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Speed 2.0
Evaluating Access to Universal Digital Highways

Gabriel M. Ahlfeldt (SERC & London School of Economics)
Pantelis Koutroumpis (Imperial College London)
Tommaso Valletti (Imperial College London, University of Rome "Tor Vergata & CEPR)

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* Spatial Economics Research Centre & London School of Economics
** Imperial College London
*** Imperial College London, University of Rome “Tor Vergata” & CEPR

Abstract
This paper shows that having access to a fast Internet connection is an important determinant of capitalization effects in property markets. We combine microdata on property prices in England between 1995 and 2010 with local availability of Internet broadband connections. Rich variation in Internet speed over space and time allows us to estimate the causal effect of broadband speed on property prices. We find a significantly positive effect, but diminishing returns to speed. Our results imply that an upgrade from narrowband to a high-speed first-generation broadband connection (offering Internet speed up to 8 Mbit/s) could increase the price of an average property by as much as 2.8%. A further increase to a faster connection (offering speeds up to 24 Mbit/s) leads to an incremental price effect of an additional 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 passes a cost-benefit test in urban and some suburban areas, while the case for universal delivery in rural areas is not as strong.

Keywords: Internet, property prices, capitalization, digital speed, universal access to broadband
JEL classification: 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 benefits.[4] 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; Baum-Snow et al., 2012; Duranton and Turner, 2011, 2012).

In this paper, we deal with a different type of speed: digital speed. Does it matter how quickly one can surf the Internet using broadband connections? The possibilities that come with a faster Internet are countless: video streaming, on line e-commerce, or telecommuting, to name just a few. In a recent best seller, Michael Lewis (2014) argues that superfast connections have even been used by high-frequency traders to rig the US equity market.[5] In contrast to the classic infrastructures mentioned above, it is normally left to the market to supply Internet connections, via Internet Service Providers 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. Predictions about the impact of the Internet and broadband infrastructure have been optimistic and sometimes outlandish. Policy makers expect broadband to lead to job creation and economic growth. In the US, 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.[6] In Europe, broadband is one of the pillars of Europe 2020, a ten-year strategy proposed by the European Commission. Its Digital Agenda identifies two targets that are even more aspiring than the US's: also by 2020, every European citizen will need access to at least 30 Mbit/s, and at least 50% of European households should have Internet connections above 100 Mbit/s.[7]

These programs are ambitious and seem to suggest that private provision may not be adequate, in that fast enough connections are not supplied to enough people in a country. Various industry

[4] Beginning with Marshall (1920), there is a long tradition of research into various forms of agglomeration benefits (e.g. Arzaghi and Henderson, 2008; Ciccone and Hall, 1996; Duranton and Puga, 2004; Fujita et al., 1999; Henderson, 2003; Lucas and Rossi-Hansberg, 2002; Redding and Sturm, 2008; Rosenthal and Strange, 2001).

[5] Using fibre-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 milliseconds (Lewis, 2014).

[6] http://www.broadband.gov/plan/

[7] http://ec.europa.eu/digital-agenda/our-goals/pillar-iv-fast-and-ultra-fast-internet-access

sources provide some reliable estimates about the infrastructure delivery costs, but we know very little about the impact of a faster Internet on demand. This makes the evaluation of universal delivery programs an educated guess, at best.

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 comprise 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 percent to a property's value." Perhaps more tellingly, the survey says that one in ten potential buyers reject a potential new home because of a poor connection, and that, while 54% considered broadband speed before moving in, only 37% looked at the local crime rate.[8] Rightmove, one of the main online real estate portals in the UK, 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.[9]

To empirically estimate the impact of broadband speed on house prices, we have access to very detailed and unique information about broadband development and residential properties for the whole of England, over a rather long period (1995-2010). We find that an elasticity of property prices with respect to speed of about 3% at the mean of the Internet speed distribution. We also find diminishing returns—that is, the increase in value is greater when starting from relatively slow connections. The average property price increased by 2.8% when going from a slow dial-up connection to the first generation of ADSL 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. 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. An average property value in London

[8] http://www.telegraph.co.uk/property/propertynews/9570756/Fast-broadband-more-important-to-house-buyers-than-parking.html

[9] http://www.rightmove.co.uk/broadband-speed-in-my-area.html. 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, e.g., : http://forums.digitalspy.co.uk/showthread.php?t=190825.

increased by 6% with the introduction of ADSL, and by an extra 2% with ADSL2+. Endowed with these findings, we then evaluate the benefits of the EU Digital Targets for each LE in England, which we compare with available costs estimates. We find that increasing speed and connecting unserved households passes a cost-benefit test in urban and some suburban areas, while the case for universal delivery in rural areas is not as strong.

In order to provide reliable estimates of the impact of broadband speed on property prices, we need to avoid the circular problem 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 that 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 UK (this would be called the Central Office in the US). 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, providing 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 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. We stress here that we estimate a very restrictive model that controls for unobserved trends that are correlated with a wide range of observable property and local characteristics. Second, we exploit variation *across* LE boundaries. 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.

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 non-marketed externalities more generally (Ahlfeldt and Kavetsos, 2014; Cellini et al., 2010; Chay and Greenstone, 2005; Dachis et al., 2012; Davis, 2004; Gibbons and Machin, 2005; Greenstone and Gallagher, 2008; Linden and Rockoff, 2008; Oates, 1969; Rosen, 1974;

Rossi-Hansberg et al., 2010). We use very similar methods and show how they also can be used in settings where, a priori, one 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 provision seems to go to the seller as a scarcity rent, and not to the broadband supplier.

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 US data, while 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 US. Some studies assess the demand for residential broadband: Goolsbee and Klenow (2006) use survey data on individuals' earnings and time spent on the Internet, while Nevo et al. (2013) employ high-frequency broadband usage data from one ISP.[10] 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, while Section 4 describes the data. The main results are shown and discussed in Section 5. Section 6 uses the empirical findings to quantify the benefits for the EU 2020 digital targets. Finally, Section 7 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 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[11] 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

[10] See, also, Rosston et. al (2010). Other socio-economic effects of the Internet that have been empirically analyzed include voting behavior (Falck et al., 2014) and school outcomes (Faber et al., 2013).

[11] This description applies to the whole of the UK, and we also have broadband data for Wales, Scotland and Northern Ireland. However, since our property data cover only England, we always refer to England alone throughout the paper.

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 lines, to each building in which customers live or work, which tend to be within two kilometers 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.

While 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 90s, 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 adapt voice telephone technology to the high-speed Internet by installing special equipment in the LEs. A breakthrough occurred with a family of technologies called DSL (Digital Subscriber Line), 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 40 compared to a standard dial-up modem and, afterwards, allowed speeds up to 8 Mbits/s.

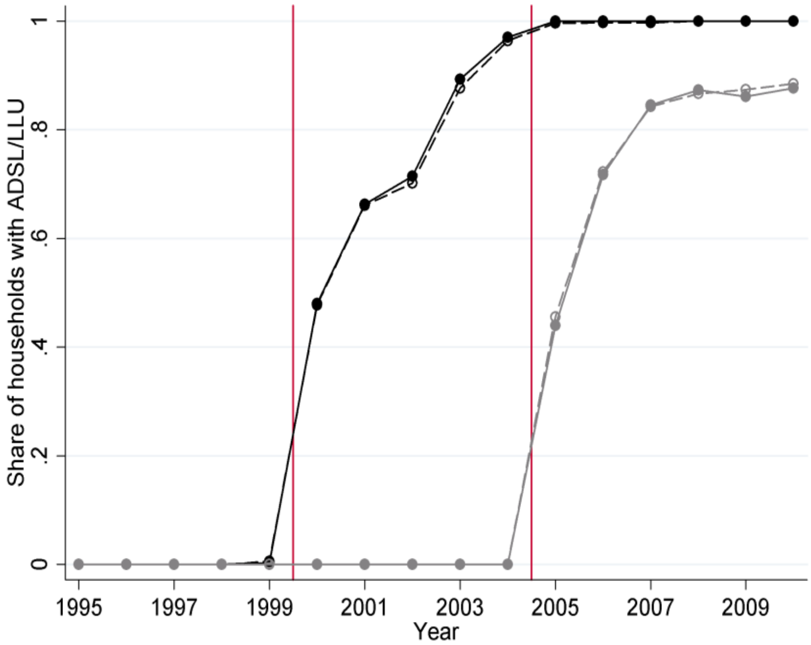
Along with technological progress, the regulatory framework also evolved over the same period. Ofcom, the UK's regulator for the communications industry, required BT to allow potential entrants to access its network. In particular, Ofcom supervised the implementation of the so-called "local loop unbundling" (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 upgrade individual lines to offer services directly to customers. LLU started to gain pace in 2005, and entrants have progressively targeted those LEs in more densely populated areas.[12]

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.

Figure 1 shows the percentage of English households in the catchment area of LEs enabled with ADSL (black solid line) or with LLU entrants (grey solid line).[13] Our data, therefore, cover the period that was crucial for the development of residential Internet. Although we have not yet

[12] Nardotto et al. (2013) analyze the entry process in UK's broadband, and the impact that regulation had on it.
[13] We do not show ADSL2+ in order not to clutter the figure with too many plots, but it would lie below the LLU curve.

introduced the dataset on property prices, the dotted curves refer to the latter. They show that our sample on property prices reflects very closely the general technological pattern, providing reassurance on its representativeness. In Appendix A, we provide further empirical evidence, showing maps of how these technological changes occurred by region and over time.

