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SPEED 2.0: EVALUATING ACCESS TO UNIVERSAL DIGITAL HIGHWAYS

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Abstract
This paper shows that having access to a fast Internet connection is an important determinant of capitalization effects in property markets. Our empirical strategy combines a boundary discontinuity design with controls for time-invariant effects and arbitrary macroeconomic shocks at a very local level to identify the causal effect of broadband speed on property prices from variation that is plausibly exogenous. Applying this strategy to a micro data set from England between 1995 and 2010 we find a significantly positive effect, but diminishing returns to speed. Our results imply that disconnecting an average property from a high-speed first-generation broadband connection (offering Internet speed up to 8 Mbit/s) would depreciate its value by 2.8%. In contrast, upgrading such a property to a faster connection (offering speeds up to 24 Mbit/s) would increase its value by no more than 1%. We decompose this effect by income and urbanization, finding considerable heterogeneity. These estimates are used to evaluate proposed plans to deliver fast broadband universally. We find that increasing speed and connecting unserved households pass a cost–benefit test in urban and some suburban areas, whereas the case for universal delivery in rural areas is not as strong. (JEL: L1, H4, R2)

1. Introduction

The importance of speed is well recognized. Higher speed brings workers and firms closer together and increases welfare due to travel-time savings and agglomeration

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benefits. Infrastructure projects—such as new metro lines, highways, high-speed rail, or airports, all of which presumably increase speed within or between cities and regions—have long been popular among policy makers. The economic impact of such projects is well understood, and supportive evidence is relatively robust (see, e.g., Baum-Snow 2007; Baum-Snow and Kahn 2000; Duranton and Turner 2011; Duranton et al. 2014; Faber 2014).

In this paper, we deal with a different type of speed: digital speed. Does it matter how quickly we can surf the Internet using broadband? The possibilities that come with a faster Internet are countless: video streaming, e-commerce, or telecommuting, to name just a few. In a recent bestseller, Lewis (2014) argues that superfast connections have even been used by high-frequency traders to rig the US equity market.[1] In contrast to the classic infrastructures mentioned above, it is normally left to the market to supply Internet connections, via Internet service providers (ISPs) such as telecom and cable providers. Policy makers have traditionally limited their interventions to a few targeted rural areas. Perhaps as a way to escape the economic crisis, this discreet approach has changed recently. In the United States, the Federal Communications Commission (FCC) launched the National Broadband Plan in 2010 to improve Internet access. One goal is to provide 100 million American households with access to 100 Mbit/s connections by 2020.[2] In Europe, broadband is one of the pillars of Europe 2020, a ten-year strategy proposed by the European Commission. Its Digital Agenda identifies targets that are as aspiring as those of the United States: also by 2020, *every* European citizen will need access to at least 30 Mbit/s.[3]

We argue that it is possible to infer the value brought by a faster Internet connection via changes in property prices. Theoretically, it is evident that fixed broadband, by far the usual way people connect to the fast Internet, comes bundled with a property whose price might, therefore, be affected. Broadband availability and speed embody just one characteristic of a property that contributes to determining its value (along with local amenities, infrastructure, and other neighborhood characteristics). Anecdotal evidence makes a strong case that broadband access is an important determinant of capitalization effects in property markets. In 2012, *The Daily Telegraph*, a major UK daily newspaper, reported the results of a survey among 2,000 homeowners, showing that a fast connection is one of the most important factors sought by prospective buyers. The article states that "[...] a good connection speed can add 5% to a property's value". Perhaps more tellingly, the survey says that one in ten potential buyers rejects a potential new home because of a poor connection, and that, although 54% considered broadband

1. Using fiber-optic cables that link superfast computers to brokers, the high-frequency traders intercepted and bought the orders of some stock traders, selling the shares back to them at a higher price and pocketing the margin. The key to this scheme was an 827-mile cable running from Chicago to New Jersey that reduced the journey of data from 17 to 13 ms (Lewis 2014).

2. https://www.fcc.gov/general/national-broadband-plan, accessed December 2015.

3. Additionally, at least 50% of European households should have Internet connections above 100 Mbit/s; see http://ec.europa.eu/digital-agenda/our-goals/pillar-iv-fast-and-ultra-fast-internet-access, accessed December 2015.

speed before moving in, only 37% looked at the local crime rate.[4] Rightmove, one of the main online real estate portals in the United Kingdom, rolled out a new service in 2013 to enable house hunters to discover the broadband speed available at any property listed on the site, along with more typical neighborhood information such as transport facilities or schools.[5]

To empirically estimate the valuation for broadband speed via the variation in house prices, we have access to very detailed information about broadband development and residential properties for the whole of England, over a rather long period (1995–2010). We find an elasticity of property prices with respect to speed of about 3% at the mean of the Internet speed distribution. However we also find diminishing returns—that is, the increase in value is greater when starting from relatively slow connections, which helps to put the empirical results in the right perspective. The average property price increased by 2.8% when going from a slow narrowband dial-up connection to the first generation of Asymmetric Digital Subscriber Line (ADSL) broadband Internet connections, which allowed a speed of up to 8 Mbit/s. The price increased by an additional 1% when a newer technology, ADSL2+, was rolled out to offer Internet speeds up to 24 Mbit/s. In other words, families are willing to pay a premium of 1% of the property price, or about £2,200 (≈$3,300) when, other things equal, the property is supplied by a fast connection compared to a normal broadband connection. This effect corresponds to an increase in school quality by one third of a standard deviation (Gibbons et al. 2013) or a reduction in distance to the nearest London underground station of one third of a kilometer (Gibbons and Machin 2005). The magnitude of the effect is smaller than, for example, the negative effect of having a convicted sex offender living nearby (4%, see Linden and Rockoff 2008) or the positive effect of a good grade awarded to the local school in a school quality review (8.7%, Figlio and Lucas 2004), but more sizable than the effect of the clean-up of a hazardous waste site (Greenstone and Gallagher 2008).

We further decompose these average results by income and degree of urbanization. It turns out that the gains are very heterogeneous, and they are highest at the top of the distribution, among the richest people living in the most densely populated areas, London in particular. Put differently, these results imply that, on average, a household would be willing to spend, over and above the subscription fee to the Internet provider, an extra £8 (≈$12) per month for the option to connect to the high speed ensured by ADSL2+ compared to an otherwise identical property that only had access to a basic ADSL connection. In rich and dense places like London the surplus can be as high as £25 (≈$37.5) per month. Endowed with these findings, we then evaluate the

4. http://www.telegraph.co.uk/property/propertynews/9570756/Fast-broadband-more-important-to-house-buyers-than-parking.html, accessed December 2015.

5. http://www.rightmove.co.uk/broadband-speed-in-my-area.html, accessed December 2015. Prior to this service, people looked for postcode-level speed information in broadband provider websites, forum discussions, and web-based speed checkers. This type of information started to appear with the launch of the first ADSL connections in the early 2000s; see, for example, http://forums.digitalspy.co.uk/showthread.php?t=190825, accessed December 2015.

benefits of the EU Digital Targets for different regions in England, which we compare with available cost estimates. We find that increasing speed and connecting unserved households pass a cost–benefit test in urban areas, whereas the case for universal delivery in rural areas is not very strong.

In order to provide reliable estimates of the valuation for broadband speed, we need to avoid the circular problem that is present in all spatial concentrations of economic activities. First, we need to separate the effect of high broadband speed on property prices from other favorable locational characteristics, such as good transport access or schools. Second, the available speed is endogenous to factors that determine broadband demand and are likely correlated with property prices, such as high levels of income and education levels. Thus, to avoid spurious correlation, we have to account for macroeconomic shocks such as gentrification that potentially affect speed and property prices simultaneously.

We are able to trace the presence of broadband, and its speed, at the level of each local delivery point, called a Local Exchange (LE) in the United Kingdom (this would be called the Central Office in the United States). Every home can be supplied by one and only one LE, which we can perfectly identify. Within a given LE area, the distance between the user's premises and the LE is, by far, the most important factor affecting the performance of a given connection. In addition, LEs have been upgraded at different points in time, with some exchanges boasting faster technologies than others. The local distribution from legacy phone networks does not influence phone quality but does affect broadband quality. This provides us with an ideal variation of speed over time within an extremely small area. We are able to identify the causal effect of digital speed on property prices from two alternative sources of variation. First, we exploit a discontinuity *across* LE boundaries over time. Adjacent properties can belong to the catchment areas of different LEs and, therefore, with different distances to the exchange and possibly also different vintages of technology. Holding constant all shocks to a spatially narrow area along the boundary of two LEs, the discontinuous changes in speed that arise from LE upgrades at both sides of such a boundary provide variation that is as good as random. In other words, we compare the house prices of two properties, located next to each other, that are observationally equivalent in terms of characteristics but for the speed available to each one of them. Second, we use variation over time *within* LEs. Because we can hold constant any macroeconomic shock that mutually determines property prices and upgrade decisions, which are made at the LE level, the conditional variation in speed is plausibly exogenous. Both identification strategies result in very similar estimates.

Our work is related to two streams in the literature. In general, our methods are common to a large literature in urban and public economics that has explored capitalization effects of local public goods or nonmarketed externalities more generally (Chay and Greenstone 2005; Davis 2004; Greenstone and Gallagher 2008; Linden and Rockoff 2008). We use similar methods and show how they also can be used in settings where, a priori, we would not think of an externality. Here, we deal with a market that is largely competitive and privately supplied, but there are still capitalization effects: a good part of the consumer surplus associated with broadband consumption seems to go to the property seller as a scarcity rent, and not to the broadband suppliers.

A second stream in the literature to which we contribute is related to the evaluation of broadband demand and of the benefits associated with Internet deployment. At a macro level, Czernich et al. (2011), using a panel of OECD countries, estimate a positive effect that Internet infrastructure has on economic growth. Kolko (2012) also finds a positive relationship between broadband expansion and local growth with the US data, whereas Forman et al. (2012) study whether the Internet affects regional wage inequality. Greenstein and McDevitt (2011) provide benchmark estimates of the economic value created by broadband Internet in the United States. Some studies assess the demand for residential broadband: Goolsbee and Klenow (2006) use survey data on individuals' earnings and time spent on the Internet, whereas Nevo, Turner, and Williams (2016) employ high-frequency broadband usage data from one ISP. To our knowledge, ours is the first study to estimate consumer surplus from Internet usage using property prices for a large economy.

The rest of the paper is organized as follows. In Section 2, we describe the development of broadband Internet in England and discuss the theoretical linkage between broadband speed and property prices. Section 3 presents the empirical strategy. The main results are shown and discussed in Section 4. Section 5 uses the empirical findings to quantify the benefits for the EU 2020 digital targets. Finally, Section 6 concludes.

2. The Broadband Market

In this section, we first describe the recent development of broadband Internet in England and then give an overview of its variation over time and space. We then describe our data sources. Finally, we provide a simple theoretical model that links broadband availability, and its speed, to property prices.

2.1. The Broadband Market in England

The market for Internet services in England[6] is characterized by the presence of a network, originally deployed by British Telecom (BT) during the first part of the 20th century to provide voice telephony services. BT was state-owned until its privatization in 1984. This network consists of 3,897 Local Exchanges (LEs). Each LE is a node of BT's local distribution network (sometimes called the "local loop") and is the physical building used to house internal plant and equipment. From the LE, lines are then further distributed locally, by means of copper cables, to each building in which customers live or work, which tend to be within 2 km from the LE. LEs aggregate local traffic and then connect up to the network's higher levels (e.g., the backbone) to ensure world-wide connectivity, typically by means of high-capacity (fiber) lines.

6. The broadband description applies to the whole of the United Kingdom. However, since our property data cover only England, we always refer to England alone throughout the paper.

Although the basic topology of BT's network was decided several decades ago, technology has proven extremely flexible. The old copper technology, until the end of the 1990s, provided a speed up to 64 kbit/s per channel via dial-up (modem) connections. Without having to change the cables in the local loop, it has been possible to supply high-speed Internet by installing special equipment in the LEs. A breakthrough occurred with a family of technologies called digital subscriber line (DSL), which use a wider range of frequencies over the copper line, thus reaching higher speeds. The first major upgrade program involved bringing the ADSL technology to each LE. BT began the program in early 2000 and took several years to complete it. This upgrade could initially improve Internet speed by a factor of 40 compared to a standard dial-up modem and, afterwards, allowed speeds up to 8 Mbit/s.

