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The (Fuzzy) Digital Divide: The Effect of Broadband Internet Use on UK Firm Performance

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Abstract

This paper applies a fuzzy regression discontinuity design to study the effects of ADSL broadband internet on the performance of firms. We exploit a geographical discontinuity in the availability of ADSL broadband, firms located one side of the divide had access to broadband services that those on the other side did not. The discontinuity stems from an historical accident, whereby the telecommunications in one area of the North East of England is delivered by a separate company to the national monopoly provider. We study the discontinuity at the boundary between these two telecommunications providers, which rolled out broadband infrastructure at different times. Our analysis strongly suggests that broadband use has no statistically significant effect on the performance of firms.

JEL classification: J23; J24; J31; O3

Keywords: broadband; firms; fuzzy regression discontinuity

1. Introduction

In this paper we exploit a technical feature of ADSL broadband infrastructure which separates firms' access to the digital economy into those that 'can' and those that 'cannot'. We then use this digital divide as an instrument for firm broadband internet adoption to test for its effects on firm performance using a fuzzy regression discontinuity (FRD) design.

Under the prevailing view, businesses on the right side of the digital-divide, with broadband access, have greater national and international connectivity and would exploit this within their sales, procurement, communication and coordination strategies. They should be more likely to create new products, new processes, new business models, increase the number of customers they reach, generate new knowledge and to participate in complex international supply-chains. (Varian et al., 2002; Antras et al., 2006; Abramovsky and Griffith, 2006, OECD, 2008). Accordingly, these firms are likely to increase sales and employment and raise their productivity.

Identification of the effects of the broadband in this paper comes from a technical feature of ADSL broadband infrastructure (the dominant form of broadband in the UK[1]) that generates a spatial discontinuity in access to broadband technology and therefore the incentive to adopt broadband.[2] To describe this simply: in our data a firm on one side of the street can have access to broadband infrastructure that a firm on the other side does not, simply because of being connected to a different local telephone exchange. Firms on the right side of the digital divide have greater access to broadband and should be more likely to adopt this technology. This discontinuity is present in the data for a period of 5 years (2000 – 2004 inclusive). This is, as far as we are aware, the first paper to use a fuzzy-regression discontinuity approach to study the effects of broadband, or information and communication technology (ICT) more generally, on firm performance.

It has long been recognised that firms do not randomly select into adopting ICT technologies such as broadband, but rather choose to do so, fully aware of the possibilities that the technology offers (Brynjolfsson and Hitt, 2003; Aral et al. 2007). The correlation between broadband use and firm performance may therefore capture the effect of an omitted factor, which the literature suggests is most likely to be differences in managerial ability. There now exists ample evidence that the productivity effects of ICT are only realised if made alongside other organisational changes including new types of management practices (Hubbard, 2003; Bartel et al., 2007; Brynjolfsson et al., 2008; Garicano and Heaton, 2010; Garicano, 2010; Bloom et al., 2012). The key advantage of using a FRD design is that, under relatively weak assumptions, it can mimic the conditions for random assignment allowing unbiased estimates of the treatment effects. Across our digital divide firms differ in their access to broadband, but not their other characteristics, allowing

[1] For example, by 2012 over 85% of firms and 55% of households had ADSL broadband connection (ONS, 2013)
[2] Other broadband internet services were available. In particular firms could purchase a leased line, which gave them a direct connection to the fibre-optic backbone of the telephone network. Such connections were expensive and therefore were used by a minority of large firms. We discuss these in further detail in Section 2.

the study of the effects of broadband on firm performance free of the influence of potentially confounding factors.

As in many European countries, in the UK the large-scale switch from narrowband to broadband internet access was made using ADSL technology. ADSL utilised and was therefore shaped by the legacy of the copper and fibre-optic wire telephone network. The telephone network in the UK is structured such that each firm or household is connected to a telephone exchange. These local exchanges are in turn connected to the fibre-optic backbone of the telephone network. The connection speeds provided by ADSL are a function of the cable distance of the customer from the telephone exchange. Internet connections speeds decline for distances beyond 2,000 metres, while customers with a distance greater than 5,500 metres were not provided with ADSL broadband.[3] For the UK we have precise information on the day on which each local telephone exchange was enabled for ADSL broadband and the location of each exchange. Using this data we can capture a spatial discontinuity in the availability of ADSL, given by the maximum distance that broadband services are provided around each telephone exchange (5,500 metres).

The existence of over 5,500 telephone exchanges within the UK offers a large number of geographical discontinuities that might be explored in the data. Out of a concern for unobserved geographic or economic factors we confine ourselves to a small sub-set of these. Within the existing literature the rollout of broadband infrastructure has been used in a number of micro data studies as an instrument for firm adoption decisions.[4] In the UK the ADSL rollout programme does not mimic the conditions for random assignment however and cannot be reliably be used as an identification strategy.[5] The costs of broadband infrastructure are substantial and the commercial firms that were involved sought to maximise the returns on their investment.[6] As a consequence, infrastructure investments occurred first in cities where per-capita incomes were highest and where there were agglomerations of firms and households. In addition, the costs of introducing new telecoms infrastructure are not equal across all geographies. For example they are lower the flatter the landscape is, and those areas with the lowest costs are more likely to receive the infrastructure first. If difficult to observe geographic factors or agglomeration economies are correlated with

[3] Within our treatment region 87% of firms lie within 2 kilometres of the nearest telephone exchange and 98% are within 3 kilometres. The effect of distance on connections speeds is not therefore a strong influence on our results.

[4] Czernich et al. (2011), Abramovsky and Griffith (2006), Bertschek et al. (2013), Haller and Lyons (2014) all construct instruments for broadband adoption based on geographic and time variation in the availability of broadband infrastructure. Kolko (2012) uses instead the average steepness of the terrain, which are shown to be correlated with the costs of enablement.

[5] In other country settings such conditions are arguably satisfied. Akerman et al. (2013) for example uses the setting of a publically funded broadband rollout out programme in Norway.

[6] Demonstration of this point can be found on the BT website http://www.superfast-openreach.co.uk/faq/ . We also thank David Clarkson (Competition Policy Director, OFCOM) for confirming this to us.

firm performance, then identification based on the timing of infrastructure rollout may not remove the link between broadband and unobserved determinants of productivity in the way that is desired.[7]

We take advantage of an unusual historic feature of telephone service provision in the UK, where for one region the timing of enablement is plausibly exogenous to any unobserved economic or geographic factors. Since the early 20th century, telecoms in the area surrounding Kingston-upon-Hull in the North East of England have been delivered by a separate local provider to the rest of the UK. Named Kingston Communications (KC) this firm owns and operates 37 telephone exchanges in this region, whereas *all* remaining telephone exchanges (5,536 exchanges) in the UK are owned by British Telecom (BT). We study the discontinuity at the boundary between these two telecommunications providers.

The exchanges owned and operated by Kingston Communications were ADSL enabled in 1999 and made available broadband services from 2000, whereas many of the exchanges owned by BT in this region of the UK were enabled for broadband as late as 2005.[8] This difference in the timing of enablement is explained by the size of the respective companies and limits on the availability of engineers to undertake the necessary upgrades to telephone exchanges. To return to our earlier characterisation: in our setting the side of the street which has access to ADSL broadband services is determined by an historical accident in the delivery of the previous telecoms technology. That this discontinuity is present for 5-years provides a reasonable time window in which to potentially identify any effects of broadband adoption on firm performance.

In Figure 1 we provide initial evidence that access to ADSL broadband services had the positive expected effect on broadband take-up we anticipate. We compare rates of broadband adoption by firms inside and outside the area where Kingston Communications ADSL was available (5,500 metres around KC exchanges). Firms inside the enabled region are denoted by positive distance and those outside, in non-enabled areas served by BT, are denoted by negative distances. As this figure shows, firms connected to Kingston Communications exchanges are more likely to have adopted broadband over this time period than those firms located in BT areas where ADSL broadband was not available.[9] The difference in propensity is around 10 percentage points.[10] As we demonstrate later in the paper, this difference in adoption does not persist after 2005, the period in which both BT and KC areas are enabled for ADSL.

[Figure 1]

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[7] These effects might be either direct or indirect. Rosentahl and Strange (2008) provide evidence that geography can affect industry agglomeration for example, while indirect effects might occur from the effect on housing supply (Saiz, 2010) and in-turn land and office prices.

[8] KC made ADSL services available for purchase in 2000. This is also the year that BT made available its ADSL service.

[9] It is also worthy of note that the spatial discontinuity exists for the availability of broadband but not other technologies, in particular mobile technologies, that developed around this time.

[10] In Figure 1, firms in BT areas have non-zero broadband take-up due to the availability of leased line and cable prior to the start of our sample. Leased line and cable was also available in areas served by Kingston Communications.

The data we employ is from two main sources. Data on firm location and characteristics is from the Office for National Statistics (ONS), known as the Annual Business Inquiry (ABI). This is the same data source used to study the effects of ICT on the productivity of UK firms by Bloom et al. (2012), on offshoring by Abramovsky and Griffith (2006) as well as many other topics. The use of this data ensures that we have both a large number of observations but also precise information on the location of firms and key indicators of performance.

We combine this with data from the ADSL Broadband Database made available by the Office of the Telecoms Regulator (OFCOM) which outlines the geographic rollout of ADSL broadband across the UK. The ADSL dataset provides the precise location (postcode) and date of ADSL enablement for each telephone exchange in the UK. As far as we are aware this is the first time within the literature that broadband infrastructure availability has been measured using the date of enablement of the local telephone exchange.[11]

OECD (2008) carefully describes the detailed ways in which broadband technology has affected the way in which managers, workers, suppliers and customers interact. These include the growing use of e-commerce, the growth of new types of firm and service, the ability to work efficiently outside of the office, and the effect on administration costs[12] amongst others. To capture the breadth of the possible effects from broadband we measure firm performance using information on firm employment (both levels and growth), sales (levels and growth), firm exit probabilities and labour productivity.[13] A final advantage of this data is its availability for time periods beyond those of the discontinuity window, allowing us to make careful comparisons of the firms located around Kingston-upon-Hull in the period before, during and after ADSL enablement took place.

To summarise briefly our main findings: as already shown using Figure 1, we find that firms located within the ADSL enabled area (served by Kingston Communications) are more likely to adopt the broadband. The instrument is a strong predictor of broadband adoption and passes all tests for weak instruments. However, broadband internet adoption has no statistically significant relationship with any measure of firm performance that we use. This includes employment, output, labour productivity and plant exit and holds irrespective of whether we use levels or growth rates of these variables. The local average treatment effect on those induced to adopt broadband because of differences in the availability of broadband infrastructure is statistically insignificant in our data. This contrasts with the positive and statistically significant relationship when estimating using OLS, confirming the expected upward bias in such estimations.

[11] More commonly broadband availability has been captured using the percentage of households that have broadband internet connections. See for example Abramovsky and Griffith (2006) or Akerman et al. (2013).

[12] As an example they cite evidence of the use of an on-line expenses software used by Oracle, which Atkinson and McKay (2007) state has reduced costs from $25 to $10 per claim, or the use by IBM of an on-line travel booking software which led to $2.5 million in monthly savings.

[13] The data necessary to construct measures of TFP would lead to the potential loss of many observations. We are also unable to consider international trade using the data available to us.

We subject these findings to a number of tests of their robustness. These include various tests for the FRD approach, such as estimations using different bandwidths around the discontinuity and testing for evidence of firm sorting. We also test that the results are not driven by the inclusion of the city of Kingston-upon-Hull. Outside of the city there exists a largely suburban and rural area where firms are connected to both KC (enabled in 2000) and BT owned exchanges (enabled in 2005). We find that our results still hold for these non-urban areas.

The application for the establishment of the original telecoms company in Kingston-upon-Hull was made by the Corporation of Hull (the local government authority) but no longer conforms to the location of local-authority administrative boundaries. We test whether our results might be driven by these local-authority boundaries. We find no evidence to suggest such effects. Finally, as already mentioned, we exploit the panel nature of the micro-data available from the ONS to test for a discontinuity in broadband adoption when all exchanges are ADSL enabled from 2005 onwards. Restricting the data to this later time period removes the existence of a broadband discontinuity within the data, further supporting our empirical design.

Our results provide an obvious challenge to the academic literature that has sought to claim that broadband has a causal effect on the performance of firms and points to the presence of confounding factors as an explanation of the correlation between firm performance and the use of communication technologies. Confounding factors determine selection into treatment and are correlated with the outcomes of interest. This finding is close in spirit to the work of DiNardo and Pischke (1997), who find that the wage premium associated with the use of computers is similar to the wage premium from jobs that use pens and pencils and require the worker to sit-down. This leads them to question whether it is ICT or some other aspect of the skill of office-workers that is being rewarded in the labour market. We discuss the relationship between our work and the existing literature in greater depth towards the end of the paper.

In addition to the academic literature on the effects of the internet, our results are likely to be of interest to policy makers. Both domestic policy makers and international agencies have supported policies aimed at improving access to and the speed of internet connections across countries. Direct policy interventions have included actions to stimulate demand as well as those to affect the supply-side such as obligations for universal service, subsides for infrastructure provision and support for R&D in telecommunications. As examples, in the last decade the European Commission have launched a number of initiatives including *e*Europe, *e*Europe2005 and *i*2010 (Falch, 2007); while US action has been provided through the *Federal Rural Broadband Access Loans* and the *Community Connect Broadband Grant Programmes* as well as other initiatives at the state (Alliance for Public Technology) and local government level (Gillet et al., 2004). In 2010 the UK Government announced a target of universal access to super-fast broadband by 2015 and for the UK to have the fastest network speeds of the 5 largest EU economies. It has committed £1.6 billion of public funds to support private investment in broadband infrastructure between

2013 and 2017 (Department for Culture Media and Sport, 2013). The Culture Secretary (Jeremy Hunt) explained the motivation behind this as "(T)he reason we want to do this is very simple—it is about jobs". There are no doubt many socio-economic effects of universal broadband access, but the impact on firms may be mute.

The rest of the paper is organised as follows. In the next section of the paper we provide a description of the spatial discontinuity that we use to identify the effect of broadband adoption. This includes a brief overview of the historical accident that led to the creation of Kingston-upon-Hull's local monopoly, an explanation of ADSL and the rollout throughout the UK, and an overview of alternative broadband technologies before discussing the construction of the spatial discontinuity. In this section we also provide a brief description of the existing literature on broadband. In Section 3 we briefly discuss the data that we use and in Section 4 we outline our empirical methodology. Sections 5 to 8 provide the main empirical results; in Section 5 we provide a graphical analysis, Section 6 provides the econometric evidence and Section 7 tests the robustness of these results and in Section 8 discuss some of the threats to identification. We use Section 9 of the paper to discuss our findings in relation to the broader literature and draw some conclusions from the paper in Section 10.

