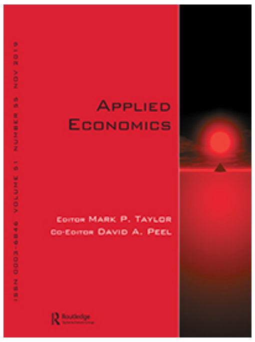

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High-speed Internet access and housing values

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ABSTRACT
A hedonic model is estimated that relates house values to high-speed Internet access while controlling for the potential endogeneity of Internet access. Results show that single-family homes with access to a 25 Mbps broadband connection have a price that is about $5,977, or 3%, more than similar homes in neighborhoods with 1 Mbps. The rural premium is lower at $5,099. A cost-benefit exercise on the viability of rural broadband shows that demand will generally not support private investment, but that the revenue gap from upgrading legacy networks could be readily covered by the Universal Service Fund and other public subsidies.

KEYWORDS
Broadband; Internet; real estate; rural neighborhoods; universal service

JEL CLASSIFICATION
R30; R21; L86

I. Introduction

Numerous factors influence the value of residential real estate, including the number of bathrooms in the home, local amenities, and air quality, or neighborhood crime. Given realtors regularly describe Internet access on MLS listing sheets, high-speed Internet service or 'broadband' may be an important consideration for homebuyers, particularly in rural locations. Traditionally supplied by local cable and telephone companies, high-speed Internet permits households to access high-bandwidth video, music and gaming services, consume Telehealth, conduct job searches, and to work productively from home. This paper empirically estimates the effect of neighborhood access to a high-speed Internet connection on housing prices.

Broadband is arguably one of the most important sectors of the economy and policy makers have discussed many proposals that would increase its deployment to United States neighborhoods. See, for example, federal infrastructure grants from the American Reinvestment and Recovery Act of 2009, the Federal Communication Commission's (FCC) 'National Broadband Plan' of 2010, and the 2014 approval of a monthly subsidy to help low-income households connect to the Internet through the Lifeline program. Academic studies that estimate the household benefits from broadband have been limited by the lack of quality data on available speeds, consumer choices, Internet plan characteristics, and prices. Detailed data on nationwide broadband presence were first made available when the National Telecommunication and Information Administration (NTIA) began publishing the National Broadband Map (NBM) in 2011. Updated twice a year, the NBM provides local information on broadband availability, the technology used to offer service, maximum speeds, and Internet service providers (ISPs).

We use the NBM and a sample of real estate transactions from 2011 to 2014 to empirically investigate the relationship between average house values and high-speed Internet while controlling for the endogeneity of Internet access. Results from a hedonic pricing model show that single-family homes with access to a 25 Mbps broadband connection have a transaction price that is about $5,977, or 3%, more than similar homes in neighborhoods with a one Mbps connection. Homes with access to a 50 Mbps connection have a price that is about $1,450 more than homes with 25 Mbps, and homes with access to a 100 Mbps connection have a price that is about $1,352 more than homes with 50 Mbps. The rural premium is lower. For example, homes with access to 25 Mbps have a price that is about $5,099 more than similar homes in neighborhoods with 1 Mbps. A cost-benefit exercise on the viability of rural broadband shows that residential demand will

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generally not support private investment, but that the revenue gap for upgrading legacy cable or telephone networks could be readily covered by the Universal Service Fund (USF) and other public subsidies.

Other studies have quantified the household benefits from high-speed Internet. Ahlfeldt, Koutroumpis, and Valletti (2014) find that upgrading from a dial-up to an eight Mbps connection increases the price of an average English home by 2.8%. Nevo, Turner, and Williams (2015) estimate usage demand and calculate consumer surplus of between $160 and $236 per month when consumers are offered a 1,024 Mbps plan. Given a monthly fee of $70 to $100, this suggests a gap between the private and social benefits from the investment. Using Goolsbee' s (2002) theoretical framework and Nevo et al.'s estimates, Boik (2017) shows that universal broadband service of 1,024 Mbps in North Carolina would be prohibitively costly even when assuming generous estimates of consumer surplus. Carare et al. (2015) use willingness-to-pay statements from a survey of non-adopting households and find that two-thirds would not consider subscribing to broadband at any price. However, their survey does not define broadband and leaves its interpretation to respondents. Using conjoint data administered by a survey, Liu, Prince, and Wallsten (2017) find that bandwidth provides relatively little additional value to households beyond 50 Mbps.

Our paper makes several contributions to this literature. First, to the best of our knowledge, this is the first analysis of the effect of high-speed Internet access on a national sample of United States houses. By using a new database of Internet availability in census block groups (CBGs), we measure speeds that include household access to a 25 Mbps connection, which is the FCC (2015) current definition of broadband. We estimate household's revealed preferences for Internet and perform a cost-benefit analysis on the viability of broadband deployment to unserved rural households. This should be interesting to policy makers looking to enhance the speed of their local networks, and when evaluating the efficiency of existing public subsidies and other programs.

The next section outlines the empirical model. Section III describes the data and the results are presented in Section IV. Section V concludes.

