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Ease vs. noise: Long-run changes in the value of transport (dis)amenities[*]

Abstract: For a complete cost-benefit analysis of durable infrastructures, it is important to understand how the value of non-market goods such as transit time and environmental quality changes as incomes rise in the long-run. We use difference-in-differences and spatial differencing to estimate the land price capitalization effects of metro rail in Berlin, Germany today and a century ago. Over this period, the negative implicit hedonic price of rail noise tripled. Our results imply income elasticities of the value of noise reduction and transport access of 2.2 and 1.4, substantially exceeding cross-sectional contingent valuation estimates.

Keywords: Accessibility, spatial differencing, noise, difference-in-differences, income elasticity, land price

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1 Introduction

Understanding how the values of locational amenities and disamenities change as incomes rise is crucial for optimal decisions regarding investments with long-term consequences. A typical example are investments in transport infrastructure, which are often undertaken publicly following cost-benefit analyses (CBA). The evidence from cross-sectional survey-based contingent valuation research suggests that the income elasticity of the value of noise reduction is positive, but less than unity (Wardman et al. 2005). The value of travel time is typically set to a fraction of the wage rate (Anderson 2014; Parry & Small 2009), which implies a unity income elasticity, but a lower elasticity has been recently suggested (Börjesson et al. 2012). It is not clear, however, whether these estimated short-run elasticities generalize to long-run comparisons. Intuitively, the inter-temporal income elasticity should be larger than unity if locational amenities and disamenities are non-necessities as typically conjectured in the literature (Brueckner et al. 1999; Glaeser et al. 2001). As real incomes rise, (dis)amenity values should then rise more than proportionately, implying that in appraisals of durable infrastructures costs and benefits need to be inflated rather than deflated to reflect demand by future generations. To date, there is little evidence to substantiate this intuition. There is at best indirect evidence in that public spending tends to increase more than proportionately in GDP, suggesting that public services, broadly defined, are luxury goods (Wagner's law, see Lamartina & Zaghini 2011; Ram 1987; Wagner 1890).

In this paper, we take a step towards filling this gap by providing the first long-run comparison of transport amenity and disamenity capitalization effects in land prices over a period as long as a century. Theoretically, besides the amenity of offering improved access, there are a range of transport-related disamenities, including congestion, pollution, and noise, which can affect outcomes such as productivity, health, and annoyance levels (Navrud, 2002). Our focus on accessibility and noise effects is driven by the empirical setting we exploit. We choose to evaluate land price capitalization effects of metro rail (*U-Bahn*) in Berlin, Germany, due to the availability of historical and contemporary property data and a transport technology that has remained approximately constant since the system's inauguration in 1902. The system is fully electrified and has exclusive right-of-way, so that the effects on pollution and road congestions are rather negligible. We find little evidence for a negative view effect, so that noise from the elevated parts of the system is arguably the primary disamenity. Our property data covers commercial and residential property; therefore, our estimated capitalization effects reflect productivity and (dis)utility effects. They likely exclude health effects given that the public awareness of noise-induced health impacts is limited (Navrud, 2002). In line with the worldwide trend, real income in Germany has increased at a rate of 2% per year since 1900, accumulating to an overall increase of about 650%.[1] Our setting, thus, allows us to compare the valuation of rail access and rail noise on real estate markets in a historical low-income scenario and a contemporary high-income scenario.

Our contribution is facilitated by a rather unique combination of suitable micro-geographic data at the turns of the 19th (1881-1914) and the 20th centuries (1990-2012). For our analyses, we digitize a series of historical maps, compiled by the chartered surveyor Gustav Müller, which provide information on land prices as detailed as to the level of individual parcels.[2] We complement these historical data with a confidential contemporary micro data set covering a complete record of property transactions. With these data at hand, we estimate that over the course of the 20th century, the land price capitalization effect of a 10-decibel decrease in rail noise increased from 4.2% to 13.0%. Accounting for the increase in the share of land in the value of housing over the same period, we infer a capitalization effect in house-price terms that increased from 1% to 4%. The land price capitalization effect of a one-kilometer reduction in distance from the nearest metro rail station, a measure that captures the value of the associated walking time (Gibbons & Machin 2005), decreased from 20.2% to15.5%. However, because the land share increased substantially over the same period, this decrease implies a sizable increase, from 3.6% to 5.0%, in terms of house-price capitalization.

These results suggest that the value attached to rail access and even more so to the disamenity from rail noise has increased over time. One interpretation is that access and a quiet environment are luxury goods on which recent generations are willing to spend more as they are richer. Making admittedly strong assumptions, we use our estimated capitalization effects to derive novel estimates of the long-run income elasticities of the amenity value of accessibility and the disamenity value of noise of 1.4 and 2.2, respectively. While we acknowledge that significant uncertainty surrounds these estimates, on balance, they likely represent lower bounds.

On top of these main insights, we contribute to the literature in several more specific respects. First, we contribute to a vast literature in the tradition of Oates (1969) that has inferred the value of non-marketed goods from house price capitalization, including clean air (Chay & Greenstone 2005; Hanna 2007), health risk (Currie et al. 2015; Davis 2004), proximity to hazardous waste sites (Greenstone & Gallagher 2008) or nuclear power plants (Tanaka & Zabel 2018), crime risk (Linden & Rockoff 2008), public school quality (Cellini et al. 2010), energy efficiency (Walls et al. 2017),

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1 Own calculations using data from the Maddison Project (Bolt & van Zanden 2014). The 2% annual growth generalizes to the mean across a sample of 170 countries. See appendix section 3.1 for details.

2 To our knowledge, the only comparable historic data are from Olcott's land values blue book of Chicago and suburbs, published regularly by G. C. Olcott's & Co., Inc. from the 1910s to the 1990s. The construction of the core of Chicago's metro rail system (the L), however, precedes this period.

aircraft noise (Boes & Nüesch 2011; Ahlfeldt & Maennig 2015), road noise (Graevenitz, 2018), wind farms (Gibbons 2015) or transport access (Gibbons & Machin 2005). We add to this literature by showing that within the same spatial context, capitalization effects of the same (dis)amenities can vary sizably in the long-run due to changes in consumer preferences.

Second, we enrich a literature on rail access capitalization effects that has recently shifted from the use of cross-sectional variation to the use of variation over time to improve identification (see Dubé et al. 2013 and appendix section 2 for a review). We expand on this line of research by proposing a novel weighted difference-in-differences (DD) estimator, which minimizes the conditional correlation between pre-announcement trends in the outcome variable (land prices) and multiple continuous treatment variables (proximity to the station and rail noise). Consequently, we minimize the risk that unobserved *trends* in property prices correlated with station access or rail noise confound our estimates.

Third, we also add to a literature on noise capitalization effects that, with few exceptions concerning the analysis of aircraft noise (Ahlfeldt & Maennig 2015; Boes & Nüesch 2011), has employed cross-sectional designs. The literature on rail noise effects is particularly underdeveloped (see Navrud 2002 and appendix section 2 for a review). Our spatially highly disaggregated, micro-geographic data sets allow us to exploit the relatively sharp change in rail noise that arises where a track enters a tunnel to vanish beneath the surface, a source of variation that has not been previously exploited in the literature. The spatial differencing (SD) approach used to assess the causal effect of noise on the price of adjacent land parcels in our contemporary analyses represent an improvement in terms of identification compared to the extant literature. Our novel estimate of the effect of a one-decibel increase in rail noise on house prices of -0.4% is close to recent estimates pointing to an aircraft noise effect of -0.5% to -0.6% (Ahlfeldt & Maennig 2015; Boes & Nüesch 2011) and a road noise effect of -0.1% to -1.4% (Graevenitz, 2018; J. P. Nelson, 2008 reports a central estimate of -0.57%).

Fourth, we explicitly disentangle the positive effects of rail access from the negative effects of rail noise in a causal analysis of rail capitalization effects. Therefore, we go beyond most of the existing work that typically focuses on the aggregate (or net) effect of countervailing rail externalities. In doing so, we also examine the degree of bias that arises when accessibility effects are estimated without controlling for noise effects and vice versa.

Fifth, we provide one of the few analyses of rail capitalization effects into land prices (e.g. Ahlfeldt, Moeller, et al. 2015; Coffman & Gregson 1998), whereas most previous studies have looked at price responses of properties or housing units. The analysis of land prices comes with the advantage of not having to control for structural characteristics. In addition, because land is scarce in an urban context and provided (almost) inelastically, adjustments in land prices can be assumed to be purely driven by demand. The analysis of house price effects, in contrast, may be mitigated by supply responses if the demand curve is locally downward sloping because of imperfect mobility and idiosyncratic location preferences (Hilber & Vermeulen 2015).

Last but not least, we provide a case study which illustrates that, due to the increase in noise aversion, the case for the construction of underground metro rail as opposed to elevated metro rail is much stronger today than in the past. In doing so, we also provide novel auxiliary findings that are interesting in their own right. We estimate the per-kilometer cost of an underground metro line at the beginning of the 20th century to be three times that of an elevated line, which is substantially larger than the contemporary rule-of-thumb factor of two. We also find that, over a period of about 130 years, the average annual nominal land price growth rate was about 5% in Berlin and, therefore, typically within the range of the opportunity cost of capital (central bank interest rates).

The remainder of the paper is organized as follows. In Section 2, we discuss the context of our study, present our data, and introduce a simple theoretical framework that will guide the interpretation of the parameters we estimate. Section 3 presents the historical analysis, followed by the contemporary analysis in Section 4. In Section 5 we relate the historical and contemporary estimates to each other and discuss policy implications. Finally, Section 6 provides our conclusions.