Along with technological progress, the regulatory framework and the competitive landscape also evolved over the same period. Ofcom, the United Kingdom's regulator for communications, required BT to allow potential entrants to access its network via the so-called "local loop unbundling" (LLU). LLU is the process whereby BT makes its local network of LEs available to other companies. Entrants are then able to place their own equipment in the LE and to offer services directly to customers. LLU started to gain pace in 2005, and entrants have progressively targeted those LEs located in more densely populated areas. Regulatory intervention is limited to wholesale prices, whereas retail prices are freely set by competing providers. A further major improvement occurred with ADSL2+. This upgrade, which allows for download speeds, theoretically, up to 24 Mbit/s, started around 2007. It was first adopted by some of the new LLU entrants, and BT followed with some lag. ADSL, LLU, and ADSL2+ are going to be major shifters of speed in our data, as they varied substantially over time and by LE. In addition, all technologies based on DSL are "distance sensitive" because their performance decreases significantly as you get further away from the relevant LE.

Of course, the diffusion of broadband Internet was not uniform across the United Kingdom, and several demand and supply factors determined different penetration rates across markets and over time. Nardotto et al. (2015) document how the entry process took off around 2005, and show that entrants improved considerably the speed available locally in each LE where they entered. First, local entry of new providers was the main reason for the adoption of broadband Internet. In order to recover entry's large investment, entrants first unbundled the larger and more profitable LE markets, and later expanded to cover a large share of the country. Second, the shape and the size of the area covered by each LE was an important determinant of entrants' costs. Finally, rapid technological progress, along with entrants' learning curves, decreased costs over time.[7]

Figure 1 shows the evolution of the share of English households in the catchment area of LEs enabled with ADSL (black solid line) or with LLU entrants (gray solid

7. See Chen and Savage (2010) for a related analysis for the United States.

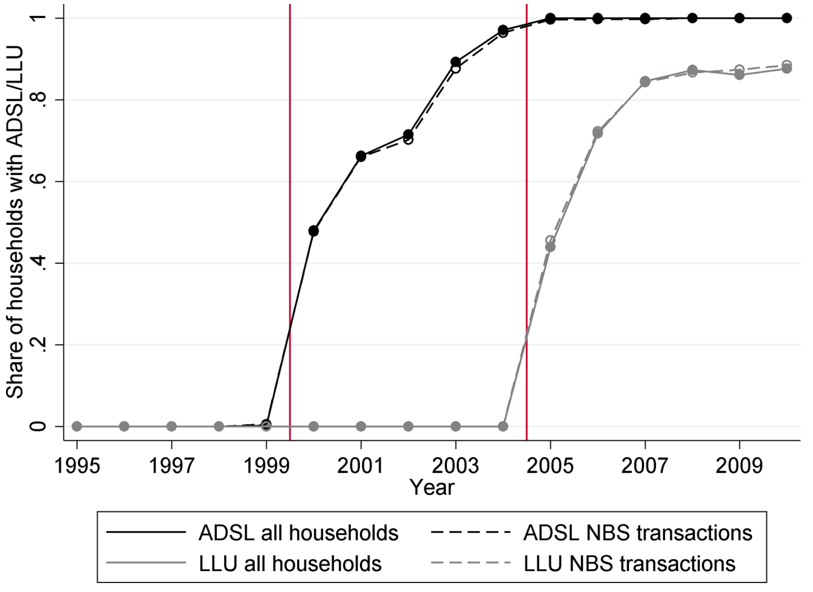

FIGURE 1. Share of households with ADSL/LLU over time. Black (gray) lines refer to ADSL (LLU) activation. Solid (dashed) lines refer to all households in England (NBS = Nationwide Building Society transactions data set). [Color online]

line).[8] We therefore cover the period that was crucial for the development of residential Internet. The share of properties in our sample reflects very closely the technological pattern in England (dashed lines), providing reassurance on its representativeness. In Online Appendix A, we provide further empirical evidence, showing maps of how these technological changes occurred by region and over time.

Figure 2 is a static map of a few LEs located north of London. The figure reports the location of the relevant LEs in that area (big black dots), and their catchment areas, based on the full postcodes served (black boundaries). Each grey dot represents the location of one transaction in the property dataset, where lighter colors correspond to increasing distances from the exchange (from red to yellow in the online version). Black icons denote groups of properties that have been matched to common boundary segments. These two figures show two important things that will inform our empirical strategy. First, there is considerable variation both in the distance between premises and the relevant LE (Figure 2), and in the technology available over time at a given LE, which should have an impact on the available speed for a specific property (Figure 1). We will, thus, be able to control for unobserved shocks to neighborhoods at very disaggregated levels and restrict identification to variation that stems from changes in the relative distribution of speeds within LEs over time. Second, there are enough

8. We do not show ADSL2+ in order not to clutter the figure, but it would lie below the LLU curve.

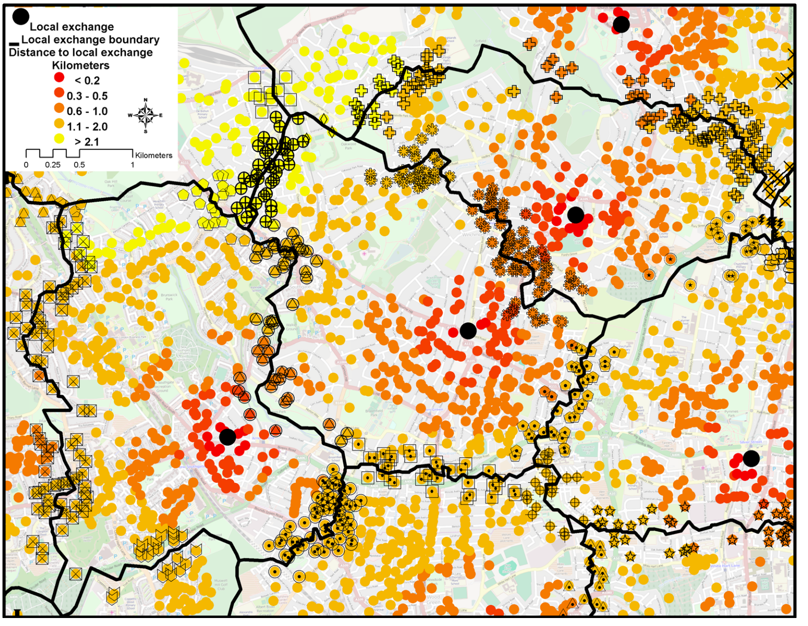

FIGURE 2. Distribution of properties and LE catchment areas. Black icons denote groups of properties within 200 m of a shared boundary segment. The gray dots are transactions from the NBS dataset. The black dots are the locations of LEs and the black boundaries are their catchment areas, both from the Ofcom dataset. [Color online]

properties at the LE boundary allowing us to exploit discontinuities in speed increases if one or both LEs are upgraded.

To complete the picture, broadband Internet can also be supplied via an alternative cable network.[9] The cable operator Virgin Media deployed its own network during the 1990s, primarily for the purpose of selling cable TV. The topology of this network is very different from that of BT. It covers roughly 50% of the premises in England, concentrating its presence in urban areas and flat parts of the country. The cable network can be upgraded to support broadband only if an area is already covered by cable, which has not expanded its reach since the 1990s. Cable technology, since it also aims at providing TV, is typically faster than ADSL, and broadband speed does not degrade substantially with distance from the exchange.

9. At the beginning of 2010, BT had a retail market share of 28%, the cable operator had a market share of approximately 22%, and the entrants (the main ones are TalkTalk, Sky, O2, and Orange) had the remaining 50% of the market. There has been little investment in fiber within the local loop, and during the period we consider here, there has been limited take-up of high-speed connections based on 3G cellular technology. Broadband access via Wi-Fi technologies, on the other hand, is included in our dataset.

2.2. Raw Data

Our dataset stems from several sources. The main block concerns the development of broadband in England over the period 1995–2010. Ofcom has made available to us all the information it collects on the broadband market for regulatory purposes. The dataset comprises quarterly information at the level of each of the 3,897 LEs in England. For each local exchange, we know the precise coverage of BT's local network—that is, all the specific full postcodes served by a certain LE—and, therefore, we know how many buildings and total lines can eventually have broadband. We remark that a full postcode unit contains about 10–15 households, which are all connected to the same LE.[10]

We can identify when a LE was upgraded to ADSL or ADSL2+, and if and when it attracted entrants via LLU. We also know, in the catchment area of the LE, whether or not cable is available. Finally, we know how broadband penetration varies over time in a given LE, as we are told the total number of subscribers (via BT, via an entrant, or via cable), which can be compared to the total lines available locally to compute broadband penetration.

This detailed information was supplemented with information on broadband speed tests carried out by individuals in 2009 and 2010. We obtained three million tests from a private company.[11] For each individual/speed test, we observe the operator, the contract option chosen by the user, the location (full postcode), as well as when the test was carried out. Thus, we can calculate the distance between the user's premises and the exact location of the relevant LE. The dataset contemplates two measures of performance: download speed and upload speed. We focus on the former, which is, by far, the more important feature for residential household users. It is important to note that, throughout the whole paper, we refer to the speed measured in the dataset on speed tests as "actual" speed. This is not the same as the speed typically advertised by operators in their plans, to which we refer as "nominal" speed.[12]

For the analysis of the capitalization effects of broadband capacity, we use transactions data related to mortgages granted by the Nationwide Building Society between 1995 and 2010. The data for England comprise more than one million observations,[13] and include the price paid for individual housing units along with detailed property characteristics. These characteristics include floor space (m^2), the

10. A full (typically, seven digit) postcode in the United Kingdom captures a narrowly defined area. There are approximately two million postcodes in the United Kingdom. A full postcode is not an address, but still covers areas that are on average within a radius of 50 m, which gets even narrower in densely populated areas (e.g., 20 m in London).

11. http://www.broadbandspeedchecker.co.uk, accessed December 2015. More information is provided in Section 3.1.

12. The discrepancy for the top plans is large and amounts to a factor of 4 (results are available on request from the authors). This factor is also in line with independent findings of Ofcom; see, for example, http://stakeholders.ofcom.org.uk/market-data-research/other/telecoms-research/broadband-speeds/speeds-nov-dec-2010/, accessed December 2015, and Figure 1.2 in particular.

13. This represents 10% of all mortgages issued in England over the period.

type of property (detached, semi-detached, flat, bungalow, or terraced), the date of construction, the number of bedrooms and bathrooms, garage or parking facilities, and the type of heating. There is also some buyer information, including the type of mortgage (freehold or leasehold) and whether they are first-time buyers. Note that the transaction data include the full UK postcode of the property sold, allowing it to be assigned to grid-reference coordinates.

With this information, it is possible with Geographic Information System (GIS) software to calculate distances to LEs. Furthermore, it is possible to calculate distances and other spatial measures (e.g., densities) for the amenities and environmental characteristics such as National Parks, as well as natural features such as lakes, rivers, and coastline. The postcode reference also allows a merger of transactions and various household characteristics (median income and ethnic composition) from the UK census; natural land cover and land use; and various amenities, such as access to employment opportunities, retail services, cultural and entertainment establishments, school quality, and measures of online services (e.g., Amazon evening delivery, Uber fleet services). A more-detailed description of all the data used is in Online Appendix B. In Online Appendix C.1, we also show that the distributions of other observable amenities do not differ discontinuously on the two sides of a LE.

2.3. A Simple Conceptual Model

Unlike local public goods such as good (public) schools, public safety, or air quality, which are often analyzed in the house price capitalization literature, households subscribed to broadband pay a price to their Internet provider. A capitalization effect of broadband is, therefore, not an obvious feature of the spatial equilibrium. The purpose of this section is to introduce a simple model that links broadband speed to property prices. Our intention is not to introduce a model for structural estimation, but, rather, to think about this link in a simple and transparent manner.

For this purpose, imagine that there are n areas, indexed by $j = 1, \dots, n$. In each area there is a population of household buyers whose total number is normalized to unity. The value of a property is denoted as V, which can be made dependent on all its characteristics, such as number of rooms, local amenities, and so forth, except for broadband availability, which is described next. The price of a property is denoted as P.

Households are heterogeneous in their value of using broadband. Value can derive from different sources—from leisure (surfing the Internet) to being able to work from home. We are not interested in the particular channel, but simply imagine that people are heterogeneous in the way that they use and value the Internet. Let $v \cdot \log(q_j)$ denote the gross utility of household type v using a broadband of quality q_j, where q_j is the Internet quality available in area j, for instance, the speed of the connection. This specification reflects diminishing marginal returns to speed, as well as the fact that everybody would enjoy faster connections, ceteris paribus, despite heterogeneity in tastes. The distribution of household types v is assumed to be uniform between 0 and a_j in area j, thus the density is $1/a_j$.[14]

The consumers' choice is whether or not to purchase broadband, conditional on having bought a property. We normalize the payoffs from not using broadband to zero. Broadband of quality q_j is sold at a price p_j. Since broadband is a durable good, all these variables are to be interpreted as flows in each period. We also assume that, at some period in the future denoted as T_j, some alternative technology that does not need fixed lines becomes available, and it will be preferred by all customers (because it is cheaper or better, or both). Think, for instance, of Long-Term Evolution (LTE) mobile technology replacing fixed broadband. The key point is that this technology will *not* be bundled with the property anymore, but it will represent a completely separate purchase that has nothing to do with a property. The cumulative utility for type v from fixed broadband access is thus $[v\log(q_j) - p_j]\Delta_j$, where $\Delta_j = \int_0^{T_j} e^{-\rho t}\mathrm{d}t = (1 - e^{-\rho T_j})/\rho$ and ρ is the discount rate. Note that, if the alternative technology never becomes available, $T_j \to \infty$ and the discount factor Δ_j simplifies to $1/\rho$, that is, the value of a perpetuity.