II. Empirical model

Baseline model

The hedonic pricing model for the typical home in neighborhood i = 1, 2, . . ., n at year t = 1, 2, . . ., T is:

$$logP_{it} = \varphi logS_{it} + X_{it}\beta + \alpha_i + \gamma_t + e_{it} \quad (1)$$

where P_{it} is the mean transaction price for the typical home in the neighborhood, S_{it} is the speed of the Internet connection in the neighborhood, $X_{it} = [X_{1it}, X_{2it}]$ is a vector of characteristics describing house prices, X_{1it} are observable time-varying home characteristics, X_{2it} are observable time-varying neighborhood characteristics and demographics, α_i are unobserved time-invariant neighborhood-specific fixed effects that equal one for the ith neighborhood and zero otherwise, γ_t are unobserved time-specific fixed effects that equal one in year t and zero otherwise, e_{it} is an error term, and φ and β are parameters to be estimated. We assume a log-log relationship between house prices and Internet speed so that the marginal implicit price of bandwidth is $\frac{\partial P_{it}}{\partial S_{it}} = \varphi \frac{P_{it}}{S_{it}}$ (Basu and Thibodeau 1998; Feng and Humphreys 2012). This specification parsimoniously captures our a priori theoretical expectation of decreasing returns to speed, and it also permits the returns to speed to vary by household wealth, as measured by the mean transaction price for the typical home in the neighborhood.

The important parameter of interest in equation 1 is φ. Rejection of the null that φ equals zero provides evidence that housing prices are related to high-speed Internet access. When $\varphi > 0$, all other things held constant, homes in neighborhoods with access to relatively higher speeds will have higher transaction prices. Just like access to open space, good air quality, and lower crime rates, for example, one may conclude that rational homeowners are able to capitalize on the benefits from high-speed Internet availability into housing prices.

Identification of the implicit price of bandwidth parameter φ comes from the variation in house prices and the available Internet speeds within neighborhoods. A key assumption is that conditional on neighborhood fixed effects, demographics and other controls, the levels of Internet speeds offered by ISPs are exogenous to factors not observed by the econometrician. This assumption can be problematic when ISPs consider unobserved time-varying local cost and demand conditions when making decisions about the deployment of their Internet speeds. Because these factors may also determine housing values, it is possible that $E[e_{it} \mid S_{it}, X_{it}, \alpha_i, \gamma_t] \neq 0$ and a standard fixed-effects (FE) estimate of φ would be biased.

Unobserved factors

Local cost and demand conditions vary with the mix of establishments served by ISPs, with non-residential customers their most profitable because they often receive customized services supplied at a relatively low incremental cost. Because of stronger demand from businesses and other enterprises, ISPs are often more likely to report higher connection speeds in neighborhoods with more non-residential activity. When omitted industrial, office and retail activity attracts popular amenities such as gyms, cafes, restaurants, etc., that increase house prices, and ISPs report higher connection speeds in these neighborhoods, the estimate of φ may have a positive bias. This finding would be consistent with several existing studies that show desired omitted location characteristics such as ‘curb appeal’ to be positively correlated with observed home characteristics and prices (Pope 2008; Bajari et al. 2012). Housing prices in neighborhoods with more non-residential activity may be adversely affected by excess industrial, office and retail activity. Industrial development is typically unpopular when there is increased pollution, heavy-vehicle traffic, and use of the local community’s water and electricity resources. Offices increase traffic and parking demand and may also create solar shadows. Retail activity also increases traffic, places stress on the public transport system, and can attract retail employees to the neighborhood seeking low-income housing (Matthews 2006; Grey 2013; Wiley 2015). When ISPs report higher connection speeds in these neighborhoods because of stronger demand from non-residential customers, estimates of φ may have a negative bias.

One way to correct for this potential bias is to include a variable in X_{2it} that directly measures non-residential Internet demand so that $E[e_{it} \mid S_{it}, X_{it}, \alpha_i, \gamma_t]$ equals zero. However, this method could be inappropriate when the preferences of non-residential Internet customers are not accurately observed. This may occur when preferences are approximated at a more aggregated level, for example, the total number of business employees in the county the CBG is located in.

Instrumental-variables

An alternative correction or test for the potential endogeneity of S_{it} is fixed-effects instrumental-variables (FE-IV) estimation. The first-stage estimates:

$$logS_{it} = Z_{it}\theta + \alpha_i + \gamma_t + u_{it} \quad (2)$$

where $Z_{it} = [X_{1it}, X_{2it}, X_{3it}]$, X_{3it} is a vector of exogenous variables excluded from equation 1, u_{it} is an error term, and θ is a vector of parameters. Replacing $\log S_{it}$ in equation 1 with its predicted value from equation 2 permits φ to be consistently estimated in the second-stage hedonic housing price equation. Since the predicted value of Internet speed is calculated from stage-one estimates, the asymptotic variance of the stage-two estimator of housing prices is not valid. Unbiased standard errors for the coefficients in stage-two are estimated using the standard correction for IV estimators.

The effect of high-speed Internet access on housing prices is identified by the FE-IV estimator from the variables in Z_{it} that are excluded from equation 1. Because a fiber network efficiently transports more data over the Internet, we use several measures of the extent of fiber deployment in the neighborhood as excluded variables. The key assumption for valid exclusion restrictions is that fiber deployment is exogenous to unobserved factors determining house values. This is plausible when the deployment of fiber infrastructure affects housing values only through the household’s access to higher Internet speeds, or when ISP decisions to deploy fiber are determined prior to the complete revelation of the neighborhood’s unobserved cost and demand conditions.

Fiber deployment may not be valid when it is related to unobserved time-varying Internet service prices. For example, a neighborhood with lower unobserved costs may attract more fiber investment and may also have lower Internet service prices. Absent suitable controls, these Internet price effects would be indirectly capitalized into housing prices through higher effective Internet quality (i.e., Internet speed per unit of price) and the estimated coefficient on speed (φ) will be overstated. We control for unobserved Internet service prices with local demographic variables, such as education, housing, population and race, and the number of ISPs providing service in the neighborhood. Our assumption of exogenous Internet prices is also supported by the national price-setting behavior of ISPs, whom typically charge the same price across all markets, rather than setting individual prices within each market (Boik 2017; Wilson, 2017). By controlling for the national market territories of each of the ISPs in our model, we alleviate remaining concerns on the validity of fiber deployment as appropriate excluded instruments. In Section IV.A we use the excluded instruments to estimate equations 1 and 2 by FE-IV and construct the Durbin-Wu-Hausman (DWH) statistic to test for differences between the FE and FE-IV estimates.