2. ADSL Broadband Discontinuity and the Existing Literature

A Brief History of UK Telephone Networks

Our identification strategy relies on a spatial discontinuity in the availability of ADSL broadband which exists as a result of a historical accident in the provision of telephone services. In the North East of England, in the area around the city of Kingston-upon-Hull, the telecommunications services are provided by Kingston Communications (later renamed KCom). Kingston Communications were born out of the 1899 Telegraph Act which allowed municipalities to establish local telephone systems to provide competition for the monopoly supplier (The National Telephone Company, NTC, which later became BT).[14] In August 1902, Hull Corporation (which later became Hull City Council) was granted a licence under the Telegraph Act to operate a telephone system in the Kingston-upon-Hull area. By 1913, six municipalities had set up telephone services under the provisions of this Act, but all except that of Hull had been bought by the NTC.[15] The Hull network was nearly sold to NTC in 1906, but a chairman's casting vote meant it remained as a separate company. The telecoms licences awarded to Kingston Communications have been renewed at various points in its history, the most recent of which is defined within the Kingston Licence granted under the 1984

[14] Instigation for the Act came from representation by the Corporation of Glasgow about the monopoly supply of the local telephone system to a Select Committee of the House of Commons in 1898.
[15] As we explore later in the paper. Various local authority boundary changes mean that the area covered by Kingston Communications is now different from the boundaries of Hull City Council.

Telecommunications Act. This Act limits defines the boundaries of the licence and these were not changed during the sample period. Kingston Communications remained as the monopoly supplier of telecoms for its boundary area until 2011, when the wholesale telecoms operator AQL completed a porting agreement with Kingston Communications that allowed any telephone number to be moved away from the existing telecoms service provider (Liffen, 2013).

What is ADSL?

Asymmetric Digital Subscriber Line (ADSL)[16] is a technology that enables the high-speed transfer of data over the existing Public Switched Telephone Network. ADSL was used in many countries as a lower-cost solution for telecommunications companies to provide broadband internet access.[17] Speeds offered by ADSL broadband were a substantial improvement on those provided by earlier narrowband technologies, such as dial-up and ISDN. Dial-up only offered speeds up to 64Kbits/second, with ISDN[18] offering speeds of up to 128Kbits/second. At this point ADSL technologies could deliver connections speeds up to 8,000Kbits/second. ADSL remains as the dominant form of broadband access for households and firms in the UK, for example, in 2012 over 85% of firms and 55% of households had ADSL broadband connection (ONS, 2013).

The telephone network in the UK, depicted in Figure 2, is configured such that each firm/household is connected to a pre-determined local exchange using copper wires, which is in-turn connected to the fibre-optic backbone of the telephone network. There are 5,630 telephone exchanges and most cities have a large number of local exchanges. For example there are 185 local exchanges in London, which had a population at this time of around 7.3 million. The telephone exchanges route telephone calls to recipients that are connected to other exchanges, potentially in another city or country. The location of these exchange buildings was determined by the historical roll out of the telephone, in some cases going back to the 19th century. The lack of inter-connections in backbone cabling beyond the telephone exchange means that it is not possible for households/businesses to switch telephone exchanges.

The average cable-distance between the local exchange and street cabinet is 1.8 kilometres, while on average, a further 500 metres of cable connect the street cabinet to each premises (Fisher, 2011). Customers with a cable-distance greater than 5,500 metres were denied access to the service, which was explained as being disqualified due to poor line quality. It is important to note that this effect of distance on

[16] The asymmetry refers to greater bandwidth allocated downstream than upstream, meaning faster download speeds at the expense of slower uploading of data.

[17] It was not until 1997-1998 that BT considered using DSL for broadband delivery (BT, 1998). Up until that point the telephone network had been used to provide narrowband internet access only.

[18] ISDN is a narrowband technology that, like dial-up, operates through the telephone network. Essentially it involves installing a second telephone line to the premises, allowing one line to operate as a dedicated data line and the other can operate for telephone calls or, when not in use, a secondary data connection. The speeds are up to 128Kbits/second, double those of dial-up, when the secondary line is not being used for telephone calls.

quality is much more dramatic than for telephone services. The signal for voice calls is boosted by so-called loading coils, meaning that the quality of telephone signals could potentially be maintained for up to 16 kilometres and at least 5 kilometres from the exchange (Macassey, 1985). Loading coils are not compatible with ADSL.

The UK provides a particularly unusual case since BT and KC had monopolies on providing ADSL infrastructure in their respective areas (aside from an area where these two companies overlap), which prevented other companies from offering ADSL services using their exchanges. To enable ADSL required that the local exchange be equipped with DSL capability and the end-user premises were fitted with a modem and micro-filter device (ADSL splitter). The ability of other providers to install their own ADSL equipment, known as Local Loop Unbundling, was negligible until at least 2005, when fewer than 2% of telephone lines were "unbundled" for other providers to offer services (Cadman, 2005).[19]

[Figure 2]

UK Rollout of ADSL

The large number of local telephone exchanges combined with a limited number of BT engineers meant that BT ADSL was rolled out across exchanges over a period of time stretching from November 1999 to 2007.[20] The BT exchanges in close proximity to the area served by Kingston Communications were only enabled by 2005. Conversely, all of Kingston Communication's 37 telephone exchanges were enabled in 1999.[21] Our sample period comprises this brief time window, 2000-2004, where there exists a spatial discontinuity in the availability of ADSL services between firms connected to KC exchanges and those in surrounding BT areas.

The following maps (Figure 3 to Figure 8) highlight the geographic rollout of ADSL by BT and KC across the UK for the years 2000 to 2005. The figures provide the location of all telephone exchanges and indicate whether they were ADSL enabled (denoted by dark circles) or were not yet enabled (denoted by clear circles) for each year. As Figures 3 to 8 make clear, there is some overlap between the areas served by BT and those served by KC, with some locations able to access ADSL through both providers. We take advantage of this in our robustness analyses, by restricting the analysis to only consider areas that are also connected to a BT exchange.

[Figure 3]

[Figure 4]

[Figure 5]

[19] This was not the case in other European countries, for example by 2005 the proportion of unbundled telephone lines in France was more than 55%, with similar figures for Germany (60%), Italy (45%) and Spain (25%).

[20] BT had been trialling ADSL since 1994 and analysis at the time suggests that BT delayed rolling out ADSL in order to protect its national monopoly on existing narrowband technologies, such as ISDN (BBC News, 1999b).

[21] Both BT and KC started the delivery of broadband services to customers connected to ADSL-enabled exchanges in 2000.

[Figure 6]

[Figure 7]

[Figure 8]

Other Broadband Technologies

The main alternative technologies for high-speed broadband access at this time were cable and, for businesses, leased line connections. Cable broadband utilises the network originally installed for cable television, which in the UK was installed before the roll out of ADSL took place. The cable network was rolled out in the UK in the early 1990s with the expansion ceasing by 1998 and thereafter, the number of premises eligible for cable broadband has remained broadly constant (Oftel, 2001). Leased line access requires a permanent, dedicated fibre-optic connection between the customer and the local exchange. These differ from ADSL primarily in that they do not rely on the pre-existing telephone copper wiring to connect the premises to the exchange and offer higher connection speeds, however the high cost of installation makes this an option only for the largest firms.[22] Leased line connections have been available since the 1990s and again do not overlap with the timing of ADSL roll out (Oftel, 2001). Together the presence of these technologies ensures that even in areas that were not ADSL enabled, broadband adoption by firms is non-zero.

Spatial Discontinuity Construction

We take advantage of a spatial discontinuity in the availability of ADSL broadband. Within the UK data, the precise cable-distances between each premises and the telephone exchange is not publicly available and so all distances we report are calculated “crow flies” based on the longitude and latitude of each firm and telephone exchanges.[23] The boundary of KC ADSL availability is 5,500 metres around each KC exchange, which is the maximum distance up to which customers were offered connections to ADSL broadband. To model the discontinuity of broadband infrastructure availability we calculate the distance of each firm from this KC ADSL boundary[24] (the plant-level data is discussed further in section 3). All KC telephone exchanges are within 5.5km of each other and therefore all firms connected to KC telephone exchanges had access to ADSL broadband services. As is made clear from Figures 3-8, the relevant boundary is provided by the maximum ADSL service boundary around the outermost KC owned telephone exchanges. This is the discontinuity that we study and we refer in the text to this as the KC ADSL boundary.

[22] As of 2014, where costs are cheaper than in the early 2000s, a leased line connection costs £300-£1,100 per month plus installation costs of £500 to £40,000 (Onestopclick, 2014).

[23] We find that the crow-flies distance is a good proxy for cable-distance. A crow-flies distance of 5,500 metres around each KC exchange encompasses all of the postcodes OFCOM identifies as being served by KC, whereas smaller distances omit some postcodes.

[24] Specifically, we use the point in the KC ADSL area that is closest to the plant to calculate this distance.

To distinguish between plants located inside and outside the KC ADSL boundary, we follow the convention in the literature and record negative (positive) distances for those plants outside (inside) the KC boundary. Plants with positive distances are located in areas with KC ADSL access; those with negative distances reflect plants located in surrounding areas served by BT, where ADSL is not available. Figure 9 displays the boundary of the area of KC ADSL availability and the location of KC exchanges. We also show local authority boundaries in this figure, to demonstrate that the area in which KC ADSL was available does not correspond neatly to any particular local authority. The KC ADSL-service area encompasses the entirety of Kingston-Upon-Hull local authority but also parts of East Riding local authority.

For our main analyses we use firms located within 40km of the KC ADSL boundary. Areas just outside of 40km include several major large UK cities such as Leeds, Bradford, Huddersfield, Barnsley and Sheffield that were ADSL-enabled by BT in 2000. In order to compare areas in which ADSL was available versus those where it was not for a long enough time window these cities were intentionally excluded. Our analysis is not dependent upon this assumption and as a robustness check we use firms within 20km of the KC ADSL boundary.

To provide background to this area of the UK and to demonstrate that areas inside and outside the KC ADSL service boundary are similar in terms of key economic and characteristics in the Appendix we provide a brief summary of some key economic variables.

[Figure 9]

ADSL and Firms

OECD (2008) provide a detailed description of the ways that broadband has altered the way that firms sell their products and organise production. Most firms now have a web-site that both advertises their products and services but allows customers to directly purchase their products, or they sell indirectly through web retailers such as Amazon. They also describe how broadband has facilitated flexible work place practices such as working-from-home or mobile working. Broadband has also impacted on the organisation of the firm by reducing the costs of communication though teleconferencing, they recruit workers through online recruitment and have on-line payment systems.

Garicano and Rossi-Hansberg (2006) formalise these ideas and show theoretically that reductions in the costs of communication, such as the internet, are distinct from technologies that increase access to and processing of knowledge. In a model where knowledge is an important input into the production process firms organise themselves into knowledge hierarchies. Improved communication technologies lead organisations to rely more on top-level managers who solve problems, increasing the centralisation of the firm. Whereas technologies that improve access and processing of information tend to decentralise decision making. These can have different impacts on the number of layers of management and on wage inequality between management and workers. Antras et al. (2006) extend this to consider the offshoring of part of the production process.

The empirical literature on the effects of broadband fits within a larger literature on ICT and because it faces the same econometric challenges and has largely developed along a similar path.[25] This might be described as a movement away from using aggregate data and providing correlations towards understanding ever more detailed micro data and focusing on the causal relationships that exist. Czernich et al. (2011) for example, report evidence for a panel of OECD countries that increased broadband internet penetration has had large positive effects on economic growth rates, while Kolko (2012) find significant effects on local economic growth in the US. Consistent with this, Gillet et al. (2004) use zip code level data on broadband access in the US and find that local employment growth increased by 1-1.4% relative to the counterfactual of no access. A smaller number of papers have explored these issues at the micro level. Using detailed micro data for Norway Akerman et al. (2013) find that firms that start to use broadband increase their use of skilled labour, while Bloom et al. (2009) explore the effects of intranets on the level of decision making in cross-European data. Evidence of other firm level impacts in a variety of country contexts can be found in Van Gaasbeck et al. (2008), Kolko (2012), Bertschek et al. (2013), Haller and Lyons (2014) and Grimes et al. (2012).[26]

3. Data

In order to conduct the analysis we rely on two main types of data from multiple sources. The first type of data provides UK firm level information on business location, performance, and broadband usage and is supplied by the UK Census Bureau (the ONS). The second provides detailed information on the geographic rollout of ADSL broadband by BT and Kingston Communications across the UK and is available from the UK telecommunications regulator, OFCOM.

The basis of our firm data is a panel of establishments called the Annual Business Inquiry (ABI) created by the ONS.[27] This covers all sectors of the economy aside from agriculture and finance. Constructed from a mandatory business survey, the ABI is a census of large businesses and a stratified random sample of smaller firms. It is the main source of firm-level data for the UK. The ABI provides information at two levels of aggregation; at the firm-level and the plant-level, and unique plant and firm identifiers permit merging with additional data. Precise location (postcode) data is available for each plant. Information on employment is available at the plant and firm level, which is then merged with data on plant exits using the Business Structure Database (BSD). The BSD provides demographic information for virtually every plant in the UK. We

[25] See Syverson (2011) and Cardona et al. (2013) for more comprehensive reviews of this broader literature.

[26] Others have shown similar effects using a case study approach. Kelley (2004) found a positive effect on business recruitment, retention and expansion when comparing Cedar Falls in Iowa, which had broadband internet access, with neighbouring Waterloo, which did not.

[27] See Griffith (1999) for a description of the data.

conduct our analysis of employment and exit decisions at the level of the plant. The other measures of performance, such as sales and labour productivity, are available only at the firm level from the ABI. For the additional firm-level regressions we use the location of the firm's largest plant (by employment).

Information on firm-level broadband adoption is obtained from the E-commerce survey, where broadband is defined as connection speeds exceeding 128Kbits/second. The survey was first introduced in the year 2000 and is available annually thereafter. It is a stratified random sample of all firms with more than 10 employees for the 2000 survey and all firms (of any size) for later surveys. The strata are defined by industry and employment, such that larger firms are over-represented. Our broadband measure reflects any fixed-line broadband connection, which captures ADSL as well as other types of broadband that rely on wire connections, such as leased line connections and cable, but excludes cellular and satellite broadband. Ideally, one would have firm-level data on ADSL broadband adoption specifically, however, the survey does not always fully disaggregate the type of broadband connection.[28]

We link the firm-level data to a unique dataset from the office of the regulator for telecommunications in the UK, OFCOM, which details the postcode location and timing of ADSL enablement of every UK telephone exchange by BT and Kingston Communications. We combine this with firm locations to map each firm to their nearest exchange using their straight line distance. As mentioned earlier, ADSL broadband has been available since 2000 for the areas served by KC, whereas the surrounding areas served by BT were only enabled by 2005. Our sample period comprises this brief time window, 2000-2004, where there exists a spatial discontinuity in the availability of ADSL and, as noted earlier, for our main analysis we focus on firms within 40km of the area served by KC.

