore, what was initially Neighbourhood 3 now becomes Neighbourhood 2, and so on such that the original eight neighbourhoods collapse to seven. Due to this merging criterion the final neighbourhood definitions are characterised by 2, 4, 7, 13, 26 and 47 neighbourhoods instead of 2, 4, 8, 16, 32 and 64 respectively.

Figure 2: Quasi-neighbourhood dividing lines

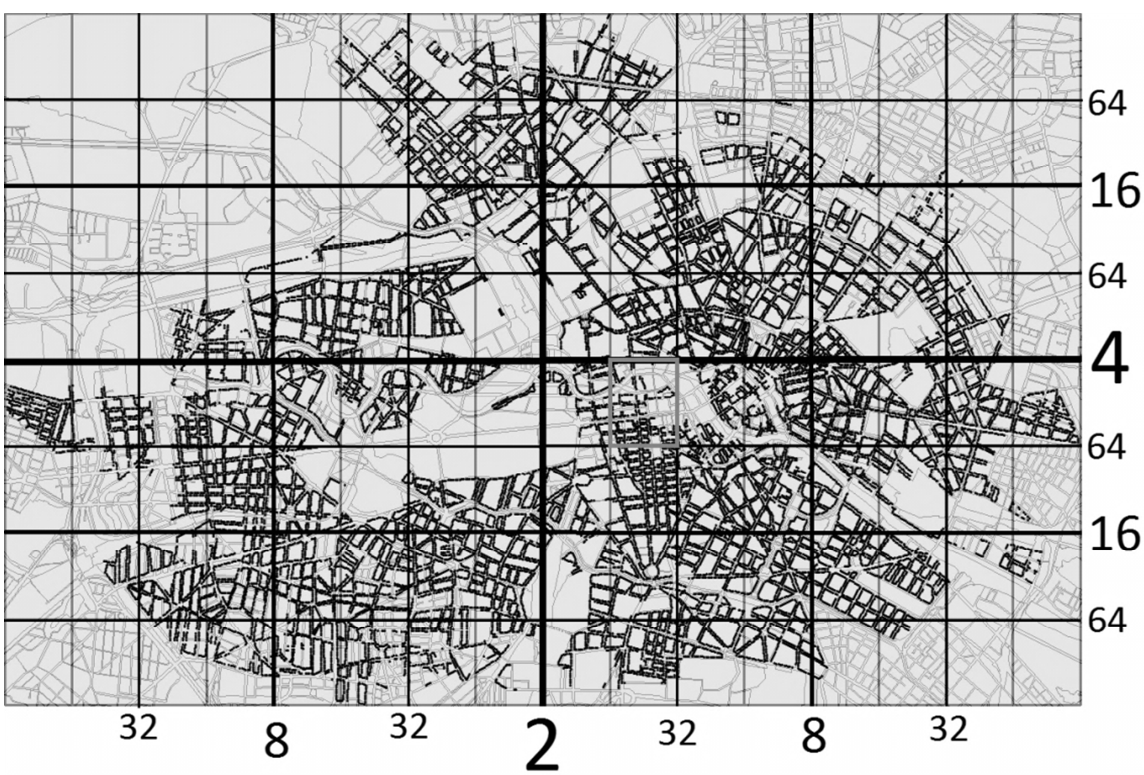


Figure 3: Quasi-neighbourhoods with N = 2 and N = 4

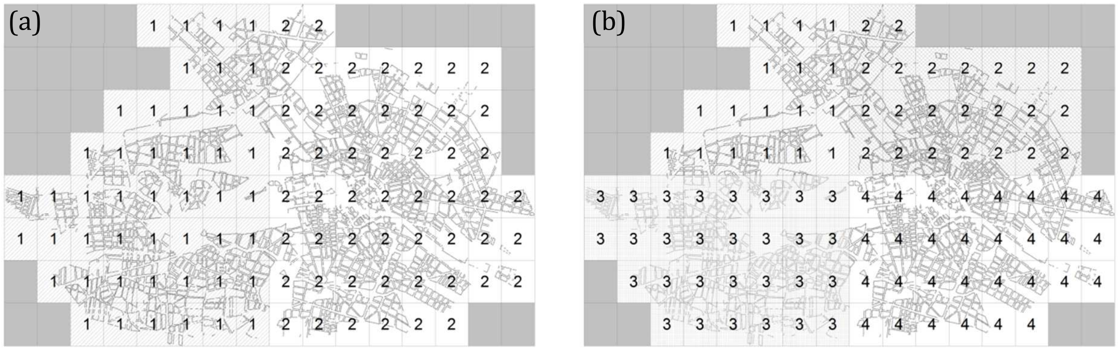
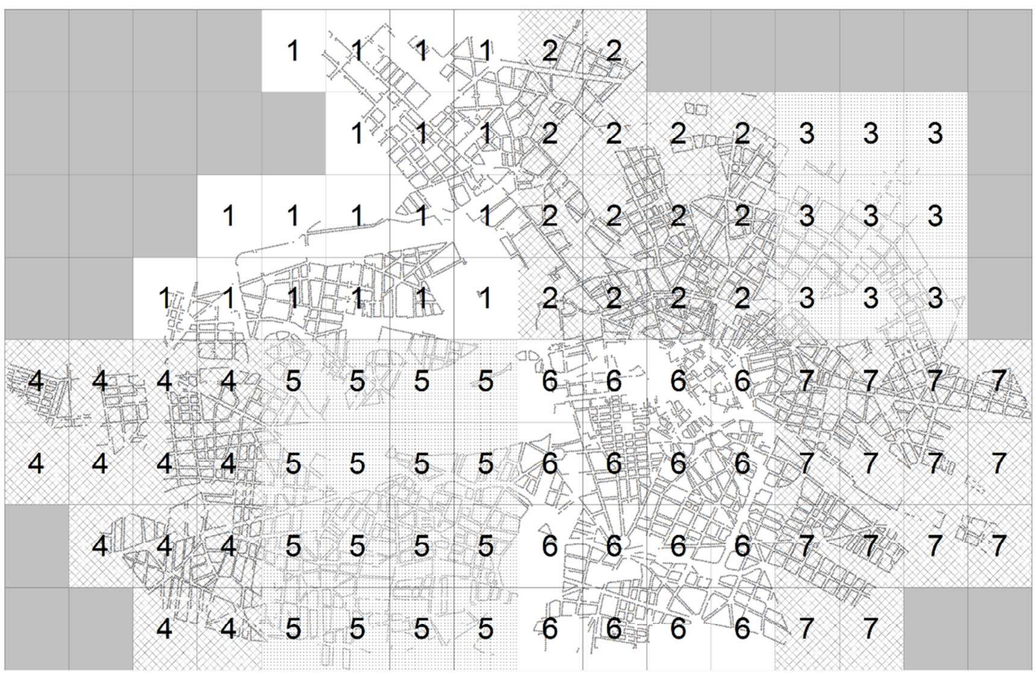