III. Data

Sample

Data on the transaction price and characteristics for over one million single-family detached homes in about 4,500 CBGs from 2011 through 2014 were obtained from RealtyTrac (2016). We sample this time because the NBM, which we use to match the Internet data to the housing data, only became available in 2011, and because 2014 was the most recent year of housing and Internet data available from RealtyTrac and the NBM, respectively. We first omitted all non-arm's length transactions, such as quitclaims, inter-family transfers, or partial interest sales, as these are unlikely to be transacted at true market values, as well as observations with a sales price in the bottom 1% and top 1% of the distribution. We then dropped all observations with missing or incomplete data on home characteristics or suspicious values for these characteristics, as they are most likely reporting or recording errors. This latter group includes houses with a negative lot size and/or more than 20 bathrooms.

We use these transactions to form an annual panel of 4,289 CBGs in 37 states from 2011 to 2014. California, Florida, and Ohio together comprise about 30% of the CBGs. We define a neighborhood to be a CBG and note that there are benefits and costs from using this unit of observation. The benefits are that we construct a panel data set of the typical home in the neighborhood i at year t and use a FE estimator to control for unobserved time-invariant neighborhood heterogeneity. Because ISP decisions to roll out access to new higher-speed services are usually made for neighborhoods, this definition also permits better matching of housing values with Internet access in equation 1 and helps alleviate measurement error in S_{it}.[1] CBGs are also the smallest unit of measurement in census data that have the observable time-varying local demographics in X_{2it} that control for the ISP's decision to deploy higher connection speeds in the neighborhood. The cost to this level of aggregation is that the CBG mean values do not fully reflect the underlying distributions of housing values in the individual transaction data provided by RealtyTrac.

Variables

The transaction price (P_{it}) is the average of the agreed contract prices of homes between buyers and sellers in the neighborhood (RealtyTrac 2016). Other measures of home values include 'assessor provided appraisal value' and 'market value as determined by assessor' for property tax evaluations. However, these assessments do not reflect true market measures as there is no buyer and seller involved in the evaluation of the properties, and the assessor's valuations are not based on real-time information. Transaction data are better because they are market prices that reflect supply and demand conditions, and because they are recorded in real time at the date of the ownership transfer. Table 1 describes price and the other variables used in the empirical analysis.

[1]Each CBG is comprised of one or more census blocks and a typical CBG has about 610 housing units and about 600 to 3,000 persons. The decision to upgrade Internet service neighborhood-by-neighborhood is common industry practice. For example, CenturyLink deployed high-speed Internet to selected neighborhoods within Denver, while Google defined 'fiberhoods' as consisting of 250 to 1,500 households and deployed their fiber service when the demand threshold reached five to 25% of these households (Molnar and Savage 2017).

Table 1. Variable descriptions.

Variable	Description and data source
P	Mean transaction price in dollars for residential single-family houses in the CBG. Source: RealtyTrac (2016).
S	Maximum advertised downstream speed in Mbps among all ISPs in the CBG that serve non-government end users with a high-speed Internet connection. Source: NBM (2011, 2012, 2013, 2014, 2015).
HOUSEAGE	Mean age of houses in the CBG in ten years. Source: RealtyTrac (2016).
LOTSIZE	Mean lot size of houses in the CBG in ten thousand square feet. Source: RealtyTrac (2016).
HOUSESIZE	Mean house sizes in the CBG in thousand square feet. Source: RealtyTrac (2016).
GARAGE	Mean garage sizes of house in the CBG in thousand square feet. Source: RealtyTrac (2016).
FIREPLACE	Likelihood that houses in the CBG have a fireplace. Source: RealtyTrac (2016).
POOL	Likelihood that houses in the CBG have a pool. Source: RealtyTrac (2016).
BATHS	Mean number of bathrooms in houses in the CBG. Source: RealtyTrac (2016).
HOUSES	Number of housing units in the CBG. Source: GeoLytics (2012).
POPULATION	Number of persons in the CBG. Source: U.S. Census Bureau (2015a, 2015b, 2015c, 2015d).
INCOME	Median household income ($1,000) for all households in the CBG. Source: U.S. Census Bureau (2015a, 2015b, 2015c, 2015d).
EDUCATION	Mean number of years of schooling of the population over 25 years of age in the CBG. Source: U.S. Census Bureau (2015a, 2015b, 2015c, 2015d).
NON-WHITE	Percentage of nonwhite persons in the CBG. Source: U.S. Census Bureau (2015a, 2015b, 2015c, 2015d).
TAX	Property tax rate in the county. Source: U.S. Census Bureau (2015a, 2015b, 2015c, 2015d).
CRIME	Number of serious crimes (defined as murder and rape) in the county divided by the county's population. Source: FBI (2012).
EMPLOYEES	Number of workers employed by business establishments in the county. Source: U.S. Census Bureau (2015e).
ISP2	One if there are two ISPs in the CBG providing high-speed Internet connections, and zero otherwise. Source: NBM (2011, 2011, 2012, 2014, 2015).
ISP3	One if there are three ISPs in the CBG providing high-speed Internet connections, and zero otherwise. Source: NBM (2011, 2011, 2012, 2014, 2015).
ISP4	One if there are four ISPs in the CBG providing high-speed Internet connections, and zero otherwise. Source: NBM (2011, 2011, 2012, 2014, 2015).
ISP5	One if there are five ISPs in the CBG providing high-speed Internet connections, and zero otherwise. Source: NBM (2011, 2011, 2012, 2014, 2015).
ISP6	One if there are six ISPs in the CBG providing high-speed Internet connections, and zero otherwise. Source: NBM (2011, 2011, 2012, 2014, 2015).
ISP7	One if there are seven or more ISPs in the CBG providing high-speed Internet connections, and zero otherwise. Source: NBM (2011, 2011, 2012, 2014, 2015).
$BRAND_f$	One when the ISP brand in the CBG is b = 1, 2, 3, …, 17, and zero otherwise. Source: NBM (2011, 2012, 2013, 2015).
FIBER_CBG	Percentage of census blocks in the CBG where fiber is available. Source: NBM (2011, 2011, 2012, 2014, 2015).
FIBER_CTR	Percentage of CBGs in the census tract that the CBG is in where fiber is available. Source: NBM (2011, 2011, 2012, 2014, 2015).
CBG_OBS	Number of annual transactions in the CBG contributing to the neighborhood average. Source: RealtyTrac (2016).