The unbalanced panel contains observations on 11,074 plants (706 firms) for the years 2000 to 2004. The sample consists of medium and large plants with a mean of 39 employees and an average (one-year) employment growth of 1% per annum. On average 9% of plants exit in a given year. The sample sizes for employment growth and plant exits are somewhat smaller, since respectively, the panel is unbalanced and not every plant can be matched with the BSD data. These plants are also predominantly service-sector, with only 10% in the manufacturing sector. The mean level of firm sales is £80million and an average annual growth of 3% and sales per worker of £174,000. The mean firm is 17 years old, 43% of firms have more than one plant and 12% are foreign-owned. For our key treatment variable, on average 66% of firms purchase a connection to broadband over our time period.

[Table 1]

[28] For example, a question may ask about whether the firm has ADSL or cable broadband?

4. Empirical strategy

We employ a fuzzy regression discontinuity (FRD) design to estimate the effect of broadband adoption on firm performance. We take advantage of a spatial discontinuity in the availability of the dominant type of broadband in the UK, ADSL, to identify the causal effect of using this broadband technology. Our sample period comprises a brief time window, 2000-2004, where there exists a spatial discontinuity in the availability of ADSL between firms connected to KC exchanges and those in surrounding BT areas. We compare firms located either side of the spatial discontinuity, contrasting locations inside the boundary area of KC with those areas outside for which BT ADSL broadband was not available.

Regression discontinuity designs rely on the probability of receiving the treatment, in our case broadband adoption, being a discontinuous function of a determining variable, here proximity to KC's ADSL service area. A sharp discontinuity approach requires that the probability of treatment jumps from zero to one either side of the boundary. We employ a fuzzy discontinuity approach, since the availability of ADSL infrastructure will not perfectly predict firms' broadband adoption. Some firms will choose not to adopt broadband, even when ADSL is available in their area, labelled "never-takers" (Imbens and Lemieux, 2008). In addition, the measure of broadband adoption in our firm-level data captures ADSL as well as other types of fixed-line broadband, such as leased line and cable connections. Some firms will therefore adopt broadband in BT areas where ADSL is not available, labelled "always-takers". A fuzzy discontinuity design explicitly allows for the presence of "never-takers" and "always-takers" by utilising the spatial discontinuity to predict a smaller jump in firms' broadband adoption propensity at the cut-off.

Specifically, we estimate the following two equations:

$$outcome_i = \alpha_0 + \alpha_1 X_i + \alpha_2 broadband_i + \alpha_3 f(distance_i) + \varepsilon_i \quad (1)$$

$$broadband_i = \beta_0 + \beta_1 X_i + \beta_2 KC_i + \beta_3 f(distance_i) + \gamma_i \quad (2)$$

where $outcome_i$ represents each of our measures of firm performance and $broadband_i$ reflects our treatment variable, whether firm i has adopted broadband. X_i is the set of firm-level controls, including firm age, foreign ownership and a multi-plant dummy. KC_i reflects the spatial discontinuity in ADSL availability, this takes the value one for firms located within the area in which the ADSL broadband service of Kingston Communications is available and zero otherwise. $distance_i$ is the rating variable, capturing the "as the crow flies" distance of the firm from the boundary of Kingston Communications' ADSL service. We follow the convention in the literature and record negative (positive) distances for those plants outside (inside) the boundary of Kingston Communication's ADSL service.

The function $f(\cdot)$ captures the relationship between proximity to the boundary of KC's ADSL-service area and the outcome and treatment variables. A key assumption of the discontinuity approach is that this functional form is correctly specified. Two distinct strategies are used in the literature to address this, parametric and non-parametric estimation (Bloom, 2012). Parametric estimation utilises all the data points to model the relationship and specifies a flexible polynomial for $f(\cdot)$ that best fits the full set of data.[29] Conversely, the non-parametric approach only uses data points close to the discontinuity, within a given "bandwidth" of the boundary, and fits a local linear model to the subset of data (following Hahn, Todd and van der Klauw (2001)). As is usual, we report evidence using both approaches.

For the parametric estimation we employ a variety of function forms for $f(\cdot)$ and choose the specification that minimises the Akaike Information Criterion (following Lee and Lemieux, 2010). We consider linear, quadratic and cubic functions of $distance_i$, both with and without slope changes at the boundary[30]. The baseline parametric estimation fits a model to all data points, here defined as 40km from the KC ADSL-service boundary. We examine the sensitivity to dropping the data points furthest from the KC boundary, reporting results using firms located within 20km of the boundary. Control variables are not required for unbiased estimates under a valid discontinuity design (Lee and Lemeuix, 2010), however these can reduce the variance of the estimated parameters. We again present parametric results both with and without control variables (X_i). All parametric results are presented with robust standard errors that are clustered at the firm-level.

Selecting the optimal bandwidth for non-parametric regressions involves a trade-off between the precision with which coefficients are estimated and the goodness of fit of the linear model. Larger bandwidths are usually associated with increased precision of the parameter estimates but are less likely to fit the data as well. Unfortunately there is no consensus on the method for selecting the optimal bandwidth. We employ the formula of Imbens and Kalyanaraman (2010) and then examine the sensitivity of the results to alternative bandwidths. These sensitivities also encompass bandwidths suggested by other methods, such as Ludwig and Miller's (2007) cross-validation procedure. We follow Imbens and Lemieux (2008) and select the same bandwidth for the first stage and second stage estimation. The optimal bandwidth is found separately for the first and second stage estimations, and we employ the minimum for both stages of the regression.

The parameter of interest, α_2, captures the treatment effect of broadband adoption on our measures of firm performance. Regression discontinuity designs are appealing because they require relatively mild conditions to make causal inferences about α_2 as compared to other non-experimental settings (Hahn, Todd and van der Klaauw, 2001). The key condition is that the potential outcomes are a continuous function of the ratings variable (distance from the KC ADSL service area) around the cut-off. Rather than having to assume that the treatment is randomly assigned, Lee (2009) formally shows that

[29] The full sample of data corresponds to an area of 40km around the area served by KC. We examine the robustness to alternative sample areas.

[30] An alternative mechanism of specification selection in sharp discontinuity designs is to employ an F-test method (Lee and Lemieux, 2010), however this is not appropriate for a fuzzy design, since two-stage least squares estimation R-squared are not informative (Wooldridge, 2010).

under this condition the discontinuity design *implies* randomisation of the treatment. Thus, the estimation will not be confounded by omitted variables and shares the same properties as a randomised experiment.

Unfortunately the continuity in potential outcomes is not directly testable, instead, we follow the literature and perform a battery of indirect tests, which are reported in section 8. Lee (2009) demonstrates that a necessary condition for continuity in potential outcomes is that individuals are not able to precisely sort around discontinuity. Note that this does not rule out manipulation around the cut-off, but excludes perfect self-selection (Lee and Lemieux, 2010). In our example, this implies that firms do not all relocate to take advantage of ADSL availability. Given the substantial costs of moving and that BT broadband was gradually being rolled out in areas outside KC, it seems highly unlikely many firms would choose to do so in our setting. To provide empirical support for this assertion, we examine the relocation behaviour of firms both during our sample period and, to check for anticipation effects, periods before the spatial discontinuity existed. Specifically, we consider whether firms initially located in areas served by BT are more likely to move to locations served by KC, than firms in areas served by KC are to move to BT areas. We do not find any evidence of firm sorting around the KC boundary., The continuity in potential outcomes condition also implies that firms are not able to precisely influence the location of the discontinuity. Again this is highly likely to be the case in our setting: the creation of KC was determined by a historical accident, was constrained by the terms of the licence to provide telephone services, and the location of the KC boundary is based on the position of exchanges for the previous telephone technology.

Another threat to validity is if there are other discontinuities in the data. In such cases, it would be difficult to separate the effect of broadband from the effects of the other discontinuities. One obvious candidate in our data could be local authority boundaries, where there exist some differences in local taxation and public service provision. As already noted, the concern does not seem likely in our setting since the area served by KC does not correspond to neatly to a particular local authority, encompassing the Hull Local Authority and parts of East Riding Local Authority. On average the East Riding (Hull) Local Authority is 6.7km outside (5.6km inside) the KC ADSL boundary for the firms in our sample. Our non-parametric estimation considers only points in the local vicinity of the cut-off, and we show that our baseline estimation uses bandwidths that are sufficiently narrow to exclude these local authority boundaries.

Finally, we examine whether there are persistent discontinuities in firm broadband adoption at the KC ADSL boundary even when there is no discontinuity in ADSL availability. The spatial discontinuity in ADSL availability persists only for the brief period 2000-2004, thereafter ADSL was available in this region of the UK from both KC and BT. If there are persistent discontinuities in broadband adoption, this may indicate the potential outcomes are not continuous at the boundary, and threatening the validity of the design. We re-perform the baseline regressions using the period 2005-2008, employing the same locations that were used in the baseline estimation, and test for discontinuities in firm broadband adoption. Specifically, we compare firms located on either side of the spatial discontinuity, contrasting locations inside the boundary area of KC with those areas outside for which BT ADSL broadband was not available five years previously.

5. Graphs of Discontinuity in Key Variables

In this section we plot the key variables used in our analysis against distance from the KC ADSL boundary. One of the key choices in presenting these figures is the choice of bin width with which to group the data. A narrow bin width can reflect large amounts of noise, however a large bin width can mask patterns in the data. We group the observations into 4km bins, which is suggested by both the F-test and bin dummy methods of Lee and Lemieux (2010).[31] To reflect the extent of noise in our data we fit local polynomial regression lines either side of the boundary following Imbens and Lemieux (2008).

As already described in the introduction, Figure 1 depicts broadband adoption against proximity to the area for which KC ADSL is available. Plants located in BT-only locations, outside the area served by KC, are shown with negative distances to the boundary and plants located within the KC area display positive distances. Graphically there appears to be a good evidence of a discontinuity in broadband adoption, with plants located just outside of KC ADSL-service area having a broadband adoption propensity at least 10 percentage points lower than those just inside. There is also clearly some noise in the data but this mainly relates to observations around 30km outside the KC ADSL area, and as suggested graphically, we find our results are robust to considering plants only 20km from KC area (see Appendix Table 19 - Table 21). Figure 10 to Figure 12 graph our main plant-level outcome variables against distance to the KC ADSL boundary. We do not observe any noticeable discontinuity in employment, employment growth or the probability of plant exit.

[Figure 10]

[Figure 11]

[Figure 12]

6. Main regressions

i. OLS

To provide a comparison with the existing literature and to confirm that our results are explained by our use of a fuzzy regression discontinuity design rather than data for North East England, we begin by reporting simple conditional correlations between the use of broadband and firm performance estimated by OLS. In Table 2 we present simple OLS regressions that show the correlation between broadband adoption and the size of the firm. Once we condition on industry differences in the size of firms (regression 2), we find those that have adopted broadband are typically larger than those that have not, confirming the positive

[31] Alternative bin widths reveal similar patterns to the 4km depicted here, these have been omitted for brevity.

relationship found between employment and broadband use by (Haller and Lyons, 2014). The relationship strengthens when we control for potentially omitted year effects and include firm-level controls for age, foreign ownership and a multi-plant dummy (regressions 3 and 4 respectively). In regression 4 we find that users of broadband are on average 28% larger than non-users. In the Appendix Table 18 we report the correlations between other firm outcomes and broadband adoption. We find adopting broadband is also significantly positively correlated with firm sales, as well as labour productivity, captured by sales per worker. It would appear to be uncorrelated with sales growth and the exit of firms.

[Table 2]

ii. Fuzzy Regression Discontinuity

We present below our baseline results for parametric and non-parametric estimation of plant-level employment, employment growth and the probability of plant exit. For all our outcome variables the parametric polynomial that minimises the Akaike Information Criterion is found to be either a linear or a linear interaction model.[32] Accordingly, we report both specifications and omit the results of higher order quadratic and cubic polynomials for brevity. Following Lee and Lemieux (2010), the non-parametric results are presented both with and without firm-level controls (firm age, foreign ownership and a multi-plant dummy). We report three non-parametric specifications. We compute the optimal non-parametric bandwidth, "h", using the method suggested by Imbens and Kalyanaraman (2010)[33] and to examine robustness, employ 50%, 100% and 200% of the optimal bandwidth (labelled "h/2", "h" and "2h" respectively).[34]

As suggested by the evidence in Figure 1, we find strong evidence of a discontinuity in broadband adoption by firms at the boundary of KC telephone exchanges (see Table 3). Across both parametric and non-parametric approaches, being inside the area served by KC significantly increases the probability of adopting broadband compared to those firms located just outside. Under parametric estimation, the results for the first-stage regressions show that being inside the KC ADSL-service boundary (denoted by the KC boundary variable) increases broadband adoption propensity by around 10%. This estimated effect is remarkably stable across different parametric models and is largely unaffected by the inclusion of firm-level covariates. The F-statistics suggest that this variable is a strong predictor of broadband adoption, comfortably exceeding the Staiger-Stock (1997) critical values for strong instruments.

[32] A linear interaction model is a linear model with a change in slope at the discontinuity.

[33] The results are not qualitatively different using the bandwidth method suggested by Ludwig and Miller (2007).

[34] In Figure 1 there was evidence of a pronounced dip in the propensity to adopt broadband some 30km from the KC boundary, which was likely owed to inclusion of rural areas. We tested the sensitivity of the parametric results to the use of observations within 20km of the KC boundary. We find the first-stage identification remains strong, with similar estimated coefficients to the baseline and again, no effect on any plant-level outcome in the second stage. The results are available from the authors on request.

The first-stage non-parametric estimates exhibit somewhat more variability in estimated size of the effect, which is to be expected given the noise observed in our raw data. The estimation using the optimal non-parametric bandwidth of 8km suggests an increase in broadband adoption of 44%. The results when using larger bandwidths are much more consistent with the parametric estimation. When using a 16km bandwidth we find that the probability of broadband use is 20% higher inside the KC ADSL area.

In the second stage regressions reported in Table 3 we find no evidence of a significant relationship between using broadband and firm performance. These results contrast with those using OLS reported in Table 2 and are consistent with an interpretation that the OLS results are upward biased. We do not observe any causal effect of broadband on plant employment once we use a methodology that controls for the effects of difficult to observe confounding factors such as managerial ability. The one exception to this occurs when we use half the optimal bandwidth (firms must be located within 4km of the ADSL-service boundary). In this regression there is weak evidence of an effect in the second stage, although this is not robust to consideration of alternative bandwidths or any parametric specification.