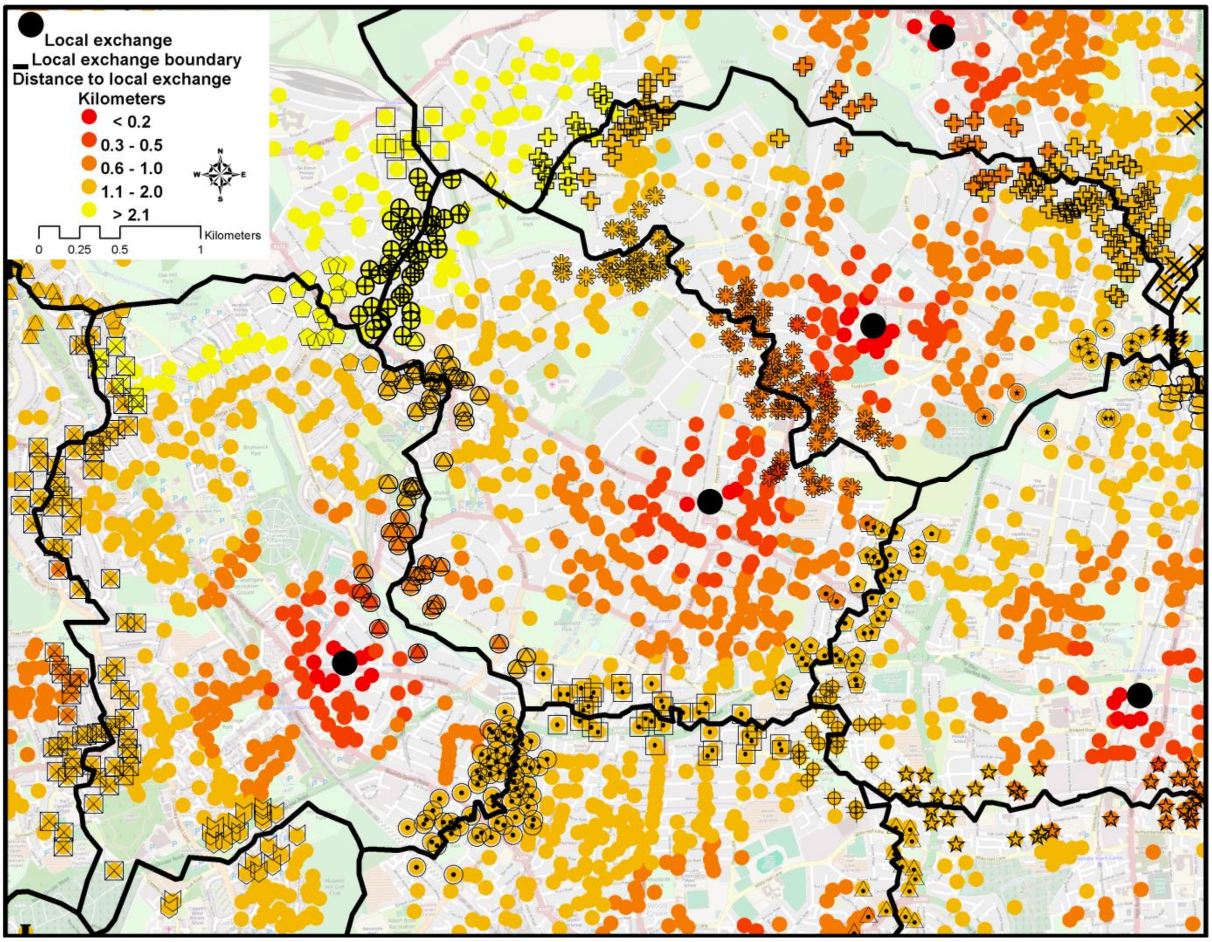


Notes: Black (grey) lines ADSL activation (LLU). Solid (dashed) lines refer to the Nationwide transactions data set (all households in England)

Figure 1: Share of households with ADSL/LLU over time

Figure 2 is a static map of a few Local Exchanges 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 colored dot represents the location (full postcode) of one transaction in the property dataset, where different colors correspond to different distances from the exchange. The figure shows two important things that will inform our empirical strategy. First, there is considerable variation in the distance between premises and the relevant LE, which should have an impact on the available speed for a specific property. We will, thus, be able to control for unobserved shocks to neighborhoods at very disaggregated levels. Second, there are enough properties at the boundaries between LEs (see the properties denoted by various icons in Figure 2), with properties that will have different technologies and distances from the exchange on either side, a discontinuity that we will be able to exploit.

To complete the picture, broadband Internet can also be supplied via an alternative cable network.[14] 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 BT's. It covers roughly 50% of premises in England, concentrating its presence in urban areas and in 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 aims at also providing TV, is typically faster than ADSL, and broadband speed does not degrade substantially with distance from the exchange.



Notes: Black icons denote groups of properties within 200m of a shared boundary segment.

Figure 2: Distribution of properties and LE catchment areas

2.2 A simple conceptual model

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

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[14] 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.

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, etc., 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 $v \cdot \log(q)$ denote the gross utility of household type v using a broadband of quality q, where q is, 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 1.[15]

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 is sold at a price p. Then, households whose value of broadband is high enough will purchase a broadband connection. In particular, the marginal broadband household is defined by $v^* = p/\log(q)$, and all types between v^* and 1 purchase broadband.

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, one 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. House prices will, therefore, be

$$P = \begin{cases} V - U \text{ for } v < v^* \text{ (households without broadband),} \\ V - U + v\log(q) - p \text{ for } v \geq v^* \text{ (households with broadband).} \end{cases} \quad (1)$$

To close the model and generate simple closed-form solutions, imagine that broadband is supplied locally by $n \geq 1$ identical oligopolistic providers at a cost c per unit of quality. For the problem to make economic sense, it must be that $c < \log(q)$, as, otherwise, not even the household with the highest willingness to pay would get a broadband subscription supplied at cost. Suppliers are modeled *à la* Cournot: let x_i denote the quantity supplied by firm i and $X = \sum_{i=1}^{n} x_i$ the aggregate supply. Since it is $1 - v^* = \sum_{i=1}^{n} x_i$, we obtain the inverse demand function $p = (1 - \sum_{i=1}^{n} x_i)\log(q)$. Thus, provider i maximizes its profits $(p - c)x_i = (1 - x_i -$

[15] The example is immediately generalizable to a more general distribution function $F(v)$ that satisfies the monotone hazard rate condition. Note that costs and benefits from using broadband are expressed in present discounted values, rather than in per-period flows, to make them directly comparable with the purchase price of a property.

$X_{-i}) \log(q)\, x_i$. Taking the FOC, and focusing on a symmetric equilibrium where $X_{-i} = (n-1)x_i$, we obtain that, at equilibrium, the broadband price is $p^* = c + \frac{\log(q)-c}{n+1}$.

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

$$P = (V-U)v^* + \int_{v^*}^{1} [V - U + v\log(q) - p^*]\mathrm{d}v = V - U + \left(\frac{n}{n+1}\right)^2 \frac{[\log(q) - c]^2}{\log(q)}. \qquad (2)$$

From (2), it is immediate that property prices increase with broadband. In particular, they increase with speed q, and at a decreasing rate if c is not too large.[16]

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. Penetration is given by

$$Penetration = 1 - v^* = \frac{n}{n+1}\left[1 - \frac{c}{\log(q)}\right], \qquad (3)$$

which is also increasing in speed q, and at a decreasing rate.

Note that the main prediction that property prices increase with speed is independent of the precise market structure of the broadband market: it is stronger when n gets large, but it holds even for a monopolist provider when n = 1. 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 unobserved and potentially correlated

[16] It is $\frac{\partial P}{\partial q} = \frac{[\log(q)^2 - c^2]}{2(n+1)^2 \log(q)} > 0$ and $\frac{\partial^2 P}{\partial q^2} = -\frac{n^2[\log(q)^3 - c^2(2+\log(q))]}{2(n+1)^2 q^2 \log(q)^3}$, which is always negative if c is small.

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 a comparison of house prices to broadband supply over time and *within* LE areas. For one thing, variation over time helps disentangle the effect of broadband supply from unobserved (spatially) correlated location factors, such as good transport access or better schools. For another thing, 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.[17] Likewise, we can identify the broadband effect from discontinuous variation in speed over time and *across* LE boundaries. By 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 an LE boundary within such a small area is plausibly exogenous and as good as random.

We follow the popular hedonic pricing method to separate various determinants of property prices. Rosen (1974) has provided the micro-foundations for interpreting parameters estimated in a multivariate regression of the price of the composite good housing against several internal and locational characteristics as hedonic implicit attribute prices. Underlying the hedonic framework is the idea that, given free mobility in spatial 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 Oats (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 (e.g. Ahlfeldt and Kavetsos, 2014; Chay and Greenstone, 2005; Dachis, et al., 2012; 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 postcode i at time t and served by LE j 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:

[17] Note that local exchange areas are relatively small. The median radius of a local exchange area is less than six km, as far as old voice telephony services are concerned. As for broadband, the area where it can be supplied effectively is even smaller, up to 2-3 km, at most, from the local exchange, as shown below in the results. In cities, the median radius of an LE is much smaller—e.g., less than two km in London.

$$\log\left(P_{ijt}\right) = \sum\nolimits_{m=1}^{2} \alpha_m \left(S_{ijt}\right)^m + \sum\nolimits_{n=1}^{4} \tau_n \left(DIST_{ij}\right)^n + (\omega_t \times \mathrm{X}_i')\mu_t + \left(\varphi_j \times \omega_t\right) + \epsilon_{ijt}, \qquad (4)$$

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, so that the speed effect is identified from variation over time alone. 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. Because our variable of interest S_{ijt} is constructed using fourth-order polynomials of $DIST_{ij}$, the control variable approach should be equivalent to postcode fixed effects in terms of its power to absorb unobserved locational effects that are correlated with S_{ijt}. X_i' is a vector of property and locational characteristics discussed in the data section, interacted with a full set of year effects ω_t, so that μ_t is a matrix of implicit prices for attribute-year combinations. Finally, we include a set of 37,804 year-LE fixed effects $\left(\varphi_j \times \omega_t\right)$ that absorb all macroeconomic shocks at the LE level.

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—e.g., 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 $\left(\varphi_j \times \omega_t\right)$. 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 respond to within LE-area shocks even if they wanted to.[18]

It is further noteworthy that the $(\omega_t \times \mathrm{X}_i')$ effects flexibly control for property price trends that are correlated with any of the observable structural and locational characteristics. Conditional

[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.

on controlling for these trends, it is less likely that within-LE differentials, which may affect the timing of an upgrade and directly impact within-LE property price trends, confound the estimated broadband speed effect. We also use program-evaluation techniques to reassure ourselves that, conditional on the strong controls employed, there are no LE trends correlated with distance to the LE that could lead to spurious broadband supply effects. For brevity and because the results support our empirical specification, we present the details of the empirical strategy and the results in Appendix C.