Figure 4: Quasi-neighbourhoods (merging example)



4.3 Rail access

Rail access is the variable of interest and the amenity for which I estimate the hedonic prices. I capture rail access by a measure of station density. The station locations are obtained from a combination of network plans and information on the historical development of the networks such as construction dates[8]. Thus, the urban rail network for Berlin was reconstructed historically for each of the 6 observation time periods in order to compute the time-variant station density variable.

The station density measure is a kernel density function generated in ArcGIS. The procedure involves fitting a smoothly curved surface a kernel around each point (station). The surface is at its highest where the station is located and moving away declines to height of zero at the specified search radius, which I define as the typically assumed maximum walking distance of 2km (Gibbons & Machin, 2005). The precise formulation of the kernel used by ArcGIS is given by the quadratic function described by Silverman (1986), p. 76, equation 4.5. The volume under the kernel for each station is equal to one. The kernel density is calculated for each land value observation as the sum of the individual kernel surfaces where they overlay that plot.

Figure 5 shows the development over the period of the mean of station density across the land value observations. The station density increases in every period, however, the largest increases are in the post-1900 period, with the single largest increase occurring between 1900 and 1904. Figure 6 shows transport network and the kernel density measures in relation to the land value plots for 1890 and 1914. There is clearly a large development of the network over the period I study, particularly in the inner-city neighbourhoods. In fact the total number of stations in Greater Berlin increased from 65 to 155 over this period. This point is also clear from the scale used to display station density in 1890 (from 0 to 0.68) compared with 1914 (from 0 to 2.45).

4.4 Control variables

In order to gain estimates of the hedonic price of rail access that are as unbiased as possible I use control variables for other urban amenities. The control variables area as follows: distance to nearest green space, distance to nearest water body, distance to the central business district, distance to the secondary centre in west Berlin, Kurfürstendamm, and to capture the disamenity of noise, distance to overground track. These distance measures are calculated for each land value plot in ArcGIS. Distance to track is calculated for each observation period, whilst the other controls are time invariant measures. Table 1 provide summary statistics of all the variables discussed in this data section.

8 This information can be found at the following websites: http://www.bahnstrecken.de/indexf.htm, http://www.bahnstrecken.de/bse.htm, http://berlineruntergrundbahn.de, www.stadtschnellbahn-berlin.de, and www.berlinerverkehr.de.

Table 1: Descriptive statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
Land values (RM)					
Land value in 1890	31,790	128.9	177.4	3	2,000
Land value in 1896	31,790	173.4	216.8	5	2,100
Land value in 1900	31,790	212.5	250.0	5	2,120
Land value in 1904	31,790	246.3	276.1	3	2,150
Land value in 1910	31,790	300.5	333.9	3	2,250
Land value in 1914	31,790	300.1	332.5	21	2,750
Station density (kernel)					
Station density in 1890	31,790	0.24	0.16	0	0.66
Station density in 1896	31,790	0.29	0.15	0	0.66
Station density in 1900	31,790	0.31	0.15	0	0.66
Station density in 1904	31,790	0.51	0.29	0	1.47
Station density in 1910	31,790	0.66	0.37	0	1.65
Station density in 1914	31,790	0.82	0.43	0	1.77
Distance controls (km) – no time variation					
Distance to Greenspace	31,790	0.25	0.17	0	1.07
Distance to Water	31,790	0.81	0.62	0	3.01
Distance to CBD	31,790	3.60	1.63	0	8.34
Distance to Kurfürstendamm	31,790	4.30	2.14	0	9.32

Note: Max station density for land value plots differs from max station density for corresponding year in Figure 6 because the figure shows station density over space, where there may not be any plots.