One possibility might be of course that the effects of broadband reveal themselves more clearly on the growth of employment rather than the level, or alternatively that they affect aggregate employment by slowing the rate at which firms are shut-down. In Table 4 and Table 5 we repeat the analysis using plant employment growth and the probability of plant exit as alternative outcomes. The sample sizes are somewhat smaller for these outcome variables (as noted in the data section). Despite this, the first-stage regression predicting broadband use by firms is similarly pronounced. We find being just inside the boundary of ADSL-service available significantly increases the likelihood of broadband adoption under both parametric and non-parametric estimation, with the estimated coefficients a comparable magnitude to those within Table 3. In the second stage, however, we do not find any effect of broadband on employment growth or the probability of plant closure under any specification. Again, a conclusion that the estimated effects of broadband are upward biased when using OLS is supported by the data and there is no causal effect from using this technology when using a methodology that corrects for this bias.

[Table 3]

[Table 4]

[Table 5]

7. Robustness of Findings

In this section we examine the robustness of our baseline plant-level results. We restrict the data sample to address possible concerns about our estimation by excluding firms located in the city of Kingston-upon-Hull. Finally, we consider whether broadband affects alternative firm outcomes.

i. Restricted Sample within KC ADSL Area - Firms Connected to BT

In our main analysis we compare plants connected to KC exchanges to those just outside the KC area connected to non-ADSL enabled BT exchanges. A plausible objection to the analysis is that the city of Kingston-upon-Hull is located within the KC area and that as a city it is not comparable with the towns and smaller cities that are located within the BT area. Since the city of Kingston-upon-Hull is located on the river bank and near the edge of the boundary of KC operations it would affect both parametric (that uses the full set of observations) and non-parametric estimations (using those near the boundary).

In Section 2 of the paper discussed the overlap in the areas served by BT and KC. To address the concern above, we take advantage of this overlap to consider the effects of broadband use on firms that could be connected to either a KC or a BT telephone exchange. The firms located in the city of Kingston-upon-Hull are now excluded from the analysis, and we are examining evidence for a discontinuity driven by firms located in more rural areas served by Kingston Communication, where they also have a BT connection. Note that the sample of firms in the BT-only areas remains unchanged. The approach has the added advantage that by only including areas served by BT, the areas either side of the discontinuity are eminently comparable.

We repeat the baseline plant-level regressions using the restricted KC locations as described above. The results reported in Table 6 to Table 8 show that the main conclusions are unaltered to this change. We continue to find robust evidence of a discontinuity in broadband adoption at the boundary of KC ADSL-services, with the strength of the identification and estimated size of the discontinuity comparable to the baseline regressions. A connection to ADSL-enabled KC-owned telephone exchanges is associated with a higher probability of using broadband compared to being connected to BT exchanges that were not enabled for ADSL. As before, in the second stage we find no evidence for any effect of broadband on employment, employment growth or plant exit. This holds irrespective of whether we use parametric or non-parametric estimation or if we consider the effects of broadband on the level of employment (Table 6), employment growth (Table 7) or the probability of shutting-down (Table 8).

[Table 6]

[Table 7]

[Table 8]

ii. Other Outcome Variables

To maximise the number of observations that were available to us the analyses presented thus far were conducted using plant-level information. In this section we examine whether the conclusions apply to other measures for performance. As discussed in Section 3 these are available at the more aggregated firm-level (although half the firms have only a single plant in the data). We consider three additional measures of firm performance, sales, sales growth and labour productivity.

It is commonly argued that one of the key effects of broadband is to increase the potential for connections with customers in both the domestic and overseas markets. The effects of broadband should therefore reveal themselves most clearly using a measure of sales, rather than employment, in particular if one of the effects of the technology is to also allow for greater offshoring/outsourcing and this impacts negatively on firm-employment. Varian et al. (2002) have also argued that broadband is a disruptive technology on a scale equivalent to the telephone and the telegraph and that this will have large productivity impacts. To reflect this literature, Table 9, Table 10 and Table 11 respectively examine the effect of broadband on firm sales, sales growth and labour productivity (captured by sales per worker).

We continue to find robust evidence of a discontinuity in broadband adoption at the KC ADSL boundary. Those firms that are connected to KC-owned telephone exchanges have a significantly higher probability of using broadband than those connected to BT-owned exchanges. The estimated discontinuity in broadband adoption is also of a similar magnitude to that found using plant-level data, although the identification is a little weaker, reflected by the F-statistics being closer to the Staiger-Stock (1997) critical values for strong instruments. Under the optimal parametric models for each outcome variable (that minimises the Akaike Information Criterion), being just inside the boundary increases the propensity to adopt broadband by 17% to 20%, and under the optimal non-parametric model (bandwidth "h") the effect is 30% to 33%.

Despite the change in the measures of firm performance and the use of firm rather than plant level data, in the second stage we again find little evidence of a robust, causal effect of broadband adoption on firm performance. There is evidence for some of the non-parametric specifications of an effect of broadband adoption on firm sales (Table 9), although the effect is not robust to consideration of larger bandwidths, nor, any parametric specification. Graphical analysis also suggests that there is no discontinuity at the boundary of ADSL broadband availability (see Appendix Figure 14). Overall, we find little to alter our conclusion that the OLS estimates are upward biased due to the potential effects of managerial ability as a confounding factor.

[Table 9]

[Table 10]

[Table 11]

8. Tests of Identification Assumptions

In this section we examine the plausibility of the assumption required for a causal interpretation of our results, continuity in potential outcomes around the cut-off. As noted earlier, this assumption cannot be directly tested and so, instead, we follow the literature and perform a number of indirect tests. Our first test exploits the historical panel data that is available from the ONS to examine whether firms relocate (either contemporaneously or in advance of the rollout of ADSL) around the discontinuity to gain access to KC ADSL broadband. Our second test explores whether there are discontinuities in broadband adoption at other geographic locations in our data. Third, we examine the robustness of the identification to consideration of narrower bandwidths around the KC ADSL boundary. Our final test again uses the panel nature of the firm-level data to examine whether any broadband discontinuity exists for periods beyond 2005, when both KC and BT areas had access to ADSL.

i. Firm Sorting

Our regression discontinuity approach relies on firms not being able to precisely sort around the discontinuity. Given the substantial costs of moving and that BT broadband was gradually being rolled out in areas outside the KC licence area, it seems highly unlikely many firms would relocate to obtain access to ADSL broadband infrastructure. In the literature, studies often do not have access to historic panel data in order to explicitly test for sorting as we have here. Instead, sorting has been tested indirectly by examining the frequency of observations either side of the cut-off (see for instance McCrary, 2008)[35]. We take advantage of our historical panel data to directly test the relocation behaviours of firms both during our sample period and, to check for anticipation effects, periods before the spatial discontinuity existed.

One would expect that if the benefits of broadband technology were fully anticipated in advance of its rollout then firms located in BT-only areas just outside the region served by KC would be more likely to move inside the KC area than firms located further away. However, this does not necessarily mean that the firms are sorting because of ADSL availability. Firms in any location are more likely to move to nearby places than those further away (Stam, 2007). Instead, our approach compares whether firms located in BT-only areas are more likely to move inside the KC ADSL area, than firms located in KC areas are to move to BT-only areas. Specifically we calculate the propensity of firms to relocate to the alternative side of the KC ADSL boundary. If there exists a discontinuity in this propensity, then that may indicate sorting.

We do not find evidence that firms are any more likely to sort inside of the KC boundary than they are to sort outside into BT-only areas (see Table 12),[36] either by parametric or non-parametric estimation. In all except one of the non-parametric regressions we find no significant effect of sorting across the KC ADSL boundary, and there is no evidence of sorting suggested by any parametric regression.

[35] In our sample, the city of Kingston-upon-Hull is located within the KC area and near the edge of the KC boundary, which superficially generates substantially more observations within the KC area than those outside. Therefore McCrary's (2008) approach is not informative in our case. However, in section 7 that our results are robust to the exclusion of firms located in the city of Kingston-upon-Hull from our analysis

[36] The parametric results within the table present marginal effects from a probit regression.

Another concern may be that firms do not necessarily sort contemporaneously, but may do so in anticipation of the KC ADSL roll-out. To mitigate these concerns we use the panel aspect of our data, which begins in 1997, to examine whether plants have relocated prior to the start of the ADSL enablement programmes by BT and KC.[37] We do not find any evidence that firms have sorted in advance (see Table 13) as indicated by the statistical insignificance of the KC boundary variable.

[Table 9]

[Table 10]

ii. Test for Other Broadband Discontinuities (Hull and East Riding Local Authority boundaries)

One potential threat to the validity of our econometric approach is if there are other discontinuities near the cut-off. In such cases, it would be impossible to separate the effect of broadband from the effects of these other discontinuities. As noted earlier, obvious candidates in our data are local authority boundaries, where there exist some differences in local taxation and public service provision.

This concern does not seem likely in our setting since the area in which telecom services are available from KC does not correspond to neatly to a particular local authority, encompassing the Hull Local Authority and parts of East Riding Local Authority. On average the East Riding Local Authority is 6.7km outside the KC ADSL boundary while the Hull Local Authority is 5.6km inside. So the bandwidth of the baseline non-parametric estimates is also sufficiently narrow to exclude these boundaries (see results using "h/2" bandwidth), but would be included in other baseline estimates.

To check the discontinuity we observe is not drive by local authority boundaries rather than ADSL availability, we examine first whether we observe a discontinuity in the use of broadband at the East Riding Local Authority boundary and then at the Hull Local Authority boundary. To test for broadband discontinuities at the East Riding Local Authority Boundary, we artificially shift the KC boundary outwards by 6.7km, and to test for the Hull Local Authority boundary we shift the KC boundary inwards by 5.6km. Following Imbens and Lemieux (2008), we test for the presence of a discontinuity at the East Riding boundary using only firms outside the KC ADSL area and then test for the Hull boundary using only firms inside the KC ADSL area. To remain consistent with all of the earlier tables we report result using the parametric and non-parametric methods used thus far but concentrate on discontinuities in broadband in the first stage regressions. The results from this exercise are reported in Table 14 and Table 15.

We fail to find any discontinuities in broadband adoption at either of the local authority boundaries using either parametric or non-parametric estimation. There is no statistical effect on the probability of using broadband at either the East Riding (Table 14) or Hull (Table 15) local authority boundaries in these tables, confirming that the identification we attribute to KC ADSL availability is not in fact being driven by discontinuities at nearby local authority boundaries.

[37] As of February 1999 BT still had not informed the public of any plans for broadband service (BBC 1999a)

[Table 11]

[Table 12]

iii. Sensitivity to Bandwidth Choice

In the non-parametric regressions presented above, we employ the formula of Imbens and Kalyanaraman (2010) to calculate the optimal bandwidth, which will differ for each particular specification. In this section, we document the robustness of the broadband discontinuity to the full spectrum of optimal bandwidths suggested in any specification considered thus far by both the Imbens and Kalyanaraman (2010) method and Ludwig and Miller's (2007) cross-validation approach. For the set of baseline regressions, the optimal bandwidth proposed by either method always falls within the range of 2.7km to 9.5km. Figure 13 plots the first-stage estimates of broadband discontinuity at the KC ADSL boundary for these ranges of bandwidths, along with 95% confidence intervals. At all bandwidths there is a positive and significant broadband discontinuity at the 95% level, and if anything the identification becomes stronger as one considers narrower bandwidths (that have the benefit of also excluding local authority boundaries).

[Figure 13]

iv. Test for Broadband Discontinuity post-2005

In the previous section we examined other geographic or points in time in our data sample where we do not expect to observe a discontinuity in broadband adoption. The final test of our identification strategy continues within this general theme and involves examining other time periods where we do not expect to observe a broadband discontinuity. The spatial discontinuity in ADSL availability persists only for the brief period 2000-2004, thereafter ADSL was available in this region of the UK from both KC and BT. If the potential outcomes are indeed continuous at the boundary, i.e. we are capturing the discontinuity in broadband access rather than some other factor, one would expect to observe no treatment effect for the periods from 2005 onwards when the spatial discontinuity does not exist.

We re-perform the baseline regressions using the period 2005-2008, employing the same locations that were used in the estimations reported in Section 6. Specifically, we compare firms located on either side of the spatial discontinuity, contrasting locations inside the boundary area of KC ADSL with those areas outside for which BT ADSL broadband was not available five years previously. We report the parametric and non-parametric estimates for the outcome plant-employment in Table 16. Since we are mainly concerned with the first-stage, to test for persistent discontinuities in broadband adoption, regressions for other outcome variables are omitted.

Consistent with the conditions for the validity of our empirical approach, we find no evidence of any persistent discontinuity in broadband adoption across the KC and BT areas once ADSL is universally available post-2005. The first-stage coefficients for the KC boundary variable reported in Table 16 are insignificant across all specifications and the F-statistics cannot reject the null of weak instruments. This strongly suggests that the discontinuity in broadband use across firms was a temporary phenomenon that coincided with the discontinuity in broadband infrastructure at this time.

[Table 16]

9. Discussion and Interpretation

In this section we discuss our results in relation to the broader literature on ICT and their external validity.

The empirical design that we use in the paper provides a causal interpretation of the effects of broadband if the confounding factors are randomised across the geographic discontinuity that divides access to broadband infrastructure. Given that our results contrast with the much of the literature discussed in OECD (2008), this would tend to suggest that the existing literature captures selection into treatment rather than the effects of broadband itself, although our research does not tell us precisely what those confounding factors are. The existing literature would tend to indicate that they are management quality and organisational form. A growing number of studies have suggested that ICT is a complement to organisational capital and the use of 'good' management practices and that ICT is a causal factor behind changes to these. Bloom et al. (2012) for example show that the returns to IT capital are higher for US multinational firms operating in the UK and that this productivity advantage is related to their management practices. Supporting evidence includes Hubbard (2003), Crespi et al. (2007), Bartel et al., (2007), Brynjolfsson et al. (2008), Garicano and Heaton (2010) and Garicano (2010).

One interpretation of our results alongside those from the literate on ICT and organisation and management is that to study the determinants of firm performance a better variable to focus on than broadband, would be organisational capital. ICT is, amongst other things, a determinant of organisational change and it is that affects firm performance, whereas there is no direct relationship between ICT and performance. Interpreting the evidence in this way then our results indicate that broadband use is not simply a proxy for organisational change.[38] On average, the firms that were induced to adopt broadband inside the KC ADSL enabled region do not appear to have undertaken organisational change that in turn impacted on their sales, employment etc. The availability of alternative means of connecting to the internet through leased lines or cable networks might provide one source of explanation. These were likely to have been adopted by larger and more information intensive firms. Further investigation of that point would appear to be a potential avenue for future research.

[38] Rather they are distinct variables. Consistent with this Bloom et al. (2014) discuss the results from a field experiment of the productivity effects of working from home. This form of work practice is one that relies on the quality of external connections provided by broadband infrastructure and to qualify for the experiment the employee needed to have a broadband internet connection at home. They find a significant productivity impact from this organisational change.