High-speed internet

Survey data from the NBM (2011, 2012, 2013, 2014, 2015) are used to determine the Internet speeds available to households in each neighborhood in June 2011 through 2014. We focus on advertised downstream speed because this is the product characteristic of Internet service plans that are predominately promoted by ISPs and realtors in their marketing.[2] For each CBG, we recorded the maximum speed range available, the number and names of the wireline ISPs, and the technology used to provide service. When counting the number of ISPs in each CBG, we excluded all firms that indicated that they deliver service to 'government end users' as classified by the NBM. Because information from the NBM on end-user-type is only available for 2013 and 2014, we accessed the web sites and annual reports of the sample ISPs and excluded from the 2011 and 2012 data those ISPs that indicated that they predominantly served large-business or government end users.

The NBM classifies speed into 11 Mbps ranges: 0.2 or fewer; 0.768 or fewer, but greater than 0.2; 1.5 or fewer, but greater than 0.768; 3 or fewer, but greater than 1.5; 6 or fewer, but greater than 3; 10 or fewer, but greater than 6; 25 or fewer, but greater than 10; 50 or fewer, but greater than 25; 100 or fewer, but greater than 50; 1,024 or fewer, but greater than 100; and greater than 1,024. Our discussions with industry and reading press releases indicated that speeds greater than 1,024 Mbps were typically targeted at small- and medium-businesses from 2011 to 2014. This suggests that residences could not actually subscribe to a speed greater than 1,024Mbps during our sample period.[3] As such, we coded about 5% of sample observations where the

[2]Upload speed is becoming more desirable as it is valuable for social networking, cloud services, operating web servers, and for working remotely from the home. However, upload speeds and download speeds are strongly correlated in most Internet service plans and collinearity makes it difficult to isolate their separate effects.

[3]See, for example, https://www.geekwire.com/2014/centurylink-gigabit/, https://corporate.comcast.com/news-information/news-feed/comcast-begins-rollout-of-residential-2-gig-service-in-greater-chicago-region, and https://corporate.comcast.com/news-information/news-feed/comcast-to-introduce-worlds-first-docsis-3-1-powered-gigabit-internet-service-in-atlanta-chicago-detroit-miami-and-nashville.

NBM listed the maximum-advertised downstream speed as 'greater than 1,024 Mbps' to the lower, but more realistic speed range of '1,024 or fewer, but greater than 100.' Our sample for estimation, therefore, comprises eight speed ranges, and we use the low end of these ranges to measure S_{it}, that is, 0.768, 1.5, 3, 6, 10, 25, 50, and 100 Mbps. For comparison, we note that a typical consumer download experience with a 0.768 Mbps non-broadband connection would be a one Megabyte (MB) book in 5.3 seconds, a four MB song in 21.3 seconds, and a 6,144 MB movie in 9 hours and 6 minutes. With a 25 Mbps broadband connection, a typical experience would be a book in 0.2 seconds, a song in 0.6 seconds, and a movie in 16 minutes. With 50 Mbps, a typical download experience would be a book in 0.1 seconds, a song in 0.3 seconds, and a movie in 8 minutes. With 100 Mbps, a typical experience would be a book in less than 0.1 seconds, a song in less than 0.1 seconds, and a movie in about 49.2 seconds (see https://www.broadbandmap.gov/classroom/speed).

Home characteristics

The vector of home characteristics (X_{1it}) is from RealtyTrac (2016) and includes: the mean age of homes in the CBG ($HOUSEAGE_{it}$); the mean lot size of homes in the CBG ($LOTSIZE_{it}$); the mean size of homes in the CBG ($HOUSESIZE_{it}$); the mean garage size of homes in the CBG ($GARAGE_{it}$); the mean number of bathrooms in homes in the CBG ($BATHS_{it}$); the likelihood, ranging between zero and one, that homes in the CBG have a pool ($POOL_{it}$); and the likelihood that homes in the CBG have a fireplace ($FIREPLACE_{it}$).

Neighborhood characteristics and demographics

Data from the U.S. Census Bureau (2015a, 2015b, 2015c, 2015d, 2015f) are used to construct neighborhood and demographic controls. The vector of variables in X_{2it} includes: number of houses in the CBG ($HOUSES_{it}$); a population of the CBG ($POPULATION_{it}$); mean number of years of schooling for the population over 25 years of age of the CBG ($EDUCATION_{it}$)[4]; percentage of non-white persons in the CBG ($NON\text{-}WHITE_{it}$); property tax rate used in the county the CBG is located in (TAX_{it}); number of murder and rape crimes per capita in the county the CBG is located in ($CRIME_{it}$); and the number of workers employed by business establishments in the county ($EMPLOYEES_{it}$).