Figure 5: Station density (mean of observations)

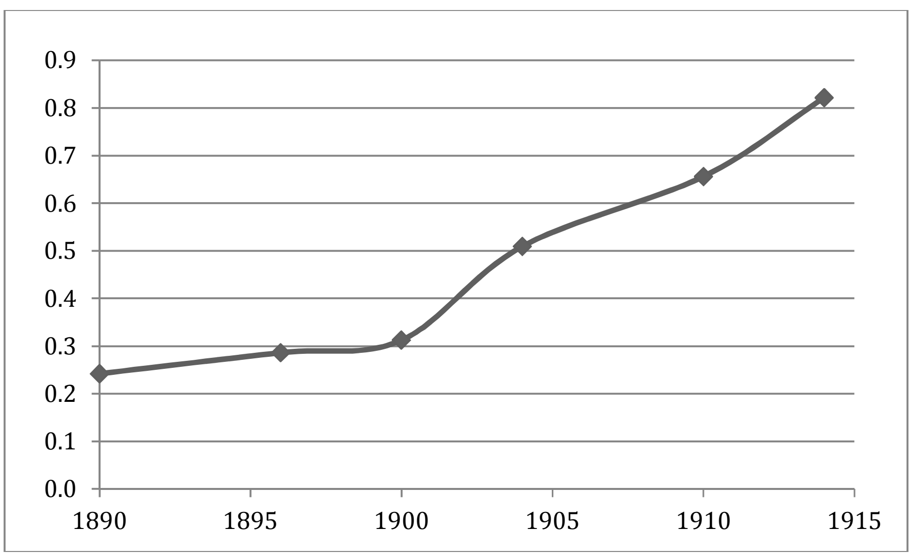
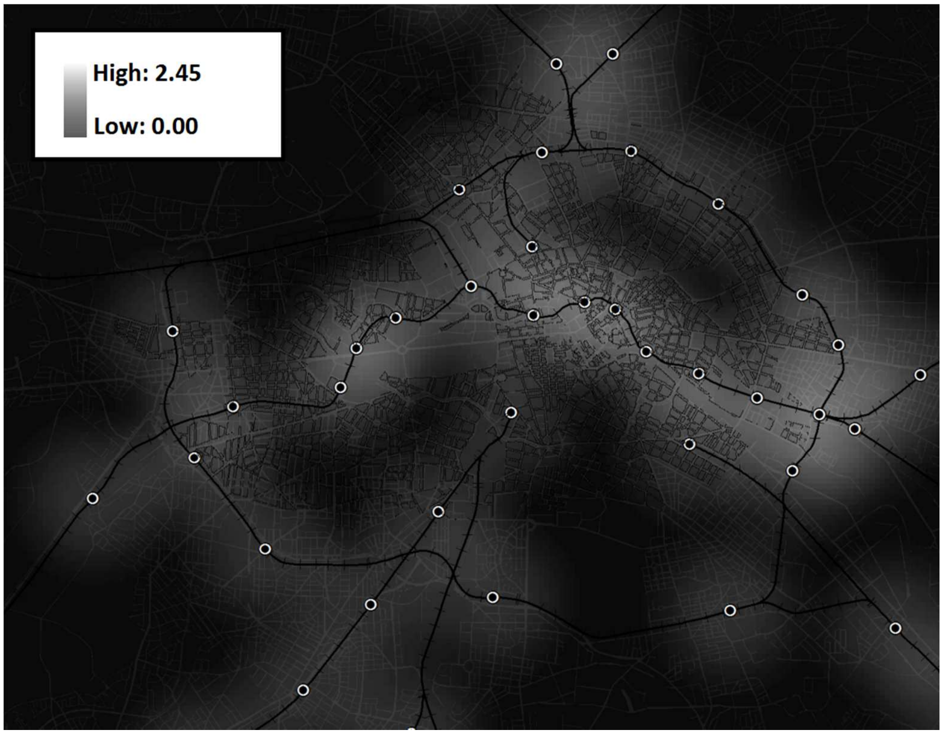
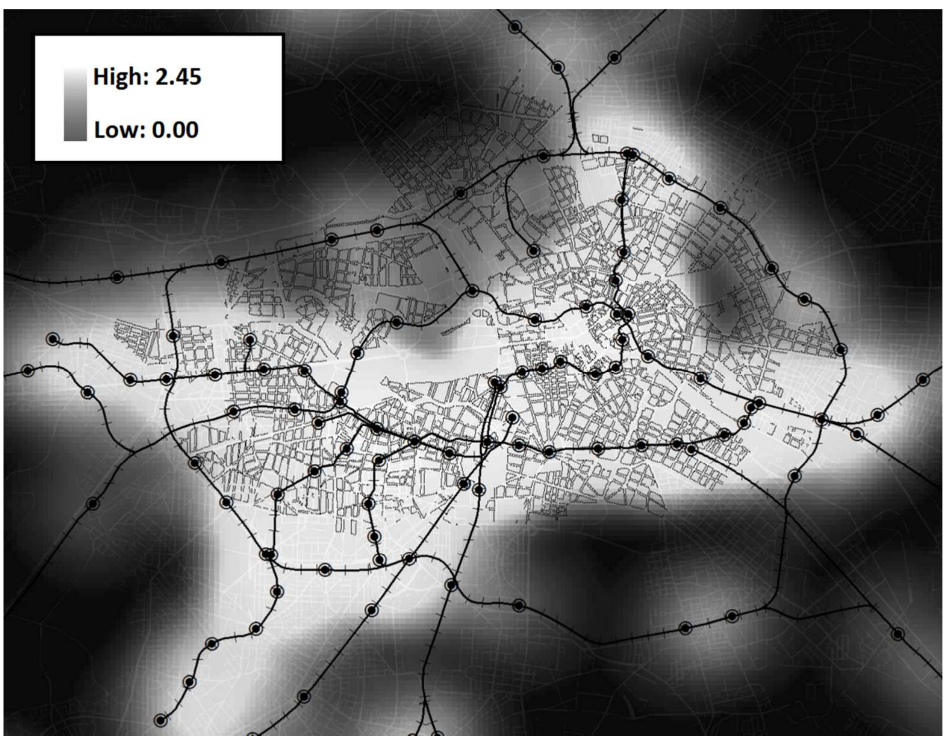