2 Empirical and theoretical context

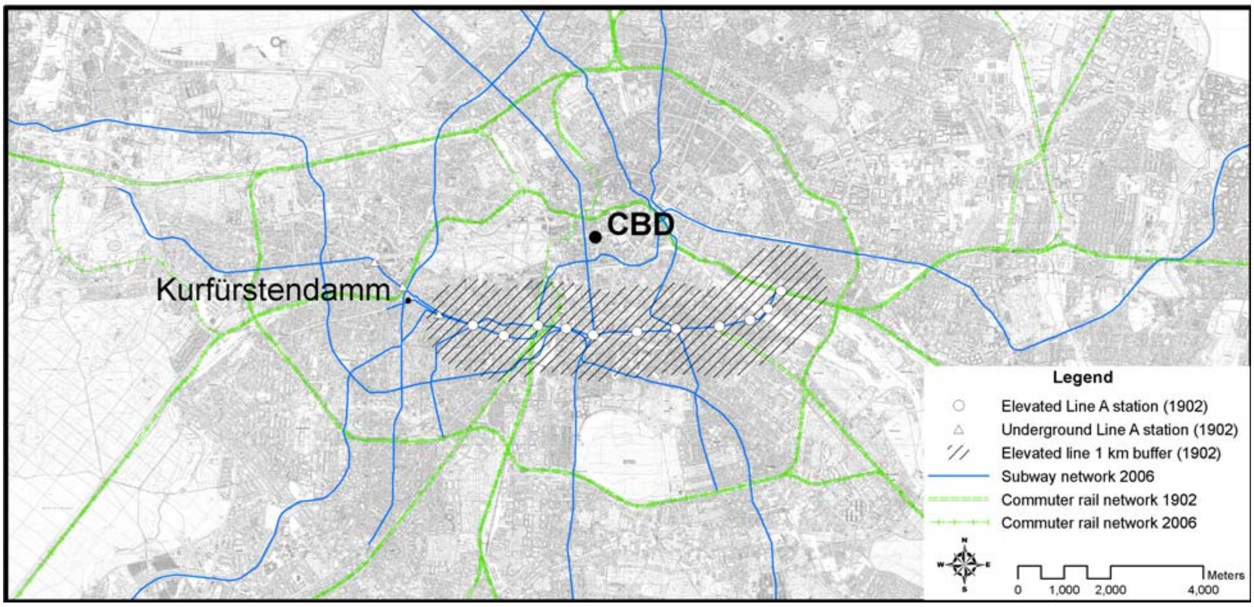
2.1 Metro rail in Berlin

In 1879, the German founder and inventor Werner von Siemens presented the first fully electrified experimental railway at the internationally renowned trade and industrial exhibition (*Gewerbeausstellung*) in Berlin. By 1891, the company Siemens & Halske had proposed a dense network of various lines to connect the inner core of "old Berlin" with its then surrounding municipalities. According to initial plans, the network was to be built entirely on elevated tracks, mainly because of strict regulation of underground activities due to construction works on the new canalization system led by James Hobrecht. In 1895, a concession was granted for the first line, which was to connect the eastern parts of Berlin, at the station Warschauer Brücke, and the wealthy western city of Charlottenburg, at the station Zoologischer Garten, running exclusively on elevated tracks. Built along one of Berlin's major boulevards this routing did not require major acquisitions of land or fundamental changes to the building structure. In 1897 (only five years before the inauguration of the line), Siemens & Halske founded the Elevated Railway Company (*Hochbahngesellschaft*) in cooperation with the Deutsche Bank to guarantee the funding.

The construction began immediately, starting from the eastern parts. However, Berlin residents increasingly expressed concerns about a viaduct's potentially unpleasant appearance. Also, Berlin's municipal planning and building control office, with its newly appointed head Friedrich Krause, was no longer generally opposed to plans for the construction of underground lines. As a result, the city of Charlottenburg managed to ensure, in a last-minute move, that the tracks ran beneath the street surface once the line reached its city boundaries. Eventually, the line was inaugurated in 1902 and called "Line A" (*Linie A* or *Stammstrecke*). The final routing negotiated between various stakeholders such as Deutsche Bank and the city of Charlottenburg was later described by historians as an outcome of agreements and accidents (Bousset 1935). The elevated section of the line consists of 11 stations, while the entire line (including the underground section) consists of 14 stations with a total length of about 10 km.

As evident from Figure 1, Line A complemented a commuter rail network consisting of various suburban lines as well as a circular line (*Ringbahn*) and an east-west connection through the CBD (*Stadtbahn*). This network was operated entirely on ground-level tracks or elevated tracks. It is comparable to today's commuter rail (*S-Bahn*) network, but the technology was different as trains were powered by steam and electrification did not start before 1924. Over time, the subway (*U-Bahn*) network was continuously expanded. Since the re-unification of the city, the combined subway and commuter rail networks comprise 475 rail km and 275 stations.

Fig. 1. Historical and contemporary geography of Berlin's metro rail network



Notes: Own illustration using the Urban Environmental Information System of the Berlin Senate Department (Senatsverwaltung für Stadtentwicklung Berlin 2006). CBD is the central business district. Kurfürstendamm is a major sub-centre.

2.2 Historical Land Prices and Contemporary Property Prices

Our main variable of interest are land prices which are extracted from various editions (1881, 1890, 1896, 1900, 1904, 1910, and 1914) of assessed land value maps for Berlin created by the renowned technician Gustav Müller in cooperation with official planning authorities. Müller's maps provide data at a remarkably disaggregated level of individual plots. The stated objective was to provide official and representative guides for both private and public investors participating in Berlin's real estate market. While Müller himself did not describe in detail the exact procedure of land valuation, the imperial valuation law (*Reichsbewertungsgesetz*) of the German Reich contained a strict order to use capital values for the assessment of commercial plots based on fair market prices. In line with the valuation laws for commercial land, Müller claims that his assessment refers to the pure value of land, which is adjusted for all building and even garden characteristics. He also corrected values for specific location characteristics such as single and double corner lots, subsoil and courtyard properties.

Müller's maps are by now an established data source. They have been used, among others, by Ahlfeldt, Moeller, et al. (2015), who also provide an extensive data appendix that describes in detail the nature of the data. More notably, the data are directly comparable to the more recent Berlin land price data (1928, 1936, 1986, 2006) used by Ahlfeldt, Redding, et al. (2015); they also share many similarities to Olcott's Chicago land values, which have been used in studies such as Ahlfeldt and McMillen (2018), Berry (1976), Kau and Sirmans (1979), McDonald and Bowman (1979), McMillen (1996), McMillen and McDonald (2002), Mills (1969), and Yeates (1965).

In contrast to previous analyses based on Müller's data, we exploit its full spatial detail at the parcel level. To preserve the highly-disaggregated nature of the original data, we digitize every single data point within a one-kilometer buffer around the newly built elevated tracks within a geographical information system (GIS) environment. After creating a balanced panel for the final analyses, this leaves us with a total of about 38,000 observations for seven points in time.

For the contemporary analyses we utilize a confidential data set, which is the same as in Ahlfeldt & Maennig (2015), containing detailed information on more than 70,000 transactions of buildings (single-family and multi-family) and the corresponding land parcels and including features such as price, transaction date, location, and a set of parameters describing building/plot characteristics. The data were obtained from the Committee of Valuation Experts Berlin (*Gutachterausschuss Berlin*). The transactions are geo-referenced (addresses and x/y coordinates), which allows them to be integrated into a GIS environment. The building characteristics include floor space, parcel area, age, land use, quality of the building stock, location within a block of houses (e.g., a corner lot), and several other amenities like basements, elevators, etc.

2.3 Rail noise

To translate the typically volatile levels of rail noise into a standardized summary statistic, engineers compute the equivalent continuous sound level, which is essentially a sophisticated mean over the varying noise levels observed during a given period. We use a highly disaggregated map, containing 2007 estimates of the continuous sound level by the source of noise (including rail) at a 10x10-meter grid from Berlin's Senate Department for Urban Development and the Environment (2013). The noise measure reflects the weighted average noise exposure over one year and all times of a day (L_{den}) at a reception point of four meters above the ground. Following the rules defined by the EU Environmental Noise Directive, the micro-geographic noise map is the result of a simulation using a 3D model that is fit to actual noise measurements. The model incorporates features of the track design (e.g. speed, squeaking noises in curves, the presence of lubrication facilities) and the terrain geography (e.g. elevation of the track, built-up structure, bridges) that affect noise dissemination. Summarizing existing research, Navrud (2002) concludes that "*[…] the elimination of noise annoyance occurs at 37-40 db*". Thus, we measure rail noise in terms of decibels exceeding 40 decibels, i.e. 45, 50, and 55 decibels correspond to 5, 10, and 15 excess decibels. As we illustrate in an auxiliary analysis presented in appendix section 3.2, our rail noise measure sharply declines with distance from the track, is higher where trains run faster, and disproportionately affects the first row of buildings facing the track.

For our historical episode, estimates of the rail noise level unfortunately do not exist as the measurement technology had not been developed (Ampel & Uzzle 1993). However, regarding the transferability of the contemporary noise measure, we note that the building footprint remained largely the same within the affected area, despite significant damage during World War II, as documented on detailed ground plans published by the Berlin Senate Department (Senatsverwaltung für Stadtentwicklung Berlin 2000).[3] Therefore, it seems reasonable to assume that contemporary rail noise levels also reflect the dissemination of sound about 100 years ago in relative terms. Moreover, the service operator was contractually required to serve all stations in at least five-minute intervals during day time, a frequency that corresponds to the current service (Lemke & Poppel 1996). Historical and contemporary timetables also reveal that the average speed remained constant over time (Ahlfeldt, Redding, et al. 2015). This is consistent with a rolling stock technology that did not

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[3] Note that for very few plots, where the building structure changed, we impute historic noise levels using adjacent plots.

change fundamentally. As discussed above, Line A was the first electrified subway system in Germany. The trains (type A1/A2) as well as the track design represented a revolutionary technology. In comparison, the subsequent improvements that came with the introduction of new trains in the 1960s (type A3, still the backbone of the fleet) were evolutionary (Lemke & Poppel 1996).