To further address the possibility that there may be within-LE trends in property prices that are correlated with distance to the LE, we estimate an alternative specification that exploits the discontinuity at the boundaries between LEs. We replace the 37,804 year x LE effects with 86,569 year x LE boundary effects, which denote boundary segments that are common to the same two LEs. We further add a set of 3,872 LE fixed effects to control for unobserved time-invariant LE effects. With this specification, we attribute differences in price changes across a common boundary to the respective differences in speed changes. We restrict our sample to properties that are close to an LE boundary to explicitly exploit the spatial discontinuities in speed changes that arise across an 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 exist that impact speed and property prices on one side of the boundary but not on the other. Such shocks are absorbed by the LE boundary x year effects. Formally, the specification is expressed as follows:

$$\log(P_{ijt}) = \sum_{m=1}^{2} \alpha_m (S_{ijt})^m + \sum_{n=1}^{4} \tau_n (DIST_{ij})^n + (\omega_t \times \mathrm{X}_i')\mu_t + (\psi_{kl} \times \omega_t) + \varphi_j + \epsilon_{ijt}, \quad (5)$$

where ψ_{kl} indexes properties that lie along the same boundary segment that separates two LE areas. To create ψ_{kl}, we match properties in LE k to the nearest property in LE $l \neq k$ and define a common fixed effect ψ_{kl} for properties in k whose nearest neighbor is in l and vice versa. Fig. 2 illustrates the matching of properties to common boundary FE.

4 Data description

4.1 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 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.[19] For each individual/speed test, we observe the operator, the contract option chosen by the user, the location (full post code), as well as when the test was carried out. Thus, we can calculate the distance between the user's premises (the geographic center of the six-digit postcode area where the test is run) 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.

For the analysis of the capitalization effects of broadband capacity, we use transactions data related to mortgages granted by the Nationwide Building Society (NBS) between 1995 and 2010. The data for England comprise more than one million observations,[20] and include the price paid for individual housing units along with detailed property characteristics. These characteristics include floor space (m^2), the 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.[21]

With this information, it is possible within GIS 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,

[19] http://www.broadbandspeedchecker.co.uk
[20] This represents 10% of all mortgages issued in England over the period.
[21] This dataset has also been used by Ahlfeldt et al. (2014), who test the predictions of a political economy model of conservation area designation.

cultural and entertainment establishments and school quality. A more-detailed description of all the data used is in Appendix B.

4.2 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 effective 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 2009-10. 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 capacity as a function of LE characteristics and the distance to the LE, as well as the interaction between the two.[22] 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 chose 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 that do not constrain broadband speed beyond the technological limitations of the LE, we run the following auxiliary regression:

$$\log(S_{ijt}) = \sum_{m=2}^{12} \alpha_m + \sum_{h=1}^{23} \alpha_h + \sum_{w=1}^{6} \alpha_w + \sum_{p=1}^{62} \alpha_p + \sum_{d=2}^{60} \alpha_d + (\varphi_j \times \omega_t) + \varepsilon_{ijt}, \qquad (6)$$

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 hours of the day effects (baseline category 0h), 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 100m bins (e.g., 2 covers distances from 150 to 250m, baseline category is 0-150m), and $(\varphi_j \times \omega_t)$ 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 operator.

[22] For a list of the factors that affect broadband speed at a given location, see, e.g., the explanation provided by BT to its customers: http://bt.custhelp.com/app/answers/detail/a_id/7573/c/. A detailed analysis of the factors that affect the performance of ADSL networks is found in Summers (1999).

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

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

Since we drop 75% of the observations compared to eq. (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 broadband speed at any postcode *i* that is served by a LE *j* over the entire period:

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

With this compact formulation, we are saying 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 in the relevant time periods 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 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.[23]

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

[23] It is important to note that, throughout the whole paper, we refer to the “nominal” speed typically advertised by operators in their plans, as this is the most commonly understood measure of speed that users look for when subscribing to a plan. This is not the same as “actual” speed, which is measured in the dataset on speed tests. The discrepancy for the top unconstrained plans is actually quite large and amounts to a factor 4 (results are available on request from the authors). This factor is also in line with independent findings of Ofcom; see, e.g., http://stakeholders.ofcom.org.uk/market-data-research/other/telecoms-research/broadband-speeds/speeds-nov-dec-2010/, and Figure 1.2 in particular).

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 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 has no impact on speed.

	(1)	(2)	(3)	(4)
	log of download speed (in 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
r2	0.174	0.160	0.198	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

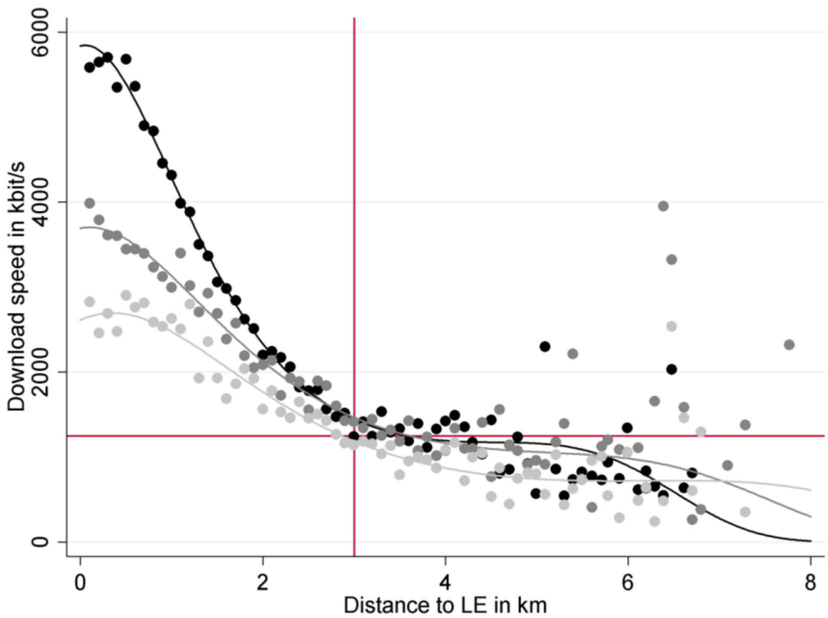
Table 1: Speed results

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 100m distance bin effects, as used in model (3). Results are shown in Figure 3. Solid lines are the fourth-order polynomials (from Table 1)[24] fitted into the raw data (not the dots). The dots indicate the point estimates of 100m bins obtained in separate regressions for each technology. The fit is quite striking, especially for distances up to 5 km from the LE—for

[24] It is worth remarking that the choice of a fourth-order polynomial for distance was simply dictated by its goodness of fit. There was no particular gain in going towards higher orders.

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).

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 an LE, which is a threshold often mentioned in the technical and policy literature.[25] 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.



Notes: Black lines and dots indicate ADSL2+ LEs, dark (resp. light) grey lines and dots are ADSL LEs with (resp. without) LLU

Figure 3: Distance decay by LE type

[25] See Summers (1999) and, e.g., "... like all copper technologies, the speed of ADSL2+ depends on line quality and distance; beyond 3 km from the exchange there is no real speed advantage over ordinary ADSL." http://www.worcestershire.gov.uk/cms/pdf/INCA-Beyond-Broadband.pdf.

5 Empirical findings

5.1 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 eq. (4), in columns (1-3), and by eq. (5), in columns (4-6). For both models, we first estimate the average effect of a 1Mbit/s increase in speed, excluding (columns 1 and 4) and including (columns 2 and 5) control x year effects ($\omega_t \times X_i'$). We then add quadratic speed terms to allow for diminishing returns, as predicted by our theory (columns 3 and 6).

	(1)	(2)	(3)	(4)	(5)	(6)
	log of sales price (in GBP)					
Imputed local broadband	0.0432***	0.0124***	0.0253***	0.0189***	0.0156***	0.0254***
capacity in MBit/sec	(0.0018)	(0.0007)	(0.0014)	(0.0022)	(0.0022)	(0.0041)
Speed^2			-0.0026***			-0.0026***
			(0.0002)			(0.0009)
4^{th} order distance poly.	YES	YES	YES	YES	YES	YES
Controls	YES	-	-	YES	-	-
Control x year effects	-	YES	YES	-	YES	YES
LE effects	-	-	-	YES	YES	YES
LE x year effects	YES	YES	YES	-	-	-
LE boundary x year eff.	-	-	-	YES	YES	YES
Boundary window (m)	-	-	-	200	200	200
r2	0.9224	0.9317	0.9318	0.9485	0.9511	0.9511
N	1,082,777	1,082,777	1,082,777	125,209	125,209	125,209

Notes: Identification in columns (1-3) derives from a comparison of house prices to broadband supply over time and within LE areas. For columns (4-6), we identify the broadband effect from discontinuous variation in speed over time and across LE boundaries. We further add controls on LE x year for (1-3) and LE boundary x year effects for (4-6). We present the boundary estimates for a 200m boundary window. The results for boundary windows ranging from 100m to ∞ is available in Appendix D, Table D1. Standard errors in parentheses are clustered on LE x year cells in (1-3) and on LE x boundary effects in (4-6). * p<0.1, ** p<0.05, *** p<0.01

Table 2: Pricing results

We find positive and significant capitalization effects of broadband speed in all models. Adding control x year effects reduces the marginal speed effect from 4.3% to 1.2% when we identify from within-LE variation. The difference is much smaller when we identify from variation across LE boundaries (1.9% vs. 1.6%). This is the expected result because shocks to property prices are arguably less likely to be correlated with speed increases across an LE boundary within a small boundary segment (see Figure 2) than with speed increases within an 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 200m on each side of an LE boundary in models (4-6) as a compromise that resulted in small boundary areas that are reasonably well populated. Note, also, that we have replicated model (6) using window sizes that ranged from 100m to 1000m. Because the estimates are very similar in all models, we present them in Appendix D.