Data from the NBM (2011, 2012, 2013, 2014, 2015) are used to construct additional neighborhood controls for Internet service prices. Following Molnar and Savage (2017), who show a positive relationship between competition and Internet speed, we include dummy variables in X_{2it} measuring the number of ISPs in the CBG ($ISP2_{it}$ equals one when there are two ISPs and zero otherwise, $ISP3_{it}$ equals one when there are three ISPs and zero otherwise, …, $ISP7_{it}$ equals one when there are seven or more ISPs and zero otherwise). The additional Internet service price controls are dummy variables corresponding to the national market territories of the top b = 1, 2, 3, …, 17 ISPs that provide wireline Internet connections to the households in our sample, $BRAND_{f(it)}$, with f(it) indicating firm f for neighborhood i at year t.

Excluded instruments

The excluded instruments are also constructed with data from the NBM (2011, 2012, 2013, 2014, 2015). They are: the percentage of census blocks in the CBG where fiber is available ($FIBER\_CBG_{it}$); the percentage of CBGs in the census tract that the CBG is in where fiber is available ($FIBER\_CTR_{it}$); and their interaction $FIBER\_CBG_{it} \times FIBER\_CTR_{it}$.

Summary statistics

Table 2 presents summary statistics for all the variables used in our empirical analysis. On average, a typical neighborhood in our sample is comprised of 35 census blocks and has about 789 housing units and about 1,950 persons. The mean number of transactions per annum in each CBG over the four-year sample is 26.3, ranging from 10.5 to 280.8. The mean transaction price for a neighborhood home in our sample is $229,025 which is higher than the median national home price over the same period of $189,195, although our sample median of $196,687 is more comparable (Parsons 2015). The typical home

[4]Household income and educational attainment are typically collinear in hedonic housing models. We also estimated the model with median household income in the CBG (INCOME), instead of EDUCATION, and the results, not reported, are almost the same as those reported in Table 4.

Table 2. Summary statistics.

Variables	Mean	s.d.	Min	Max
P	229,025	134,026	16,900	660,000
S	74.74	31.89	0.768	100
HOUSEAGE	3.530	1.953	0	16.87
LOTSIZE	1.518	1.206	0.096	8.712
HOUSESIZE	1.784	0.500	0.649	5.070
GARAGESIZE	0.272	0.217	0	3.084
FIREPLACE	0.472	0.393	0	1
POOL	0.107	0.182	0	1
BATHS	2.075	0.803	0	17.42
HOUSES	4.846	29.62	0.467	987.6
POPULATION	3,406	3,217	1.532	34,929
INCOME	72,599	32,568	2,499	250,001
EDUCATION	13.25	1.158	6.225	16.92
NON-WHITE	0.200	0.197	0	1
TAX	1.162	0.528	0.158	3.108
CRIME	0.0003	0.0002	0	0.002
EMPLOYEES	423,499	603,227	721	3,932,904
ISP2	0.417	0.493	0	1
ISP3	0.296	0.457	0	1
ISP4	0.123	0.329	0	1
ISP5	0.081	0.273	0	1
ISP6	0.038	0.192	0	1
ISP7	0.019	0.136	1	13
FIBER_CBG	0.273	0.446	0	1
FIBER_CTR	0.167	0.320	0	1
CBG_OBS	26.30	19.66	10.50	280.8

NOTES. s.d. is standard deviation. 17,156 observations.

is 35 years old, has an overall size of 1,784 square feet, a garage of 272 square feet, and is located on a lot size of 15,182 square feet. About 47% of the homes in our sample are likely to have a fireplace and about 11% of homes are likely to have a pool.

Table 3 shows that just under 8% of homes in our sample are in neighborhoods with access to a maximum-advertised downstream speed of 10 Mbps or less. About 6% of sample homes can access a 25 Mbps connection and about 28% can access 50 Mbps. The remaining 58% of sample homes can access 100 Mbps. Speeds less than 100 Mbps can be offered by most cable and telephone companies with their traditional technologies and speeds of 100 Mbps can be provided by cable companies, with additional network upgrades and investment, and by telephone companies with fiber technology. Connection speeds are generally higher in urban neighborhoods. About 94% of urban homes have access to a broadband connection of at least 25 Mbps compared to about 85% of rural homes.

Although we have higher levels of broadband accessibility in our sample, our estimated gap of about 10% is the same as the well documented 'digital divide' between rural and urban areas (Gabe and Abel 2002; Prieger 2003; Fairlie 2004; Goldfarb and Prince 2007; Prieger and Hu 2008). Whitacre (2016) notes that 74% of households in urban areas in the United States had residential broadband connections in 2015, compared with only 64% of rural households. This is not that surprising from the supply-side perspective given the low population density and relatively high deployments costs in rural neighborhoods. The fixed cost of deployment per location has two components. The first is the share of the cost of the outside plant which extends the network from the ISP's central office past the subscriber's home. This includes the cost of permitting, gaining access to rights-of-way, and construction. The second cost is the equipment and installation costs from connecting the actual home to the outside plant. Because the former cost is lower in markets with more household density, the fixed cost per location is lower in urban areas relative to rural areas and small-town communities.

A comparison of selected sample demographics with the population, not reported, suggests that the neighborhoods in our sample have, on average, lower population density, smaller size, and higher income. Because of this, the empirical results presented in Section IV should be interpreted with the qualification that they may pertain to the relatively denser populated, wealthier urban and rural neighborhoods of the United States. We account for this in our cost-benefit analysis of the viability of rural broadband in Section IV.C with sensitivity analysis that discounts the high-

Table 3. Neighborhood downstream speed.