Households whose value of broadband is high enough will purchase a broadband connection. In particular, the marginal broadband household in area j is defined by $v_j{}^* = p_j/\log(q_j)$, and all types between $v_j{}^*$ and a_j purchase broadband in that area in every period.

On the property supply side, we assume that homes in a given area are scarce, such that sellers can always extract all buyers' net surplus. Alternatively, we can also assume that sellers are able to observe buyers' types—during negotiations, for example—and make take-it-or-leave-it offers leading to the same outcome. Households are assumed to be perfectly mobile, with reservation utility U. In a spatial equilibrium, house prices in area j will, therefore, be

$$P_j = \begin{cases} V - U \quad \text{for } v < v_j{}^* \text{ (households without broadband),} \\ V - U + [v\log(q_j) - p_j]\Delta_j \quad \text{for } v \geq v_j{}^* \text{ (households with broadband).} \end{cases} \tag{1}$$

Since the econometrician will not observe types, but just the average prices in a given area with or without broadband subscription, we can calculate these averages from (1) as

$$\overline{P}_j = \frac{(V - U)v_j{}^*}{a_j} + \int_{v_j{}^*}^{a_j} \frac{[V - U + (v\log(q_j) - p_j)\Delta_j]}{a_j}\mathrm{d}v = V - U + K_j\Delta_j, \tag{2}$$

where

$$K_j \equiv \frac{(a_j q_j - p_j)[(a_j q_j + p_j)\log(q_j) - 2q_j p_j]}{2a_j q_j^2}.$$

14. The example is generalizable to a more general distribution function $F(v)$ that satisfies the monotone hazard rate condition.

It is a matter of simple maths to show that[15]

(a) $\frac{\partial \overline{P}_j}{\partial q_j} = \Delta_j \frac{\partial K_j}{\partial q_j} > 0$ and $\frac{\partial \overline{P}_j^2}{\partial q_j^2} < 0$,

(b) $\frac{\partial \overline{P}_j}{\partial a_j} = \Delta_j \frac{\partial K_j}{\partial a_j} > 0$,

(c) $\frac{\partial \overline{P}_j}{\partial T_j} = K_j \frac{\partial \Delta_j}{\partial T_j} > 0$.

Equation (2) and the associated comparative statics confirm the intuition that broadband speed gets capitalized into house prices. In particular (part (a)), prices should increase in those areas with higher available speed q_j, and they increase at a decreasing rate (decreasing returns to speed). Prices should also increase (part (b)) in those areas where there is a higher willingness-to-pay (WTP) for the Internet, because of the heterogeneity in the population that we have modeled via a_j (which may be related to income, something we do observe at the level of an area in our data). Places with the highest price premium for speed are likely also to have residents with the greatest taste for speed. Equation (2) also makes a point about sorting: the coefficient estimates from the hedonic price regressions that we will run should return the mean marginal valuations of properties (Bayer, Ferreira, and McMillan 2007), and we need to be careful when conducting policy evaluation involving levels of speed different from those observed. Finally (part (c)), the capitalization effect depends on whether there is an expectation that fixed line broadband will be displaced by technologies that are not bundled with the property. If these technologies do not exist, our results effectively capture a perpetuity in the value of broadband, else they will capture only the net present value from a shorter period.

The model also has an ancillary prediction about broadband penetration in a given area. This provides a useful check for the robustness of our main results and a way to evaluate the channels through which the capitalization effect operates. Penetration is given by

$$Penetration = 1 - \frac{v_j^*}{a_j} = 1 - \frac{p_j}{a_j \log(q_j)}, \tag{3}$$

which is also increasing in speed q_j, and at a decreasing rate. Equation (3) also says that—ceteris paribus—penetration in a certain area is driven by Internet characteristics (q_j and p_j) and by population characteristics (a_j), but not amenities that depend themselves on the availability of fast broadband (e.g., cybercafés).

Note that we left the broadband subscription price p_j unmodeled, thus the main prediction that property prices increase with speed is independent of the precise market structure of the local broadband market: intuitively, it is stronger when the broadband

15. One just needs that $p_j < a_j \log(q_j)$, which must hold true for the problem to make economic sense, otherwise, not even the household with the highest willingness to pay would get a broadband subscription.

supply is very competitive, but it holds even for a monopolist provider. In other words, there are limits to the consumer surplus that ISPs can appropriate when speed increases. Competition is the upper limit, in fact, broadband subscription fees cannot increase with willingness to pay for speed when competition is intense, as they will just reflect costs. But even a monopolist would be constrained by its inability to observe different types perfectly and would, therefore, leave some information rent to higher types. Our approach presumes that all remaining consumer surplus from broadband, over and above the broadband price paid to the provider, is appropriated by the seller of the property. If this were not the case, then the impact that broadband might have on property prices would underestimate the consumer surplus from broadband use. We will return to this point in our conclusions.

3. Empirical Framework

The primary aim of our empirical strategy is to provide a causal estimate of the impact of high-speed broadband supply on house prices. The empirical challenge in estimating this causal effect is to separate the effect of broadband supply from other unobserved and potentially correlated determinants of house prices. In particular, we must ensure that there are no omitted variables that simultaneously determine broadband supply and house prices. We argue that robust identification can be achieved from discontinuous variation in speed *over* time and *across* LE boundaries. Variation over time helps disentangle the effect of broadband supply from unobserved (spatially) correlated locational factors, such as good transport access or better schools. By further placing properties into groups that are near to and share the same LE boundary, it is possible to control for shocks at a very small spatial level. We argue that variation in speed over time across a LE boundary within such a small area is plausibly exogenous and as good as random. We also run an alternative identification that relies on the comparison of house prices to broadband supply *over* time and *within* LE areas. Decisions that affect the broadband supply of a property are generally taken at the level of the LE serving an area. Conditional on shocks to a certain LE catchment area—such as a sudden increase in income or education of the local population—within-LE variation in speed over time that results from the distance of a property from the relevant exchange can be assumed to be exogenous.[16]

We follow the popular hedonic pricing method to separate various determinants of property prices. Rosen (1974) has provided the microfoundations for interpreting parameters estimated in a multivariate regression of the price of the composite housing good against several internal and locational characteristics as hedonic implicit attribute prices. Underlying the hedonic framework is the idea that, given free mobility in spatial

16. Note that local exchange areas are relatively small. The median radius of a local exchange area is less than 6 km, as far as old voice telephony services are concerned. As for broadband, the area where it can be supplied effectively is smaller, up to 2–3 km from the local exchange, as shown below in the results. In cities, the median radius of a LE is further reduced—for example, less than 2 km in London.

equilibrium, all locational (dis)advantages must be offset by means of property price capitalization. There is a long tradition in the literature—dating back at least as far as Oates (1969)—that made use of the hedonic method to value local public goods while holding confounding factors constant. One of the typical challenges faced by such hedonic valuation studies is the potential for bias due to omitted variables that are correlated with a phenomenon of interest. Recent applications of the hedonic method have tackled this problem by making use of variation over time to identify the effects of locational improvements from unobserved time-invariant locational factors (Ahlfeldt and Kavetsos 2014; Chay and Greenstone 2005; Davis 2004; Linden and Rockoff 2008).

Both of the empirical specifications we employ are drawn from this line of research. We model the (log) price of a property sold at a full postcode i at time t, served by LE j and lying on the LE boundary segment k as a function of the available broadband speed, as well as a range of internal and locational property characteristics that are partially observed and partially unobserved. Our baseline empirical specification is a variant of a spatial boundary discontinuity design (BDD):

$$\log(P_{ijkt}) = \sum\nolimits_{m=1}^{2} \alpha_m (S_{ijt})^m + \sum\nolimits_{n=1}^{4} \tau_n (DIST_{ij})^n + X_i' \mu_t + \psi_{kt} + \varphi_j + \varepsilon_{ijt}, \tag{4}$$

where S_{ijt} is the available broadband speed, and $DIST_{ij}$ is the Euclidian distance from a postcode i to the relevant LE j. We use a quadratic specification for broadband speed to allow the property price to vary non-linearly with speed, as predicted by our simple model. The distance polynomial controls for unobserved time-invariant locational characteristics that are correlated with distance to the LE. As discussed in more detail in the next section, our variable of interest S_{ijt} is constructed using fourth-order polynomials of $DIST_{ij}$ following an engineering literature. Because S_{ijt} varies over time, the speed effect, after controlling for the time-invariant distance trend, is identified from variation over time. The control variable approach is therefore equivalent to postcode fixed effects in terms of its power to absorb unobserved locational effects that are correlated with S_{ijt}. Compared to the alternative of using postcode fixed effects, we prefer this control variable approach because of a relatively limited number of repeated sales at the same postcode level.[17] X_i' is a vector of property and locational characteristics discussed in the data section. This is interacted with a full set of year effects, so that μ_t is a matrix of implicit prices for attribute-year combinations. φ_j is a dummy to control for unobserved time-invariant LE effects. Finally, k indexes properties that lie along the same boundary segment that separates two LE areas. We match properties in LE j to the nearest property in LE $l \neq j$ and define a common time-varying fixed effect ψ_{kt} for properties in j whose nearest neighbor is in l and vice

17. Less than half (15%) of the full postcodes in the Nationwide data set contain two (three) or more transactions. On average, there are 2.15 transactions per full postcode over the 15-year period we cover.

versa. These fixed effects ensure that we identify from a differential increase in speed at the two sides of the boundaries, holding constant all other time-varying effects that are common to both sides of a boundary. Figure 2 illustrates the matching of properties across adjacent LEs.

This specification exploits the discontinuity at the boundaries between LEs. Overall, there are 86,569 LE boundary × year effects in our data, which denote boundary segments that are common to the same two LEs. With this specification, we attribute differences in price changes over time across a common boundary to the respective differences in speed changes over time. We restrict our sample to properties that are close to a LE boundary to explicitly exploit the spatial discontinuities in speed changes that arise across a LE boundary if the broadband infrastructure is altered. We note that a discontinuity arises not only if just one of two adjacent LEs is upgraded, but also if both LEs are upgraded, and the distance to the respective LEs differs significantly at both sides of the LE boundary. Because, at a local level, the allocation of a property to either side of the same boundary is as good as random, it is unlikely that unobserved shocks affect speed and property prices on one side of the boundary but not on the other. Even in this unlikely event, such shocks are absorbed by the LE boundary × year effects.

We also estimate an alternative specification in which we replace the LE boundary × year effects with a set of 37,804 LE × year fixed effects φ_{jt} that control for all macroeconomic shocks at the LE level:

$$\log(P_{ijt}) = \sum\nolimits_{m=1}^{2} \alpha_m (S_{ijt})^m + \sum\nolimits_{n=1}^{4} \tau_n (DIST_{ij})^n + X_i' \mu_t + \varphi_{jt} + \varepsilon_{ijt}. \quad (5)$$

With this specification we focus on a different source of variation, compared to equation (4). Instead of exploiting discontinuous variation in speed over time across LE boundaries we now identify exclusively from continuous variation in speed over time within LEs. In estimating equation (5) we also use the universe of transactions and variation in speed, which helps addressing the external validity problem inherent to all boundary discontinuity designs. This specification delivers a causal effect of broadband speed on house prices under the identifying assumption that year-specific shocks that potentially determine broadband capacity are uncorrelated with distance to the LE within the area that the LE serves. This is a plausible assumption for two reasons. First, any change to the LE technology will affect the entire catchment area served by the LE, so it is rational for broadband suppliers to base decisions on the average trend in this area. It is, therefore, unlikely that within-LE shocks that might affect property prices—for example, an income increase among the population near the LE relative to other areas—would also affect the technological upgrading decisions above and beyond their effect on the LE area average, which is captured by φ_{jt}. Second, LEs serve relatively small areas, with a layout that was defined decades ago and boundaries that do not line up with spatial statistical units, such as census wards. The catchment area of each LE is typically known only to providers and is not used to create any other related boundaries. Reliable information on year-on-year changes at the sub-LE area level is difficult to obtain, which makes it unlikely that providers would be able to respond within LE-area shocks even if they wanted to.[18] This specification is arguably more open to criticism because there may be within-LE trends in property prices that are correlated with distance to the LE, something that is absent with the previous specification relying on the boundary discontinuity. It is noteworthy that the interactions of year effects and attributes X_i' flexibly control for property price trends that are correlated with any of the observable structural and locational characteristics. Conditional on these controls, it is less likely that within-LE trends, which are correlated with but not causally related to changes in speed within LEs over time, confound the estimated broadband speed effect. Moreover, we can also use difference-in-differences techniques to reassure ourselves that, conditional on the strong controls employed, there are no within LE trends correlated with distance to the LE that could lead to spurious broadband supply effects.