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. Moreover, the control x year effects seem to do a good job in capturing within LE trends, making model (3) our preferred model as it is estimated from our universe of property transactions and exploits the full variation in speed.

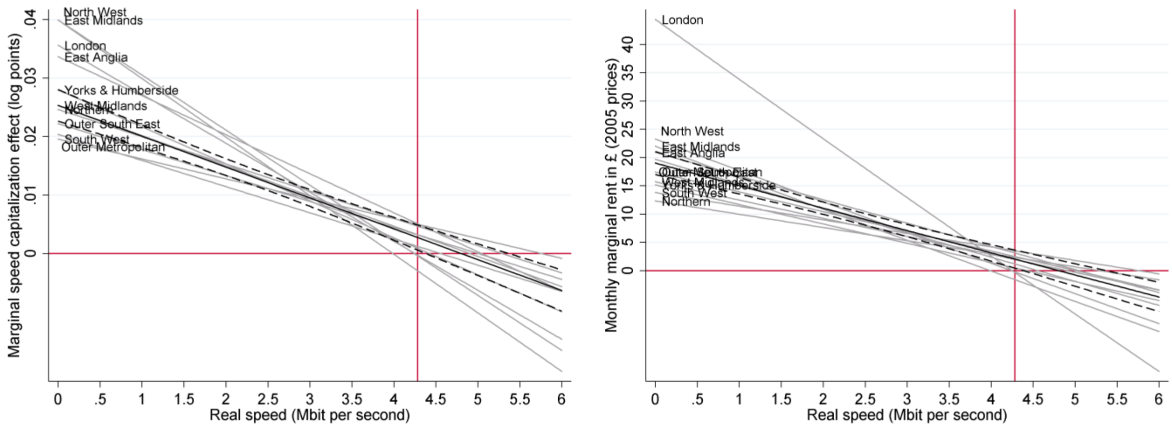
The point estimates in models (3) and (6) imply a marginal effect of 1.4% at a (post-2000) mean (real) speed of 2.2 Mbit/s. This corresponds to a 3% elasticity of property prices with respect to speed. The marginal effect of speed becomes zero at a real speed of about 5Mbit/s, which corresponds to about 20Mbit/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 (≈$13600) for a property worth £220,000 (≈$358,000, the mean house price in 2005, which is the middle point of the 2000-2010 period of Internet development we cover).[26] It is interesting to see that the marginal effect (i.e., the impact of a marginal increase in 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, independently from who appropriates it.

Using our preferred specification, we have produced results that show the capitalization effect by region. These are summarized in Figure 4. It is reassuring that the marginal effects look relatively similar. 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 in London, so they cannot really price-differentiate accordingly. It is sellers in London that 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

[26] This premium is comparable to, e.g., an increase in floor size of about 8 square meters, holding all other housing characteristics (e.g., the number of rooms) constant, or a reduction in distance to the nearest underground station by about 1200 m (Gibbons and Machin, 2005).

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.



Notes: 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 $R_r{}' = \bar{P}_r \times c/12 \times (\exp(\alpha_{r1} + 2\alpha_{r2}S) - 1)$ using the following ingredients: A 2005 adjusted mean sales price $\bar{P}_r$ in English regions recovered from the region fixed effects φ_R of an auxiliary hedonic regression of type $\log(P_{it}) = \tilde{X}_i'\mu + \sum_{t\neq 2005}\omega_t + \varphi_R + \epsilon_i$; 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 eq. (4) for each of the ten English regions. Grey solid lines show the respective marginal effects estimated from the regional samples. Black solid and dashed lines illustrate the marginal effect (Table 2, column 3) and the 95% confidence band for the entire sample. The red vertical line indicates the 95th percentile in the (post-2000) speed distribution across the country.

Figure 4: WTP by regions

5.2 Robustness checks

To empirically support our benchmark model (Table 2, column 3) results and to substantiate our economic interpretations of the findings, we have run a series of models. The results are summarized in Table 3. 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. Column (1) uses transactions up to 2004, when most ADSL activations occurred. Likewise, column (2) 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.

One concern with our benchmark model is that there may be within-LE trends in property prices that are accidently correlated with distance to the LE, which could bias our speed results. To control for a long-run trend correlated with distance to the LE and not absorbed by control x year effects, we add an interaction between the fourth-order distance to LE variables and a linear time trend in column (3). Our benchmark results are, again, largely confirmed.

	(1)	(2)	(3)	(4)	(5)	(6)
					Penetration (share)	
	Natural logarithm of sales price				ADSL	Cable
Imputed local broadband capacity in MBit/sec	0.0273***	0.0214***	0.0269***	0.0316***	0.0779***	0.0028
	(0.004)	(0.0062)	(0.0014)	(0.0021)	(0.0066)	(0.0018)
Speed^2	-0.0023*	-0.0014**	-0.0018***	-0.0038***	-0.0111***	-0.0005
	(0.0013)	(0.0007)	(0.0003)	(0.0003)	(0.001)	(0.0003)
4th order pol. dist. to LE	YES	YES	YES	YES	-	-
4th ord. pol. x (year – 2000)	-	-	YES	-	-	-
2Mbit/s pre-ASDL cap	-	-	-	YES	-	-
LE effects	-	-	-	-	YES	YES
LE x year effects	YES	YES	-	-	-	-
Controls x year	YES	YES	YES	YES	-	-
TTWA x year	-	-	-	-	YES	YES
LE trend effects	-	-	-	-	YES	YES
Cable coverage	ALL	ALL	ALL	ALL	ALL	>65%
Units	Trans.	Trans.	Trans.	Trans.	LE	LE
Period	1995-04	2005-10	1995-10	1995-10	2005-10	2005-10
r2	0.91	0.89	0.933	0.932	0.354	0.53
N	729,133	353,644	1,082,777	1,082,777	70,074	13,228

Notes: In column (1), we identify the simple ADSL speed upgrade effects in the earlier period (up to 2004), and in column (2) the combined effects from LLU and ADSL2+ upgrades (after 2005). In column (3), 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 (4), we use a different speed panel variable that accounts for the 2Mbit/s cap for the period prior to 2006. In columns (5-6), we check the effects of speed on LE penetration for ADSL technologies and Cable, respectively, using LE, TTWA x year effects and individual LE trends. LE trends are included by first differencing the baseline model. Standard errors in parentheses clustered on LE x year cells in (1-4), and LE in (5-6). * p<0.1, ** p<0.05, *** p<0.01.

Table 3: Robustness checks and complementary evidence

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 2Mbit/s. In column (4), 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.

As a final check, we recall that our theoretical model makes an ancillary prediction about broadband penetration in a given area, which we can use to lend further robustness to our findings and to gain insights into the channels through which the broadband effect operates. 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 eq.

(3)). 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 (2). Because we cannot exploit within-LE variation, we cannot add LE x year effects to control for unobserved macroeconomic shocks at the LE level. Still, to strengthen identification, we allow for TTWA x year effects and individual LE trends (on top of LE effects). As the model predicts, we find a positive speed effect on penetration that diminishes in speed (column 5). 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 (column 6). 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.

6 Evaluation of the EU Digital Targets

In this section, we propose an evaluation of the EU Digital Agenda. As discussed in the Introduction, by 2020, every EU country will have to meet the following two targets:

- Target 1: every household should have access to at least 30 Mbit/s;
- Target 2: 50% of households should have access to at least 100 Mbit/s.

In order to conduct the counterfactuals, we use the estimated capitalization effects from the hedonic regressions in order to make welfare comparisons. As put by Kuminoff et al. (2013, p. 1038) this interpretation is valid 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 show below how to extend our estimates to each catchment area covered by LEs, which can be distinguished by urbanization and by income levels. As for the time-variation of the gradient of the price function, we did not find any particularly worrying variation at least between the sub-periods pre- and post-2005 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.[27] However, people moving into properties may sort themselves according to their preference for broadband speed, which we do not observe. Here, there is not much we can do with our data. However, we can 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 it is too costly 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 speed of the Internet. This is particularly relevant for the first target that states that *every* household should have at least 30 Mbit/s. 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. The results from the previous section do not directly allow us to make judgments regarding the Digital Agenda. In order to provide an estimate of the costs and benefits of the proposed targets, one 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 4.

[27] 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.

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)

Table 4: Predicted broadband speeds in England by 2020

We make some small adjustments to account for the fact that the DCMS refers to the sum of upload and download speeds, while the EU Digital Agenda refers only to download speeds.[28] It turns out that, with a very good degree of approximation, the first target implies bringing every household to at least the average speed of the second decile of the speed distribution, while the second target is equivalent to connecting 50% of households to the average speed of the fourth decile.

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 Appendix E for more details). Within this distribution, we take the average speeds of the second and fourth deciles, which became our “target-equivalent” speeds. Let us denote them by T_1 and T_2, respectively.

Having identified the “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 run an augmented version of our benchmark model allowing for interaction among speed, income and urbanization

$$\log(P_{ijt}) = \sum_{m=1}^{2} \alpha_m (S_{ijt})^m + \beta_1 (S_{ijt} \times I_i) + \beta_2 ({S_{ijt}}^2 \times I_i) + \gamma_1 (S_{ijt} \times U_i) \qquad (9)$$
$$+ \gamma_2 ({S_{ijt}}^2 \times U_i) + \sum_{n=1}^{4} \tau_n (DIST_{ij})^n + (\omega_t \times \mathrm{X}_i')\mu_t + (\varphi_j \times \omega_t) + \epsilon_{ijt}.$$

This is essentially the same as eq. (4), having added the income I of an LE (calculated at the 2005 ward level) and its urbanization U (share of urbanized area within a 1km^2 grid).

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

[28] See European Parliament (2013). The upload speed is roughly 10-20% of the download speed.