Figure 6: Station kernel density in 1890 (top) and 1914 (bottom)





5 Results

5.1 Stage one: hedonic price estimates

In column (1) of Table 2 I present the results of estimating equation (1) for a single neighbourhood (i.e. $N = 1$). Station density is interacted with year effects and the corresponding coefficients indicate the hedonic price evolution for the whole of Berlin. It is apparent that there is a positive amenity value to station density, which in the initial period (1890) has a coefficient of 0.916 and is significant at the 1% level. The interactions with year effects indicate that the hedonic price is higher in the next two periods compared with the initial period, and lower for the remaining three periods. Since the dependent variable is the log of land values, the coefficient can be interpreted as an elasticity. A one percent increase in station density is therefore associated with a 0.916% increase in land value in 1890. The size of this coefficient is not entirely surprising given that rail access was scarce in that time period. It is natural therefore that it should be associated with a large response.

I also report the coefficients for the control variables, although only for 1890 to save space. Distance to green space (-0.537, or 71% per km) and distance to water bodies (-0.144, or 15% per km) are found to be amenities that capitalise into land values. Distance to track, which is intended to capture the effect of rail noise, has a positive coefficient of 0.452 (57% per km) indicating that it is indeed a disamenity. The squared term highlights that the disamenity effect is non-linear and decreases to zero at a distance of about 2km. The coefficient for distance to CBD in 1890 is -0.965, which is interpreted as a 162% decrease in land values per km further from the CBD. Whilst this seems fairly steep it is roughly in line with other estimates of CBD gradients in historical contexts (Ahlfeldt & Wendland, 2011 provide a summary). Furthermore, the positive coefficient on the squared distance from the CBD suggests this gradient gets flatter further out. The distance to Kurfürstendamm (*Ku'damm* for short) captures the amenity effect associated with proximity to the Berlin's most important subcentre. The coefficient of 0.05 has the opposite sign to what is expected in the one-neighbourhood case probably due to significant non-linearities not captured by the binomial. However, in the two-neighbourhood case the first neighbourhood, in which Ku'damm is located, has the expected signs. Here the coefficient implies a decrease in land values of 69% per km, and the squared term suggests that this effect flattens to zero at around 5km of distance.

Table 2: Hedonic estimates of price of transport accessibility

	(1)	(2)	
		n=1	n=2
Log station density x 1890	0.916***	1.205***	1.174***
	(0.029)	(0.051)	(0.039)
Log station density x 1896	1.264***	2.009***	1.227***
	(0.035)	(0.066)	(0.042)
Log station density x 1900	1.054***	0.578***	1.318***
	(0.033)	(0.053)	(0.042)
Log station density x 1904	0.130***	0.340***	-0.188***
	(0.015)	(0.032)	(0.019)
Log station density x 1910	0.364***	0.529***	0.059***
	(0.014)	(0.021)	(0.019)
Log station density x 1914	0.256***	0.381***	0.076***
	(0.011)	(0.023)	(0.017)
Distance to green space x 1890	-0.537***	-0.227***	-0.335***
	(0.018)	(0.026)	(0.025)
Distance to water body x 1890	-0.144***	-0.533***	-0.028***
	(0.006)	(0.011)	(0.007)
Distance to track x 1890	0.452***	0.410***	0.767***
	(0.018)	(0.027)	(0.023)
Distance to track squared x 1890	-0.223***	-0.351***	-0.280***
	(0.008)	(0.013)	(0.010)
Distance to CBD x 1890	-0.936***	-2.047***	0.014***
	(0.008)	(0.016)	(0.002)
Distance to CBD squared x 1890	0.054***	0.173***	0.173***
	(0.001)	(0.002)	(0.002)
Distance to Ku'damm x 1890	0.104***	-0.526***	0.221***
	(0.006)	(0.014)	(0.020)
Distance to Ku'damm squared x 1890	-0.007***	0.101***	0.101***
	(0.001)	(0.002)	(0.002)
Observations	190,740	190,740	
R^2	0.77	0.80	