We finally note that equations (4) and (5) are complementary. Adding LE × year fixed effects φ_{jt} to equation (4) would partially absorb the identifying discontinuous variation in speed over time across LE boundaries. Likewise, adding LE × year boundary fixed effects ψ_{kt} to equation (5) would partially absorb the identifying continuous variation in speed over time within LEs. Because the two equations are designed to identify the broadband capitalization effect from two different types of variation, consistent estimates will be particularly indicative of their robustness.

3.1. The Relationship Among Technology, Distance, and Speed

As said above, we have very detailed information on the exact broadband capacity to deliver achievable speeds at a specific property at a high spatial detail, but not over the entire period. We know, however, the technology available in each LE at different points in time. We now establish the technological relationship between actual Internet speed, the technology of a LE, and the distance from a test location to the LE, using the comprehensive data set of Internet speed tests in the sub-period 2009–2010. Combining both ingredients, it is possible to generate the micro-level Internet speed panel variable we require for a robust identification of the causal effect of broadband capacity on house prices.

We model broadband actual speed as a function of LE characteristics and the distance to the LE, as well as the interaction between the two. In doing so, we first need to account for a significant proportion of speed tests that are likely constrained not only by technological limitations (distance to the LE and LE characteristics), but also by the plans users have chosen to subscribe to. In other words, speed can be low not because technology is limited, but because a subscriber with small consumption choses a plan with limitations. We want to get rid of these plans so that we can unravel the true speed that a certain technology can potentially supply. To identify the plans

18. It is telling that all the regulatory analysis done by Ofcom, which relies on information supplied by the broadband operators, is, indeed, conducted at the LE level, instead of at a more disaggregated level, such as street cabinets. This is because the regulator believes that the relevant market for business decisions is the LE, which is where most investments have to be sunk.

that do not constrain broadband speed beyond the technological limitations of the LE, we run the following auxiliary regression:

$$\log(S_{ijt}) = \sum\nolimits_{m=2}^{12} \alpha_m + \sum\nolimits_{h=1}^{23} \alpha_h + \sum\nolimits_{w=1}^{6} \alpha_w + \sum\nolimits_{p=1}^{62} \alpha_p + \sum\nolimits_{d=2}^{60} \alpha_d + \varphi_{jt} + \varepsilon_{ijt}, \tag{6}$$

where S_{ijt} is the actual broadband speed test score measured at postcode i served by local exchange j at time t. α_m are month of the year effects (baseline category is January), α_h are hour of the day effects (baseline category 0 h), α_w are day of the week effects (baseline category Sunday), α_p are Internet plan effects (baseline category is missing information), α_d are distance to LE effects captured by 100 m bins (e.g., 2 covers distances from 150 to 250 m, baseline category is 0–150 m), and φ_{jt} are a set of LE-year specific fixed effects that capture unobserved LE characteristics in a given year. For the ensuing analysis, we keep observations whose α_p falls in the upper quartile, as the plans that realize the fastest actual speeds are unlikely to be constrained by the provider.

Using this subsample of speed tests that should be constrained only by technology, we then establish the technological relationship between available actual broadband speed S_{ijt} and distance to the relevant LE ($DIST_{ij}$) for each technological category $Q = \{\text{ADSL, ADSL + LLU, ADSL2+}\}$ in separate regressions of the following type:

$$\log(S_{ijt}) = \sum\nolimits_{m=2}^{12} \alpha_{mQ} + \sum\nolimits_{h=1}^{23} \alpha_{hQ} + \sum\nolimits_{w=1}^{6} \alpha_{wQ} + \sum\nolimits_{n=0}^{4} \alpha_{nQ} (DIST_{ij})^n + \varphi_{jQ} + \omega_{tQ} + \varepsilon_{ijtQ}. \tag{7}$$

The fourth-order polynomial is used to capture the non-linearities reported in the technical literature.[19] Since we drop 75% of the observations compared to equation (6) and split the remaining sample into three categories in order to find technology-specific effects, we account for location and year effects separately, rather than accounting for their interaction, to save degrees of freedom in sparsely populated LEs. Based on the estimated distance decay parameters α_{nQ} and the known Q-type upgrade dates T_j^Q, it is then straightforward to predict the available actual broadband speed at any postcode i that is served by a LE j over the entire period:

$$S_{ijt} = \begin{cases} ISDN = 128\,\text{kbit/s} & \text{if} \quad t < T_j^{ADSL} \\ \exp\left[\sum_{n=0}^{4} \alpha_{nQ} (DIST_{ij})^n\right] & \text{if} \quad T_j^Q \le t < T_j^{Q'} \end{cases}. \tag{8}$$

19. For a list of the factors that affect local broadband speed, see, for example, the explanation provided by BT: http://bt.custhelp.com/app/answers/detail/a_id/7573/c/, accessed December 2015. A detailed analysis of the factors that affect the performance of ADSL networks is found in Summers (1999). We note that the choice of a fourth-order polynomial for distance was dictated by its goodness of fit. There was no gain in going toward higher orders.

TABLE 1. Speed results.

	(1)	(2)	(3)	(4)
	log of download speed (kbit/s)			
Technology	Broadband ADSL	Broadband ADSL+LLU	Broadband ADSL2+	Cable
Distance from test postcode to LE in km	0.184	0.057	0.053	0.016
	(0.145)	(0.121)	(0.071)	(0.032)
Distance^2	−0.293***	−0.287***	−0.491***	0.016
	(0.097)	(0.097)	(0.055)	(0.029)
Distance^3	0.058**	0.070**	0.141***	−0.001
	(0.024)	(0.028)	(0.017)	(0.010)
Distance^4	−0.003*	−0.005**	−0.011***	−0.001
	(0.002)	(0.002)	(0.002)	(0.001)
Constant	7.869***	8.214***	8.672***	8.334***
	(0.098)	(0.065)	(0.036)	(0.017)
LE effects	Yes	Yes	Yes	Yes
Month effects	Yes	Yes	Yes	Yes
Day of the week effects	Yes	Yes	Yes	Yes
Hour of the day effects	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
*r*2	0.358	0.318	0.242	0.034
N	53,961	64,447	310,256	290,067

Notes: Only observations falling into the top-quartile of contracts are used in the regressions. Standard errors in parentheses are clustered on LEs. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

This compact formulation says that, before broadband is rolled out in LE j, the line is served with a basic ISDN technology, as a voice telephony line is in place. Then, ADSL brings its upgraded speed at any period after T_j^{ADSL}. The decay parameters may further change if the LE additionally receives, at a certain point in time $T_j^{Q'}$, technology $Q' = \{\text{ADSL} + \text{LLU},\ \text{ADSL2+}\}$.

We start by reporting the results on the physical relationship among speed, technological characteristics of the LE, and distance between the premise and the LE, as described by model (7). Our findings are shown in Table 1.

Although, due to space limitations, we do not detail the various fixed effects in the table, they all show a very reasonable behavior. The time of day is an important factor: the average connection speed reaches its peak at 5 a.m., when download speed is about 12% faster than the reference speed at midnight. It then gradually declines, with speed 3% lower at noon, 11% lower at 6 p.m., and close to 20% lower at 8 p.m., when the worst daily speed is attained. From then on, the average speed of a connection gradually increases until 5 a.m. The day of the week also determines average speed: it is lowest over the weekend, when residential users tend to be at home. These findings are due to obvious local congestion when most people are online simultaneously. Congestion

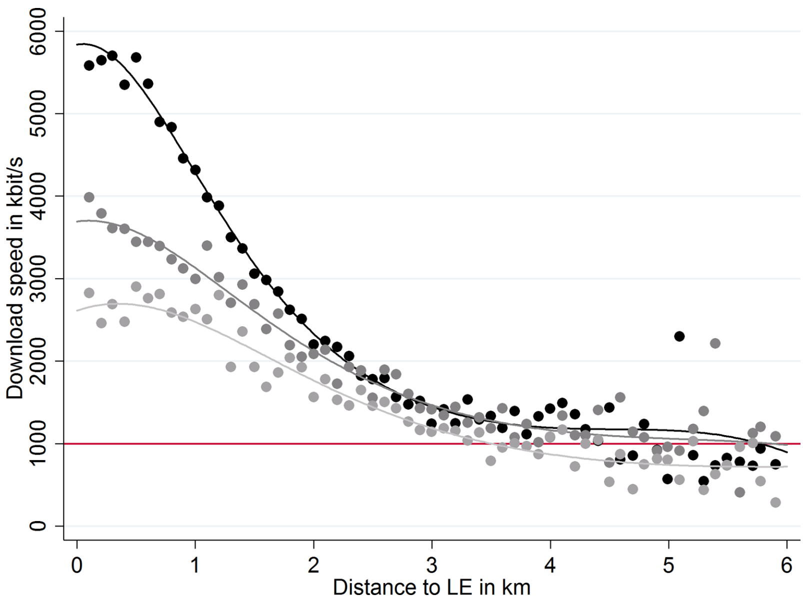

FIGURE 3. Distance decay by LE type. Black lines and dots indicate ADSL2+ LEs, dark (respectively, light) gray lines and dots are ADSL LEs with (respectively, without) LLU. [Color online]

is, thus, another facet of speed that shows striking analogies in the digital and the real worlds (see, e.g., Couture et al. 2012; Duranton and Turner 2011).

Turning to the impact of distance, which is of more direct interest for our purposes, this is shown in columns (1), (2), and (3) of Table 1 for ADSL, LLU, and ADSL 2+, respectively. Distance plays a statistically very significant role for all of them. Table 1, column (4) also runs a placebo test. The cable technology, which is available only in some parts of the country, does not rely on copper wires and does not suffer from distance-decay problems. Thus, the distance of a home from any exchange should not impact speed. Column (4) reports the results for one set of cable contracts offered by the cable provider, and, indeed, distance is found to have no impact.

One way of showing the relevance of the results is to evaluate the fit of the polynomial approximation. We estimate the distance relationships replacing the polynomial, as estimated in Table 1, with a set of 100 m distance bin effects, as used in equation (6). Results are shown in Figure 3. Solid lines are the fourth-order polynomials (from Table 1) fitted into the raw data (not the dots). The dots indicate the point estimates of 100 m bins obtained in separate regressions for each technology. The fit is quite striking, especially for distances up to 5 km from the LE—for greater distances, there is also more noise because there are few observations beyond that distance. We are, thus, confident that we can approximate the real speed sufficiently precisely so that attenuation bias can be ignored in equations (4) and (5). We further note that we use estimated parameters of a physical relationship that depends on distance and LE technology to approximate our speed capacity variable.

TABLE 2. Pricing results.

	(1)	(2)	(3)	(4)	(5)	(6)
	log of sales price (in GBP)					
Imputed local broadband speed (Mbit/s)	0.0188*** (0.0022)	0.0157*** (0.0022)	0.0254*** (0.0041)	0.0431*** (0.0018)	0.0125*** (0.0007)	0.0251*** (0.0014)
Speedˆ2			−0.0026*** (0.0009)			−0.0026*** (0.0002)
Fourth order distance polynomial	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	–	–	Yes	–	–
Control × year effects	–	Yes	Yes	–	Yes	Yes
LE effects	Yes	Yes	Yes	–	–	–
LE boundary × year effects	Yes	Yes	Yes	–	–	–
LE x year effects	–	–	–	Yes	Yes	Yes
Boundary window (m)	200	200	200	–	–	–
$r2$	0.9486	0.9512	0.9512	0.9225	0.9318	0.9318
N	125,209	125,209	125,209	1,082,777	1,082,777	1,082,777

Notes: For columns (1–3), we identify the broadband effect from discontinuous variation in speed over time and across LE boundaries. Identification in columns (4–6) derives from a comparison of house prices to broadband supply over time and within LE areas. We further add controls on LE boundary × year effects for (1)–(3) and LE × year for (4)–(6). We present the boundary estimates for a 200 m boundary window. The results for boundary windows ranging from 100 m to ∞ are available in Online Appendix E, Table E.1. Standard errors in parentheses are clustered on LE boundary × year effects in (1)–(3) and on LE × year cells in (4)–(6). $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

These results confirm the key role played by distance. First, there is strong speed decay by distance: as a building happens to be farther away from the relevant LE, its actual speed goes down compared to another dwelling connected to the same LE with the same technology, but closer to the exchange. This phenomenon is particularly strong within 3 km (2 miles) around a LE, which is a threshold often mentioned in the technical and policy literature.[20] Second, speed decay exists for each technology, but in different ways. ADSL2+ is the newest technology (within our sample period) that can ensure the highest speeds, but it also suffers from relatively faster decay. The different sensitivity of speed to distance by technology is something that we can exploit in our main pricing models, which we discuss next.