$\alpha_{1j} = \alpha_1 + \beta_1 I_j + \gamma_1 U_j,$

$\alpha_{2j} = \alpha_2 + \beta_2 I_j + \gamma_2 U_j,$

where I_j and U_j are the means of the properties transacted within LE *j*. The marginal effect is

$$\left(\frac{\partial logP}{\partial S}\right)_j = \alpha_{1j} + 2\alpha_{2j}\, S.$$

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 notes for details), just at a more local level (using finer fixed effects). The other approach is to make the price income and urbanization specific—i.e., estimate prices as function of U and I:

$$\log(P_{it}) = a_I I_i + a_U U_i + \widetilde{X}_i'\mu + \sum\nolimits_{t\neq 2005} \omega_t + \epsilon_i. \tag{10}$$

The advantage of this approach is that it is possible to express the rent entirely as a function of S, U, I.[29]

For each local exchange, we also know the average speed (T) and the proportion of households (x) that have access to broadband. We report here the results for the first target and relegate results for the second target to Appendix E.

In every LE, we proceed as follows:

- If $T > T_1$, then no speed upgrade is needed in that LE. If one interprets "access" in the Digital Agenda as "technological availability," then nothing should happen in that LE. If, instead, one interprets the target more strictly—i.e., 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 T_1 (starting from a basic connection, corresponding to ISDN, as they will have a telephone line): we call this possible benefit "coverage upgrade."
- If $T < T_1$ 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 T to T_1 in that LE: we call this benefit "speed upgrade." As above, if the unconnected households also must

[29] It is $r = \frac{c}{12} \times \exp(a_0 + a_U U + a_I I) \times (\exp(\alpha_1 + 2\alpha_2 S + \beta_1 I + 2\beta_2 S \times I + \gamma_1 U + 2\gamma_2 S \times U) - 1)$.

be connected, the "coverage upgrade" benefit is similarly calculated by giving them the target speed T_1 (starting from a basic connection).

Having described our methodology to get an estimate for the benefits from the upgrade, we need to have a view about the corresponding costs. We borrow this information from existing studies. While 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. According to how deeply fiber is deployed, the most expensive solution is fibre 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.[30] These are reported in the top two rows of Table 5.

The results of the benefits for T_1 are shown in the third and fourth rows of Table 5. 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 broadband but will need to be "covered" to meet the target. This corresponds also to two different interpretations of the EU digital agenda.

	Population density in residents/km^2		
Costs/*Benefits* per HH (GBP)	> 500 (Urban)	> 100 & < 500 (Suburban)	< 100 (Rural)
Cost (FTTH)	416	1,018	2,522
Cost (FTTB)	310	885	2,301
Speed upgrade benefit	*668*	*330*	*376*
Coverage upgrade benefit	*8,855*	*4,645*	*3,065*
LEs affected	183	257	1,075
Households affected:			
Upgrade ($T < T_1$)	851,880	387,743	584,874
Coverage (x < 100%)	5,066,954	432,781	319,468

Notes: Cost estimates by density categories are taken from the EIB (Hätönen, 2011)

Table 5: Estimated costs and benefits for the 1st Target 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

[30] 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. (forthcoming) 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 5, not the estimated benefits which are related to speed only, not to the delivering technology.

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 one could also argue that these households are simply not interested in broadband, and never will be, unless additional actions are also taken—e.g., to increase their degree of digital literacy (especially for households with older people). If one takes a stricter interpretation of the Digital Agenda, such that *every* household must have broadband of a certain minimum speed, one 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 FTTH than 40% of its cost. If a small percentage of the coverage benefits could also be realized, one could also argue for FTTB or even 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 one is willing to accept that at 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 5 give some sense of the total impact of the policy. Almost two hundred 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 1.8m households, and possibly fewer than 1.3m 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 5m. 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 analysis.

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, forthcoming). 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. While 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.[31]

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. When we run RDDs for each technological upgrade (see Appendix C), we find some genuine discontinuities in property prices associated with the upgrades that cannot be explained by trends that existed prior to the upgrade.

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. While 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

[31] 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/).

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, while the coverage upgrade estimates should be taken with more caution.

7 Conclusions

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 very bad to a very good connection increases the value, on average, by 3.8%. This is 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 welfare implications of current EU policy proposals aimed at increasing digital speed. We show that urban areas pass a cost-benefit test, while the case for these policy interventions is not very strong in rural areas.

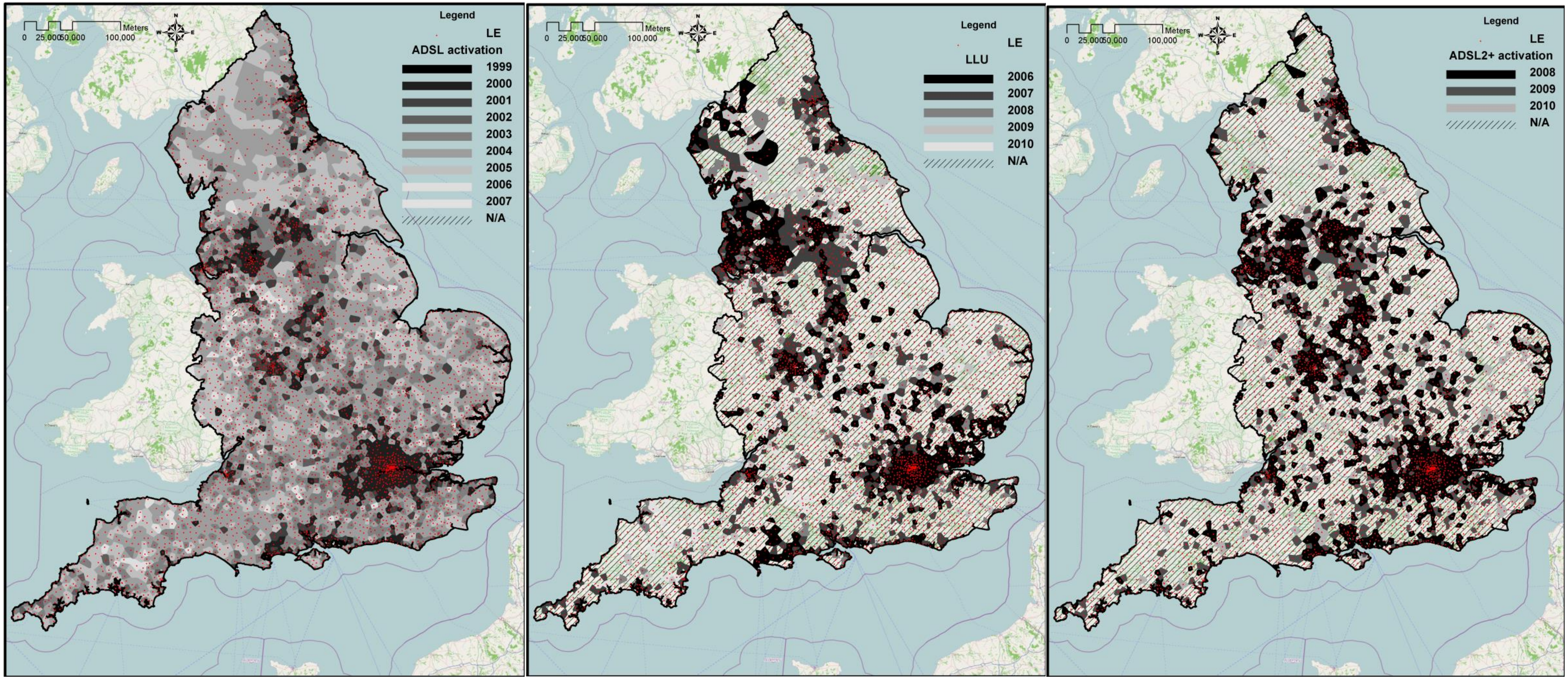
Since it is largely urban areas that pass a cost-benefit test, the question arises: Why do ISPs supply sub-optimal speed in those areas, where there seems to be a willingness to pay that is in excess of costs? The reason is that the broadband rent goes to the "wrong" economic agent. The broadband speed 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. In fact, competition among ISPs is actually tougher in urban areas, where property prices are typically higher: an ISP that tried to charge its customers more would just lose market share.

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. While 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—freeriding 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-markets 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).

Appendices

Appendix A: Evolution of Broadband in England

Figure A1 below shows the evolution of the availability of ADSL (first panel), LLU (second panel panel), and ADSL2+ (last panel) in every area of England over the study period. The red dots show the location of all the LEs in England. The first panel shows that ADSL became ubiquitous by the end of the period, though upgrades happened at different points in time in different areas. The second and last panels show that LLU and ADSL2+ did not diffuse everywhere, and a considerable part of the country (the hatched areas, which are concentrated in the rural parts of the country) did not attract sufficient economic interest from providers to bring faster broadband there.



Note: Red dots illustrated the location of LEs. LE boundaries are approximated using Thiessen polygons

Figure A1: The evolution of ADSL, LLU and ADSL2+ in England

Appendix B: Data Description

In this appendix, we introduce the additional non-broadband speed-related covariates we use in the capitalization regressions in more detail. Table B1 provides a summary. See, also, Ahlfeldt et al (2014).

Neighborhood characteristics

The main variables used for estimating capitalization effects of neighborhood characteristics are median income and ethnic composition. The income data provide a model-based estimate of median household income produced by Experian for Super Output Areas of the lower level (LSOA). This is assigned to the transaction data based on postcode. The data on ethnicity were made available by the 2001 UK Census at the level of Output Area (OA). Shares of each of the 16 ethnic groups and a Herfindahl index[32] were computed to capture the ethnic composition of neighborhoods.

Environmental variables

The environmental variables capture the amenity value of areas e.g. designated as natural parks, various features of the natural environment, and different types of land cover and use.

Geographical data (in the form of ESRI shapefiles) for UK National Parks, Areas of Outstanding Natural Beauty, and National Nature Reserves are available from Natural England. National Parks and Areas of Outstanding Natural Beauty are protected areas of countryside designated because of their significant landscape value. National Nature Reserves are "established to protect sensitive features and to provide 'outdoor laboratories' for research." Straight-line distances to these designations were computed for the housing units as geographically located by their postcodes. Furthermore, density measures that take into account both the distance to and the size of the features were created. We apply a kernel density measure (Silverman, 1986) with a radius of 2km, which is considered to be the maximum distance people are willing to walk (Gibbons and Machin, 2005).