Our analysis also leaves open the possibility that the indirect effects of broadband might missed in our data because it involves compositional changes to employment, procurement or sales that we cannot capture. Lower-level managers might be replaced by higher-level managers, or on-line sales might replace those through physical retail stores for example. Garicano and Rossi-Hansberg (2006) show in a model where knowledge is an important input into the production process that firms organise themselves into knowledge hierarchies. Improved communication technologies lead organisations to rely more on top-level managers who solve problems, increasing the centralisation of the firm. These outcomes contrast with the effects of technologies that improve the access to and processing of information tend to decentralise decision making, which can have different impacts on the number of layers of management and on wage inequality between management and workers. Garicano and Heaton (2010) and Bloom et al. (2009) find empirical support using data on ICT adoption by US police departments and a large sample of US and European manufacturing firms respectively.

Whilst it is possible that we miss the fine detail of the changes that might occur within a firm, it would be surprising that there are no effects on any of the measures of performance that we include. While Garicano and Heaton (2010) find little evidence that IT adoption improves productivity of police departments, measured by clearance rates and crime rates, they do find an effect on the size of the department for example.

An alternative explanation might be that the firms in the region of the UK that we study are different from elsewhere and thus our findings lack external validity. We lack the data to provide a discussion of this with regard to the confounding factors of organisation or management quality. We can however provide evidence however for more aggregated outcomes of the region as a whole and for firm performance measures prior to the start of the ADSL enablement programme in the UK.

The city of Kingston-upon-Hull and its surrounding region, both inside and just outside of the area served by Kingston Communications is well-known as a relatively poor region. Per capita income is lower, unemployment is higher and educational attainment is lower than the UK average. However, in the Appendix we provide evidence that the region served by Kingston Communications is not substantially different from surrounding regions in the North of England and is by no means an outlier for the UK. We can also find no evidence that the performance characteristics of firms (measured prior to the enablement of ADSL broadband) are significantly different from firms in the rest of the UK. This holds irrespective of whether we compare firm size (employment or sales), their growth, the average wage, or the likelihood that they have multiple plants or are foreign owned. We also find that the firms that adopt broadband in this region were already larger and had faster employment growth than non-adopters in 1999, consistent with the expected correlation between broadband use and firm size. This would leads us to suggest that the lessons learnt from this region of the UK are applicable elsewhere.

10. Conclusion

In this paper we test for the effects of broadband internet on firm performance using a fuzzy regression discontinuity design. The empirical approach is predicated on two key points. Firstly, firms are more likely to adopt the internet within regions where there is greater availability of broadband infrastructure. Secondly, that the legacy of the telecoms network on which ADSL broadband, the most commonly used type of broadband in the UK, is based generates discontinuities in the availability of broadband infrastructure. We provide technical and empirical support for these views. The discontinuity that we study exists for a 5 year time period, based on differences in the timing of broadband availability across two telecoms providers in a particular region of the UK.

Using this empirical design we find evidence in support of the view that greater access to broadband infrastructure significantly increases the likelihood of adoption. However, we find no evidence that using broadband, as a result of availability of ADSL, has an effect on firm performance, no matter how it is measured. Given the positive correlations observed for the OLS approach, it points to the influence of confounding factors in the OLS estimates and leads us to a conclusion that there is no causal relationship from ADSL broadband adoption to employment, sales, labour productivity or firm survival.