4. Empirical Findings

4.1. *The Impact of Speed on Property Prices*

We now give an empirical answer to our main question: Does broadband speed have an impact on property prices? Table 2 shows the result of estimating the model given by equation (4), in columns (1–3), and by equation (5), in columns (4–6). For both

20. See Summers (1999).

models, we first estimate the average effect of a 1 Mbit/s increase in speed, excluding (columns (1) and (4)) and including (columns (2) and (5)) control × year effects. We then add quadratic speed terms to allow for diminishing returns, as predicted by our theory (columns (3) and (6)).

We find positive and significant capitalization effects of broadband speed in all models. Adding control × year effects reduces the marginal speed effect from 4.3% to 1.2% when we identify from within-LE variation (columns (4) and (5)). The difference is much smaller when we identify from variation across LE boundaries (1.9% vs. 1.6%; columns (1) and (2)). This is the expected result because shocks to property prices are arguably less likely to be correlated with speed increases across a LE boundary within a small boundary segment (see Figure 2) than with speed increases within a LE area that depends on distance to the LE. In our preferred models (3) and (6), we find virtually identical point estimates, even though we identify from different sources of variation and samples that, in terms of observations, differ by a factor of 10. Note that we have chosen a spatial window of 200 m on each side of a LE boundary in columns (1–3) as a compromise that resulted in small boundary areas that are reasonably well populated. Note, also, that we have replicated model (3) using windows of varying sizes (Online Appendix E.1). Likewise, we have excluded varying windows from model (6) to make the samples used in (3) and (6) mutually exclusive. Because the estimates are very similar in all models, we present them in Online Appendix E.

Given the virtually identical point estimates in (3) and (6), we conclude that the differences in the average effects reported in columns (2) and (5) are a composition effect, as the full sample includes more properties close to LEs where the highest speeds are realized.[21] Moreover, the control × year effects seem to do a good job in capturing within-LE trends, making model (6) our preferred model for the counterfactual analysis, as it is estimated from our universe of property transactions and exploits the full variation in speed.

The point estimates in models (3) and (6) imply a marginal effect of 1.4% at a (post-2000) mean (real) speed of 2.2 Mbit/s. This corresponds to a 3% elasticity of property prices with respect to speed. The marginal effect of speed becomes zero at a real speed of about 5 Mbit/s, which corresponds to about 20 Mbit/s in nominal terms and roughly the 99th percentile in the overall speed distribution in our data. The implied effect on property prices at this point is 3.8% and, thus, £8,360 (≈$12,540) for a property worth £220,000 (≈$330,000, the mean house price in 2005, which is the middle point of the 2000–2010 period of Internet development we cover).[22] It is interesting to see that the marginal effect (i.e., the impact of a marginal increase in

21. When we calculate the elasticity of property prices with respect to speed, as implied by specifications (3) and (6), we obtain remarkably identical values of 0.031 at the mean of each sample.

22. This premium is comparable to, for example, an increase in floor size of about 8 m^2, holding all other housing characteristics (e.g., the number of rooms) constant, or a reduction in distance to the nearest underground station by roughly 1 km (Gibbons and Machin 2005). We can compare our findings with available figures from works that have followed different approaches. Rosston, Savage, and Waldman (2010) estimate demand from the US survey data (the survey was administered online) and report that the representative household is willing to pay $48 per month for an improvement in speed from slow to very

speed on net consumer surplus in our model) is about zero close to the maximum actual speed that we observe in the data. There would be no particular reason for suppliers to provide speed above the maximum observed levels in our data, as no further surplus could be created.

Using our preferred specification (6), we have produced results that show the capitalization effect by region. These are summarized in Figure 4. The left panel (in logs) shows the results as percentages, whereas the right panel (in levels) converts the findings in monetary rents. It is reassuring that the marginal effects in the left panel look relatively similar.[23] It seems important to acknowledge that prices differ substantially across English regions. Similar marginal capitalization effects may, therefore, imply different rents. In fact, the striking, though perhaps not surprising, result is that we get a broadband marginal monetary rent that is about twice as high in London as in any other English region. After having estimated separate effects for each region, London shows higher than average willingness to pay for broadband, but it is not an outlier in this distribution. The difference in the marginal rent is, instead, attributable to the higher house-price levels in London. Usage is probably also a lot higher in London than in the rest of the country, but competition among broadband providers is very intense too, so they cannot really price differentiate accordingly. It is property sellers in London who ultimately receive a higher rent from broadband usage.

Our results do suggest that a broadband rent exists in general. Local characteristics, however, also seem to be important. The rent is rather low in regions with a higher share of low-income rural areas, which is probably where access to broadband is a problem. It seems that the benefits are relatively small where the policy maker is most likely to intervene. If the subsidies required are sufficiently low, there may still be some rationale for interventions. What also seems to be important is that the rent is declining in speed. For policy, this may imply that what is really important is to make sure that everyone gets access to some decent broadband connection. Getting access to very high speeds should, perhaps, not be the priority. This is what we analyze in the policy section. Before doing so, however, we conduct some further checks to reassure that broadband speed does, indeed, cause an increase in property prices.

fast. Their speed variable takes only three categorical values (slow/fast/very fast), whereas we have the actual available speed. Still, it is reassuring to find that their consumer surplus estimates, when translated into a perpetuity using a 5% interest rate, gives \$11,520 which is very close to our \$12,540 estimate of the effect of going from slow to very fast. A 5% interest rate is a reasonably high discount rate as, in our data, if one buys a property into an area that has not been upgraded to the latest technology, the disadvantage compared to other areas is likely to persist over time because also in the future one would be likely to receive upgrades later. The capitalization effect thus captures an anticipated stream of rents over a relatively long period.

23. The English regions defined in the NBS dataset are: East Anglia, East Midlands, London, North West, Northern, Out Metropolitan, Outer South East, South West, West Midlands, Yorkshire, and Humberside. We do not label all of them in Figure 4 to improve readability.

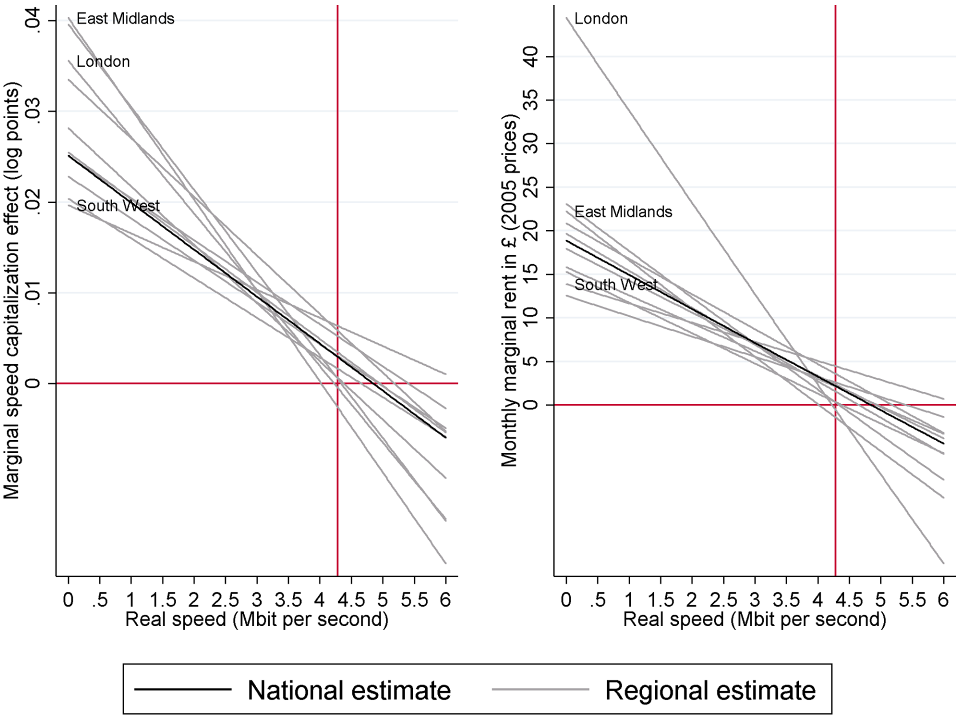

FIGURE 4. WTP by regions. The left panel shows the marginal speed capitalization effects by regions. The right panel computes the corresponding monthly monetary rent. The monthly marginal rent R_r' is constructed as $R_r' = \overline{P}_r \times c/12 \times (\exp(\alpha_{r1} + 2\alpha_{r2} S) - 1)$ using the following ingredients: A 2005 adjusted mean sales price $\overline{P}_{\mathrm{r}}$ in English regions recovered from the region fixed effects ϕ_{R} of an auxiliary hedonic regression of type $\log(P_{it}) = \widetilde{X}_i'\mu + \sum_{t\neq 2005} \omega_t + \varphi_R + \varepsilon_{it}$; an opportunity cost of capital of $c = 5\%$; the region-specific speed parameters α_{r1} (linear speed term) and α_{r2} (quadratic speed term) obtained from separate estimations of equation (5) for each of the ten English regions. Gray solid lines show the respective marginal effects estimated from the regional samples. Black solid lines illustrate the marginal effect (Table 2, column (3)) for the entire sample. The vertical line indicates the 95th percentile in the (post-2000) speed distribution across the country. [Color online]

4.2. Sources of Identification and Robustness Checks

In this section we shed further light on the sources of identification that underlie the results presented above as well as their robustness.

Figure 5 illustrates the nature of the identification from discontinuous changes in speed over time across LE boundaries exploited by equation (4). Specific to each boundary segment, we define the period before the first upgrade took place as the *BEFORE* period. The remaining period is the *AFTER* period. Within each boundary segment, we define the side of the boundary with the higher speed in the *AFTER* period as the *FAST* side (positive distance from the LE boundary). Likewise the side with the lower speed is the *SLOW* side (negative distance from the boundary). The figure pools

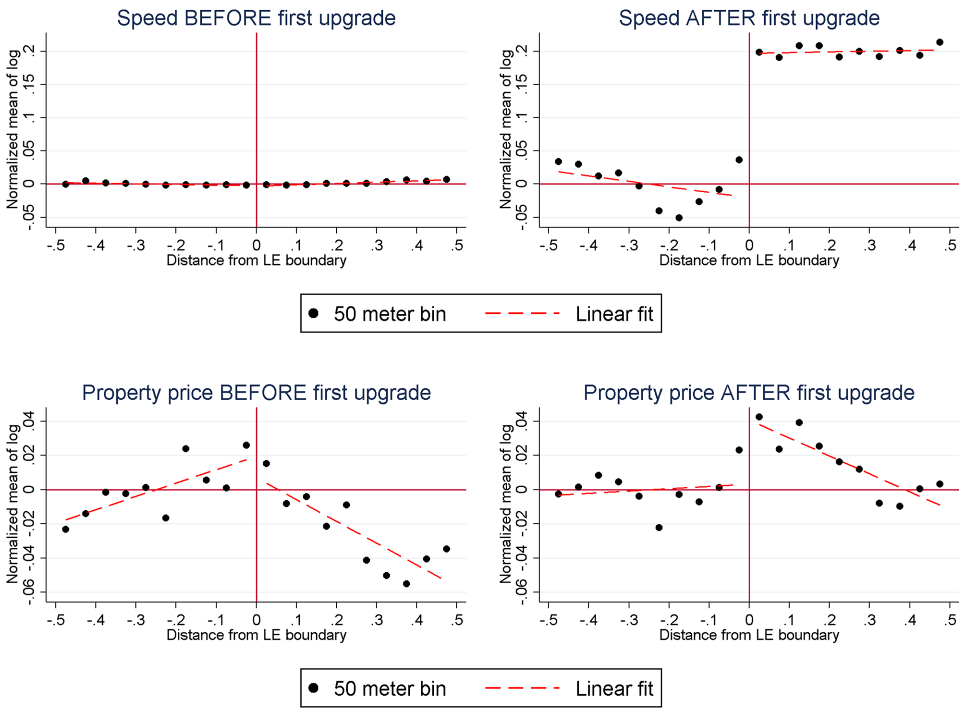

FIGURE 5. Boundary discontinuities in speed in property prices. Negative distances indicate locations within the side of the boundary segment that showed lower speeds after the first upgrade of either side. Dots are means across transaction prices and real speeds within 50 m distance bins. [Color online]

all the raw data together, as this is the most transparent way to show the main source of variation in our identification strategy. Figure 5 shows that there was a flat distribution of speeds before the first upgrades took place (upper left). After the first upgrade, there is an evident discontinuity with higher speeds on the *FAST* sides. Note that for the purpose of illustration we keep the allocation to *FAST*/*SLOW* after the first upgrade constant over time, even thought it may change in reality. This creates some potential fuzziness in the figure. This problem does not arise in the actual capitalization models that we estimate as we capture speed as a variable that changes continuously in space and over time. Still, Figure 5 illustrates that on average across the *AFTER* period speeds are significantly higher within the side that was first upgraded. In line with these higher speeds on the *FAST* side during the *AFTER* period, we see higher property prices on the on the *FAST* side during the *AFTER* period. There is also a notable discontinuity in the distance trend. Neither the positive difference in prices on average nor the positive discontinuity at the boundary as one moves towards the *FAST* side does exist during the *BEFORE* era. The implication is that the higher prices within the *FAST* side in the *AFTER* period are unlikely caused by time-invariant features that are specific to the *FAST* area.