The exact changes in noise levels from the first to the second generation are not documented, but it seems likely that technological progress even within a similar technology at constant speed and frequency has resulted in an at a least moderate reduction of noise levels. New generations of rolling stock tend to reduce noise levels of inter-city trains by about 10 decibels (Clausen et al. 2012; Murphy & King 2014), although a smaller reduction is expected for urban rail since trains operate at lower speeds. Moreover, less tree coverage in the past may have implied less noise mitigation. Importantly, passive noise insulation was probably weaker in the past, although the characteristic wooden double box windows (*Doppelkastenfenster*) from the late 19th century have remained popular in Berlin. All in all, it seems reasonable to assume that our contemporary noise measure represents a lower-bound estimate of the noise levels experienced in the early 20th century.

2.4 Visual disamenity

In addition to a noise disamenity, an elevated line may cause a visual disamenity. The routing of Line A follows major roads which were sufficiently wide to accommodate a viaduct in the middle of the sides. Because the elevated line generally does not obstruct views of open spaces such as parks or lakes, the visual disamenity is less obvious than the noise disamenity in the present case. Moreover, addressing the concerns raised by Berlin residents mentioned above, the elevated tracks and stations were eventually executed with some attention to architecture (Bohle-Heintzenberg 1980). To empirically disentangle the effects from the noise disamenity and the visual disamenity, we create a dummy variable that takes the value of one if a parcel has a direct view of the elevated track and zero otherwise. Moreover, subways cause vibrations that potentially transmit to nearby buildings, where they can be perceived as a disamenity (Kurzweil 1979). Because the effects are highly localized and normally reach no further than to the first row of houses (Melke 1988), a potential disamenity effect should also be captured by the view dummy. Previewing our results, we do not find evidence for a direct view effect conditional on the noise effect and find similar noise effects when excluding parcels with a direct view from the analysis. We therefore generally interpret our noise estimates as originating purely from noise.

2.5 Other spatial data

We utilize the complete transport network data for post-unification Berlin processed by Ahlfeldt, Redding, et al. (2015). The network data consists of electronic maps (shapefiles) of streets (used for walking and driving), buses, trams, subway (*U-Bahn*) and commuter rail (*S-Bahn*). In addition, we digitize the underground and elevated sections of Line A as well as the other historical transportation networks, including horse-powered buses, horse-powered trams (one line), steam-powered trams (one line), electrified trams (the great majority of tram lines), and commuter rail (powered by steam). To compile the historical network data (and the associated speeds) we combine the contemporary transport networks with historical network plans.[4] An illustration of the historical and contemporary transport networks is in appendix section 3.3.

We complement our key data sets (property, access, noise) with several spatial characteristics, which we merge in GIS, including contemporary measures of distance from the central business district (still at the historical location), distance from the Kurfürstendamm sub-center, distance from nearest lake, river or canal, distance from nearest park or forest, distance from nearest landmark building, distance from nearest playground, distance from nearest main street, and street noise (excluding rail noise).

2.6 Interpretation of estimated implicit prices

Our historical and contemporary analyses utilize different types of data. In our historical analysis, we exploit the spatiotemporal distribution of land prices. In our contemporary analysis, the dependent variable is the ratio of transaction price of a parcel of land, including the structure, over the parcel size. To theoretically link the estimated coefficients from these distinct models to each other as well as to a vast literature analyzing house prices, it is useful to assume a Cobb-Douglas housing production function and a competitive construction sector (Epple et al. 2010).

Assume that housing services H are produced using the inputs capital K and land L as follows: $H = K^{\delta} L^{1-\delta}$. Housing space is rented out at bid-rent ψ while land is acquired at land rent Ω. Combining the first order condition $K/L = \delta/(1-\delta)\,\Omega$ (where the price of capital is the numeraire) and the non-profit condition $\psi H = K + \Omega L$ gives $\psi H/L = 1/(1-\delta)\Omega$. Log-linearization yields a relationship with a slope of one, which implies that estimated parameters from our historical models (in which the dependent variable corresponds to $\ln(\Omega)$) and our contemporary models (in which the dependent variable corresponds to $\ln(\psi H/L)$) are directly comparable. From the first-order condition and the non-profit condition, it is further immediate that $\ln(\psi) = (1-\delta)\ln(\Omega) + c$, where c is a constant that cancels out in first-differences, i.e., $\Delta\ln(\psi) = (1-\delta)\Delta\ln(\Omega) = (1-\delta)\Delta\ln(\psi H/L)$. In log terms, it is, therefore, possible to translate the capitalization effects from our historical and

[4] Network plans are also available online; see, for instance, http://www.berlineruntergrundbahn.de and http://www.berliner-verkehr.de.

contemporary models into a floor space price capitalization effect, by multiplying the former by a land share parameter.

It is important to note that housing services as defined by Epple et al. (2010) are not identical to housing space. Units of housing services can be thought of as bundles of features, including housing space, the quality of materials, sophistication of design, and access to communal and private exterior space, that generate equivalent consumption utility. Especially in places where building volumes are subject to binding regulations, such as in central Berlin, supply of housing services can be elastic (at a price the elasticity $dln(H/L)/dln(\psi) = \delta/(1-\delta) > 0$) even if supply of housing space is not, because developers choose to invest in housing quality (better materials and designs require more K/L) to achieve higher rents ψ. In fact, the building fabric in the study area is still dominated by the late19th century stock and where the buildings have been replaced, the quantity of housing space has been regulated by floor area ratio limits. Yet, H has increased over time as the historic building capital has been upgraded, e.g. by retrofitting central heating, private bathrooms, modern kitchens, or balconies (Hämer 1990). In appendix section 6.1, we show that $\psi H/L$ is correlated with various observable features of building capital, conditional on housing space. There, we also show that various features that are presumably correlated with housing capital and housing services, including housing space, decrease significantly in station distance and rail noise, as predicted for disamenities.

The Cobb-Douglas formulation of the production function implies that the elasticity of substitution between land and capital is unity at any given point in time, such that as the price of land increases, developers invest in capital (via maintenance, upgrades, or replacements) at rates that ensure constant factor shares. It does not preclude that the land share and the price elasticity of housing services change over time due to factors that are exogenous to developers' decisions on factor inputs. As discussed by Ahlfeldt and McMillen (2018), the intensity of capital use varies over time as the structure of demand, regulation, or construction technology change. To account for such trends, we borrow separate historical (1900) and the contemporary (2000) estimates of the share of land in total housing value in Germany of $1-\delta_{1900} = 0.18$ and $1-\delta_{2000} = 0.32$ from Knoll, Schularick, and Steger (2017).

3 Historical estimates

3.1 Empirical strategy

Our baseline empirical strategy for the estimation of historical capitalization effects combines hedonic (Rosen 1974) and difference-in-differences (DD) methods (Ashenfelter & Card 1985). We employ the hedonic approach to express the price of a parcel of land as a function of various attributes, including rail noise and rail access, and their implicit prices. The DD method then allows us to identify a treatment effect (e.g., of rail access or rail noise) by differentiating across space (with different degrees of exposure) and time (before and after exposure). Our baseline empirical specification takes the following form:

$$\ln(P_{it}) = f(S_i, N_i, t) + \mu_i + \theta_t + \varepsilon_{it}, \quad (1)$$

where P_{it} is the land price of a parcel i at time t, μ_i is a parcel fixed effect controlling for unobserved time-invariant locational amenities such as pollution, onto which we cluster standard errors (Bertrand et al. 2004), and θ_t is a year fixed effect controlling for common macroeconomic shocks. $f(S_i, N_i, t)$ is a treatment function that expresses the effects of the metro line as a function of the straight-line distance to the nearest station S_i, the emitted noise N_i, and time t.

While the opening date of the line (1902) is known a priori, the exact temporal structure of the capitalization of the effects of the line into land prices is not. Capitalization will occur gradually rather than immediately if the service is an experience good and it takes some time before transit riders adjust their behavior to take full advantage of the new option. If the semi-strong (or strong) efficient market hypothesis (Fama 1970) holds, markets will respond to all information made publicly available, which can result in anticipation effects as soon as the new line is announced. In setting up our DD model, we begin by estimating a series of time-varying treatment effects that reveal the temporal adjustment path in a flexible manner:

$$f(S_i, N_i, t) = \sum_{z=1890,1896,\ldots}^{1914} [\alpha_z^S S_i \times I(t = z)_t + \alpha_z^N N_i \times I(t = z)_t], \quad (2)$$

where $I(t = z)_t$ is an indicator variable, which takes the value of one if the condition is met and zero otherwise. Parameters α_z^S and α_z^N each represent an individual DD parameter reflecting how land prices for parcels exposed differently to noise and accessibility effects (first differences) changed from 1881 to year z (second differences).

We note that, because there was no metro rail noise prior to the elevated rail line, our noise measure reflects the increase in noise due to the elevated rail line (such that $N_i = \Delta N_i$, where ΔN_i is the before-after change in noise). Therefore, α_z^N provides a first-difference estimate of the effect of rail noise on land prices that can be interpreted as a hedonic implicit price. In contrast, α_z^S gives the change in the hedonic implicit price of distance to station locations from year 1881 to year z, i.e. $\alpha_z^S = \vartheta_z^S - \vartheta_{1881}^S$, where ϑ_z^S is the hedonic implicit price in given year z. α_z^S can still be interpreted as the hedonic implicit price of proximity to a station ϑ_z^S since in 1881 the stations could not be anticipated and, thus, $\vartheta_{1881}^S = 0$.