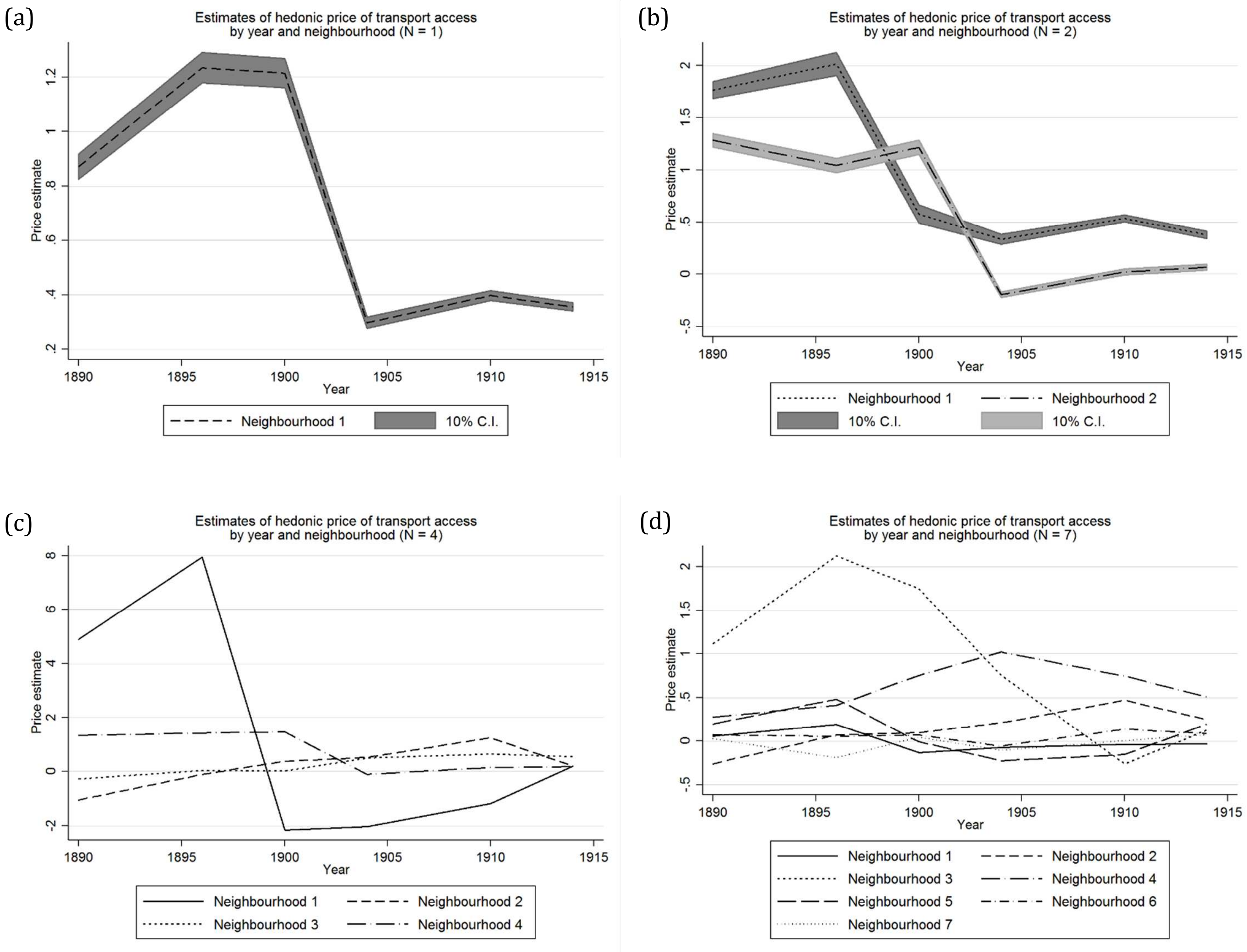
Dependent variable is logged land value. The second model shows coefficients from the two-neighbourhood case, estimated in the same specification, where the n=1 column displays coefficients that are interacted with the first neighbourhood dummy and the n=2 column with the second neighbourhood dummy. Only the 1890 control variable interactions are shown here to save space. Standard errors in parentheses.
* p<0.1, ** p<0.05, *** p<0.01

Next I estimate hedonic prices of rail access that vary by neighbourhoods. I begin with the neighbourhood definition that comprises two neighbourhoods ($N = 2$). The results of this specification are presented in column (3). The estimates are divided into two columns where the coefficients in column (3: n=1) represent estimates for Neighbourhood 1 and (3: n=2) for Neighbourhood 2. I then estimate the model in a similar fashion for more numerous neighbourhoods. In order to save space the hedonic prices for versions with numerous neighbourhoods are not reported as tables. Instead, the estimates for 1, 2, 4 and 7 neighbourhoods are displayed in Figure 7. Quadrants (a) and (b) plots the hedonic price evolution based on estimates from the 1- and 2-neighbourhood specifications already discussed. Quadrants (c) and (d) present the hedonic price evolution for the 4- and 7-

neighbourhood specifications. Similar panels were created for 13, 26 and 47 neighbourhoods but would be too crowded to display as line plots.