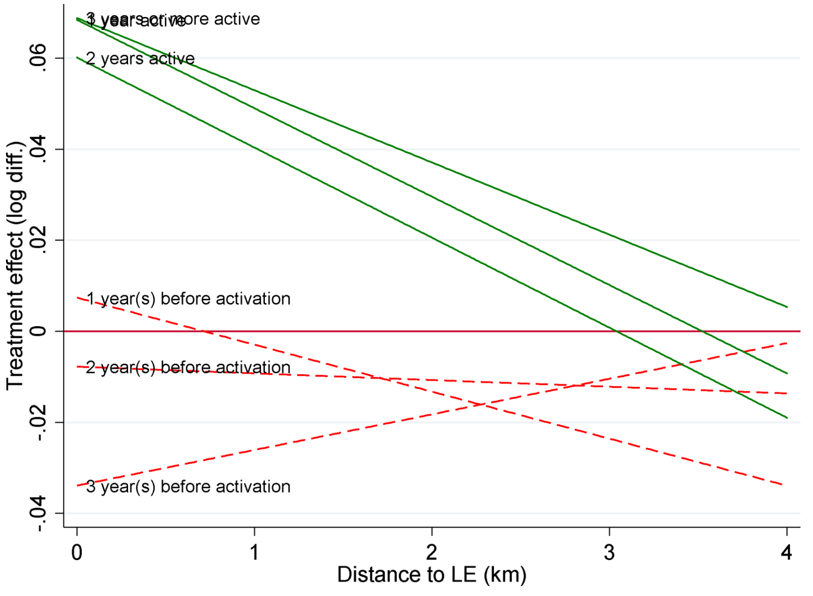

FIGURE 6. Difference-in-differences results with spatiotemporal variation: ADSL. Gray dashed (black solid) lines show difference-in-differences estimates for periods before (after) the ADSL upgrade took place. [Color online]

We note that the endowment of various types of amenities tends to be symmetric on both sides of the boundary and there are no clear discontinuities at the boundary (see Figure C.1 in Online Appendix C). It is therefore unlikely that the discontinuity in prices during the *AFTER* period shown in Figure 5 is caused by time trends correlated with these amenities.

There is also little evidence that our estimated effect of broadband speed on property prices is driven by changes in the composition of buyers or property characteristics. In Table C.1 in Online Appendix C we present estimates of equation (4) using a range of buyer or property related characteristics as dependent variables. We find no significant effect of broadband speed on whether a buyer is a first-time buyer or signs a leasehold contract, on the size of transacted properties, on whether these properties are new, have central heating or are flats (instead of houses).

In a similar spirit, we now illustrate in a transparent way the spatiotemporal adjustment in property prices to LE upgrades within LE areas in Figure 6. Our methodology is explained in detail in Online Appendix D, where we discuss a reduced-form difference-in-differences (DD) specification, expanded to account for spatial heterogeneity and for a temporal structure in the treatment effect of a LE upgrade. Figure 6 allows us to investigate how the relationship between property prices and distance to the LE changes up to three years prior to the ADSL upgrade (*PRE* placebo effects) as well as up to three years after the ADSL upgrade (*POST* treatment effects), in each case relative to the period three or more years before the upgrade. We note

TABLE 3. Robustness checks.

	(1)	(2)	(3)	(4)	(5)	(6)
	log of sales price (in GBP)					
	OLS	OLS	OLS	OLS	OLS	2SLS
Imputed local broadband speed (Mbit/s)	0.0267*** (0.0014)	0.0254*** (0.0014)	0.0281*** (0.004)	0.0210*** (0.0063)	0.0317*** (0.0021)	0.0288*** (0.0015)
Speedˆ2	−0.0018*** (0.0003)	−0.0026*** (0.0003)	−0.0026* (0.0015)	−0.0014** (0.0007)	−0.0038*** (0.0003)	−0.0036*** (0.0003)
Fourth-order distance polynomial	Yes	Yes	Yes	Yes	Yes	Yes
Fourth-order polynomial × (year—2000)	Yes	–	–	–	–	–
2 Mbit/s pre-ASDL cap	–	–	–	–	Yes	–
LE × year effects	Yes	Yes	Yes	Yes	Yes	Yes
Controls − year	Yes	Yes	Yes	Yes	Yes	Yes
Period	1995–2010	1995–2010	1995–2004	2005–2010	1995–2010	1995–2010
Property type	All	Houses	All	All	All	All
*r*2	0.932	0.935	0.91	0.89	0.932	0.932
N	1,082,777	932,878	729,133	353,644	1,082,777	1,082,777

Notes: In column (1), we add an interaction between the fourth-order distance to LE variables and a linear time trend to account for within-LE trends in property prices that are accidently correlated with distance to the LE. In column (2) we exclude flats. In column (3), we identify the simple ADSL speed upgrade effects in the earlier period (up to 2004), and in column (4) the combined effects from LLU and ADSL2+ upgrades (after 2005). In column (5), we use a different speed panel variable that accounts for the 2 Mbit/s cap for the period prior to 2006. In column (6), we use three indicator variables for ADSL/LLU/ADSL2+ as well as three interactions of these indicator variables with LE distance as predictors for Speed and Speedˆ2. Standard errors in parentheses clustered on LE × year cells. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

that Figure 6 shows the average effect across all ADSL upgrades estimated conditional on LE and year effects. All estimated *PRE*-treatment ADSL effects are near to zero and most are even slightly negative. Property prices did not tend to be higher close to LEs before the ADSL upgrade, despite notable correlations between various forms of amenities and LE distance (see Figure D.1 in Online Appendix D). With the upgrade, prices increase close to the LEs, which is in line with a significant positive effect of real broadband speed that declines in distance from the LE. Although there is a slight orientation over the three years preceding the ADSL activation toward a more negative distance gradient, the level shift *after* the upgrade is very substantial. The effects for the three *POST* periods are very consistent, and it seems fair to conclude that these cannot be explained by trends that existed *prior* to the upgrade.

We now return to the empirical models of Section 4.1. To support our benchmark model results and to substantiate our economic interpretations of the findings, we have run a series of additional models. The results are summarized in Table 3. To control for a long-run trend correlated with distance to the LE and not absorbed by control × year effects, we add an interaction between the fourth-order distance to LE variables and a linear time trend in column (1). This is a strong control as it is likely to partially absorb the effect of speed upgrades if capitalization occurs smoothly over time. In line with the discontinuous pattern in Figure 6, the speed effect, however, remains remarkably close to the benchmark model, pointing to speed capitalization effects that occur discontinuously in time.

Our results could be biased in the presence of externalities at a very disaggregated level, for instance at the building level. One possibility is that speed might attract particular people to a block of flats first, and subsequent buyers might be enticed by the proximity to those original buyers rather than by speed per se. To reduce this possibility, we rerun our model excluding flats, thus concentrating only on detached, semi-detached, or terraced houses where only a single family could move. Results in column (2) of Table 3 are virtually identical to those reported in column (6) of Table 2 (similarly for the model with boundary discontinuities, not reported here for the sake of brevity).

Because LLU and ADSL2+ are both advancements that started only in 2005, it is possible to divide our sample to identify the speed effect from variation that stems from two separate technological innovations. A priori, results could go either way. Prior to 2005, email and browsing were the prevalent Internet activities for residential users, whereas phenomena such as YouTube or Facebook were only limited. The older applications were, however, much less bandwidth intensive, in a period when available bandwidth was also much more restricted. Although broadband speed is clearly very important today (because of changes in complementary technology), actually, at the margin, the willingness to pay for additional Mbit/s could be either higher or lower in the early days compared to more recent periods, as supply was much more constrained by technology. Column (3) of Table 3 uses transactions up to 2004, when most ADSL activations occurred. Likewise, column (4) uses transaction from 2005 onwards and, thus, exploits LLU and ADSL2+ activations. Results are very much in line with our benchmark model, as the differences between periods are not marked enough to be a source of alarm.

Because we have no access to speed-test data from before 2008, we are not able to fully control for some technological improvements that occurred to the basic ADSL technology. In its early years, ADSL speed was capped at 2 Mbit/s, and this constraint was removed only in 2006, allowing for the maximum nominal speed of 8 Mbit/s. Our best possible attempt to approximate the respective technological parameters is to estimate equation (7) using speed tests of users who subscribed to plans that cap the maximum speed at 2 Mbit/s. In column (5), we assign values implied by this speed–distance function to all transactions that occurred after ADSL activation, but before 2006 or LLU. The results are qualitatively identical and quantitatively similar to those of our benchmark model.

One could argue that our estimated engineering relationship between speed, technology, and distance is rather sophisticated (though it is sufficient that we have access to a website that performs the test without knowing the underlying formula, or that the available speed is known to the local estate agent that then transmits the information to prospective buyers). Also, we rely on speed tests that are initiated by users. To address these concerns, we use ADSL/LLU/ADSL2+ indicator variables, plus the interactions with LE distance as predictors for *Speed* and *Speed*ˆ2 in a 2SLS model in column (6). This way, we restrict the identifying variation to stem purely from LE technology and distance, which is a fairly transparent structure for identification that we also use in the difference-in-differences models (see Figure 6 and Online Appendix D). In Table E.3 in Online Appendix E we apply the same strategy to the boundary specification and also consider a spline distance approach to predict real speed. All results consistently show that our findings do not depend on the functional form derived on the engineering analysis in Section 3.1, although the latter is our preferred specification as it does not depend on ad hoc assumptions and generates precise estimates.

4.3. Heterogeneity and Capitalization Channels

In this section we engage with some ancillary predictions of our conceptual model. To allow for heterogeneity in the willingness-to-pay for the Internet (modeled via a_j in our conceptual model in Section 2.3) we augment equation (5) as follows:

$$\log(P_{ijt}) = \sum_{m=1}^{2} \alpha_m (S_{ijt})^m + \sum_{m=1}^{2} ((S_{ijt})^m \times A_i)\beta_m^A + \sum_{n=1}^{4} \tau_n (DIST_{ij})^n + X_i' \mu_t + \varphi_{jt} + \varepsilon_{ijt}, \quad (9)$$

where A_i is a vector of time-invariant characteristics of property i, capturing population characteristics (average income), urbanization (share of urban land, labor market accessibility), amenities (school quality, proximity to rail stations, restaurant density, retail density), and Internet services (Amazon evening delivery, Uber, number of retailers dispatching online orders), which are discussed in more detail in Online Appendix B. $\beta_{m=1,2}^A$ are the respective parameter vectors capturing spatial heterogeneity in the WTP for speed. Because the estimates of these interaction terms between the quadratic speed term and the relatively highly correlated locational variables are difficult to interpret, we relegate the presentation and a more detailed discussion of the results to Table F.1 in Online Appendix F. Briefly summarized, we find that the marginal effect of real broadband speed is larger in more urban areas with higher incomes and more amenities, suggesting that such areas are inhabited by households with a relatively high willingness-to-pay for speed. In this context it is worth noting that in Table F.2 in Online Appendix F we rerun our preferred models (columns (3) and (6) in Table 2) separately for buyers who did and did not purchase a property for the first time. We do not find any notable difference between the two groups on the willingness to pay for speed, both in the overall sample, and at the boundaries.