Informed by this analysis, we then estimate an extended DD model which provides a before-and-after comparison, controlling for the effects during an identified adjustment period:

$$f(S_i, N_i, t) = \alpha^S[S_i \times I(t > 1902)_t] + \alpha^N[N_i \times I(t > 1902)_t] + \sum\nolimits_A [\alpha_A^D S_i \times I(t = A) + \alpha_A^N N_i \times I(t = A)], \quad (3)$$

where $I(t > 1902)_t$ is an indicator variable taking the value of one for years after the line opening and $I(t = A)_t$ is the same for a vector of years A during which land prices appear to be adjusting to a new equilibrium. Note that compared to dropping those years, controlling for adjustment effects offers the advantage of processing more information for identification of covariate effects (introduced in robustness checks) and fixed effects (μ_i, θ_t).

The critical and essentially untestable assumption of any DD analysis is that, in the absence of a treatment, all subjects (irrespectively of the intensity of treatment) would have followed the same trend. A selection problem exists if the treated and the non-treated subjects differ in observable or unobservable dimensions, and these differences imply heterogeneous responses to common shocks. In the context of the analysis of transport infrastructure effects, it is a notorious concern that the placement may be endogenous to location characteristics which may be correlated with trends. A variety of techniques have emerged to address selection problems, many of which aim at weighting observations in such a way that the treatment assignment becomes orthogonal to observable covariates. Examples include the inverse probability weighting (Hernán et al. 2001) and the special case of entropy balancing (Hainmueller 2012), the propensity score matching (Rosenbaum & Rubin 1983), or the synthetic control method (Abadie & Gardeazabal 2003). The problem with the application of these tools to the present case is that they serve the purpose of evaluating singular treatments and not multiple correlated treatments.

In the absence of a suitable off-the-shelf matching technique, we use a simple sledgehammer approach to defining parcel weights that minimize the conditional correlations between both treatment variables and the 1881-1890 trend in land prices, a period for which we are confident that the line has not been anticipated. We note that this is the first application of this weighted parallel trends (WPT) DD approach. To save space, we relegate a more technical discussion, including a Monte-Carlo evaluation of the small-sample properties of the estimator, to a companion paper

(Ahlfeldt 2018).[5] In line with other weighting-based matching techniques, we view the 1881-1890 trend in land prices as a covariate to be balanced; however, balancing must be achieved with respect to two correlated treatment assignments, noise and station distance. Under the identifying assumption that the correlation between treatments and unobserved factors that interact with time are time-invariant, successful elimination of treatment-trend correlations during the pre-treatment period implies that non-parallel trends are also removed in potential outcome trends during the post-treatment period. To achieve this purpose, we define the following parcel weights:

$$W_i = \frac{w_i}{\sum_i w_i}, w_i = \sum_m q_m K\left(\lambda_m, M_{i,m}\right), \tag{4}$$

where, $Q(q_1, \dots, q_m)$ are parameters to be identified. $M_{i,m}$, is one of m variables capturing observable time-invariant parcel characteristics that enters the weights in a Gaussian transformation:

$$K(\lambda_m, H_{i,m}) = \frac{1}{\lambda_m \sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{M_{i,m} - \bar{M}_m}{\lambda_m}\right)^2\right), \tag{5}$$

where the bandwidths λ_m are set according to the Silverman (1986) rule and the upper bar indicates the mean of a distribution. We use the Gaussian transformation because we presume that parcels that are more "normal" with respect to a plot characteristic $M_{i,m}$ are more likely to be on a similar trend. Furthermore, we presume that parcels that are representative with respect to different characteristics $M_{i,m}$ are likely on different trends. This approach has been chosen so as to mix these different trends in a way that ensures that the average trend in the weighted sample is orthogonal to the treatments. A positive collateral of the Gaussian transformation is that all $K_{i,m} = K\left(\lambda_m, M_{i,m}\right)$ are positive and in the same dimension. In the baseline, we use distance from the CBD, distance from a sub-centre, and 1881-1890 price growth as parcel characteristics M_m in the algorithm. In searching for a vector Q that minimises the objective function, we search over a parameter space defined by $q_1 = 0, 0.01, 0.02, \dots, 1$, $q_2 = 0, 0.01, 0.02, \dots, 1$, $q_3 = 0, 0.01, 0.02, \dots, 1$, which equates to 101^3=1,030,301 combinations. We select Q that minimizes the sum of squared partial correlations between our treatment measures (rail noise and station access) and the land price growth over the 1881 to 1890 period.[6]

[5] The companion paper cites an earlier working paper version of this paper.

[6] To this end, we run r regressions of the form $\Delta\ln(P_{i,1890}) = c_r^0 + c_r^S \tilde{S}_i + c_r^N \tilde{N}_i + \varepsilon_{ri}$, where $\Delta\ln(P_{i,1890})$ is the change in log land price from 1881 to 1890 and tilde denotes normalization by standard deviation. In each regression, observations are weighted by W_i, which depends on the vector $(q_1, \dots, q_m)$. We select the combination of parameters that minimizes $\sum_{V=(S,N)}\left(\widetilde{c_r^V}\right)^2$.

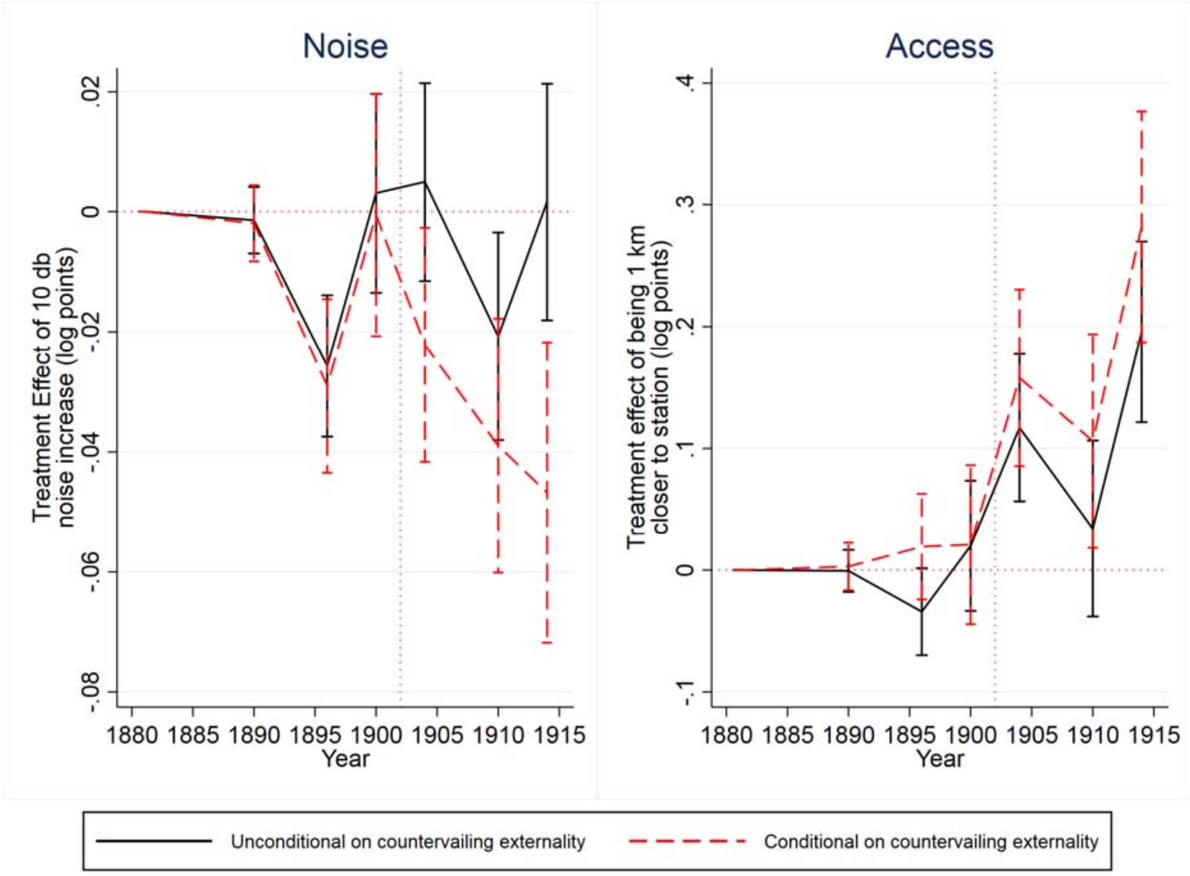
To overidentify our parcel weights, we use information that did not enter the weights construction. We have two more pre-opening periods in our data set (1890-1896, 1896-1900) which we use to evaluate whether the common trends assumption holds within the weighted sample. We have experimented with alternative sets of parcel characteristics and objective functions and our choices are based on their performance in the overidentification test reported in appendix section 4. There, we also evaluate whether the weighting changes the composition of the sample with respect to observable parcel characteristics. The weighted sample resembles the unweighted sample in terms of observable characteristics (see appendix section 4.1). While every weighted analysis results in a local estimate, in our case it is at least not obvious that the weighted DD effects are identified from parcels with very particular characteristics that would impede generalizability within our sample.

3.2 Baseline results

In Figure 2, we illustrate the time-varying treatment effects, estimated according to the DD model (1) using the treatment function (2) and the weights defined in (4) and (5). We report rail noise and station distance effects, estimated unconditional (solid lines) and conditional (dotted lines) on each other. Estimated station distance effects are multiplied by -1 to ensure that positive numbers mean normatively positive effects. Our weighted estimation approach achieves its purpose of eliminating pre-trends, i.e., there is no significant correlation between the 1881-1890 land price trend on the one hand and proximity to stations or exposure to rail noise on the other. Proximity effects are insignificant in 1896 and 1900 and the noise effect is insignificant in 1900 (years that were not used in the construction of the weights), indicating that the common trends assumption holds within the weighted sample.