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Figures

Figure 1: Broadband Adoption Propensity

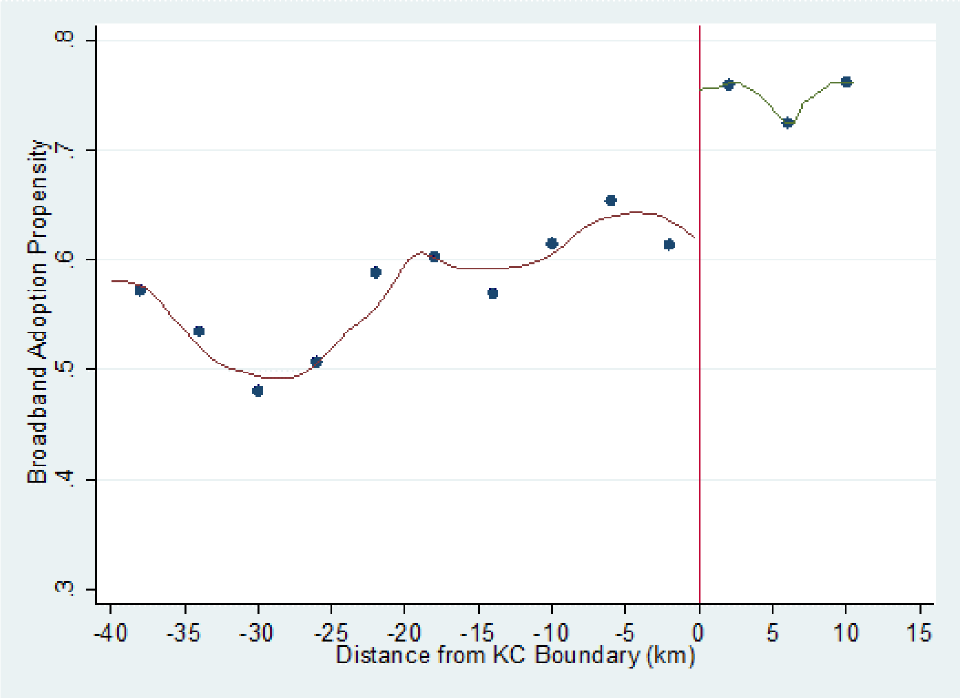


Figure 2: Summary of UK Telephone Network

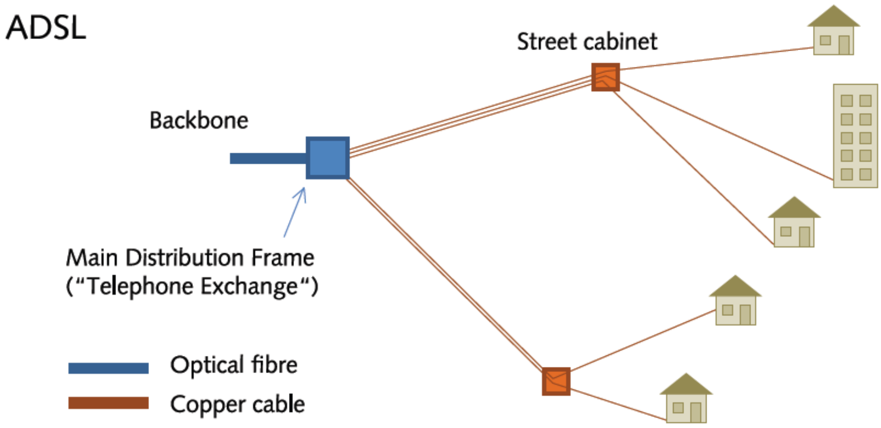


Figure 3: ADSL Enabled Exchanges - 2000

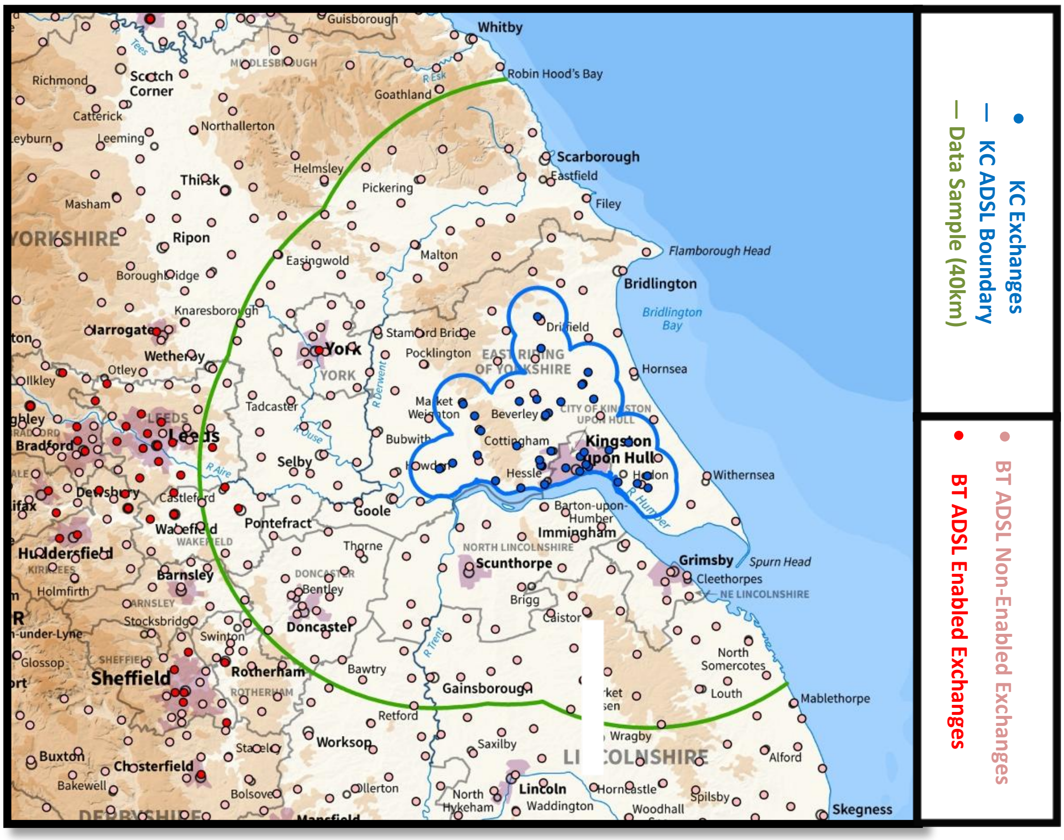


Figure 4: ADSL Enabled Exchanges - 2001

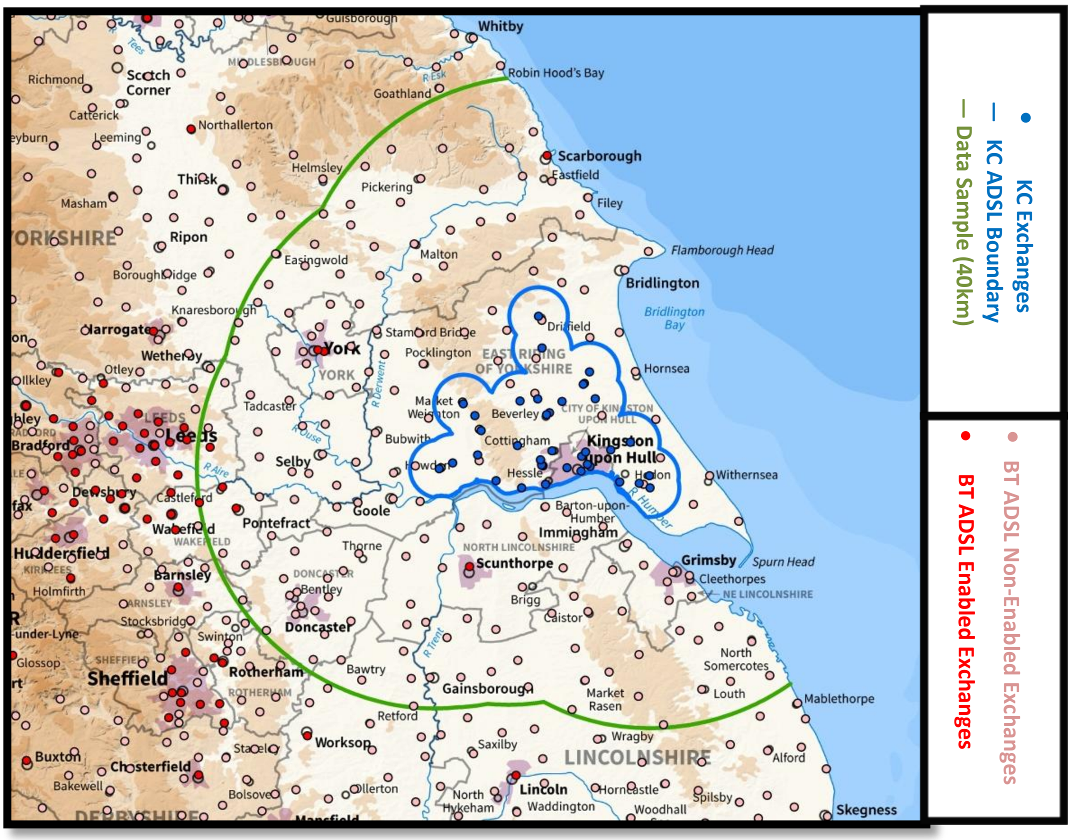


Figure 5: ADSL Enabled Exchanges - 2002

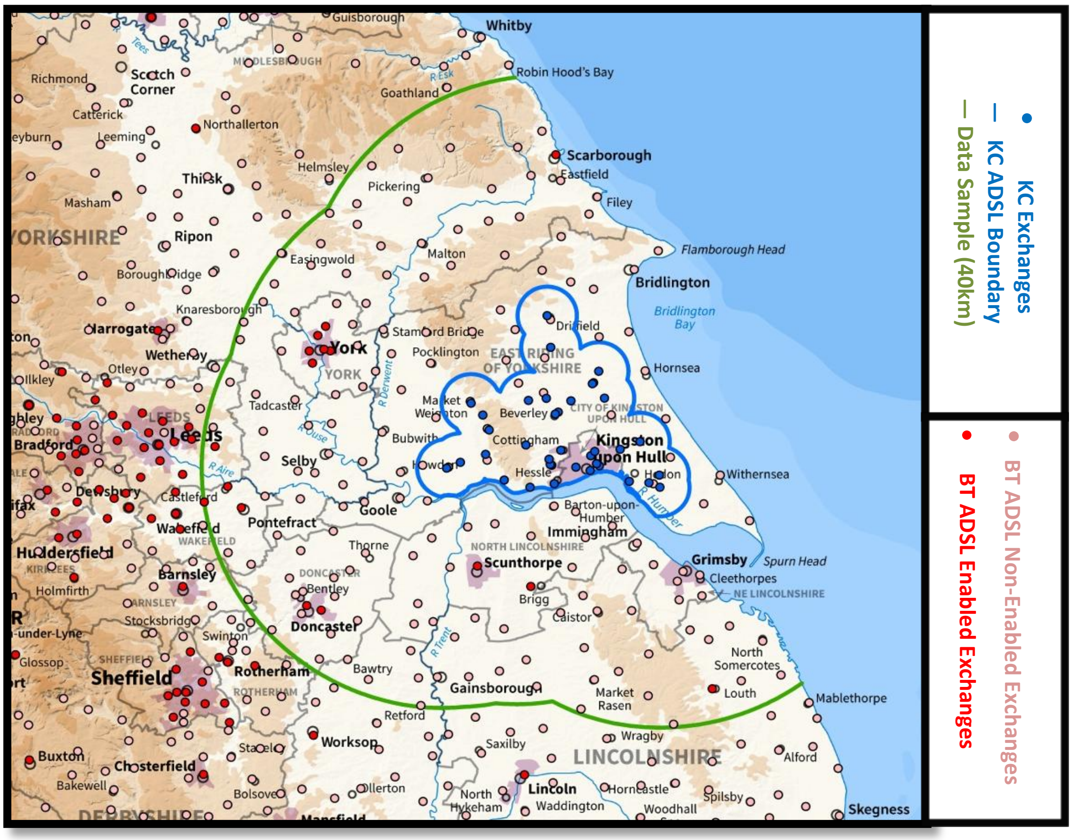


Figure 6: ADSL Enabled Exchanges - 2003

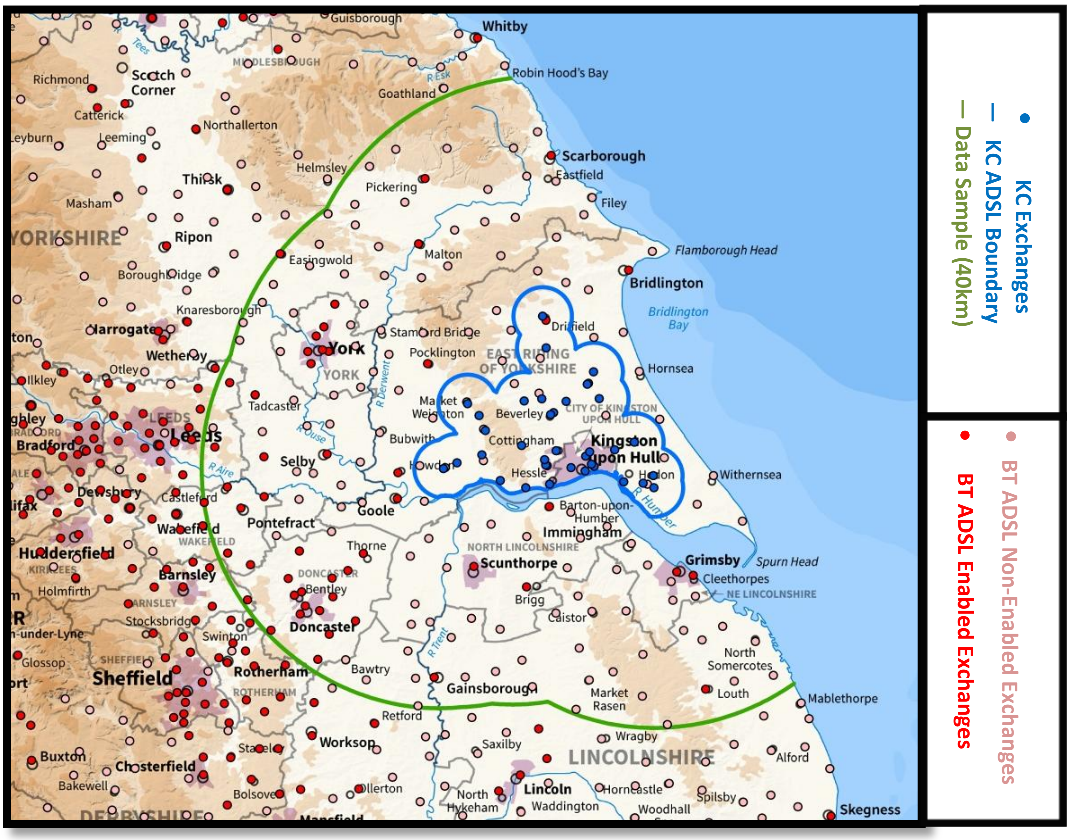


Figure 7: ADSL Enabled Exchanges - 2004

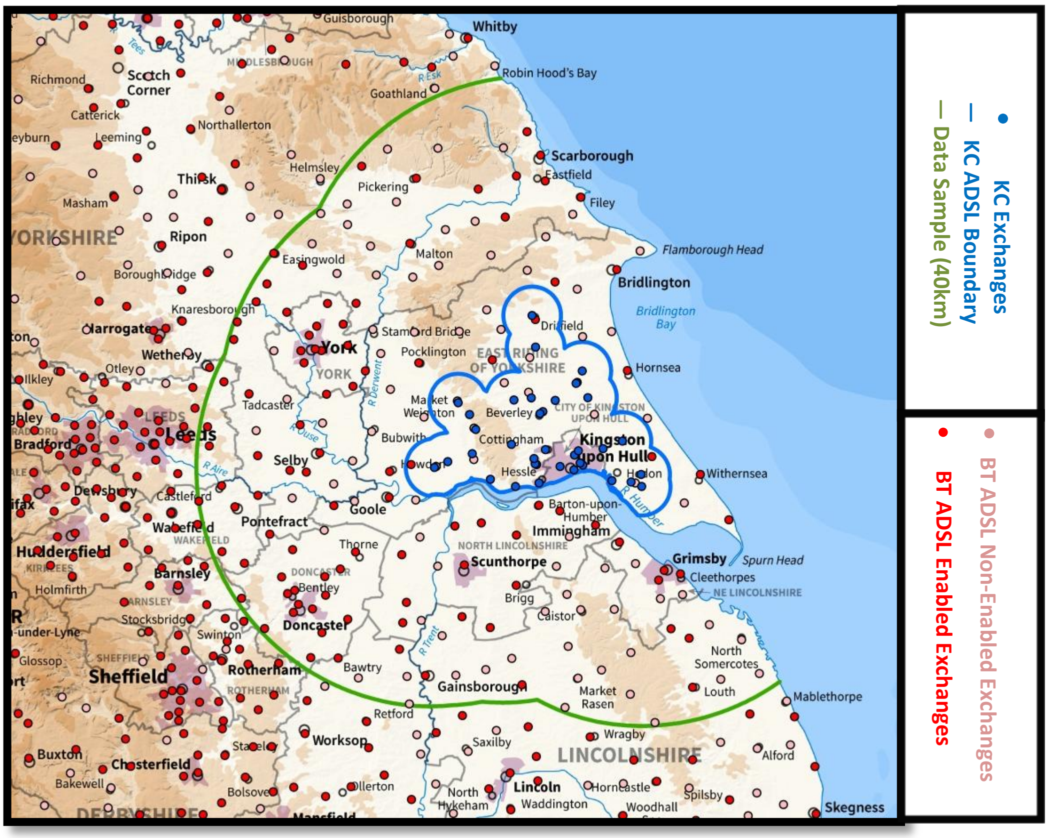


Figure 8: ADSL Enabled Exchanges - 2005

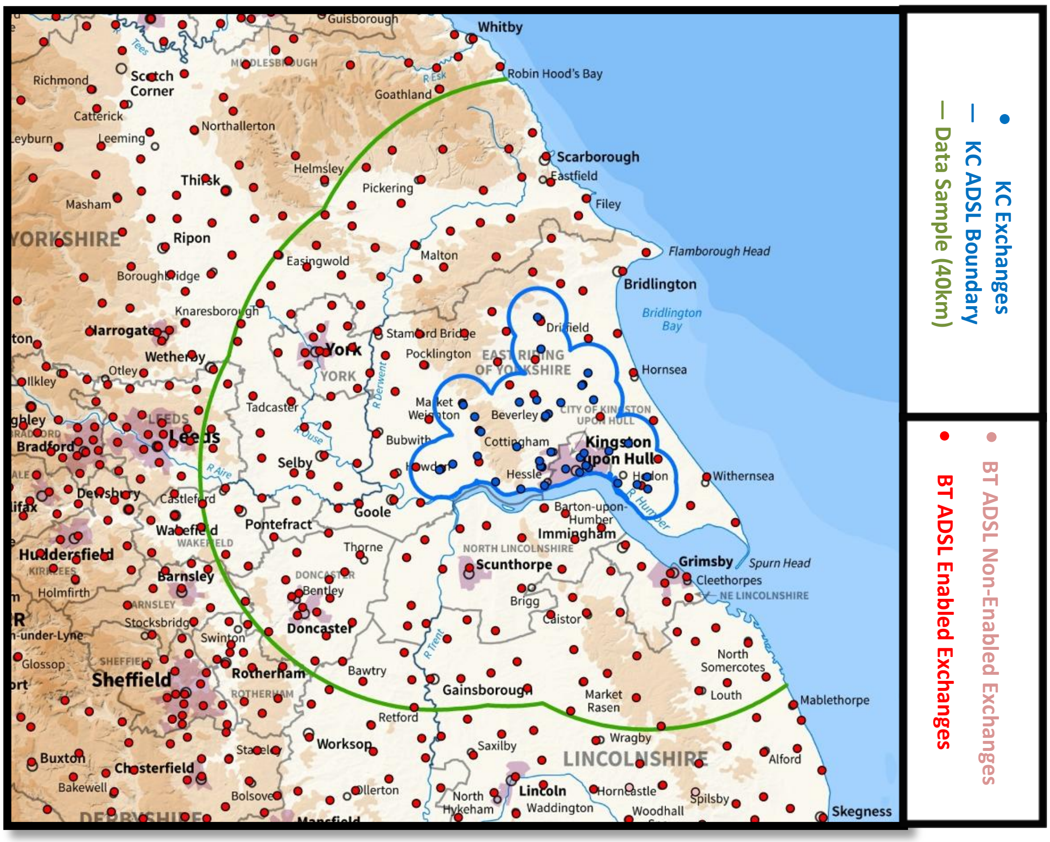


Figure 9: Spatial Discontinuity and Local Authority Boundaries

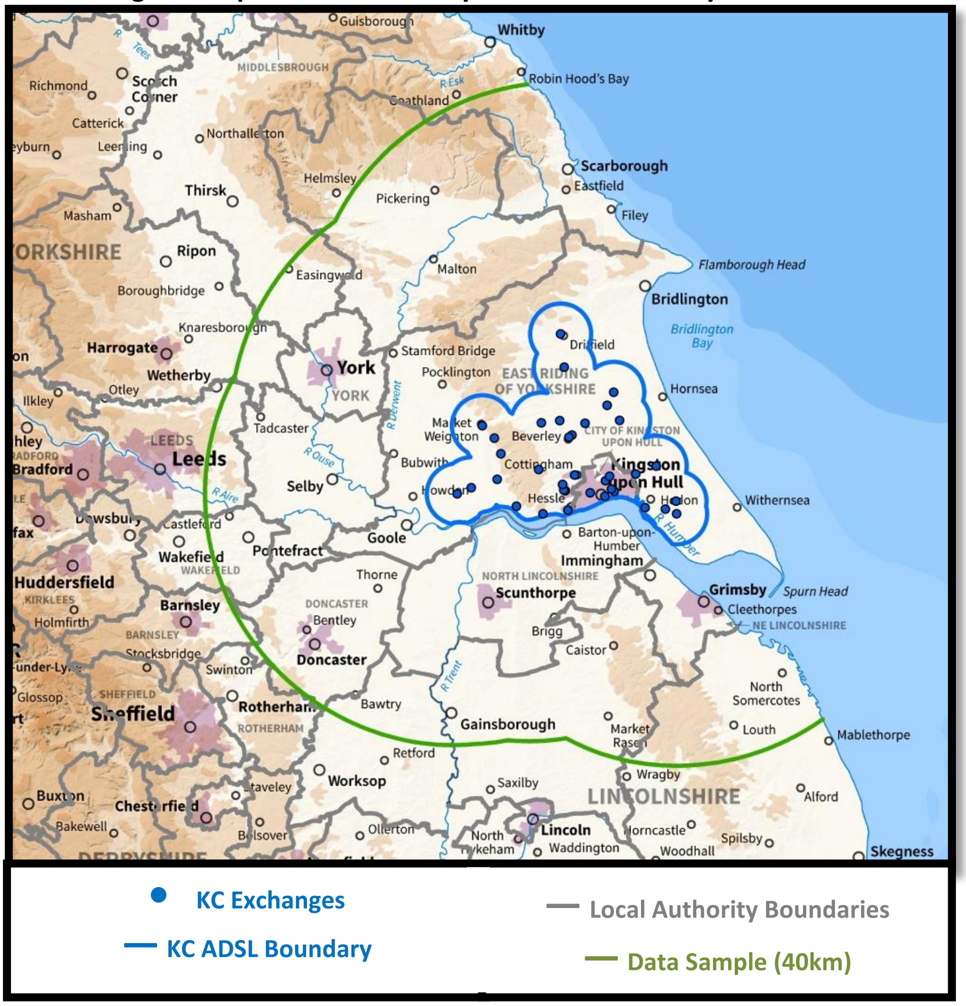


Figure 10: Plant Employment

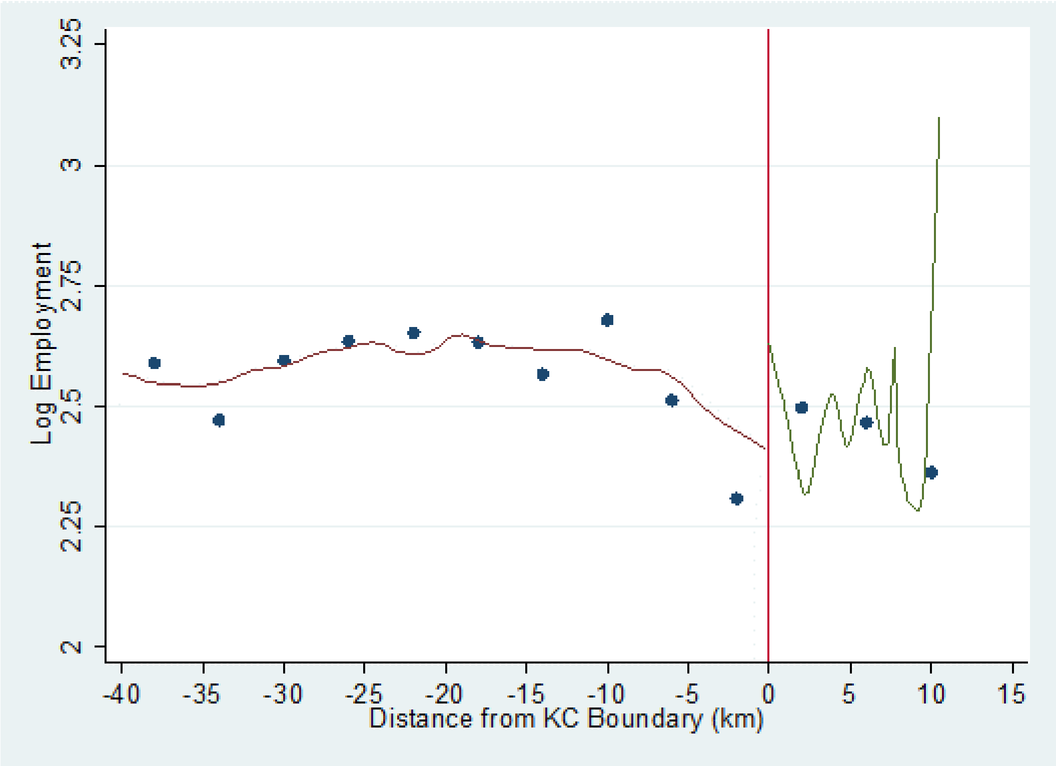


Figure 11: Plant Employment Growth

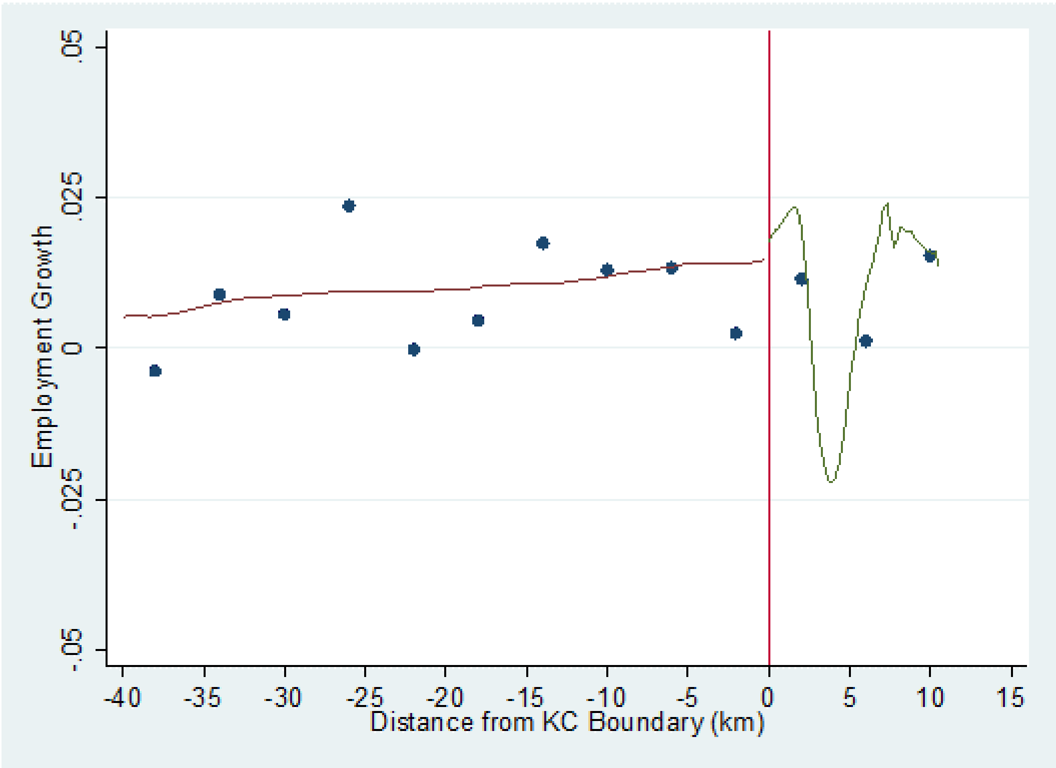


Figure 12: Plant Exit Propensity

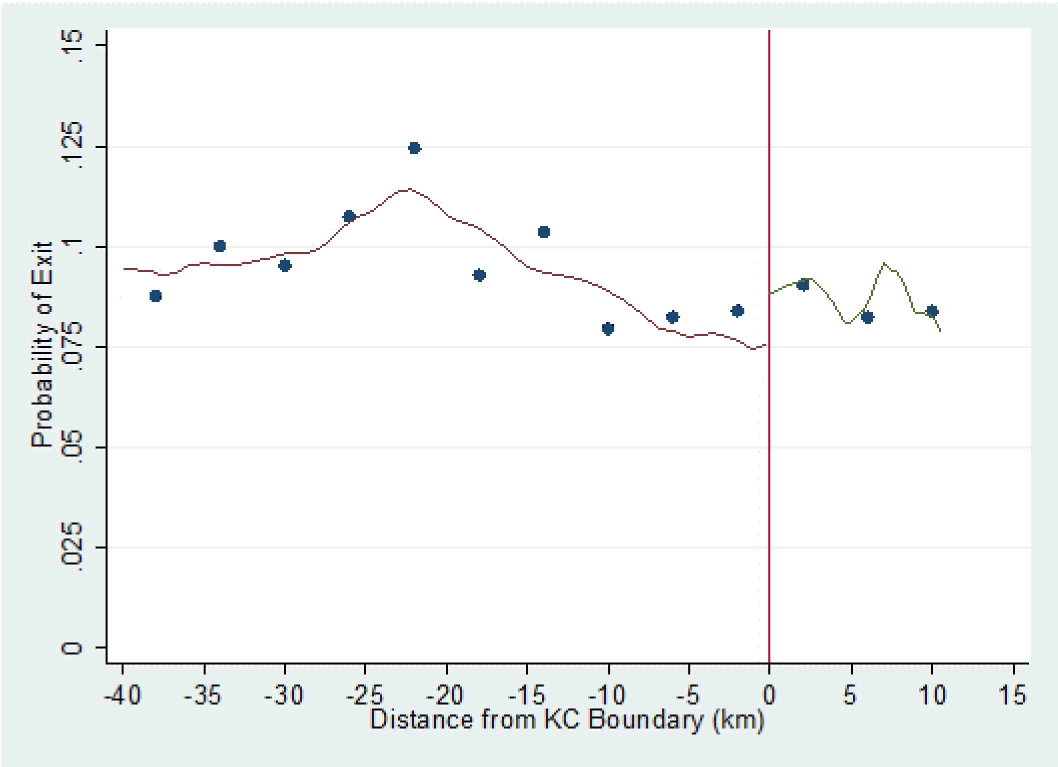
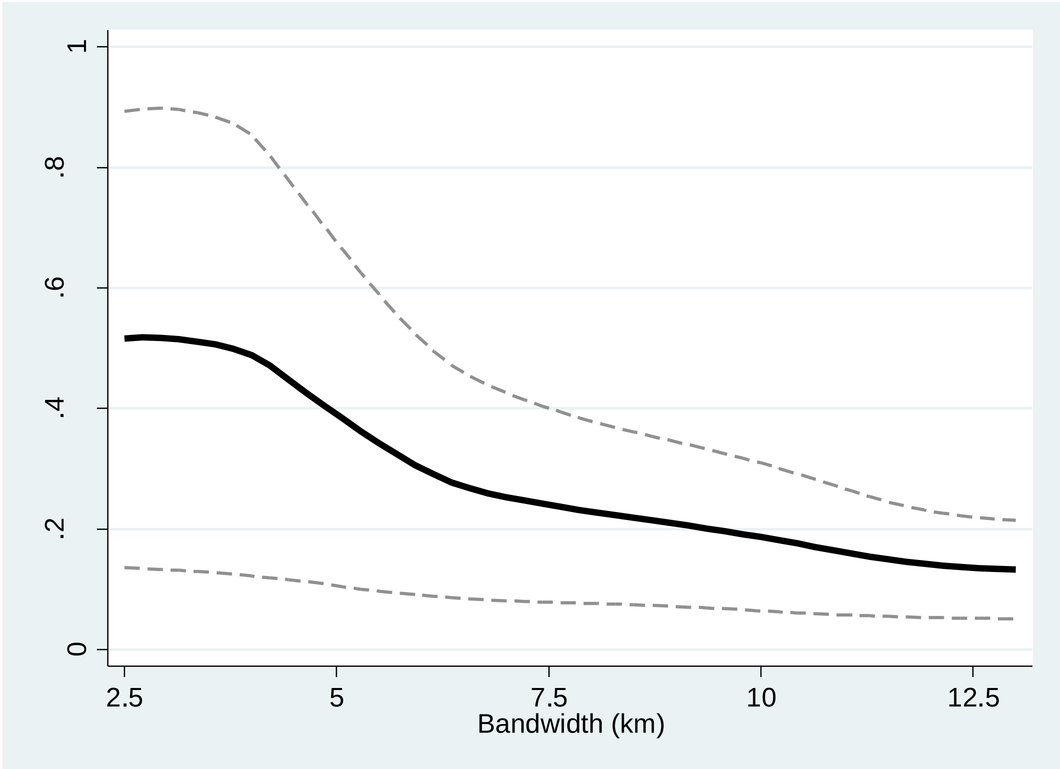


Figure 13: Non-Parametric Estimates of Broadband Discontinuity at Various Bandwidths



Tables

Table 1: Summary Statistics

Variables	**N**	**Mean**	**Standard Deviation**
Employment	11,045	39	124
Employment Growth	7,668	0.010	0.375
Plant Exit	8,301	0.092	0.289
Broadband	11,074	0.656	0.475
Firm Sales	706	79,681	321,889
Firm Sales Growth	615	0.027	0.648
Firm Sales per Worker	703	174	519
Firm Age	684	17	9
Multi-plant	706	0.429	0.120
Foreign Owned	706	0.120	0.326
Service Sector	11,074	0.898	

Note: Sales and Sales per Worker are in 1000s and are in pound sterling, Employment reflects the plant employee headcount. Firm Age is measured in Years. All growth variables refer to a one year difference in logs.

Table 2: OLS Regressions of Plant Employment and Broadband Adoption

Dependent Variable:	Log Employment			
Broadband	0.017 (0.077)	0.154*** (0.057)	0.242*** (0.065)	0.248*** (0.067)
Industry FE		√	√	√
Year FE			√	√
Control Variables				√
Obs	11,045	11,045	11,045	10,934

Table 3: Regression Discontinuity Effects of Broadband on Employment

	Dependent Variable: Log Employment						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	-0.793	-0.522	-0.7687	-0.492	1.162	2.087*	1.898
	(0.771)	(0.724)	(0.8127)	(0.775)	(1.209)	(1.226)	(1.389)
First Stage							
KC Boundary	0.103***	0.111***	0.097***	0.102***	0.439***	0.714**	0.201***
	(0.027)	(0.027)	(0.027)	(0.027)	(0.171)	(0.364)	(0.068)
Control Variables			√	√			
Cragg-Donald F-statistic	40.932	44.706	36.593	38.940	-	-	-
Kleinbergen-Papp F-Statistic	14.793	17.464	13.191	14.975	-	-	-
Akaike Information Criterion	38,350	37,855	37,893	37,399	-	-	-
Obs	11,045	11,045	10,934	10,934	4,382	3,033	6,042

Table 4: Regression Discontinuity Effects of Broadband on Employment Growth

	Dependent Variable: Employment Growth						
	Parametric				**Non-Parametric**		
	Model 1	**Model 2**	**Model 1**	**Model 2**	**h**	**h/2**	**2h**
Second Stage							
Broadband	-0.275	0.000	-0.020	0.012	0.182	0.273	0.072
	(0.154)	(0.144)	(0.167)	(0.159)	(0.226)	(0.322)	(0.231)
First Stage							