Now I turn to a discussion of the evolution of hedonic prices in Figure 7. The general trend in hedonic prices is downwards, as best illustrated in the 1-neighbourhood case. In particular the hedonic price decreases most significantly in the period after 1900. A potential explanation for this is that this price decrease coincides with the period that has largest increases in station density, as illustrated in Figure 2. In the multiple neighbourhood cases, this general trend holds but with individual neighbourhoods deviating around the trend. For some individual neighbourhoods there are some periods where the hedonic price is even negative. Such a situation could occur where dramatic changes to the transport infrastructure reverse the rank of locations by their access to train stations, requiring a complete reconfiguration and land use. In such a case land values may be slow to represent new patterns of rail accessibility. On a visual inspection, no neighbourhood appears to have large and persistent deviations in hedonic price of rail access in comparison with any other neighbourhood. In the next section, I test formally if these panel datasets of hedonic prices are cointegrated.

Figure 7: Estimates of the hedonic price of rail access (N=1, 2, 4 and 7)



5.2 Stage two: unit root test of hedonic price differences

I estimate Blander and Dhaene's unit root test for price differences according to equation (2). The results of these tests for various neighbourhood sizes are illustrated in Figure 8 and Figure 9. Figure 8 illustrates the estimates for the unit root parameter φ and whether the null hypothesis ($\varphi = 1$) can be rejected at the 5% level. In each figure, the first unit root parameter is for the hedonic price series itself (not price differences) and this is always shown to be non-stationary[9]. The remaining estimates are based on the panel unit root test of price differences, but in each case changing the reference neighbourhood. This ensures that the results are not artefact of the choice of reference neighbourhood. For example, with $N = 4$, Figure 8(a) shows that in each case the null of non-stationarity is rejected in favour of convergence to LOP. This is indicated by the fact that the top of the bar (5% confidence band) around the point (phi estimate) falls underneath the dotted line at $\varphi = 1$. The remaining charts of Figure 8 indicate that, the unit root is rejected for all neighbourhood sizes. Only in one case, is there dependence on the choice of base neighbourhood. In Figure 8(c) ($N = 13$) I fail to reject a unit root when Neighbourhood 8 is chosen as the base neighbourhood. However the vast majority of the evidence is in favour of convergence to LOP. A half-life can be computed from the phi estimate to give an idea of the speed of convergence[10]. If I average the phi estimates from models with different reference neighbourhoods then the half-life is calculated to be 1.14 years when there are four neighbourhoods, 0.28 years for $N = 7$, 0.86 years for N=13 and 0.27 years for N=26. Overall, there appears to be no clear relationship between neighbourhood size and speed of convergence. However, notably, the shortest convergence speed is measured for the smallest neighbourhood size definition. This could reflect the fact that smaller neighbourhoods allow for the estimation of large but temporary local deviations from the equilibrium, which are quickly eliminated.

Finally I aim to distinguish between the absolute and relative versions by examining the individual fixed effects. Again I aim to obtain robust results by reporting results for every possible base location. Therefore there are $N - 1$ fixed effects for each specification and a total

9 This result is not of particular relevance to the questions posed by this paper, however, it is interesting that hedonic prices share the property of non-stationarity that is typically the case with market prices. This result also rules out the possibility of testing LOP in the short run as explained in Section 2.

10 This is calculated as $\frac{1}{2}\log(0.5)/\log(\varphi)$.

of N specifications[11]. The fixed effects coefficients are displayed in Figure 9. The x-axis indicates which neighbourhood is used the reference neighbourhood for the price differences and the y-axis indicates the neighbourhood that the reported fixed effect is for. For example in Figure 9(a), the first column of coefficients reports the individual fixed effects estimated in the unit root test of price differences when Neighbourhood 1 is used as the reference. The coefficient for Neighbourhood 2 indicates that there is a constant -1.4 difference in the hedonic price between this neighbourhood and the reference neighbourhood (1). Significant coefficients are displayed with a black bar and insignificant with grey. So whilst there are reported differences between hedonic prices across neighbourhoods, all but one of the coefficients (mirrored it is two) is statistically insignificant in the case of $N = 4$. For the other neighbourhood sizes, too, there are some instances of significant fixed effects indicating the relative version holds in some cases. In total, however, these represent only 7.7% of the cases across all specifications[12]. The overall evidence is therefore in support of the absolute version of LOP.

As discussed in the theory, I do not necessarily expect price difference to converge to zero. Even in an intra-city case there may be persistent differences in price as a result of differences in the marginal willingness to pay of individuals sorted across locations. Hence this result could merely reflect the fact that some locations have significantly different hedonic prices for rail access. On the other hand, the individual fixed effect are estimated using only a single series of price differences of only 6 time periods, hence, there is little power to reject the null of a zero coefficient. This means that in reality there may be far more instances of price differences between locations than I show statistically.