Station distance effects remain insignificant during all years prior to the opening of the line and become significantly positive afterwards, with a tendency to increase over time. The absence of anticipation effects in combination with the gradual adjustment after the opening of the line are consistent with an interpretation that the line represents a novel mode of transportation whose benefits were yet to be experienced. Controlling for rail noise, a one-kilometer decrease in distance from the station increases land prices in the long-run by some notable 0.3 log points (35%).

Fig. 2. Difference-in-differences: Time-varying treatment effects (WPT models)



Note: Time-varying treatment effects (α_z^S and α_z^N) based on baseline DD equation (1) and treatment function (2). WPT models use weights constructed to minimize the conditional correlations between noise and the 1881-1890 land price trend as well as access (distance from station) and the 1881-1890 land price trend. Access parameters (effects of distance from station) multiplied by -1 so that positive shifts indicate positive economic effects. Vertical error bars indicate the 95% confidence interval based on standard errors that are clustered on parcels. Solid vertical lines denote the year of opening of the metro line (1902).

The estimated weighted rail noise effects also display an intuitive pattern. Controlling for station distance effects, a 10-decibel increase in rail noise is associated with a reduction in land prices by slightly more than 4% in the long-run. In contrast to our results for station distance effects, we find notable anticipation effects of rail noise for 1896. This finding is plausible in light of the intense public debate about the aesthetic appeal of elevated rail lines. The conflict was settled after the announcement to improve the architectural design of the stations and the viaduct and the decision to build an underground line within the boundaries of the city of Charlottenburg, explaining why the anticipation effect disappears in 1900. In keeping with intuition, estimated station distance effects increase by about one third if rail noise effects are controlled for. The effect of controlling for station distance effects on rail noise effects is even larger.

Informed by Figure 2, we now proceed to estimating parametric before-after DD effects, using our baseline specification (1), the treatment function (3), and, again, the weights defined in (4) and (5). The results are reported in Table 1. For comparison, we present weighted DD estimates of station distance effects not controlling for rail noise effects (columns 1-2) and rail noise effects not controlling for station distance effects (columns 3-4). In columns (5-6) of the table, we then report our preferred station distance and rail noise effects estimated conditional on each other. We control for anticipation effects in 1896 and 1900 as indicated.

When we do not control for rail noise effects, our estimation results indicate that the price of a parcel located right at a station increases by 12.7% (=exp(0.120)-1) after the opening of the line, compared to a parcel one kilometer away from a station. Rail noise effects are close to zero and statistically insignificant if station accessibility is ignored. Controlling for anticipation effects in either case has a minor impact on the estimated rail effects. A comparison of these results to columns (5-6) highlights the importance of jointly identifying a transportation infrastructure's amenity and disamenity effects. As shown in column (6), the station distance effect increases to 20.2% in our preferred model. Moreover, in line with Figure 3, the (negative) rail noise effect is now statistically significant. The point estimates indicate that a 10-decibel increase in rail noise causes a relative decline in land prices by 3.7%. Comparing our estimates across the different specifications, the bias that results from ignoring countervailing (dis)amenity effects amounts to as much as about 35% ($[0.184 - 0.119]/0.184$) in station distance effects and to about 85% in rail noise effects. In this context, it is worth noting that consistent with the insignificant noise effect in columns (3-4), our preferred estimates in column (6) suggest that positive accessibility effects about offset the negative noise effect for the parcels exposed to the highest levels of noise (see appendix section 4.2 for details).

The treatment effects reported in Table 1 are derived from a comparison of the mean land price at the parcel level in the periods 1881-1890 and 1904-1914. Since this model ignores price trends after the opening of the line, the effects are smaller than the 1914 treatment effects reported in Figure 2. These parametric estimates, however, are closer to the standard approach in the literature, therefore providing a more reasonable starting point for a comparison of our quantitative results to contemporary estimates in the literature.

Tab. 1. Noise and distance effects: Historical weighted difference-in-differences estimates

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln land price (1881-1914)					
Distance (km) x after	-0.120***	-0.119***			-0.173***	-0.184***
$(S_i \times (t > 1902)_t)$	(0.025)	(0.032)			(0.031)	(0.040)
Noise (10 db) x after			0.001	-0.004	-0.029***	-0.036***
$(N_i \times (t > 1902)_t)$			(0.006)	(0.008)	(0.007)	(0.010)
Parcel effects	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Anticipation effects	-	Yes	-	Yes	-	Yes
N	37,933	37,933	37,933	37,933	37,933	37,933
r2	.93	.93	.93	.93	.93	.93

Notes: Weighted models use weights constructed to minimize the conditional correlations between noise and the 1881-1890 land price trend as well as access (distance from station) and the 1881-1890 land price trend. After is a dummy variable indicating years after the line opening (1902). Announcement effects are distance and noise variables interacted with 1896 and 1900 effects. Balanced panel of repeated parcel observations for 1881, 1890, 1896, 1900, 1904, 1910, 1914. Standard errors in parentheses are clustered on parcels. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

3.3 Robustness checks and complementary analyses

We have performed a number of perturbations of the baseline model reported in column (6) of Table 1 to address various concerns. For instance, we obtain similar results when we use different covariates and objective functions in the weights-generating algorithm. We also find that the baseline results are reasonably robust to allowing for time-varying implicit prices of various location characteristics (captured by controls × year effects interactions). Allowing for interactions of noise and distance variables with separate time trends before and after the opening of Line A results in cumulated effects after 10 years that are very close to the baseline estimates. Adding a dummy variable indicating parcels with an unobstructed view of the elevated line does not significantly affect the noise (or the distance) effect. Similarly, the results hardly change if all parcels with a direct view of the elevated line are excluded. A view effect is only significant if the noise measure is excluded from the model. Not controlling for noise, parcels with a direct view experienced a relative decrease in the land price of 4.4%, which is substantially less than implied by the noise effect at the same location (about -9.5%; see previous paragraph). It is, therefore, unlikely that our noise estimates are confounded by a view disamenity effect or a disamenity from subway vibrations (as both effects should be highly correlated). We have also evaluated the spatial decay in the distance effect using a series of dummies denoting parcels in mutually exclusive 100-meter station distance bins. We find that the distance effect is largely confined to the first 400 meters, with no evidence for negative congestion effects at close distances. Comparing the effect in the innermost ring versus the outermost residual category results in an effect that is almost identical to the one-kilometer distance effect from the baseline model. We have also evaluated the stability of the hedonic function (Kuminoff and Pope, 2014) around the opening dates by comparing marginal effects of other spatial attributes over time and experimented with varying levels of spatial clustering. These robustness tests and complementary analyses are presented and discussed in detail in appendix section 4, where we also present the results of an unweighted OLS analyses for the interested reader. As a final and particularly powerful robustness check, we also evaluate the noise effect exploiting a discontinuity in noise at the tunnel entrance close to Nollendorfplatz, finding qualitatively and quantitatively similar results. This analysis is presented in appendix section 5.

4 Contemporary estimates

4.1 Empirical strategy

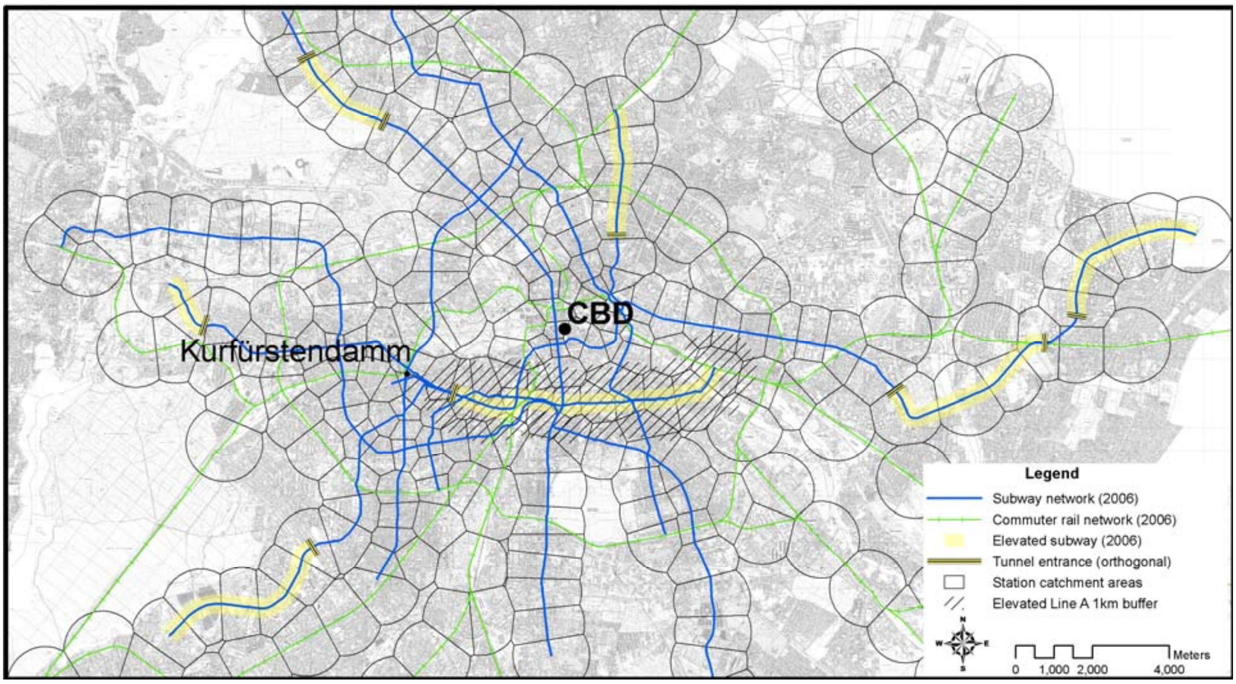
In the absence of variation over time in the metro rail network during the contemporary study period (1990-2012), we estimate a cross-sectional model. To improve the identification of noise effects, we restrict the identifying variation to the sharp change in noise that arises at nine tunnel entrances where elevated lines turn into underground lines. The reasons for the transition and the selection of the location of the tunnel entrances are often specific to the line (Bohle-Heintzenberg, 1980). In particular, we estimate models of the form:

$$\ln(p_{jtce}) = \alpha^S S_j + \alpha^N N_j + Y_{jt} b + (\rho_c \times \theta_t) + (\varsigma_e \times \theta_t) + \varepsilon_{jst}, \quad (6)$$

where p_{jtce} is the property transaction price normalized by the lot size of a property j selling at time t within the catchment area of station c and within a network corridor e. As discussed in section 2.6, this specification accounts for endogenous housing quality and yields marginal effects of rail noise and rail access that are directly comparable to the historic land price effects estimated in section 3. In contrast to conventional hedonic analyses using sales prices (corresponding to ψH in notations of section 2.6), housing attributes like the number of bathrooms or bedrooms must not be controlled for. $p \mathrel{\widehat{=}} \psi H/L$ is directly observed in the data and theoretically only depends on factors that affect the land price, i.e. locational characteristics. In contrast to the theoretical framework outlined in section 2.6, however, housing is durable such that the actual building capital does not necessarily correspond to the equilibrium value since capital depreciates (see appendix section 6.1 for estimates of the depreciation rate). Therefore, we control for age in the vector Y_{jt}, which also contains a host of locational control variables.

The variables S and N are our respective measures of station distance and rail noise as before, ρ_c is a fixed effect for station catchment areas and θ_t is a year fixed effect. Since subway and commuter rail use a similar technology in the contemporary period, we treat both types of stations as perfect substitutes. Station catchment areas are, therefore, defined for groups of properties sharing the same nearest station. In our baseline specification, we restrict the sample to areas within one kilometer of the nearest station. As evident from Figure 3, the density of stations is relatively high within the central parts of Berlin, further reducing the size of a catchment area. The mean catchment area is just 1.3 square kilometers (about 0.8 square miles) as opposed to more than three square kilometers implied by a circle with a one-kilometer radius. With the interaction effects $\rho_c \times \theta_t$, we, thus, provide a strong control for unobserved location characteristics such as pollution, changes in locational characteristics and changes in the implicit prices of location characteristics.

Fig. 3. Contemporary rail network and station catchment areas



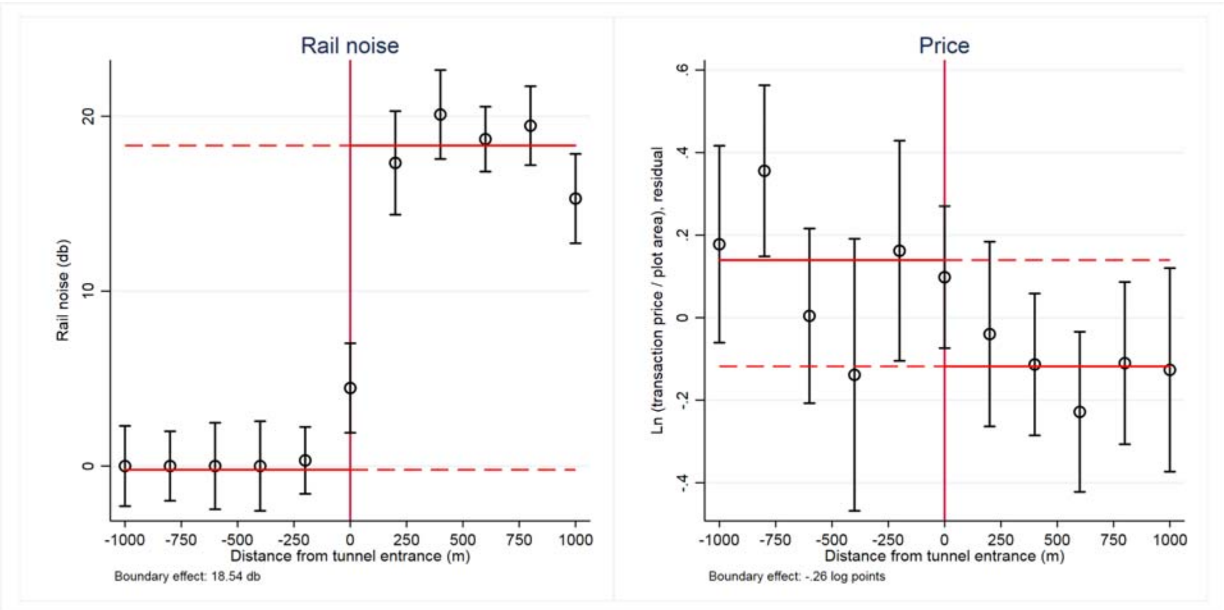
Notes: Own illustration using the Urban Environmental Information System of the Berlin Senate Department (Senatsverwaltung für Stadtentwicklung Berlin 2006).

Critical for the identification of the noise effect, ς_e is a set of fixed effect for rail corridors. Each corridor is centered on the intersection of the rail network and one of the nine tunnel entrances indicated by the orthogonals in Figure 3. We use corridors defined based on a track distance of 100 meters and a distance from the orthogonal of 1000 meters. The interaction fixed effects $(\varsigma_e \times \theta_t)$ capture arbitrary shocks to any of these corridors. We define an auxiliary running variable D_{je} that takes the distance from the nearest tunnel entrance (negative distances in the tunnel section) within a corridor e and a value of zero elsewhere. We then use a dummy variable indicating the elevated parts of those corridors $I(D_{je} > 0) \times K_e$ (K_e is one within any of the corridors) as an instrument for noise to restrict the identification to the difference in noise across elevated and underground segments within corridors.

4.2 Baseline results

Figure 4 illustrates rail noise and contemporary property prices along the rail corridors and tunnel entrances. We present mean values of outcomes within 100-meter bins and confidence intervals that summarize whether the within-bin mean is significantly different (at the 90% level) from the mean across all observations within a corridor on the other side of a tunnel entrance.

Fig. 4. Contemporary spatial differences in noise and property prices



Notes. Each circle illustrates the mean value of a dependent variable within a grid cell. One dimension of the grid cells are 200-m bins defined based on the distance from the tunnel entrance. The other dimension is a 100-m-distance buffer around the track. Negative distances from the tunnel refer to the underground section. Solid horizontal lines indicate the means (weighted by the number of observations) within the underground (negative distance) and elevated (positive distance) segments. Error bars are the 90% confidence intervals based on robust standard errors from separate parcel-level regressions (within the buffer). For each outcome, we run one regression of the outcome against dummies indicating positive distance (≥ 0) bins, and another regression of the outcome against dummies indicating negative distance (<0) bins. For each bin, the error bar represents a test if the mean within the bin is different from the spatial counterfactual (the dashed line). The boundary effect corresponds to the difference between the two horizontal lines. Transaction prices are the residuals plus the block fixed effect component from regressions of the natural log of the transaction price normalized by lot size against a host of hedonic controls, year effects, and block fixed effects, several distance variables, including distance from the central business district, distance from the nearest lake, river or canal, distance from nearest park or forest, distance from nearest landmark building, distance from nearest playground, distance from nearest main street, street noise (excluding rail noise).

Within these rail corridors, the levels of rail noise along the elevated segments exceed that of the underground segments by about 18 decibels. The additional noise comes with a discount on land prices of -0.26 log points. Four out of five high noise bins (elevated section) have mean prices that are significantly lower than the mean price within the low noise (underground) section and four out of six low noise (underground section) bins have mean prices that are significantly higher than the mean price within the high noise (elevated) section. The implied price effect of a 10-decibel increase in rail noise is about -0.14 log points, more than three times the land price capitalization effect in the historical period.

Table 2 reports the estimates for several variants of equation (6). In columns (1-3), we present, for comparison, the results of a conventional hedonic model, which excludes all corridor-related variables and does not use the instrument. Our preferred SD specifications for the noise effects identification are tabulated in columns (4-6). For both variants, we report results of models that exclude (1 and 4) and include (2 and 5) station catchment × year effects as well as models that use all transactions (1-2 and 4-5) or samples restricted to properties within one kilometer of the nearest station (3 and 6).

The estimated station distance effects are relatively stable across all specifications. Our preferred estimate of the per-kilometer station distance effect is the $(\exp[-0.144]-1)/100=-15.4\%$ estimate from column (3), for several reasons. In model (3), station catchment × year effects control for arbitrary shocks at a relatively local level. Moreover, the restriction to a one-kilometer station radius further increases the strength of this control and makes the results more comparable to our historical analysis. Importantly, the model controls for noise along all elevated segments of the network whereas in the SD specification much of the variation in noise is intentionally wiped out by the instrument.

The SD models consistently point to relatively large and negative noise effects. The most conservative estimate suggests that a 10-decibel increase in noise reduces the property price per land unit (and under the assumptions made in section 2.6 also the land price) by about 11.5%. Given the geography of the Berlin rail network, it is intuitive that the hedonic models in columns (1-3) yield smaller estimates. The subway network often follows major boulevards that were laid out in the 1862 Hobrecht-Plan (Bernet 2004), which borrowed many features from Haussmann's designs for Paris (de Moncan 2009). These boulevards provide the necessary space for the construction of viaducts for elevated lines or facilitate the cost-effective open construction of tunnels. Such boulevards, however, also possess desirable features such as distinctive architecture, tree coverage, shops, boutiques and restaurants, which are not observed in the data. If these features are empirically confounded with rail noise, the noise disamenity will be underestimated.