KC Boundary	0.104***	0.112***	0.097***	0.103***	0.304***	0.656***	0.128***
	(0.035)	(0.034)	(0.035)	(0.034)	(0.085)	(0.156)	(0.039)
Control Variables			√	√			
Cragg-Donald F-statistic	29.00	32.01	25.91	27.90	-	-	-
Kleinbergen-Papp F-Statistic	8.93	10.76	7.69	8.96	-	-	-
Akaike Information Criterion	6,719	6,714	6,717	6,713	-	-	-
Obs	7,668	7,668	7,643	7,643	3,905	2,860	5,271

Table 5: Regression Discontinuity Effects of Broadband on Plant Exit

	Dependent Variable: Probability of Plant Exit						
	Parametric				**Non-Parametric**		
	Model 1	**Model 2**	**Model 1**	**Model 2**	**h**	**h/2**	**2h**
Second Stage							
Broadband	0.047	0.046	0.049	0.051	-0.033	-0.071	0.180
	(0.115)	(0.113)	(0.129)	(0.129)	(0.219)	(0.203)	(0.209)
First Stage							
KC Boundary	0.102***	0.109***	0.092***	0.096***	0.287***	0.694***	0.115***
	(0.033)	(0.033)	(0.033)	(0.032)	(0.088)	(0.160)	(0.038)
Control Variables			√	√			
Cragg-Donald F-statistic	30.80	33.10	25.61	26.65	-	-	-
Kleinbergen-Papp F-Statistic	9.62	11.23	7.84	8.77	-	-	-
Akaike Information Criterion	2,983	2,983	2,774	2,780	-	-	-
Obs	8,301	8,301	8,211	8,211	4,243	3,067	5,645

Table 6: Regression Discontinuity Effects of Broadband on Employment – Firms Connected to Both BT

	Dependent Variable: Log Employment						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	-3.118*	-1.668	-2.766*	-1.465	1.354	1.035	0.859
	(1.824)	(1.528)	(1.526)	(1.321)	(1.286)	(1.051)	(1.556)
First Stage							
KC Boundary	0.082**	0.098**	0.089***	0.111***	0.239***	0.513***	0.090**
	(0.034)	(0.039)	(0.033)	(0.038)	(0.082)	(0.196)	(0.041)
Control Variables			√	√			
Cragg-Donald F-statistic	13.48	11.17	16.54	14.66	-	-	-
Kleinbergen-Papp F-Statistic	5.91	6.25	7.52	8.54	-	-	-
Akaike Information Criterion	29,008	25,489	27,776	24,773	-	-	-
Obs	6,829	6,829	6,766	6,766	1,455	620	3,403

Table 7: Regression Discontinuity Effects of Broadband on Employment Growth – Firms Connected to Both BT

	Dependent Variable: Employment Growth						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	-0.162 (0.253)	-0.025 (0.224)	-0.170 (0.235)	-0.047 (0.198)	0.238 (0.216)	0.289 (0.303)	0.084 (0.256)
First Stage							
KC Boundary	0.085** (0.043)	0.117** (0.047)	0.091** (0.042)	0.132*** (0.045)	0.326*** (0.089)	0.687*** (0.160)	0.137*** (0.047)
Control Variables			√	√			
Cragg-Donald F-statistic	10.08	10.85	12.25	14.52	-	-	-
Kleinbergen-Papp F-Statistic	3.95	6.18	4.81	8.64	-	-	-
Akaike Information Criterion	4,388	4,195	4,414	4,207	-	-	-
Obs	4,707	4,707	4,686	4,686	1,035	425	2,414

Table 8: Regression Discontinuity Effects of Broadband on Plant Exit – Firms Connected to Both BT

	Dependent Variable: Probability of Plant Exit						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	0.125 (0.226)	0.112 (0.239)	0.109 (0.209)	0.102 (0.205)	0.066 (0.216)	-0.115 (0.202)	0.241 (0.236)
First Stage							
KC Boundary	0.081** (0.041)	0.111** (0.045)	0.088** (0.040)	0.126*** (0.044)	0.218*** (0.072)	0.526*** (0.123)	0.114*** (0.041)
Control Variables			√	√			
Cragg-Donald F-statistic	10.01	10.85	12.27	14.72	-	-	-
Kleinbergen-Papp F-Statistic	3.94	6.04	4.87	8.36	-	-	-
Akaike Information Criterion	2,103	2,070	1,947	1,932	-	-	-
Obs	5,034	5,034	4,985	4,985	1,502	743	2,988