The location of lakes, rivers and coastline is available from the GB Ordinance Survey. The distance to these features is also computed for the housing units from the transaction data. The UK Land Cover Map produced by the Centre for Ecology and Hydrology describes land coverage by 26 categories, as identified by satellite images. We follow Mourato et al. (2010), who construct nine broad land cover types from the 26 categories. Shares of each of these nine

[32] The Herfindahl index (HI) is calculated according to the following relation: $HI = \sum_{i=1}^{N} s_i^2$, where s_i is the share of ethnicity i in the LSOA, and N *i*s the total number of ethnicities.

categories in 1km grid squares are calculated, and the housing units take on the value of the grid square in which they reside.

The generalized Land Use Database (GLUD) available from the Department for Communities and Local Government gives area shares of nine different types of land use within Super Output Areas, lower level (LSOA). These nine types are domestic buildings, non-domestic buildings, roads, paths, rail, domestic gardens, green space, water, and other land use. These shares are assigned to the housing units based on the LSOA in which they are located.

Amenities

The locational amenities variables capture the benefits a location offers in terms of accessibility, employment opportunities, school quality, and the proximity of cultural and entertainment establishments.

Employment accessibility is captured both by the distance to Travel to Work Area (TTWA) centroid and by a measure of employment potentiality. TTWAs represent employment zones, and the distance to the center of these zones is a proxy for accessibility to employment locations. A more complex measure of accessibility is the employment potentiality index. This is computed at the Super Output Area, lower level (LSOA) and represents an average of employment in neighboring LSOAs, weighted by their distance.

Key Stage 2 (ages 7–11) assessment scores are available from the Department for Education at the Super Output Area, middle layer (MSOA). School quality is captured at the house level by computing a distance-weighted average of the KS2 scores of nearby MSOA centroids.

Geographical data on the locations of motorways, roads, airports, rail stations and rail tracks are available from the GB Ordinance Survey. Distances were computed from housing units to motorways, A-roads, B-roads and rail stations to capture accessibility. Buffer zones were created around the motorways and roads along with distance calculations to rail tracks and airports in order to capture the unpleasant noise effects of transport infrastructure.

Further data on local amenities were taken from the Ordinance Survey (police stations, places of worship, hospitals, leisure centers) and OpenStreetMap (cafés, restaurants/fast food outlets, museums, nightclubs, bars/pubs, theaters/cinemas, kindergartens and monuments, attractions). The number of listed buildings was provided by English Heritage. Kernel densities for these amenities were computed for housing units using a kernel radius of 2km and a quadratic kernel function (Silverman, 1986). The radius of 2km is consistent with amenities having a significant effect on property prices only when they are within walking distance.

Dependent Variable	
Price	Log transaction price in GBP of a property from the Nationwide Building Society (NBS).
Independent Variables	
Housing information	Set of property variables from the NBS including: Number of bedrooms, number of bathrooms, floor size (in square meter), new property (dummy), building age (years), tenure (leasehold/freehold), central heating (full: gas, electric, oil, solid fuel), central heating (partial: gas, electric, oil, solid fuel), garage (single or double), parking space, property type (detached, semi-detached, terraced, bungalow, flat-maisonette).
Neighborhood information	Set of neighborhood variables including: median income (2005, LSOA level), share of white population at total population (2001 census, output area level), share of mixed population at total population (2001 census, output area level), share of black population at total population (2001 census, output area level), share of Asian population at total population (2001 census, output area level), share of Chinese population at total population (2001 census, output area level), Herfindahl index of ethnic segregation (including population shares of White British, White Irish, White others, Mixed Caribbean, Mixed Asian, Mixed Black, Mixed other, Asian Indian, Asian Pakistani, Asian others, Black Caribbean, Black African, Black other, Chinese, Chinese other population, 2001 census output area).
Environment Characteristics and Amenities	Set of locational variables processed in GIS including: National Parks (distance to, density), Areas of Outstanding Beauty (distance to, density), Natural Nature Reserves (distance to, density), distance to nearest lake, distance to nearest river, distance to nearest coastline, land in 1km square: Marine and coastal margins; freshwater, wetland and flood plains; mountains, moors and heathland; semi-natural grassland; enclosed farmland; coniferous woodland; broad-leaved/mixed woodland; urban; inland bare ground.
Other amenities	Set of locational variables created in GIS including: Average key stage 2 test score (MSOA averages as well as interpolated in GIS), distance to electricity transmission lines, A-Roads (distance to, buffer dummy variables within 170m), B-Roads (distance to, buffer dummy variable within 85m), motorway (distance to, buffer dummy variable within 315m; buffer distances refer to the distance were noise of maximum speed drops drown to 50 decibel), distance to all railway stations, distance to London Underground stations, distance to railway tracks, distance to bus stations, distance to airports, densities of cafés, restaurants/fast food places, museums, nightclubs, bars/pubs, theaters/cinemas, kindergartens, monuments (memorial, monument, castles, attraction, artwork), hospitals, sports/leisure centers, police stations and worship locations, distance to Travel to Work Areas, employment potentiality.

Source: Ahlfeldt et al (2014).

Table B1: Variable description

Appendix C: Program Evaluation

1. Empirical framework

Given the distance decay in the effect of broadband, an upgrade of an LE can be viewed as an event that should exert spatially variant effects on nearby property prices. The effect of the event on property prices can, thus, be analyzed using quasi-experimental research designs that have become popular in the program evaluation literature. In this appendix, we complement the empirical analysis presented in the main paper using variants of the difference-in-differences (DD) methodology. The effects discussed in this section are reduced-form in that they reflect the joint effect of distance to the LE on broadband speed on the one hand and the effect of broadband speed on property prices on the other.

1.1. Baseline difference-in-differences model

Our baseline reduced-form empirical specification is a mix of hedonic modeling, panel econometrics, and a DD method, which we extend to accommodate multiple treatment dates. The point of departure is the following specification, which can be used to identify the treatment effect on treated subjects in a pooled spatial cross-section:

$$\log(P_{ijt}) = \sum_{Q} \beta_Q POST_{jt}^{Q} + \mathrm{X}_i'\mu + \varphi_j + \omega_t + \varepsilon_{ijt},$$

where P is the sales price of a property that sells in postcode i served by LE j in year t, X_i' is a vector of structural, location and neighborhood variables and μ is a vector of implicit hedonic prices. φ_j is a fixed effect for whether a property is located within the catchment area of an LE j, ω_t is a year fixed effect and ε_{ijt} a random error term. $POST_{jt}^{Q}$ are 0,1 indicator variables indexing whether at time t, LE j had been upgraded to quality level $Q = \{\text{ADSL}, \text{LLU}, \text{ADSL2}+\}$. Because the equation includes LE and year fixed effects, the treatment coefficients β_Q identify the conditional mean difference in property prices before and after an upgrade for the group of upgraded (treated) LEs relative to all other (control) LEs.

1.2. Difference-in-differences models with spatial variation

The baseline model estimates three DD parameters β_Q that reflect property price changes that are averaged over all distances to the LE. We allow for spatial heterogeneity in the treatment effect within an area served by an LE as follows:

$$\log(P_{ijt}) = \sum_{Q} \beta_{0Q}(POST_{jt}^{Q}) + \sum_{Q} \beta_{1Q}(POST_{jt}^{Q} \times DIST_{ij}) + \beta_3 DIST_{ij} + \mathrm{X}_i'\mu + \varphi_j + \omega_t + \varepsilon_{ijt}$$

In this specification, the treatment effect of a certain type of LE upgrade Q on property prices at a given distance from an upgraded LE is given by $\beta_{0Q} + \beta_{1Q} DIST_{ij}$. The DD comparison relative to LEs that were not upgraded and the period before the upgrade is, thus, made at every distance from the upgraded LEs. To allow for a more flexible distance effect, we group postcodes into a full set of mutually exclusive 250m distance bins B_{ijm}, where $B_{ijm=1}$ contains all postcodes within 0-250m of the nearest LE j, $B_{ijm=2}$ contains all postcodes within 250m-500m, and so forth.

$$\log(P_{ijt}) = \sum_{Q} \beta_{0Q} POST_{jt}^{Q} + \sum_{Q}\sum_{m} \theta_{m}^{POST}\left(B_{ijm} \times POST_{jt}^{Q}\right) + \sum_{m} \theta_{m} B_{ijm} + \mathrm{X}_i'\mu + \varphi_j + \omega_t + \varepsilon_{ijt}$$

In this specification, all parameters θ_{m}^{POST} represent separate DD parameters that compare the price change in a distance cell to the respective change in LEs that were not upgraded.

1.3. Difference-in-differences models with spatiotemporal variation

A typical concern in DD analyses are temporal trends that are correlated with but not causally related to the treatment. Identification, in general, cannot be considered credible if changes in property prices near to LEs following an upgrade can be explained by (relative) trends in the neighborhoods that existed prior to the upgrade. The concern is relevant in our case because the assignment of the LE upgrade is not technologically random. Therefore, we expand the spatial DD model to allow for a temporal structure in the treatment effect of an LE upgrade.

In the first step, we allow for additional spatially varying DD effects for each of the three years immediately preceding an upgrade. Because we do not expect capitalization effects in anticipation of an upgrade, these effects can be viewed as placebo-treatment effects.

$$\log(P_{ijt}) = \sum_{Q} \beta_{0Q} POST_{jt}^{Q} + \sum_{Q} \beta_{1Q}\left(POST_{jt}^{Q} \times DIST_{ij}\right) + \sum_{Z}\sum_{Q} \beta_{0ZQ}\left(PRE_{Zjt}^{Q}\right) + \sum_{Z}\sum_{Q} \beta_{1ZQ}\left(PRE_{Zjt}^{Q} \times DIST_{ij}\right) + \beta_3 DIST_{ij} + \mathrm{X}_i'\mu + \varphi_j + \omega_t + \varepsilon_{ijt},$$

where PRE_{Zjt}^{Q} indexes an LE x year cell Z years before a Q-type upgrade of LE j. Note that these *PRE* effects provide a DD comparison relative to LEs that where not upgraded and the period four or more years before an activation. In a further expansion, we replace the *POST* effects with separate DD effects for each of the two first years subsequent to an upgrade and a residual category that contains all subsequent years.