Tab. 2. Contemporary analysis

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln property transaction price / lot size					
Distance (km)	-0.128***	-0.126***	-0.144***	-0.127***	-0.126***	-0.152***
	(0.003)	(0.007)	(0.021)	(0.003)	(0.007)	(0.022)
Rail noise (10 decibel)	0.050***	-0.021	-0.032**	-0.166***	-0.143***	-0.122**
	(0.011)	(0.015)	(0.015)	(0.032)	(0.049)	(0.049)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	-	-	Yes	-	-
Station x year effects	-	Yes	Yes	-	Yes	Yes
Corridor x year effects				Yes	Yes	Yes
Noise instrument				Yes	Yes	Yes
Sample	All	All	Station distance < 1 km	All	All	Station distance < 1 km
N	71,313	71,313	46,143	71,313	71,313	46,143
r2	.259	.584	.608	.261	.586	.61

Notes: Unit of analysis is property transaction. Controls include structure age, dummies for location within a block (corner lot, street front, backyard, etc.), dummies for building condition (poor, good), distance from nearest lake, river or canal, distance from nearest park or forest, distance from nearest landmark building, distance from nearest playground, distance from nearest main street, street noise (excluding rail noise). Station effects identify groups of properties which have the same nearest rail station. Corridor effects identify groups of properties within 100-meter buffers along a rail line, spreading 1,000 meter in both directions from a tunnel entrance. Noise instrument is a dummy variable taking the value of one with the elevated segment of any rail corridor and zero otherwise in models (4-6). Standard errors in parentheses are robust in (1) and (4), clustered station x year effects in all other models. * p < 0.10, ** p < 0.05, *** p < 0.01.

4.3 Robustness checks and complementary analyses

We have expanded the analysis of contemporary property price effects in several directions. We have evaluated the ancillary prediction from the theoretical framework in Section 2.6 that increases in land values due to locational amenities should be accompanied by investments in building capital and a larger quantity of housing services. We find that increases in station distance by one kilometer and increases in rail noise by 10 decibels reduce the supply of floor space per land unit by more than 20% and about 10%, respectively. There is also a negative effect on building conditions as well as the propensity of buildings with features such as elevators, basements, or underground parking. To allow for a more explicit comparison to the historical analysis, we estimate distance and noise effects within the one-kilometer buffer surrounding the elevated part of Line A depicted in Figure 1. The amenity and disamenity effects within the buffer are very similar to the rest of the city area. If anything, the distance effect appears to be somewhat larger (-19.3% per kilometer), although the difference between the effects in both areas is not significant. With a similar aim, we estimate the distance effect for the subway (*U-Bahn*) and commuter rail (*S-Bahn*) network separately. The distance effect for the subway network of 21.9% per kilometer is, again, somewhat larger than in the baseline. In robustness checks, we analyze the sensitivity of the results to variations in the definition of the rail corridor and different attempts to achieve a more local identification in a reduced-form framework (using the noise instrument as an explanatory variable). Narrower definitions of the rail corridor (75 or 50 meters) result in similar point estimates, but larger standard errors. Further restricting the identification to variation closer to the tunnel entrance by weighting observations by distance or adding distance trends results in larger noise estimates. A complementary analysis of non-linear distance effects reveals that the distance effects largely capitalize within the first 500 meters, with no evidence for negative congestion effects at close distances. The peak capitalization effect close to the station relative to the one-kilometer station distance margin, at about 20%, is somewhat larger than implied by the baseline estimate. We also find that conditional on controls the difference in road noise within elevated and underground segments of our rail corridors is close to and not statistically distinguishable from zero. Thus, with the chosen research design, road noise is unlikely a potential confounder for rail noise effects, and so are other disamenities such as pollution that are likely correlated with road noise. A more complete presentation and discussion of the extensions and robustness checks is in appendix section 6.

5 Interpretation

5.1 Comparison of historical and contemporary estimates

Thus far, we have provided contemporary and historical estimates of capitalization effects of noise and rail access into land prices. Using the theoretical framework discussed in Section 2.6, it is possible to retrieve the implied house price capitalization effects. To obtain estimates of the long-run income elasticities of (dis)amenity values of noise and access, we make some further assumptions. In particular, we assume that, within each period (historic and contemporary), (i) preferences for all goods (including noise and access) are homogeneous, and so are expenditure shares on housing and land shares in the production of housing (this does not preclude differences across periods); (ii) real incomes grow at a constant rate for all population groups (this does not preclude level-differences across groups); and (iii) the estimated marginal effects of noise and access are causal and constant across the distributions (for noise this concerns values exceeding 40 decibels). We can then define the willingness to pay (WTP) for a unit amenity increase in period t as the product of the capitalization effect in house price terms $(1-\delta_t)\alpha_t$ ($1-\delta$ is the land share as defined in section 2.6), income I_t, and the expenditure share on housing η_t: $WTP_t = (1-\delta)\alpha_t \times I_t \times \eta_t$. Taking log-differences and rearranging the WTP equation gives the income elasticity of the amenity value:

$$\frac{\Delta \ln WTP}{\Delta \ln I} = 1 + \frac{\Delta \ln(\alpha)}{\Delta \ln I} + \frac{\Delta \ln(1-\delta)}{\Delta \ln I} + \frac{\Delta \ln \eta}{\Delta \ln I}, \tag{7}$$

Of course, the assumptions made are disputable and are subject to a critical assessment in appendix section 7, where we also provide a detailed discussion of the calibrated values for $\Delta \ln(1-\delta)$, $\Delta \ln \eta$ and $\Delta \ln I$. Acknowledging that considerable uncertainty surrounds our estimates of both long-run income elasticities, we provide a summary of our main takeaways below.

5.1.1 Noise

Over a period of about 100 years, the effect of a 10-decibel increase in noise on land prices roughly tripled from -4.2% (Table 2, column 3) to -13.0% (Table 3, column 6). Under the assumptions made, this corresponds to an increase in the per-decibel house price capitalization effect from - 0.1% to - 0.4%, the latter being within the range of contemporary estimates of aircraft noise (Boes and Nüesch, 2011 report - 0.5% per decibel) and road noise effects (Graevenitz, 2018 reports a range of - 0.1% to - 1.4% per decibel). The implied income elasticity of the noise disamenity value is 2.2. This long-run income elasticity estimate is without precedent, but complements cross-sectional stated-preference estimates that point to an income elasticity of the marginal cost of noise below unity (Wardman et al. 2005 cite a central estimate of 0.5).

One possible concern with the inter-temporal comparison we make is that we do not observe historic rail noise. For the reasons discussed in section 2.3, contemporary rail noise levels likely understate historical noise levels, implying that our historical noise estimates are upwardly biased and the long-run income elasticity of the noise disamenity value is likely larger than the value we infer. Another concern is that, in the past, road noise levels were likely lower due to the absence of affordable mass-produced cars. This will be a potential problem if we relax the assumption of a constant marginal effect of noise. If the disamenity effects of rail and road noise were mutually reinforcing, an increase in road noise over time would lead to a higher noise capitalization effect even in the absence of a change in noise aversion. However, in an ancillary analysis, we find that the rail noise capitalization effect decreases in the presence of higher levels of road noise, i.e. rail noise matters less if there is already a lot of road noise. So, without a presumed increase in road noise levels over time, the rail capitalization effect today would likely be even greater, implying, again, a larger income elasticity. If we relax the assumption of homogeneous preferences, it seems reasonable to expect that after 100 years of sorting most noise sensitive households will have left the noisiest areas (Kuminoff and Pope, 2014). This, again, mutes the contemporary noise capitalization effect and increases the implied income elasticity. However, the overall increase in noise levels across the city could also lead to the marginal buyer in a noisy area being more noise sensitive, so that the net effect of sorting is ambiguous. Importantly, rapid rail transit in Berlin was relatively more popular among wealthy people in the past since fares where relatively higher and, in the absence of cars, rapid transit was the fastest mode. So, likely, average income in the study area increased at a rate lower than calibrated, implying a likely downward bias in our income elasticity estimate. Thus, on balance, we believe that 2.2 is a lower-bound estimate of the income elasticity of the noise disamenity value.

5.1.2 Access

According to our estimates, the land price capitalization effect of a one-kilometer reduction in distance from the nearest metro station (treating subway and commuter rail as substitutes) declined from about 20.2% to 15.5%. Because of the increase in the share of land in the value of housing this decrease in the land price capitalization effect corresponds to an increase in the house price capitalization effect from 3.6% to 5.0%. This is within the range of recent difference-in-difference estimates such as by Gibbons & Machin (2005), who report a 1.5% to 5% range, or Dubé et al. (2013), whose estimates imply a per-kilometer effect of 7%. The implied income elasticity of the access amenity value is 1.4. Because the distance-from-station capitalization effect captures the value of the associated walking time (Gibbons & Machin 2005), the income elasticity of the value of station access should generalize to the value of time. It is therefore notable that our estimates are significantly larger than the cross-sectional estimates of the income elasticity of travel time value in the literature, which tend to be below unity (Börjesson et al. 2012 report a central estimate of 0.6-0.7).