	All		Urban		Rural	
Mbps	Frequency	Percent	Frequency	Percent	Frequency	Percent
≤ 10	1,324	7.72	683	5.38	641	14.37
25	992	5.78	732	5.77	260	5.83
50	4,783	27.88	3,674	28.94	1,109	24.87
100	10,057	58.62	7,607	59.92	2,450	54.93
Total	17,156	100	12,696	100	4,460	100

speed Internet valuations of 'lower income' rural households by 15% according to Rosston, Savage, and Waldman (2010).[5]

IV. Results

The empirical model and data described in Sections II and III are used to investigate the relationship between and housing prices and high-speed Internet. We estimate several alternative model specifications with the FE and FE-IV estimators on the full sample of neighborhoods, and on sub-samples of urban and rural neighborhoods. Because the sample data represent CBG averages and likely vary by the number of houses used to calculate the averages, we expect the error variances from equation 1 to also vary with the number of houses in the neighborhood contributing to the average. We improve the efficiency of our estimators by addressing this form of heteroskedasticity with a weighted least squares procedure that divides the hedonic price equation 1 through by the square root of the number of houses in the neighborhood contributing to the average.

All neighborhoods

Estimates of the hedonic housing price equation on all neighborhoods are presented in columns one through four of Table 4. Our prior is that the functional relationship between high-speed Internet access and housing prices is log-log and we focus our discussion below on the results from these specifications, reported in columns two through four. For comparison, column one presents estimates from the log-linear specification.

The FE estimates from the log-log specification, presented in column two, show that the hedonic model is reasonably well specified with a within R^2 of 0.425. A test for the joint significance of the neighborhood-specific fixed effects ($F(4{,}288,\ 12{,}829) = 29.79$; $Prob > F = 0.00$) indicate they are important controls for unobserved time-invariant heterogeneity. The estimated coefficients on $HOUSEAGE_{it}$, $LOTSIZE_{it}$, $HOUSESIZE_{it}$, $GARAGE_{it}$, $FIREPLACE_{it}$, $POOL_{it}$, and $BATH_{it}$ have expected signs, are of plausible magnitudes, and are statistically significant at conventional levels. For example, when evaluated at the sample median house price, an additional 1,000 square feet of home is associated with a $48,304 increase in the value of the typical home, an additional 1,000 square feet of garage is associated with a $38,141 increase, and an additional bathroom is associated with a $5,588 increase. Many of the individual neighborhood controls are not statistically different from zero, but the significant estimated coefficients indicate that house prices are higher in neighborhoods with more population and business employees, and with lower numbers of houses, and rates of crime. The year-specific fixed effects indicate about a 1.8% annual increase in the mean house price in 2012, about a 9% increase in 2013, and about a 6% increase in 2014. This is similar to the trend in the Case-Shiller 20-city composite home price index over the same period (Parsons 2015).

The estimate of φ equals 0.011, is statistically significant at the 1% level, and implies that neighborhood access to higher Internet speeds is positively associated with housing prices. Figure 1 uses the estimated φ to plot the marginal effects of bandwidth for the 25th, 50th, and 75th percentile house prices, and shows the marginal effects decreasing in speed, and increasing in housing values. Focusing on the median house price, we calculate that, all else held constant, single-family homes with access to a 25 Mbps broadband connection have a transaction price that is about $5,977, or 3%, more than similar homes in neighborhoods with a one Mbps connection. Homes with access to a 50 Mbps connection have a price that is about $1,450 more than homes with 25 Mbps, and homes with access to a 100 Mbps connection have a price that is about $1,352 more than homes with 50 Mbps. These latter findings are qualitatively similar to Liu, Prince, and Wallsten (2017), who show that bandwidth provides relatively little additional value to households beyond 50 Mbps.

Section II.B explained when the zero-conditional-mean assumption may fail in the standard FE estimator and suggests the alternative FE-IV estimator as a correction for endogeneity. Results from the FE-IV estimator are reported in columns three and four of

[5]Rosston, Savage, and Waldman (2010) estimate high-speed Internet valuations for low-income households (annual income less than $25,000) that are about 15% lower than high-income households (annual income of $75,000 or more).

Table 4. Estimates of house values.