In summary, the results demonstrate that price differences are stationary in the vast majority of cases. The few instances when this is not true may be explained by poorly estimated hedonic prices, perhaps due to particular neighbourhood specific biases. It could also be that the neighbourhoods that do not exhibit convergence are somehow in reality different to the other locations. Perhaps they are subject to some regulations or rent control that means they are not adjusting flexibly to shocks to amenity levels. Overall, though, the majority of the evidence is in favour of convergence.

11 Note that the diagonal indicates the fixed effect for Neighbourhood n when Neighbourhood n is the reference and is therefore always zero since price differences from itself are always zero. All fixed effect above the diagonal mirror those below, in that they are equal and of opposite sign.

12 In total there are 33 significant constants from a possible 430 estimated across all specifications. For N=4 there is one significant individual constants. For N=7, there are 3 significant from 21 parameters. For N=13, there are 9 from 78. For N=26, there are 20 from 325.

Figure 8: Unit root parameter estimates (Blander-Dhaene) for hedonic price of rail access

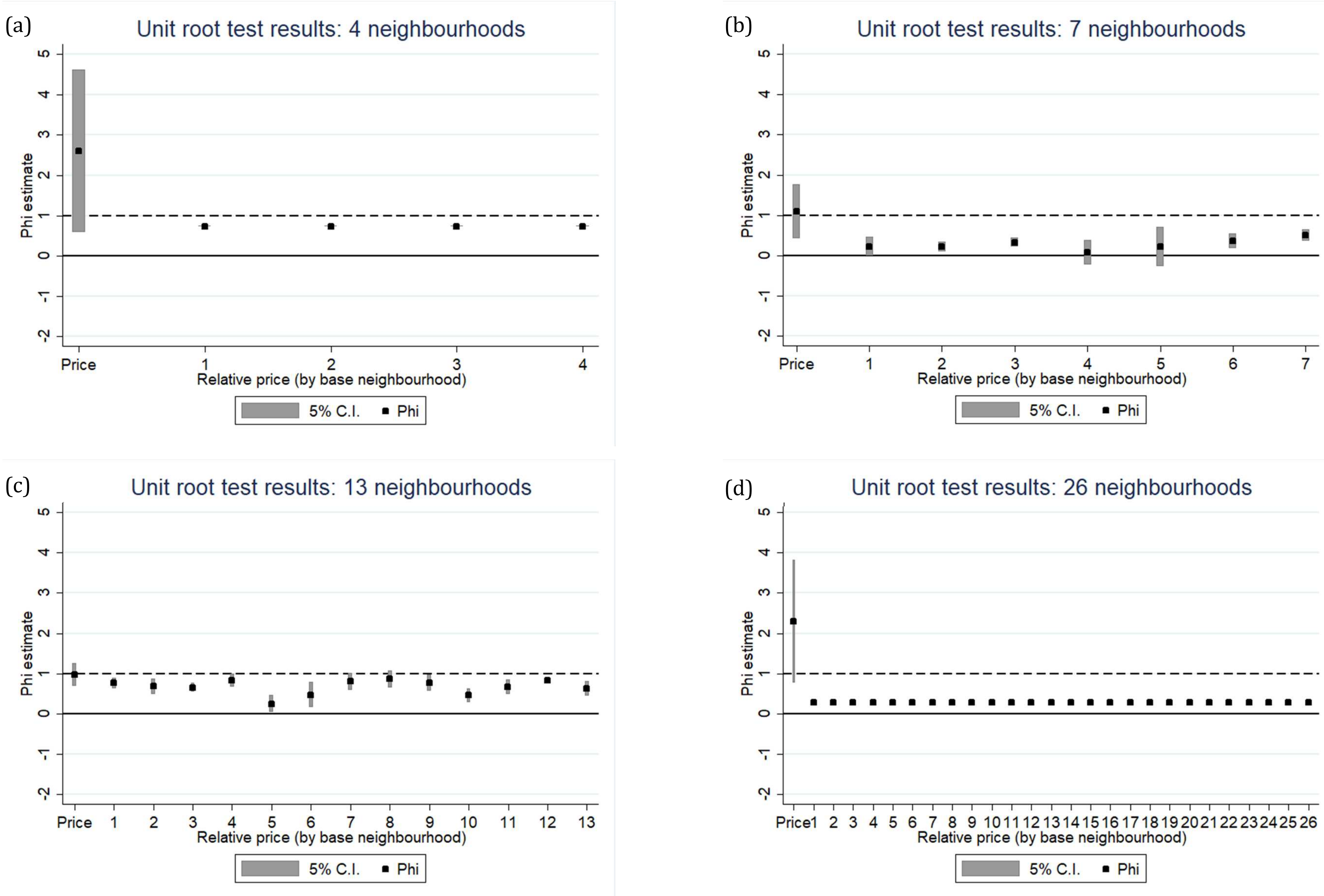
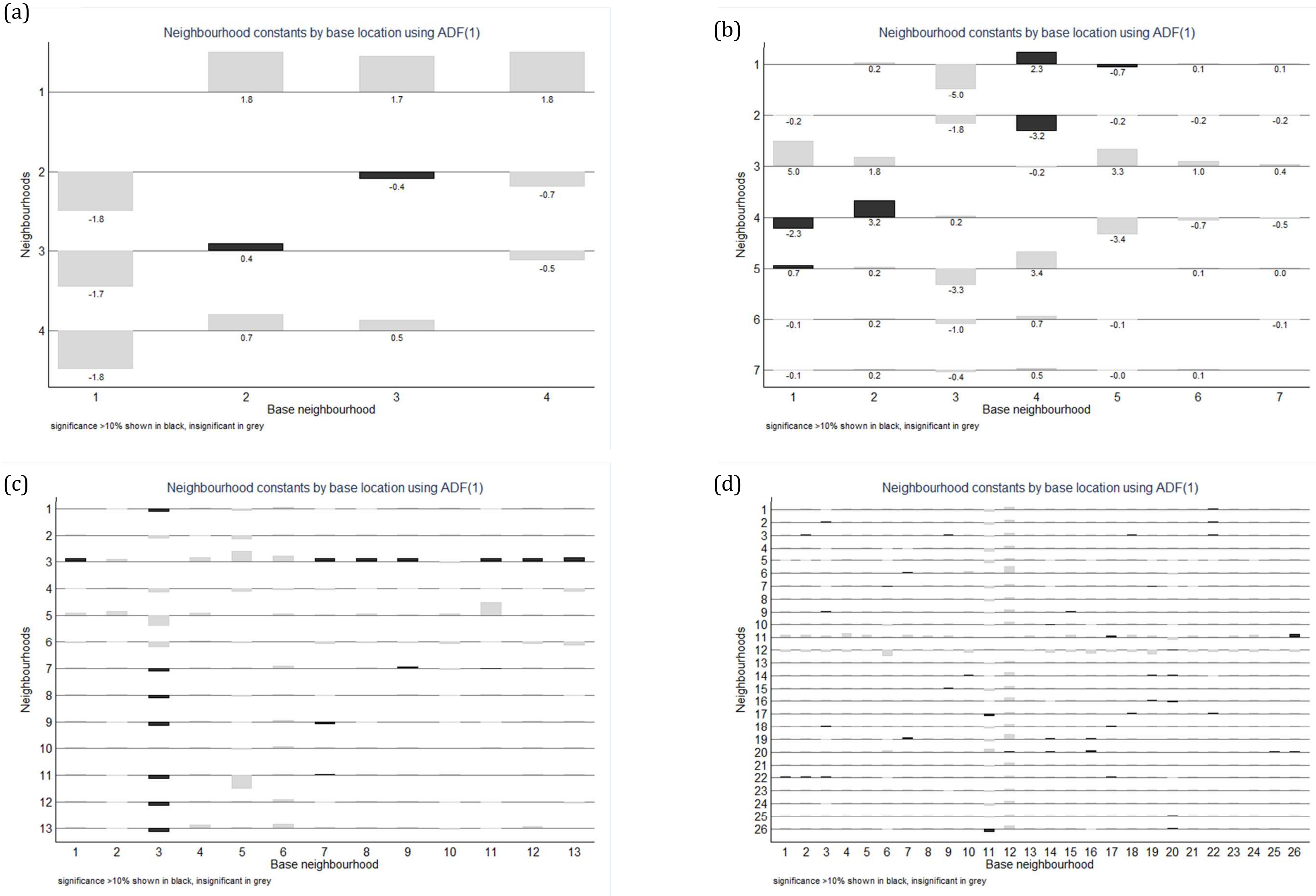