2. Empirical results

Table C1, column (1) presents a naïve DD analysis using the baseline DD model and excluding all controls but the LE and year fixed effects. In terms of property price, areas that were connected to ADSL outperformed other areas by about 6%. This is a very large effect, especially given that it is an average across the LE area and, thus, includes areas that gain relatively little due to the spatial decay in effective speed. With some arguably strong controls for heterogeneous appreciation trends, the ADSL effect about halves, but, with 2.5% across the entire LE area, remains large. These results rationalize the anecdotal evidence reported in the news, where it has been claimed that good broadband may increase property value by as much as 5% (see the Introduction). It is notable that incremental improvements, such as LLU and ADSL2+, are associated with significantly lower increases, even though an ADSL2+ upgrade can come with an especially substantial speed increase. These results are in line with the findings in the main paper that point to diminishing returns to speed.

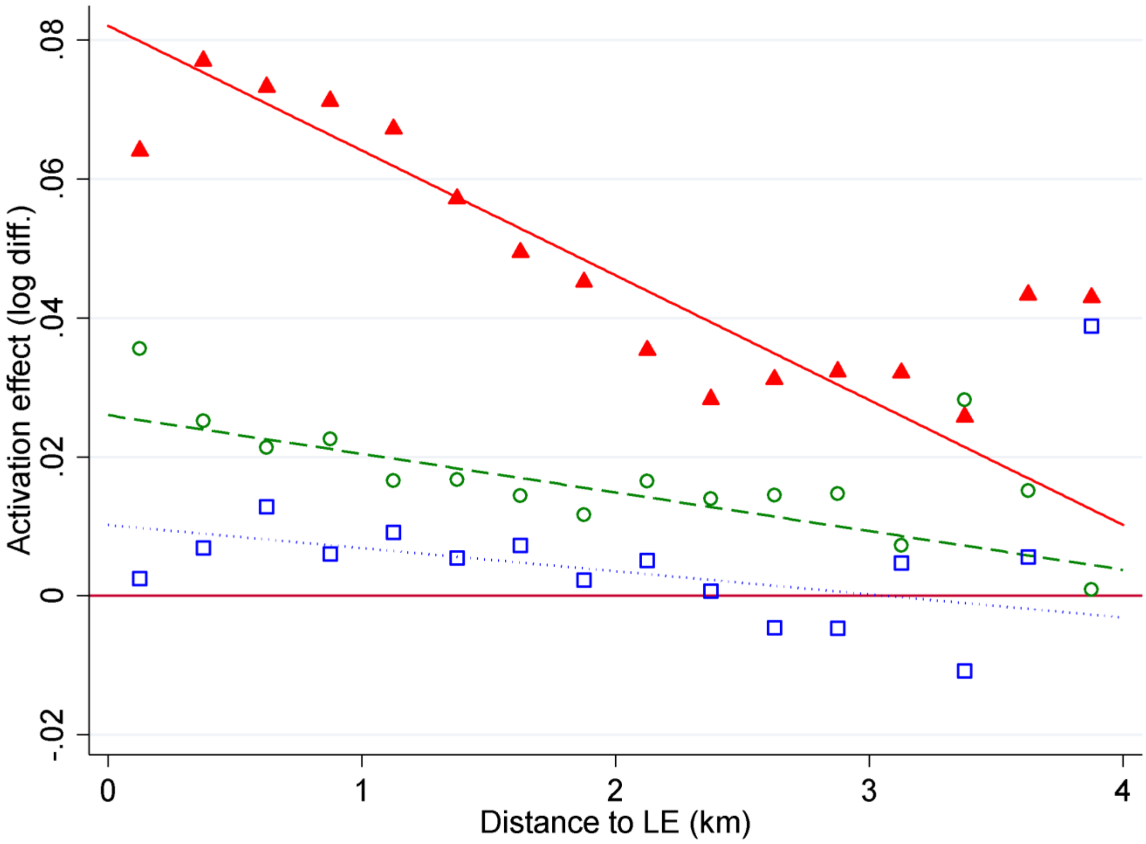
	(1)	(2)	(3)	(4)	(5)
	Natural logarithm of sales price				
ADSL active	0.059***	0.060***	0.063***	0.023***	0.025***
	(0.004)	(0.004)	(0.001)	(0.002)	(0.002)
LLU active	0.010***	0.017***	0.006***	0.025***	0.001
	(0.003)	(0.003)	(0.001)	(0.002)	(0.001)
ADSL2+ active	0.009**	0.004*	0.003	0.003**	0.002
	(0.004)	(0.002)	(0.002)	(0.002)	(0.002)
LE effects	YES	YES	NO	YES	YES
Year effects	YES	YES	YES	NO	NO
Postcode effects	NO	NO	YES	NO	NO
Controls	NO	YES	YES	YES	YES
TTWA × year effects	NO	NO	NO	YES	YES
Controls × year effects	NO	NO	NO	NO	YES
r2	0.669	0.916	0.975	0.924	0.928
N	1,082,777	1,082,777	1,082,777	1,082,777	1,082,777

Notes: Standard errors in parentheses are clustered on LEs. * p<0.1, ** p<0.05, *** p<0.01

Table C1: Baseline DD results

Figure C1 visually summarizes the spatial DD model results. The estimates of the parametric version are also presented in Column 1 of Table C1. The baseline model corresponds to Column (3) in Table C1. For the estimation of spatial effects, we exclude properties beyond 4km of an LE because these areas are very sparsely populated (less than 1% of the sample).

The results indicate significant and spatially varying effects associated with each of the three upgrade waves. The effects are generally larger close to the LE, which is in line with the spatial decay that exists in broadband quality. The parametric estimates imposing a linear distance effect generally follow the distance bin effects relatively closely. Especially in the ADSL effects, however, an S-shape is evident that vaguely resembles the shape of the spatial decay in broadband download speed. As before, incremental technological upgrades are associated with smaller effects, which indicate diminishing marginal benefits of increases in broadband speed.



Notes: Red solid (green dashed) [blue dotted] lines and triangles (circles) [squares] indicate ADSL (LLU) [ADSL2+] effects.

Figure C1: Spatial DD results.

Next, we turn our attention to spatiotemporal trends around the upgrade dates. To keep the tabular presentation compact, we report parametric results for models in which we add the *PRE* placebo DD effects, but no separate *POST* effects (column 2 in Table C2). In the graphical illustration in Figure C2, we also allow DD effects to vary across some *POST* year x LE cells. To save space, we do not show the corresponding figures for the LLU and ADSL2+ upgrades, but we discuss the results in the text.

	(1) Natural logarithm of sales price		(2) Natural logarithm of sales price	
ADSL active	0.082***	(0.005)	0.071***	(0.004)
LLU active	0.026***	(0.004)	0.056***	(0.005)
ADSL2+ active	0.010***	(0.003)	-0.004	(0.004)
ADSL x DIST	-0.018***	(0.002)	-0.018***	(0.002)
LLU x DIST	-0.006***	(0.002)	-0.008***	(0.003)
ADSL2+ x *DIST*	-0.003**	(0.001)	-0.001	(0.002)
$\mathrm{PRE}_1^{\mathrm{ADSL}}$			0.012***	(0.003)
$\mathrm{PRE}_2^{\mathrm{ADSL}}$			-0.004	(0.003)
$\mathrm{PRE}_3^{\mathrm{ADSL}}$			-0.030***	(0.003)
$\mathrm{PRE}_1^{\mathrm{ADSL}}$ x DIST			-0.011***	(0.002)
$\mathrm{PRE}_2^{\mathrm{ADSL}}$ x DIST			-0.002	(0.002)
$\mathrm{PRE}_3^{\mathrm{ADSL}}$ x DIST			0.007***	(0.002)
$\mathrm{PRE}_1^{\mathrm{LLU}}$			0.036***	(0.006)
$\mathrm{PRE}_2^{\mathrm{LLU}}$			0.041***	(0.005)
$\mathrm{PRE}_3^{\mathrm{LLU}}$			0.048***	(0.004)
$\mathrm{PRE}_1^{\mathrm{LLU}}$ x DIST			-0.006	(0.004)
$\mathrm{PRE}_2^{\mathrm{LLU}}$ x DIST			0.000	(0.002)
$\mathrm{PRE}_3^{\mathrm{LLU}}$ x DIST			-0.005**	(0.002)
$\mathrm{PRE}_1^{\mathrm{ADSL2+}}$			-0.012**	(0.006)
$\mathrm{PRE}_2^{\mathrm{ADSL2+}}$			-0.018***	(0.003)
$\mathrm{PRE}_3^{\mathrm{ADSL2+}}$			-0.020***	(0.003)
$\mathrm{PRE}_1^{\mathrm{ADSL2+}}$ x DIST			-0.001	(0.004)
$\mathrm{PRE}_2^{\mathrm{ADSL2+}}$ x DIST			0.004**	(0.002)
$\mathrm{PRE}_3^{\mathrm{ADSL2+}}$ x DIST			0.007***	(0.002)
LE Effects	YES		YES	
Year Effects	YES		YES	
Controls	YES		YES	
Distance to LE	YES		YES	
r2	0.916		0.916	
N	1070197		1070197	