	FE	FE	FE-IV		FE	FE
	House values (P)	House values (P)	Speed (S)	House values (P)	House values (P)	House values (P)
	All CBGs (Log-Linear)	All CBGs (Log-Log)	All CBGs (Log-Log)		Urban CBGs (Log-Log)	Rural CBGs (Log-Log)
S	0.0004***	0.0108***		0.0124	0.0124***	0.0090*
	(0.0001)	(0.0028)		(0.0346)	(0.0033)	(0.0055)
HOUSEAGE	−0.0363***	−0.0364***	0.0027	−0.0364***	−0.0405***	−0.0354***
	(0.0025)	(0.0025)	(0.0078)	(0.0025)	(0.0035)	(0.0039)
LOTSIZE	0.0225***	0.0225***	−0.0075	0.0225***	0.0623***	0.0046
	(0.0037)	(0.0037)	(0.0114)	(0.0037)	(0.0063)	(0.0050)
HOUSESIZE	0.2477***	0.2481***	0.0843***	0.2480***	0.2172***	0.2669***
	(0.0082)	(0.0082)	(0.0254)	(0.0087)	(0.0112)	(0.0132)
GARAGE	0.1963***	0.1959***	0.0118	0.1959***	0.2521***	0.1605***
	(0.0223)	(0.0223)	(0.0691)	(0.0223)	(0.0307)	(0.0343)
FIREPLACE	0.0862***	0.0860***	−0.0460	0.0860***	0.0537***	0.1205***
	(0.0130)	(0.0130)	(0.0402)	(0.0131)	(0.0163)	(0.0222)
POOL	0.0468***	0.0473***	−0.0474	0.0474***	0.0649***	−0.0057
	(0.0169)	(0.0169)	(0.0522)	(0.0169)	(0.0198)	(0.0319)
BATHS	0.0289***	0.0287***	−0.0174	0.0287***	0.0353***	0.0252***
	(0.0052)	(0.0052)	(0.0161)	(0.0052)	(0.0084)	(0.0072)
HOUSES	−0.0001***	−0.0001***	0.0001**	−0.0001***	−0.0002***	−0.0001***
	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0000)	(0.0000)
POPULATION	0.0000***	0.0000***	−0.0001**	0.0000***	0.0000***	0.0000**
	(7.0e-06)	(7.0e-06)	(0.0001)	(7.2e-06)	(8.1e-06)	(0.0000)
EDUCATION	−0.0042	−0.0043	−0.0218	−0.0042	−0.0025	−0.0043
	(0.0050)	(0.0050)	(0.0156)	(0.0051)	(0.0055)	(0.0116)
NON-WHITE	−0.0320	−0.0317	−0.0211	−0.0317	−0.0189	−0.0651
	(0.0267)	(0.0267)	(0.0827)	(0.0267)	(0.0287)	(0.0267)
TAX	−0.0157	−0.0247	−1.1822***	−0.0228	−0.0213	−0.1028*
	(0.0275)	(0.0275)	(0.0844)	(0.0493)	(0.0308)	(0.0609)
CRIME	−58.923***	−59.377***	−191.04***	−59.071***	−106.31***	−2.7469
	(18.786)	(18.806)	(58.162)	(19.859)	(24.882)	(30.164)
EMPLOYEES	0.0104***	0.0104***	−0.0090***	0.0104***	0.0085***	0.0162***
	(0.0006)	(0.0006)	(0.0019)	(0.0007)	(0.0006)	(0.0019)
ISP2	0.0284	0.0295	0.6269***	0.0284	0.0514*	0.0085
	(0.0210)	(0.0211)	(0.0650)	(0.0305)	(0.0293)	(0.0333)
ISP3	0.0290	0.0309	0.6860***	0.0297	0.0577*	−0.0032
	(0.0218)	(0.0219)	(0.0676)	(0.0335)	(0.0302)	(0.0353)
ISP4	0.0261	0.0286	0.7002***	0.0273	0.0592*	−0.0200
	(0.0224)	(0.0225)	(0.0697)	(0.0347)	(0.0308)	(0.0369)
ISP5	0.0307	0.0331	0.6579***	0.0319	0.0675**	−0.0388
	(0.0228)	(0.0229)	(0.0709)	(0.0337)	(0.0311)	(0.0389)
ISP6	−0.0048	−0.0019	0.6335***	−0.0031	0.0299	−0.0803*
	(0.0233)	(0.0233)	(0.0726)	(0.0341)	(0.0313)	(0.0418)
ISP7	−0.0312	−0.0269	0.7752***	−0.0283	−0.0124	−0.0933**
	(0.0244)	(0.0244)	(0.0757)	(0.0380)	(0.0324)	(0.0438)
γ_{2012}	0.0152***	0.0182***	0.4375***	0.0175	0.0186***	0.0162**
	(0.0037)	(0.0037)	(0.0107)	(0.0155)	(0.0043)	(0.0071)
γ_{2013}	0.1032***	0.1085***	0.7178***	0.1073***	0.1149***	0.0963***
	(0.0049)	(0.0049)	(0.0138)	(0.0252)	(0.0058)	(0.0093)
γ_{2014}	0.1638***	0.1702***	0.8338***	0.1689***	0.1819***	0.1469***
	(0.0055)	(0.0055)	(0.0152)	(0.0294)	(0.0064)	(0.0106)
FIBER_CBG			0.7972***			
			(0.1148)			
FIBER_CTR			0.2297*			
			(0.1223)			
FIBER_CBG× FIBER_CTR			−1.0651***			
			(0.1229)			
CONSTANT	11.262***	11.248***			11.302***	11.340***
	(0.0836)	(0.0845)			(0.0971)	(0.1812)
F(fixed effects)	28.79***	28.71***			30.15***	19.54***
F(first-stage)			29.07***			
SH(χ^2)				0.242		
DWH(χ^2)				0.002		
R-squared	0.425	0.424		0.424	0.461	0.372
Observations	17,156	17,156	17,156	17,156	12,696	4,460
CBGs	4,289	4,289	4,289	4,289	3,174	1,115

NOTES. Standard errors in parenthesis. ***significant at the 0.01 level; **significant at the 0.05 level; *significant at the 0.1 level.

NOTES. Standard errors in parenthesis. ***significant at the 0.01 level; **significant at the 0.05 level; *significant at the 0.1 level. Neighborhood-fixed effects and $BRAND_f$ dummy variables are not reported. F(fixed effects) tests the joint significance of the neighborhood-fixed effects. F(first-stage) tests the joint significance of the excluded instruments. SH(χ^2) is the Sargan–Hansen test for overidentification. DWH(χ^2) is the Durbin-Wu -Hausman test for the endogeneity of Internet speed.