We also find evidence for a complementarity between broadband speed and availability of local Internet services. In Figure 7 we illustrate the distribution of the estimated marginal speed effects across properties distinguishing between locations where local Internet services such as Amazon evening delivery or Uber are supplied (solid lines) and those where they are not (dashed lines). Evidently, the distributions

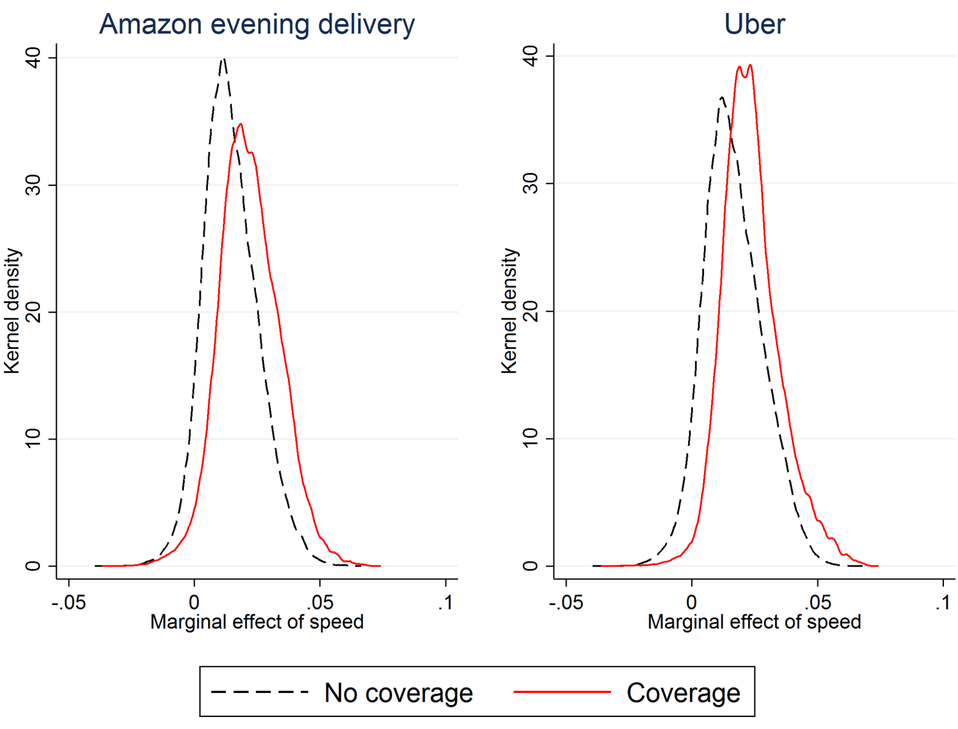

FIGURE 7. Marginal speed effects in areas with and without local Internet services. The marginal speed effect is defined as: $\partial \log P_{ijt}/\partial S_{ijt} = \alpha_1 + A_i\beta_1^A + 2\alpha_2 S_{ijt} + 2(S_{ijt} \times A_i)\beta_2^A$ and derived from model (3) in Table F.1 in Online Appendix F, which allows the speed effect to vary in population characteristics (average income), urbanization (share of urban land, labor market accessibility), amenities (school quality, proximity to rail stations, restaurant density, retail density), and available Internet services (Amazon evening delivery, Uber, number of retailers dispatching online orders). Kernel is Epanechnikov. A Kolmogorov–Smirnov test rejects the null of the distribution for "coverage" and "no coverage" to be the same (KS = 0.267 for Amazon and KS = 0.268 for Uber; p-value < 0.01 for both). [Color online]

are shifted to the right in areas with such services, suggesting that higher broadband speed is valued more by buyers in those areas. In Figure F.2 in Online Appendix F we similarly show that the marginal speed effect increases in the number of grocery chains that dispatch online orders to a certain location. Even though such spatial heterogeneity may be partially attributable to differences in socioeconomic status, these results represent a significant addition to the scarce evidence on how the value of broadband depends on the supply of complementary Internet services (Forman et al. 2008).

The result that having fast and reliable Internet is more valuable where delivery of online orders is fast and more retailers can bring groceries at home seems to suggest that the consumer surplus we are measuring arises from consumption of Internet services at home (as opposed to amenities such as Internet cafes). This is supported by the magnitude of our estimated consumer surplus, which is in line with studies that have focused on broadband consumption at home using different methods (see footnote 22).

TABLE 4. Penetration results.

	(1)		(2)	
	Penetration (share)			
	ADSL		Cable	
Imputed local broadband speed (Mbit/s)	0.0779***	(0.0066)	0.0028	(0.0018)
Speedˆ2	−0.0111***	(0.001)	−0.0005	(0.0003)
LE effects	Yes		Yes	
TTWA × year effects	Yes		Yes	
LE trend effects	Yes		Yes	
Cable coverage	All		>65%	
*r*2	0.354		0.53	
N	70,074		13,228	

Notes: Penetration rate is defined as the ratio of the number of households connected to broadband over all households in a certain area. Study period is 2005–2010. To accommodate LE trends we estimate the model in first differences including LE effects. Standard errors in parentheses clustered on LEs. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

To substantiate this interpretation we provide a direct test of the ancillary prediction of our model that faster broadband should not only lead to positive capitalization effects, but also to higher penetration rates. In particular, penetration, defined as the ratio of the number of households connected to broadband over all households in a certain area, should increase in broadband speed at a decreasing rate (see equation (3)).

In Table 4 we use a strongly balanced panel of penetration rates available quarterly across LEs, ranging from the last quarter of 2005 to the second quarter of 2010, the same period as used in model (4) of Table 3. Because we cannot exploit within-LE variation, we cannot add LE × year effects to control for unobserved macroeconomic shocks at the LE level. Still, to strengthen identification, we allow for travel to work areas (TTWA) × year effects and individual LE trends (on top of LE effects).[24] As the model predicts, we find a positive speed effect on penetration that diminishes in speed (column (1)). To evaluate whether unobserved shocks (e.g., gentrification) that impact broadband demand (penetration) and upgrade decisions (and, thus, speed) are driving the results, we also conduct a falsification test using cable broadband penetration rates as the dependent variable. Cable is a completely separate technology that should not, per se, be affected by the speed of the ADSL-based network. As cable is available only in some parts of the country, we restrict the analysis to those LEs with high potential cable coverage according to the Ofcom definition (more than 65% of households in a given catchment area are “passed” by cable and, thus, have potential access to cable). Reassuringly, we do not find a significant effect of speed in this placebo test

24. TTWAs are self-contained labor market areas defined by the Office for National Statistics. At least 75% of an area’s resident workforce work in the area and at least 75% of the people who work in the area also live in the area. According to the 2007 definition there are 243 TTWAs in the United Kingdom.

(column (2)). Because unobserved macroeconomic shocks that are correlated with our speed measure and increase broadband demand should also show up in higher cable penetration rates, we conclude that the ADSL penetration effect is unlikely to be spurious. These results support our main finding that households value broadband. Moreover, they suggest that the benefits from broadband are at least partially incurred through consumption of broadband at home, and not only through the attraction of amenities such as Internet cafes, or places of cultural production and consumption that depend on a decent broadband connection to operate.

5. Evaluation of the EU Digital Agenda

In this section, we propose an evaluation of the EU Digital Agenda. As discussed in the Introduction, by 2020, every EU household should have access to at least 30 Mbit/s. In order to conduct the counterfactuals, we use the estimated capitalization effects from the hedonic regressions in order to make welfare comparisons.

The conclusion about willingness to pay for broadband upgrades requires us to think carefully about the nature of heterogeneity in broadband demand. As put by Kuminoff et al. (2013, p. 1038) it is legitimate to make welfare comparisons using results from hedonic regressions only when the analyst can reasonably answer "yes" to the following questions: "Do the data describe a single geographic market connected by a common hedonic price function? Was the gradient of the price function constant over the duration of the study period? Are the "treated" houses in the sample representative of the population of interest?" As for the single geographic market, we have already shown how to extend our estimates to make them specific to local markets. As for the time variation of the gradient of the price function, we did not find any particularly worrying variation at least between the pre- and post-2005 periods that we could test in Table 3. The final point is instead more controversial and harder to tackle in a reduced-form framework like ours. For sure, the buildings in our sample seem to be representative of the population. Figure 1 already gave some information about this, and we run several other reassuring tests in this direction.[25] From our tests for speed effects on buyer and property characteristics (see Table C.1 in Online Appendix C) we also know that buyers and properties before and after speed upgrades are similar. However, people moving into properties may sort themselves according to their preference for broadband speed and, depending on whether fast Internet connections are abundant or scarce, the recovered willingness to pay by marginal buyers may under- or overstate the average willingness to pay. The virtually immediate capitalization of increases in broadband available speed (see Figure 6) seems to suggest that fast connections during our study period were relatively scarce, thus, the sorting effect will likely be upward.

As already discussed, we do not find any notable difference on the willingness for speed between first-time buyers and other buyers (see Table F.2 in Online Appendix F).

25. We find that our sample of property transactions closely resembles the full population of postcodes in terms of the kernel distribution of distances to the nearest LE, which is the most important determinant of speed.

TABLE 5. Predicted broadband speeds in England by 2020.

Density decile	1	**2**	3	4	5	6	7	8	9	10
Speed (Mbit/s)	3.88	**32.23**	75.84	120.06	169.18	218.40	250.41	277.96	294.88	332.77

Source: DCMS (2013).

Although this is reassuring with respect to sorting, we are aware of the limitations of our data in that we lack additional household characteristics. Keeping this limitation in mind, we now offer guidance on how to interpret our results. In our policy experiment, we are going to increase Internet speed available locally to some households. If a household was interested in this higher level of speed, but could not find it as it was not available for various reasons (for instance, because of the high fixed costs to deploy a faster technology in that area), we can indeed use our results to estimate the benefit to that household from a speed increase. However, if a household was not interested in the Internet, and decided not to subscribe, it is also likely that this household will be reluctant to subscribe also when we change the broadband speed. This is particularly relevant as the EU target states that *every* household should have at least 30 Mbit/s, and thus broadband supply would have to be expanded considerably. Using the results from existing subscribers to inform the welfare attributable to these households is likely to lead to an overestimation of the true benefits from speed. For these reasons, we propose below to distinguish between benefits from "speed upgrades" and those from "coverage upgrades". This distinction keeps the welfare results separate between households with and without a broadband connection, as the former results are probably more credible than the latter.

We now present our policy experiment. In order to provide an estimate of the costs and benefits of the proposed targets, we would need to first establish the counterfactual—that is, what speeds will be reached by 2020 *without* interventions? The targets themselves must be interpreted, as the EU guidelines are not very clear. For instance, "having access" may simply mean that the target speed is technologically available in a certain area or, alternatively, that each household must effectively subscribe to that target speed.

In order to move forward, we have to make some explicit assumptions. We propose the following methodology. First, we take advantage of a useful and timely report published in November 2013 by the DCMS, the UK government's department responsible for the Internet. The report forecasts the distribution, by density decile, of the broadband speeds that will be reached in England by 2020 in the absence of interventions. This is shown in Table 5.

We make some small adjustments to account for the fact that the DCMS refers to the sum of upload and download speeds, whereas the EU Digital Agenda refers only to download speeds.[26] It turns out that, with a very good degree of approximation, the

26. See European Parliament (2013). The upload speed is roughly 10% of the download speed.

EU target implies bringing every household to at least the average speed of the second decile of the speed distribution. We use this information to anchor our data. Of course, the broadband market will evolve between now and 2020. Our maintained hypothesis is, however, that the current relative distribution of speeds is informative as to where the market will go. Someone currently in the bottom decile of the distribution will also be at the bottom of the distribution in 2020, and so forth. Everyone will likely move towards higher speeds, but in a proportional manner.

If one is prepared to accept our assumption, then the rest of the exercise follows quite naturally. Since we can estimate benefits from broadband at the LE level, we take the 2010 distribution of speeds in England at the same LE level (see Online Appendix G for more details). Within this distribution, we take the average speed of the second decile, which becomes our "2010 target-equivalent" speed to which everybody should aspire by 2020, according to the Digital Agenda. We thus interpret the policy "as if" everybody should have access to at least the speed of the second decile, which we denote as S_{DA}.

Having identified the "2010 target-equivalent" speed in our data, we turn to the benefits for each LE, as this is where the targets might have an impact. To calculate LE-specific estimates of the broadband benefits, we use equation (9). For the counterfactual exercise we allow the effect of speed to vary in income I (calculated at the 2005 ward level) and urbanization U (share of urbanized area within a 1 km^2 grid) (see column (1) in Table F.1 in Online Appendix F). We considered models with richer sets of interactions (columns (2) and (3) in the same table), but because most amenities are highly correlated with income and urbanization these models produced implausible outliers in the speed effects for various LEs without adding much explanatory power.