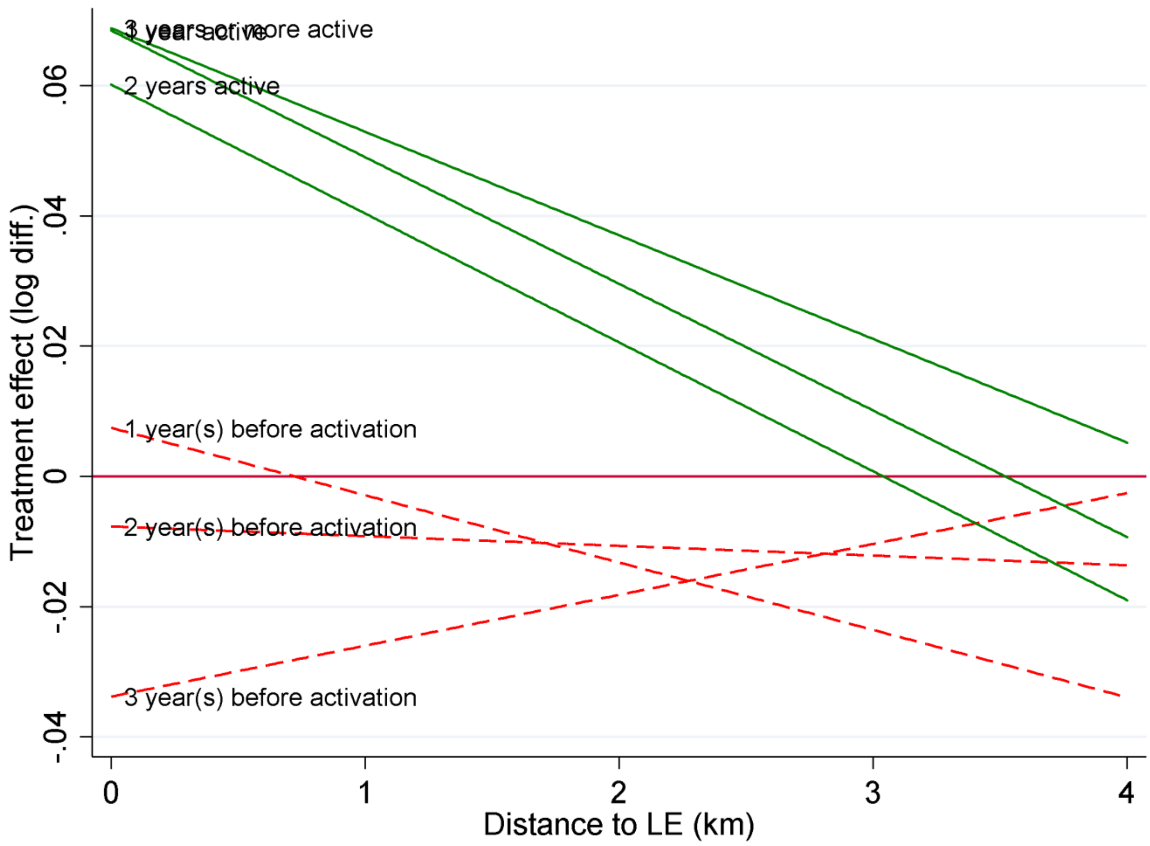
Notes: Standard errors in parentheses are clustered on LEs. * p<0.1, ** p<0.05, *** p<0.01

Table C2: Difference-in-differences with spatial variation

All estimated *PRE*-treatment ADSL effects are near to zero and most are even slightly negative. While there is a slight orientation over the three years preceding the ADSL activation towards 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.

The pattern of time-varying LLU effects is more complex. All *POST* effects show the expected pattern with a positive level shift that flattens out towards the fringe of the LE. The effect increases notably from the first to the second *POST* period and moderately afterwards. Two of the three *PRE*-effects are not in line with a successful falsification test at first glance. The effects are highly positive, and one even shows a notable negative slope. A closer inspection reveals, however, that the *PRE* effects decline towards the activation date. Also, the negative slope tends to disappear over time. Pre-trends, thus, are negatively correlated with the treatment and are reversed just at the time of the upgrade, which makes a particularly strong case for impact.

The ADSL2+ effects show a similar pattern. In the model with separate *PRE*-effects (where the comparison is made relative to four and more years before activation), the ADSL2+ *POST* effect turns out to be negative at all distances to the LE. This is not the expected result, even though there is negative decay, as expected. The *POST* effect is, however, significantly more positive than any of the three *PRE* effects, at least within areas that are relatively close to the LE. Moreover, the earlier *PRE* effects show a positive distance trend, which is reversed only one year before the ADSL2+ activation. As with the LLU effects, the inspection indicates that pre-trends are negatively correlated with the treatment, which strengthens the sense of impact.



Notes: Red solid (green dashed) lines show difference-in-differences estimates for periods before (after) the upgrade took place.

Figure C2: Difference-in-difference results with spatiotemporal variation: ADSL

Appendix D: Varying window sizes in boundary models

Table D1 below presents estimates of eq. (5) for varying boundary window sizes. The models are otherwise identical to model (6) in Table 2.

	(1)	(2)	(3)	(4)	(5)
	Natural logarithm of sales price (£)				
Imputed local broadband capacity in MBit/sec	0.026***	0.025***	0.026***	0.026***	0.024***
	(0.001)	(0.002)	(0.002)	(0.004)	(0.007)
Speed^2	-0.003***	-0.003***	-0.003***	-0.002***	-0.003*
	(0.000)	(0.000)	(0.000)	(0.001)	(0.002)
4^{th} order distance poly.	YES	YES	YES	YES	YES
Control x year effects	YES	YES	YES	YES	YES
LE effects	YES	YES	YES	YES	YES
LE boundary x year eff.	YES	YES	YES	YES	YES
Boundary window (m)	ALL	1,000	500	200	100
r2	0.940	0.942	0.944	0.951	0.961
N	1,082,777	656,353	338,982	125,209	56,640

Notes: Standard errors in parentheses and clustered on LE x boundary effects in (4-6). * p<0.1, ** p<0.05, *** p<0.01

Table D1: Varying boundary windows

Appendix E: Policy Impact of the Digital Targets

Table E1 below reports the distribution of actual speeds by LE in our sample, organized by population decile. While this distribution is not exactly by density, as for the DCMS document, it is a good approximation, as faster broadband is typically deployed in more densely populated areas, while slower broadband exists in rural parts of the country. The distribution becomes our starting point for comparison with the speeds forecasted by the DCMS in 2020, presented in Table 4 in the main text. Notice that our speeds are *observed* actual speeds (see footnote 23), while the DCMS forecasts are in terms of the theoretical maximum speed attainable with a technology. Another reason for the large differences between our deciles and those in Table 4 is that our tests exclude cable subscribers, who generally connect to higher speeds.

Decile	1	**2**	3	**4**	5	6	7	8	9	10
Speed 2010 (in Mbit/s)	1.95	**2.68**	2.71	**2.97**	3.15	3.29	3.41	3.51	3.62	4.22
% of population with broadband connection	76.01	72.58	73.32	72.43	74.03	72.75	73.45	76.3	75.78	79.39

Table E1: Actual broadband speeds in England in 2010

We then follow the definitions of the EIB to attribute each LE to one of the three types of areas defined for the purpose of calculating costs (see Hätönen, 2011). According to these definitions, out of 22,925,211 English households, 85.89% are in LEs attributable to urban areas, 7.98% are in suburban areas, and the remaining 6.13% are in rural areas.

In Section 6, we report benefits at the household level to allow for comparisons of the speed upgrade and coverage upgrade. Hence, it does not actually matter how many people have to be connected when discussing values per household. Looking at the bigger picture, it is important to assess the aggregate benefits of the speed upgrade and coverage upgrade approach. For this, we proceed as follows. We add 10% to population covered, as, according to Ofcom, this is the percentage of people using mobile only for broadband purposes, which, therefore, will not need to be upgraded.[33] Then, we compute benefits in each LE, as reported in Table 5, and multiply those benefits per household times the number of households affected in that LE. We obtain aggregate total benefits of GBP 0.916bn for the upgrade and GBP 47.859bn for the coverage upgrade; see the first two columns of Table E2.

We now explore the EU agenda's second target for 2020. This target requires the upgrade of 50% of households to the average speed equivalent to the fourth decile of the speed distribution

[33] See http://stakeholders.ofcom.org.uk/binaries/research/cmr/cmr13/UK_5.pdf.

(2.97 Mbit/s in our sample). If 50% of households already subscribe to speeds above 2.97 Mbit/s in our sample, we do nothing. If not, we calculate how many households need to be upgraded until we reach the target. We find that 1,778,095 households in England need to be upgraded (7.76% of the total). We employ two different strategies for this target.

	National impact from 1st target (GBP)	**% HH affected**	**National impact from 2nd target (GBP)**	**% HH affected**
Speed upgrade	916,218,199	7.96	487,385,224	7.76
Coverage upgrade	47,859,461,165	25.40	18,244,275,126	7.76

Table E2: Implementing the targets of the EU digital agenda

In the first approach, we rank LEs by speed and start from the top. In each LE, we connect non-subscribers and add the total number of households we upgrade. We continue until we reach the 50% target. All results appear in Table E3 (coverage upgrade row), which is equivalent to Table 5 in the main text. In the second approach, we rank LEs by speed and start from the LEs that are below the threshold (2.97 Mbit/s). We then upgrade the connected subscribers in those LEs until we reach the 50% target. The results are presented in Table E3 (speed upgrade row). Then we compute the corresponding aggregate benefits, obtaining GBP 0.487bn for the speed upgrade and GBP 18.244bn for the coverage upgrade; see the last two columns of Table E2.

	Population density in residents/km²		
Costs/*Benefits* per HH (GBP)	> 500 (Urban)	> 100 & < 500 (Suburban)	< 100 (Rural)
Cost (FTTH)	416	1,018	2,522
Cost (FTTB)	310	885	2,301
Speed upgrade benefit	*300*	*163*	*82*
Coverage upgrade benefit	*10,699*	*4,789*	*3,347*
LEs affected:			
Upgrade	238	122	192
Coverage	454	96	45
Households affected:			
Upgrade	1,491,444	181,158	105,494
Coverage	1,649,953	108,614	19,528

Notes: Cost estimates by density categories are taken from the EIB (Hätönen, 2011)

Table E3: Estimated costs and benefits for the 2nd Target of the EU Digital Agenda

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Spatial Economics Research Centre (SERC)
London School of Economics
Houghton Street
London WC2A 2AE

Tel: 020 7852 3565
Fax: 020 7955 6848
Web: www.spatialeconomics.ac.uk

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