One concern regarding the comparability of the historic and contemporary estimates is that rail transit was relatively more valuable in the past since mass-produced cars were not yet available as affordable substitutes. At the same time, the metro rail network has expanded substantially over time, now offering connections to a greater variety of locations, which should increase its value. In a network analysis, we find that the two offsetting effects are likely of comparable magnitude. The effects of sorting with respect to the access amenity go, again, both ways. Preference-based sorting over a century makes it more likely that households with large preferences for rail transit locate close to stations. However, the expansion of the network makes it more likely that the marginal buyer in a well-connected area today has a relatively lower preference for rail access than in the past. Given that income sorting likely leads to us using an exaggerated value for income growth near metro stations, we tentatively conclude that 1.4 is a lower-bound estimate of the income elasticity of the rail access amenity value.

5.2 Fiscal case for underground metro lines

Building an underground line is significantly more expensive than building an elevated line. Underground lines, conversely, avoid sizable disamenities. In this section, we provide some simple back-of-the-envelope calculations to evaluate how long it takes to refinance the extra costs via property tax revenues. To this end, we estimate the extra cost of a hypothetical underground Line A, the extra property value generated in this counterfactual, and the associated extra tax revenues.

5.2.1 Extra cost

Bousset (1935) reports the per-kilometer construction costs for 31 segments of the Berlin metro rail network opened by 1930, including per-kilometer cost of about two million Reichsmark (RM) for a five-kilometers long sub segment of the elevated part of Line A. Multiplying the per-kilometer cost by the total length of the elevated section of eight kilometers yields construction costs of about 16 million RM. To approximate the extra cost associated with a hypothetical underground section, we run an auxiliary regression of the natural log of per-kilometer construction costs against a dummy indicating underground sections, controlling for track width and period (five years) effects. The results, reported in Section 8 in the appendix, indicate that building an underground section in the early 20th century in Berlin was about three times as expensive as building an elevated section. Multiplying the estimated construction cost of Line A by this factor yields a counterfactual construction cost of about 50 million RM and an extra cost for the underground line of about 34 million RM. It is noteworthy that the current rule of thumb suggests costs of an underground line are about twice the cost of an elevated line (Flyvbjerg et al. 2008). So, the extra cost for the construction of underground lines have declined over time.

5.2.2 Extra property value

To compare the extra cost of construction to the aggregated effect on property values, we aggregate the plot-level land price observations to a 50×50-meter grid, which allows for rich spatial variation in rail noise and, at the same time, ensures that we cover the entire built-up area. Under the assumptions made in section 2.6, the noise-induced change in property value in each grid cell is $d\psi H = \psi H(\partial \ln \psi / \partial N)dN$, where dN is noise level attributable to Line A and $\partial \ln \psi / \partial N = (1-\delta)\partial \ln \Omega / \partial N$ is the relative house price capitalization effect of a one-decibel increase in noise. Since the Cobb-Douglas housing production function implies that $\psi H = 1/(1-\delta)\Omega L$, we can express the impact on property value as a function of the estimated house price capitalization effects and the aggregate land value:

$$d\psi H = \frac{1}{(1-\delta)} \Omega L \frac{\partial \ln \psi}{\partial N} dN, \tag{8}$$

Intuitively, in equation (8), we hold the capital stock constant such that the value of the property increases due to an increase in the value of the underlying land, exclusively. This way, we only account for the incidence on the immobile factor, i.e. we avoid the problem that a policy-induced increase in the quantity of housing stock at one location displaces demand in other areas. The resulting land price effects by grid cell are illustrated in the appendix (section 9). In this context, it is worth emphasizing that our plots include all types of land uses; the aggregate land value effect, therefore, reflects both changes in utility and productivity.

Table 3 provides a comparison of the extra cost for an underground variant of Line A and the aggregated impact on building values that would result from the associated noise reduction. We provide the comparison for the actual historical scenario (using our historical land price capitalization estimates) and a counterfactual scenario in which we apply the contemporary estimate of the land price capitalization effect $\tilde{\alpha}_{1900}^{N}$. This counterfactual land price capitalization effect inflates the estimated contemporary land price capitalization effect α_{2000}^{N} by the ratios of the contemporary over the historical land $(1-\delta)$ and housing expenditure (η) shares to reflect that the same willingness to pay with lower share parameters implies a larger percentage land price capitalization effect: $\tilde{\alpha}_{1900}^{N} = \alpha_{2000}^{N} \frac{(1-\delta_{2000})\eta_{2000}}{(1-\delta_{1900})\eta_{1900}}$.

Based on our historical noise estimates, the aggregate increase in property values in a counterfactual scenario with an underground Line A amounts to slightly more than one half of the extra cost of going underground (18.6 million RM). It is important to note that these results do not reject a welfare case for an underground Line A since positive health benefits are likely important, but unlikely to fully capitalize into property prices due to lack of public awareness (Navrud, 2002). Also, an underground line relative to an elevated line generates wider benefits to other than local residents and firms (e.g., to visitors and tourists). Yet, applying the counterfactual contemporary land price capitalization effect, the generated property value alone already more than offsets the extra costs of going underground. In theory, local landlords would be able to bear the extra cost for an underground line without making losses.

5.2.3 Extra tax revenues

While land value capture schemes are often difficult to implement in practice, the increase in the property tax base mechanically generates revenues and, therefore, may be a less controversial means of refinancing in the long-run. In Germany, the property tax is determined as the product of the tax base (the assessed value of the property, the so called *Einheitswert*), a tax rate (*Grundsteuermesszahl*) and a tax factor (*Hebesatz*). Since the *Einheitswert* is fixed at a historic value, property tax revenues are insensitive to changes in locational (dis)amenities. However, property transaction taxes respond immediately as they are levied on actual transaction prices. To approximate the yearly tax revenues resulting from noise-induced changes in property value, we consider the 6% property transaction tax rate currently applicable in Berlin as well as a historic (pre-1998) rate of 3.5%. Moreover, we consider 5% and 10% probabilities of any property being transacted in a given year since empirical evidence points to average holding periods between 10 and 20 years (Collett et al., 2000: Fisher et al, 2004). In appendix section 11, we discuss the German property tax environment in greater detail and show that in more conventional property tax settings similar fiscal revenues would be generated.

In a further set of auxiliary regressions of the natural log of land price on location fixed effects and a year trend, we find that annual land price appreciation rates tended to fluctuate around 5% in Berlin from the late 19^{th} century to the early 21^{st} century, which is close to the mean interest rate across years in the same period. Moreover, there is a positive correlation between the two variables (see section 10 in the appendix). Thus, it seems reasonable to make the simplifying assumption that in the long-run land prices grow at a rate that equates to the opportunity cost of capital.

Tab. 3. The fiscal case for an underground line

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Noise preference	Historic				Contemporary			
Rail noise capitalization effect on hsoue prices	0.41%	0.41%	0.41%	0.41%	3.32%	3.32%	3.32%	3.32%
Estimated total cost (million 1900 RM)	15.94							
Estimated underground extra cost (1900 RM)	34.36							
Aggregated noise effect building value (million RM)	18.6	18.6	18.6	18.6	151	151	151	151
Transaction tax rate	0.04	0.04	0.06	0.06	0.04	0.04	0.06	0.06
Transaction probability	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10
Yearly tax revenue (million 1900 RM)	0.03	0.07	0.06	0.11	0.26	0.53	0.45	0.91
Years to recover underground extra costs	1056	528	616	308	130	65	76	38

Notes: Contemporary land price effect adjusted for changes in land share and housing expenditure share (land price capitalization effect inflated by the ratio of contemporary over historic shares). Cost estimates based on Bousset (1935). Estimated total cost result from multiplying the reported 1902 per km costs of over elevated sections by 8 km (the length of the elevated sections of the Line A). The estimated underground extra cost result multiplying the total cost by the percentage extra costs for underground segments obtained from an auxiliary regression reported in Section 5 of the appendix. Years to recover extra costs are calculated under the assumption that property values grow at a rate similar to cost of capital (see appendix 9 for a justification).

Under the assumptions made, it turns out that based on our estimates of the historical land price capitalization effects, it would have taken hundreds of years to recover the extra costs via property taxes. Therefore, it is perhaps no surprise that Line A was built as an elevated line and that it took major protests and political pressure to force the line underground within the boundaries of Charlottenburg. In contrast, under the counterfactual contemporary capitalization effect, tax-revenues, depending on the assumed tax rate and transaction probability, would have refinanced the extra cost for an underground line within 38 to 130 years and, thus, likely within the past lifetime of Line A.

6 Conclusions

We use difference-in-differences and spatial differences designs to estimate the land price capitalization effects of the contemporary metro rail network in Berlin and Germany's first electrified metro rail line, Line A, which opened more than a century ago. We find that the land price (implied house price) capitalization effect of a 10-decibel reduction in rail noise increased from 4.2% to 13.0% (1% to 4%). The effect of a one-kilometer reduction in distance from the nearest station decreased (increased) from 20.2% to 15.5% (3.6% to 5.0%.). From these estimates, we infer novel estimates of the long-run income elasticities of the value of noise reduction and transport access of 2.2 and 1.4. While significant uncertainty surrounds these elasticity estimates, we view them as likely lower-bound estimates. Thus, our tentative conclusion is that the long-run income elasticities of transport (dis)amenity values likely exceed their short-run counterparts which have been estimated at below-unity values.

This finding has important implications for transport infrastructure appraisals as it suggests that time and environmental quality are luxury goods whose values will likely increase in absolute and relative terms as incomes rise. While the existing below-unity cross-sectional income elasticity estimates are certainly relevant for the assessment of the distributional consequences of investments within generations, larger values may be required for the assessment of distributional consequences across generations. As we demonstrate, using Berlin's Line A as a case in point, the welfare case for constructing underground rail lines is much stronger today than a century ago because the value of a quiet environment has increased more than proportionately to income. In anticipation of likely increases in real incomes, infrastructure appraisals that seek to fully capture net-benefits to future generations, should inflate rather than deflate contemporary (dis)amenity values.

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