Table 9: Regression Discontinuity Effects of Broadband on Sales

	Dependent Variable: Log Sales						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	0.445	2.817	1.805	2.225	4.843**	4.340***	1.425
	(3.158)	(2.065)	(1.562)	(1.463)	(2.364)	(1.445)	(3.134)
First Stage							
KC Boundary	0.143*	0.182**	0.194***	0.210***	0.333**	0.609***	0.188**
	(0.075)	(0.080)	(0.066)	(0.073)	(0.131)	(0.130)	(0.096)
Control Variables			√	√			
Cragg-Donald F-statistic	5.84	8.69	11.80	12.58	-	-	-
Kleinbergen-Papp F-Statistic	3.63	5.17	8.63	8.28	-	-	-
Akaike Information Criterion	3,314	3,144	2,757	2,758	-	-	-
Obs	701	701	679	679	360	267	490

Table 10: Regression Discontinuity Effects of Broadband on Sales Growth

	Dependent Variable: Sales Growth						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	0.101 (0.449)	-0.062 (0.396)	0.040 (0.290)	-0.104 (0.307)	-0.348 (0.411)	-0.101 (0.285)	-0.334 (0.670)
First Stage							
KC Boundary	0.136* (0.077)	0.169** (0.083)	0.209*** (0.067)	0.223*** (0.075)	0.299** (0.132)	0.589*** (0.131)	0.163 (0.104)
Control Variables			√	√			
Cragg-Donald F-statistic	4.86	6.82	12.75	13.15	-	-	-
Kleinbergen-Papp F-Statistic	3.12	4.14	9.68	8.80	-	-	-
Akaike Information Criterion	1,222	1,218	1,222	1,222	-	-	-
Obs	615	615	615	615	321	236	428

Table 11: Regression Discontinuity Effects of Broadband on Labour Productivity

	Dependent Variable: Sales per Worker						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Second Stage							
Broadband	-1.956 (1.959)	-1.241 (1.400)	-0.949 (1.029)	-0.681 (0.974)	-0.001 (1.009)	-0.414 (0.949)	-1.362 (1.554)
First Stage							
KC Boundary	0.142* (0.075)	0.181** (0.080)	0.196*** (0.066)	0.212*** (0.073)	0.334** (0.131)	0.609*** (0.130)	0.189** (0.096)
Control Variables			√	√			
Cragg-Donald F-statistic	5.79	8.61	12.03	12.81	-	-	-
Kleinbergen-Papp F-Statistic	3.60	5.13	8.82	8.45	-	-	-
Akaike Information Criterion	2,586	2,376	2,188	2,134	-	-	-
Obs	699	699	677	677	360	264	489

Table 12: Firm Sorting Across KC ADSL Boundary

Reduced Form	Dependent Variable: Probability of Moving Across KC Boundary at time t						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
KC Boundary	0.001 (0.004)	-0.001 (0.002)	0.001 (0.004)	-0.001 (0.002)	-0.002 (0.006)	0.012* (0.007)	0.001 (0.003)
Control Variables			√	√			
Akaike Information Criterion	223	218	227	222	-	-	-
Obs	11,074	11,074	10,961	10,961	6,042	4,391	8,050

Table 13: Firm Sorting in Advance Across KC ADSL Boundary

Reduced Form	Dependent Variable: Probability of Moving Across KC Boundary up to time t						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
KC Boundary	0.001 (0.004)	-0.001 (0.003)	0.001 (0.004)	-0.001 (0.003)	0.002 (0.003)	-0.001 (0.007)	0.003 (0.002)
Control Variables			√	√			
Akaike Information Criterion	387	384	383	380	-	-	-
Obs	11,074	11,074	10,961	10,961	8,036	6,016	10,758

Table 14: Falsification Test of Broadband Discontinuities at East Riding Local Authority Boundary

	Dependent Variable: Broadband						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Reduced Form							
East Riding Boundary	0.011 (0.035)	0.044 (0.053)	-0.006 (0.034)	-0.011 (0.051)	-0.056 (0.067)	-0.128 (0.094)	-0.074 (0.045)
Control Variables			√	√			
Obs	5,750	5,750	5,691	5,691	1,328	582	5,239

Table 15: Falsification Test of Broadband Discontinuities at Hull Local Authority Boundary

	Dependent Variable: Broadband						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**h/2**	**2h**
Reduced Form							
Hull Boundary	0.000 (0.038)	-0.027 (0.041)	-0.010 (0.038)	-0.040 (0.040)	-0.005 (0.044)	-0.025 (0.071)	-0.024 (0.039)
Control Variables			√	√			
Obs	5,324	5,324	5,270	5,270	2,699	1,173	5,347

Table 16: Falsification Test of Discontinuities post-2005

	Dependent Variable: Log Employment						
	Parametric				**Non-Parametric**		
	Linear	**Linear Interaction**	**Linear**	**Linear Interaction**	**h**	**2h**	**h/2**
Second Stage							
Broadband	-17.708	-24.143	-18.226	-24.471	3.889	-1.926	56.643
	(29.506)	(37.007)	(29.233)	(36.187)	(9.226)	(8.631)	(108.783)
First Stage							
KC Boundary	-0.010	-0.009	-0.010	-0.009	0.067	0.114	0.012
	(0.015)	(0.013)	(0.014)	(0.012)	(0.075)	(0.212)	(0.022)
Control Variables			√	√			
Cragg-Donald F-statistic	3.69	2.67	3.80	2.79	-	-	-
Kleinbergen-Papp F-Statistic	0.42	0.49	0.46	0.53	-	-	-
Akaike Information Criterion	55,343	61,039	55,319	60,675	-	-	-
Obs	10,964	10,964	10,885	10,885	3,791	2,349	5,065

Appendix

i. Summary Regional Information

Kingston Communications serves an area that is less affluent than the UK as a whole. The boundary of Kingston Communications is encompassed within the region of East Yorkshire and North Lincolnshire. This region has is relatively deprived compared to the rest of the UK, with higher unemployment, lower education attainment, household income and GDP per capita than the UK average (see Table 17).

Table 17: Summary Statistics by UK Region

Region (NUTS2)	East Yorkshire and North Lincolnshire	Lincolnshire	South Yorkshire	West Yorkshire	North Yorkshire	Derbyshire and Nottingham shire	UK
GDP per capita (€)	20,500	18,500	18,500	24,500	23,500	21,700	27,500
Mean gross household income (€)	15,900	17,200	16,000	17,300	19,500	16,400	19,500
Unemployment Rate	6.7%	4.5%	6.9%	5.6%	4.9%	5.7%	5.6%
Tertiary Education Attainment	20.9%	17.2%	20.8%	26.3%	19.5%	16.4%	28.5%

Source: Eurostat, for the year 2000

However, the prosperity of the area served by Kingston Communications is not out of line with the surrounding regions, nor is it an outlier for the UK. The most affluent surrounding region, North Yorkshire, still has lower education attainment, GDP per capita and higher unemployment than the UK average. Some of the adjacent areas are at least as poor as East Yorkshire and North Lincolnshire. For example, South Yorkshire has lower GDP per capita than East Yorkshire and North Lincolnshire, and is comparable for other figures.

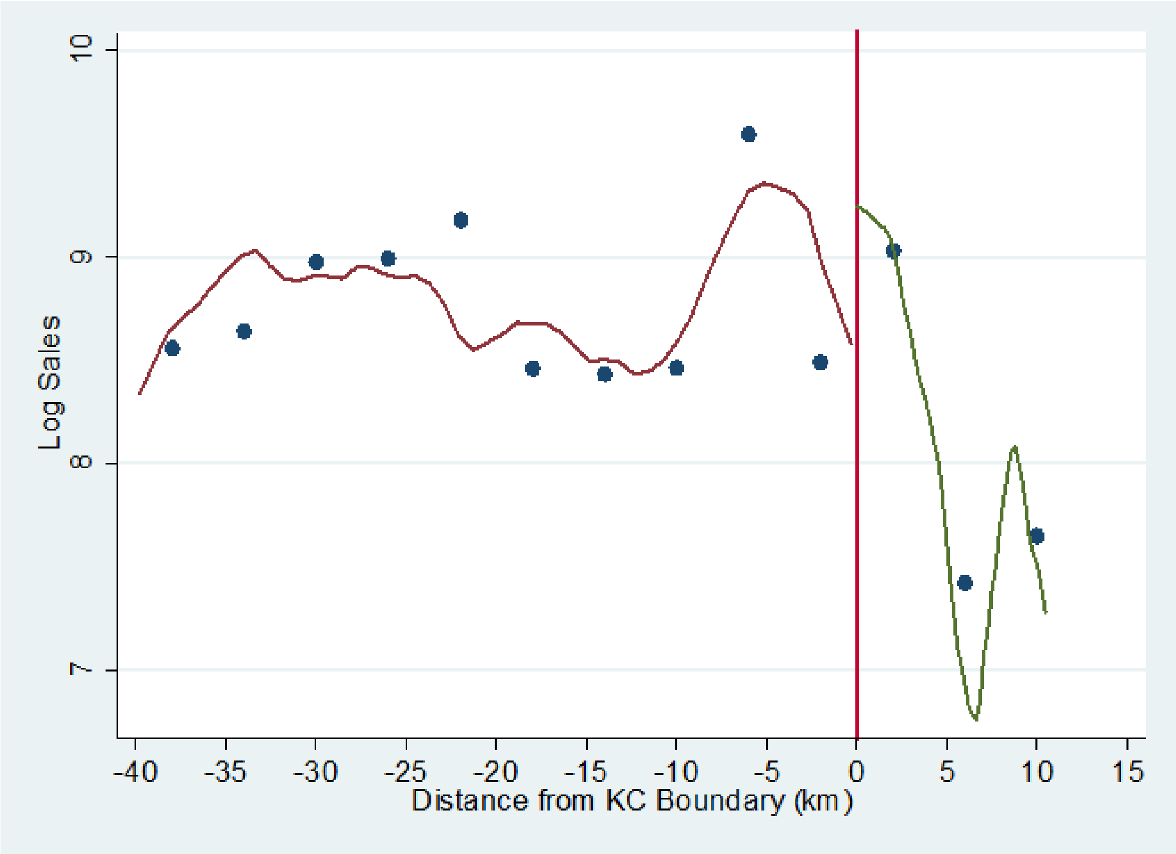
ii. Further OLS results

Table 18: OLS Regressions of Firm Outcomes and Broadband Adoption

Dependent Variable:	Employment Growth		Probability of Plant Exit		Log Sales		Sales Growth		Sales per Worker	
Broadband	-0.003	0.013	0.008	0.026	2.787***	1.912***	-0.032	-0.022	0.325***	0.395***
	(0.011)	(0.014)	(0.020)	(0.023)	(0.219)	(0.197)	(0.049)	(0.053)	(0.109)	(0.110)
Industry FE		√		√		√		√		√
Year FE		√		√		√		√		√
Control Variables		√		√		√		√		√
Obs	7,668	7,643	8,301	8,301	701	679	615	615	699	677

iii. Graphical Analysis of Firm Sales

Figure 14: Firm Sales



iv. 20km from the KC ADSL Boundary

Table 19: Regression Discontinuity Effects of Broadband on Employment – 20km from KC ADSL Boundary

	Dependent Variable: Log Employment						
	Parametric				**Non-Parametric**		
	Model 1	**Model 2**	**Model 1**	**Model 2**	**h**	**h/2**	**2h**
Second Stage							
Broadband	0.7605 (0.9400)	0.7674 (1.1248)	0.9138 (1.0136)	0.9097 (1.1634)	1.0651 (1.1403)	2.9500 (2.4361)	1.6868 (1.3391)
First Stage							
KC Boundary	0.1205*** (0.0327)	0.1066*** (0.0358)	0.1114*** (0.0320)	0.1017*** (0.0343)	0.4683** (0.1868)	0.5461 (0.4310)	0.2177*** (0.0730)
Control Variables			√	√			
Cragg-Donald F-statistic	25.550	17.653	22.323	16.392	-	-	-
Kleinbergen-Papp F-Statistic	13.545	8.87	12.138	8.777	-	-	-
Akaike Information Criterion	27769.83	27780.93	27589.74	27585.78	-	-	-
Obs	8,126	8,126	8,044	8,044	4,188	2,905	5,644

Table 20: Regression Discontinuity Effects of Broadband on Employment Growth – 20km from KC ADSL Boundary

	Dependent Variable: Employment Growth						
	Parametric				**Non-Parametric**		
	Model 1	**Model 2**	**Model 1**	**Model 2**	**h**	**h/2**	**2h**
Second Stage							

Broadband	0.333 (0.1646)	-0.0109 (0.1923)	0.0502 (0.1756)	0.0067 (0.1963)	0.2736 (0.3199)	0.5502 (0.7043)	0.1758 (0.2240)
First Stage							
KC Boundary	0.1383*** (0.0408)	0.1284*** (0.0448)	0.1303*** (0.0398)	0.1254*** (0.0428)	0.6406*** (0.1550)	0.8917*** (0.1638)	0.2938*** (0.0828)
Control Variables			√	√			
Cragg-Donald F-statistic	23.488	17.791	21.693	17.646	-	-	-
Kleinbergen-Papp F-Statistic	11.515	8.204	10.734	8.575	-	-	-
Akaike Information Criterion	4760.428	4744.815	4772.434	4748.695	-	-	-
Obs	5,666	5,666	5,648	5,648	2,907	2,064	3,944

Table 21: Regression Discontinuity Effects of Broadband on Plant Exit – 20km from KC ADSL Boundary

	Dependent Variable: Probability of Plant Exit						
	Parametric				**Non-Parametric**		
	Model 1	**Model 2**	**Model 1**	**Model 2**	**h**	**h/2**	**2h**
Second Stage							
Broadband	0.1427 (0.1454)	0.1859 (0.1770)	0.1376 (0.1606)	0.1599 (0.1816)	-0.0729 (0.2081)	0.0733 (0.1235)	0.0370 (0.2124)
First Stage							
KC Boundary	0.1221*** (0.0389)	0.1111*** (0.0423)	0.1100*** (0.0376)	0.1055*** (0.0399)	0.6394*** (0.1521)	0.9419*** (0.1445)	0.2455*** (0.0774)
Control Variables			√	√			
Cragg-Donald F-statistic	20.239	14.682	17.035	13.712	-	-	-

Kleinbergen-Papp F-Statistic	9.827	6.887	8.563	6.979	-	-	-
Akaike Information Criterion	2268.645	2467.299	2074.899	2169.398	-	-	-
Obs	6175	6175	6108	6108	3,284	2,305	4,360