We can calculate LE-specific estimates of the broadband benefits as

$$\alpha_{1j} = \alpha_1 + \beta_1^I I_j + \beta_1^U U_j,$$

$$\alpha_{2j} = \alpha_2 + \beta_2^I I_j + \beta_2^U U_j,$$

where I_j and U_j are the means of the properties transacted within LE j and β_1^I, β_1^U, β_2^I, and β_2^U are part of the vectors β_1 and β_2 in equation (9) moderating the interactions between speed and speedˆ2 and the locational characteristics. The marginal effect is

$$(\partial \log P/\partial S)_j = \alpha_{1j} + 2\alpha_{2j} S.$$

To get to the marginal rent, we require some LE-level mean prices that account for differences in income and urbanization. One approach would be to use local means estimated in a similar way to the regional prices used in Figure 4 (see figure caption for details), just at a more local level (using finer fixed effects). The other approach is to make the price income and urbanization specific—that is, estimate prices as function of U and I

$$\log(P_{jt}) = a_I I_j + a_U U_j + \widetilde{X}_i' \mu + \sum\nolimits_{t \neq 2005} \omega_t + \varepsilon_{jt}. \tag{10}$$

The advantage of this approach is that it is possible to express the rent entirely as a function of S, U, I.[27]

For each local exchange, we also know the average speed (S) and the proportion of households (x) that have access to broadband. In every LE, we proceed as follows:

- If $S > S_{DA}$, then no speed upgrade is needed in that LE. If we interpret "access" in the Digital Agenda as "technological availability", then nothing should happen in that LE. If, instead, we interpret the target more strictly—that is, literally all households should actually subscribe to broadband with a minimum speed—then the unconnected households will need to be covered as long as x is less than 100% in that LE. For these households, the benefit is calculated by giving them the target speed S_{DA} (starting from a basic connection, corresponding to ISDN, as they will have a telephone line): we call this possible benefit "coverage upgrade".
- If $S < S_{DA}$ in a given LE, the households with broadband will need a speed upgrade, leading to an increase in benefits corresponding to an increase in speed from S to S_{DA} in that LE: we call this benefit "speed upgrade". As above, if the unconnected households also must be connected, the "coverage upgrade" benefit is similarly calculated by giving them the target speed S_{DA} (starting from a basic connection).

Having described our methodology to get an estimate of the benefits from the upgrade, we need to have a view about the corresponding costs. We borrow this information from existing studies. Although there are many technologies that could achieve very high speeds, it is agreed that fiber has the most promising chances of being rolled out to the mass market (and has already started in some places across England). According to how deeply fiber is deployed, the most expensive solution is fiber to the home (FTTH). A slightly less expensive solution that could still allow for very high speeds is fiber to the building (FTTB). The cost of rolling out these technologies varies by area, as they are typically cheaper in densely populated areas and more expensive in rural areas. The European Investment Bank (EIB) gives an estimate of the average NPV cost, per technology and per area, in the EU.[28] These are reported in the top two rows of Table 6.

The results of the benefits for S_{DA} are shown in the third and fourth rows of Table 6. The results by LE are aggregated by area type, to make them directly comparable with the cost estimates. We present the findings distinguishing between the gains predicted for those who already have broadband, and will just need an "upgrade" to close the speed gap, as opposed to the gains accruing to those that currently do not have

27. It is $r = c/12 \times \exp(a_0 + a_U U + a_I I) \times (\exp(\alpha_1 + 2\alpha_2 S + \beta_1 I + 2\beta_2 S \times I + \gamma_1 U + 2\gamma_2 S \times U) - 1)$.

28. The cost assessment is based on a combination of population densities, technology, and labor costs. It refers to the fixed costs per household needed to bring a technology to a certain area. We use the 2010 average EUR/GBP exchange rate to calculate the figures for England. See Hätönen (2011) and Gruber et al. (2014) for more details on the approach. Notice that, should mobile technology be used to bring high-speed broadband to rural areas, instead of fiber, this would affect only the cost rows in Table 6, not the estimated benefits which are related to speed only, not to the delivering technology.

TABLE 6. Estimated costs and benefits for the 30 Mbit/s Target of the EU Digital Agenda.

	Population density in residents (km^2)		
Costs/*benefits* per HH (GBP)	>500 (urban)	>100 and <500 (suburban)	<100 (rural)
Cost (FTTH)	416	1,018	2,522
Cost (FTTB)	310	885	2,301
Speed upgrade benefit	*668*	*337*	*393*
Coverage upgrade benefit	*8,815*	*4,690*	*3,145*
LEs affected	183	257	1,075
Households affected			
Upgrade ($S < S_{\mathrm{DA}}$)	851,880	387,743	584,874
Coverage ($x < 100\%$)	5,066,954	432,781	319,468

Note: Cost estimates by density categories are taken from the EIB (Hätönen 2011).

broadband but will need to be "covered" to meet the target. This corresponds also to two different interpretations of the EU digital agenda.

We believe this is the most transparent way to organize and discuss our findings. Benefits are calculated as an average per household in each LE. Although we do account for differences in urbanization and income among LEs, we cannot control for other sources of unobserved heterogeneity. Hence, the "upgrade" results are probably the more credible, as they refer to households that are interested in broadband and already subscribe to it. These results are also in line with the looser interpretation of the targets, whereby technology must be available, but subscription decisions are left to individuals.

The "coverage" results apply, instead, to households that currently do not have a basic version of broadband, even in areas where fast broadband is available. This could be due to affordability issues, in which case our results on coverage would stand if appropriate subsidies were also given to those households. But we could also argue that these households are simply not interested in broadband, and never will be, unless additional actions are also taken—for example, to increase their degree of digital literacy (especially for households with older people). If we take a stricter interpretation of the Digital Agenda, such that *every* household must have broadband of a certain minimum speed, we cannot just ignore the issue. Instead of arguing one way or another, we give each set of results separately.

Households in urban areas clearly pass the cost–benefit test. The benefits of the upgrade per household are already sufficient to cover its cost, even with the most expensive FTTH technology. As for suburban households, FTTB might be considered, but the benefits of the speed upgrade alone are still less than 40% of its cost. If a small percentage of the coverage benefits could also be realized, we could also argue for FTTB in suburban areas. Rural areas are, instead, the most problematic: this is where costs are highest and benefits lowest. The benefits from the speed upgrade are about

15% of the cost of bringing fast broadband. Only if we are willing to accept that at least two thirds of the coverage benefits will also be realized, then the case for FTTB passes a cost–benefit test under the stricter interpretation of the Digital Agenda in rural areas.

The last rows in Table 6 give some sense of the total impact of the policy. Almost 200 LEs would need to be upgraded in urban areas, but they would affect large numbers of households, as the population density is high. Overall, the speed upgrade would affect just over 1.8 m households, and possibly fewer than 1.3 m if rural areas were thought to fail the cost/benefit test. Connecting the unconnected is, instead, a more ambitious goal, which puts the number of affected households well over 5 m. These large differences are due to the ambiguity in interpreting the policy targets.

Our welfare assessment is based on the costs to supply broadband—and net household benefits from using it—over and above the price paid to Internet Service Providers. We have been silent so far on the actual broadband price that subscribers pay. This is not a problem if the price is competitive, so that ISPs themselves make no extra rents. If, though, there were private rents to ISPs, then our analysis would underestimate welfare effects since ISPs' profits are excluded from our study.

We finish this exercise by commenting on the possible direction of bias in our results. First, our whole approach depends on estimating broadband value from property scarcity prices. If the property market were oversupplied instead, then we would systematically underestimate consumer surplus from broadband consumption, as sellers would not be able to capture broadband rents. In this respect, it is well documented that the supply of properties in England is severely constrained by the planning system (Hilber and Vermeulen 2016). More land is covered by greenbelts that prevent expansion of developed areas (and in some areas even by golf courses) than by housing. This restriction of developable land leads to the economically paradoxical combination of skyrocketing house prices (more than tripled in England and more than quadrupled in London over the past 15 years) and historically low construction levels (Cheshire 2014). Still, it is safe to say that our estimates should provide a lower bound to net consumer surplus.

Second, and more relevant for the policy exercise, the relative scarcity of properties may be lower in rural areas compared to urban areas. If that were the case, then the underestimation would be more severe for the former than for the latter. Although it is beyond the scope of the current work to use a measure of the tightness of the property market, we have information about the number of days it takes, on average, to sell a property from when it is first put on sale, which is an indication of how many active prospective buyers there are for that property. On the basis of this imperfect metric, there is no evidence that the supply of properties in rural areas is considerably more elastic than in urban areas.[29]

29. For instance, in January 2007, before the financial crisis, it took, on average, 86 days to sell a property in Greater London, the most densely populated area in England, and 95 days to sell one in rural Devon. After the crisis, these went up to 178 days and 206 days, respectively, but the relative ratio did not change (see "Time on the market report for England", http://www.home.co.uk/guides/).

Third, if buyers anticipated broadband speed increases over time, the present value of a technological upgrade would be reduced, and we would similarly underestimate the consumer surplus. We find in our data that the sequence in which LEs were upgraded to ADSL, LLU, and ADSL2+ was similar, implying that relative speed advantages should tend to persist over time. Also, when we run DDs for each technological upgrade (see Figure 6 and Online Appendix C.2), we find some genuine discontinuities in property prices associated with the various generations of broadband technologies, which reveals that the benefits of the introduction of ADSL and of its subsequent upgrades were not fully anticipated by consumers.

Fourth, we calculate the benefits from the digital targets in a certain LE by eventually changing only the speed in that LE, and keeping all other parameters constant. Although this is not particularly controversial for urbanization, we also keep income constant. If, say, broadband became available in rural area *A*, and some rich people were induced, as a consequence, to move to that area *A* from some other area *B*, we would have to use their income to evaluate the policy (starting with the speed level available in their original area *B*). Since none of this information is available, our policy experiment is valid to the extent that there is very low mobility among LEs.

Fifth, we estimate only the private gains from residential broadband Internet. Therefore, we may be missing various positive network externalities linked to high-speed communications. It is notable, however, that urban areas already pass the cost–benefit test and rural areas fail by a large margin. Because most economic activity concentrates in urban areas, it is unlikely that the qualitative conclusions from our policy exercise would change if, for instance, the effects on firms were taken into account.

Sixth, and as we acknowledged more generally at the beginning of this section, we cannot tell what part of our property capitalization effects could be due to pure sorting. This is why we decided to be as transparent as possible by presenting the benefit results split into two parts. Perhaps the results are less credible at the extensive margin (bringing people to fast Internet for the first time) than at the intensive margin (giving a faster connection to those who already use the Internet). If this is the case, as already argued above, our most convincing estimates of broadband benefits are those capturing the speed upgrade, whereas the coverage upgrade estimates should be taken with more caution.

6. Conclusions

This paper evaluates the extent to which broadband speed is capitalized into house prices. We estimate consumer surplus associated with broadband Internet speed by using microdata on property prices in England between 1995 and 2010. We find a 3% elasticity of property prices with respect to speed at the mean of the speed distribution in our data. Because of significant diminishing returns to speed, this elasticity applies only to marginal changes and properties with average Internet connections. Upgrading a property from a normal (8 Mbit/s) to a fast (24 Mbit/s) connection increases the value, on average, by 1%. This is still a large effect. We argue that this is a good measure of net consumer surplus associated with broadband usage. This is true as long as properties are scarce and sellers are, thus, able to extract buyers' consumer surplus, or else our results would underestimate the impact on consumer surplus. We also find considerable heterogeneity of these benefits in each area where the Internet is locally deployed. We then use the estimates to evaluate the benefits associated with government initiatives to upgrade digital speed. We show that urban areas pass a cost–benefit test of current EU policy proposals, whereas the case for these policy interventions is not very strong in rural areas.

Since it is largely urban areas that pass a cost–benefit test, the question arises: Why do ISPs supply suboptimal speed in those areas, where there seems to be a willingness to pay that is in excess of costs? The reason is that the broadband rent goes to the "wrong" economic agent. The broadband speed rent is, in fact, appropriated by the seller, not by the ISPs. The ISPs supply broadband according to supply and demand conditions in the broadband market, which is largely a competitive one. But these conditions do not necessarily reflect the scarcity rents that exist in the property market. To upgrade their local networks, ISPs need to recover substantial fixed costs (especially for fiber) over the relevant catchment area. ISPs can recover these fixed costs only in part via the premium prices charged to subscribers, since they are still restrained by the competitive landscape.

An implication of our results is that there may be a coordination problem among sellers and landlords in the undersupplied areas that pass the cost–benefit tests, perhaps because they are unaware or, most likely, because of their fragmentation. Although it would be collectively rational for these sellers and landlords to get together and pay some of the ISPs' delivery costs of upgraded technologies—as, then, their properties would become more valuable—free-riding problems make this scenario unlikely. As with other infrastructures, the coordination problem, therefore, rationalizes the public delivery of broadband to undersupplied areas in combination with levies charged to sellers and landlords to recover part of the costs. The political economy of the housing-market literature suggests that homeowners and landlords would support such initiatives as long as the anticipated capitalization gain exceeds the infrastructure levy (Ahlfeldt et al. 2014; Dehring et al. 2008; Fischel 2001; Oates 1969).

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Supplementary Data

Supplementary data are available at *JEEA* online.