Figure 9: Individual constants from unit root test (Blander-Dhaene)



6 Summary and conclusions

This paper has asked whether the law of one price holds for hedonic prices. The literature on LOP has been reviewed for different interpretations of the law and appropriate methods and for testing whether it holds. I have highlighted that the LOP literature does not strictly require prices to be equal across location and identified the panel unit root test as the appropriate method for testing whether price differences converge across locations and for distinguishing between the relative and absolute versions of the law.

I construct a panel dataset for historical Berlin (1890-1914) that includes rare data on land values, rail access, and amenities such as green space and water bodies. In a two-step approach I use this dataset to test whether the law of one price holds for hedonic prices. In the first step I estimate a panel of hedonic prices of rail access that varies by neighbourhood and time period. In second step, I test whether price differential are mean-reverting using a unit root test that is particularly well suited to the short panel dataset at hand.

My main result is that differences in the hedonic price of rail access across different city neighbourhoods converges to the law of one price. This finding means that hedonic prices across locations are tied together in a long run equilibrium relationship. Based on the unit root parameter, the speed of convergence is estimated to be approximately 0.28—1.14 years. A secondary finding was that the individuals fixed effects from the panel unit root tests are insignificant in the majority of cases. This indicates that there is no persistent difference in hedonic prices of rail access across locations. Therefore, the findings suggest that the absolute version, rather than the relative version, of LOP holds for the within-city case for hedonic prices. The findings are robust to using neighbourhood definitions of a wide range of sizes, and to using different neighbourhood as the base neighbourhood for computing the price differentials.

The major contribution of this paper is the finding that hedonic price differences across locations exhibit convergence. This is theoretically consistent with the existence of spatial equilibrium, providing some support to the assumption and results that rely on it. There has been little or no previous research into the validity of this assumption. The approach developed in this paper could potentially be applied in other contexts in order to establish if the result generalises to different cities or time periods.

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