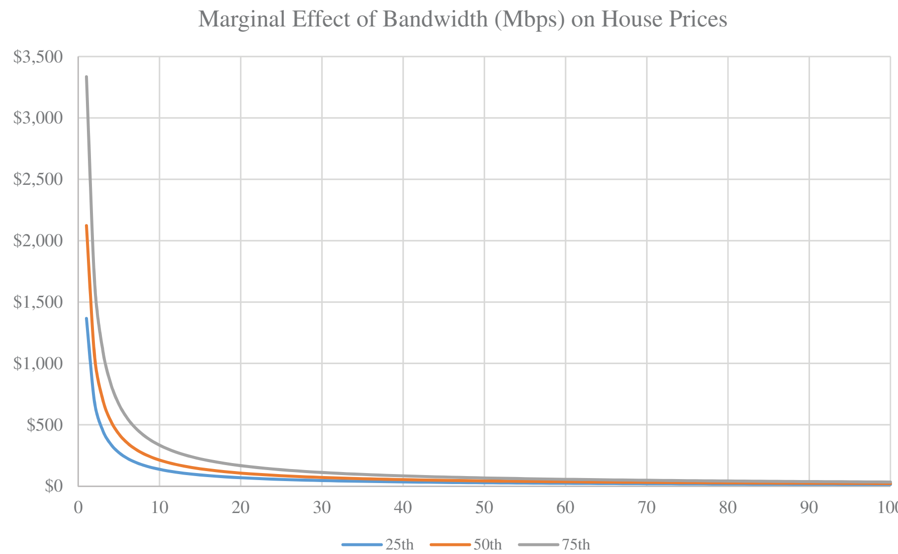

Figure 1. Marginal effect of bandwidth (Mbps) on house prices.

Table 4.[6] An F test statistic for the joint significance of $FIBER\_CBG_{it}$, $FIBER\_CTR_{it}$, and $FIBER\_CBG_{it} \times FIBER\_CTR_{it}$ ($F(3, 12{,}827) = 29.07$; $Prob > F = 0.00$) indicates the excluded instruments are relevant and that our FE-IV estimator does not suffer from a weak instruments problem. In the second stage, a Sargan–Hansen (SH) test of the overidentifying restrictions is not rejected ($\chi^2(2) = 0.242$; $Prob > \chi^2 = 0.886$) and supports instrument validity. The FE-IV estimate of $\varphi = 0.012$ is slightly higher than the FE estimate of 0.011 but is imprecisely estimated. The DWH test statistic ($\chi^2(1) = 0.002$; $Prob > \chi^2 = 0.962$) indicates that the FE and FE-IV estimates are not significantly different from one another. This suggests that controlling for neighborhood-fixed effects, observable demographics and Internet market structure in the FE specification may be sufficient (in this setting) to identify the effect of high-speed Internet on housing values.

Urban and rural neighborhoods

Universal service is the communications policy that all households have access to a minimum level of telephone and Internet service. Federal programs such as Lifeline, Linkup, and the Universal Service High-Cost Subsidy typically vary across rural and urban regions because of differing demand and cost conditions in these neighborhoods. While costs are higher due to lower density, Forman, Goldfarb, and Greenstein (2005) suggest that because they typically travel greater distances for amenities, services, and work, rural home buyers may be willing to pay more for faster Internet access. To explore potential heterogeneity in the marginal implicit price of bandwidth across different neighborhoods, we re-estimate equation 1 on subsamples of urban and rural neighborhoods, respectively. We use the Department of Defense's definition of less than 1,000 persons per square mile to assign CBGs to rural neighborhoods and note that about 26% of our sample neighborhoods are rural according to this definition.

FE estimates of the hedonic model for urban neighborhoods are reported in column five of Table 4. The within R^2 is 0.461 and the estimated coefficients for almost all house and neighborhood control variables are qualitatively similar to those reported for the full sample of neighborhoods in column two. The estimate of φ equals 0.012, is statistically significant at the 1% level, and is used to calculate the marginal effects of bandwidth on urban house prices. All else held constant, single-family homes with access to broadband have a transaction price that is about $6,787, or

[6]The signs for most of the significant coefficients in the first-stage have plausible interpretations. ISPs provide higher speeds in neighborhoods with more houses, larger houses (perhaps reflecting Greenfield developments), and with lower crime rates. The positive coefficients on the ISP dummy variables indicate a quality-competition effect in Internet markets. ISPs provide higher speeds in neighborhoods with lower property taxes. This seems counter-intuitive, however, low-tax ('low-income') neighborhoods also tend to have overhead lines and cables whereas higher income neighborhoods may have more buried lines and cables, which is more expensive to upgrade.

3.5%, more than similar homes in neighborhoods with a one Mbps connection. Homes with access to a 50 Mbps connection have a price that is about $1,647 more than homes with 25 Mbps, and homes with access to a 100 Mbps connection have a price that is about $1,536 more than homes with 50 Mbps.

Column six of Table 4 reports FE results for rural neighborhoods. The within R^2 is 0.372 and, again, the estimates for most of the control variables are qualitatively similar to those reported in columns two and five of Table 5. As an interesting check for model robustness, the estimated coefficient on $LOTSIZE_{it}$ is positive and significant for urban neighborhoods, but insignificant for rural neighborhoods. This indicates that lot size is more valuable in urban versus rural regions. The estimate of φ equals 0.009, is statistically significant at the 10% level, and is used to calculate the marginal effects of bandwidth on rural house prices. All else held constant, single-family homes with access to broadband have a price that is about $5,099, or 2.5%, more than similar homes in neighborhoods with a one Mbps connection. Homes with access to a 50 Mbps connection have a price that is about $1,237 more than homes with 25 Mbps, and homes with access to a 100 Mbps connection have a price that is about $1,154 more than homes with 50 Mbps. Given the potential demand-side benefits discussed in the digital divide literature, the lower marginal effects in rural neighborhoods are somewhat surprising as they show that rural residents are unwilling to pay a larger premium than urban residents for faster Internet access. They may be just as satisfied to live in a more remote rural setting with a somewhat slower connection and they are unwilling to move.

Policy discussion

Figure 2 shows that private broadband infrastructure costs may sometimes exceed variable profits in high-cost, low-demand rural regions, but not variable profits plus consumer surplus (Goolsbee 2002; Boik 2017). In this case, an entry subsidy up to the amount of consumer surplus not extracted by the ISP may be an appropriate instrument for local governments to meet rural universal service objectives. Given it can

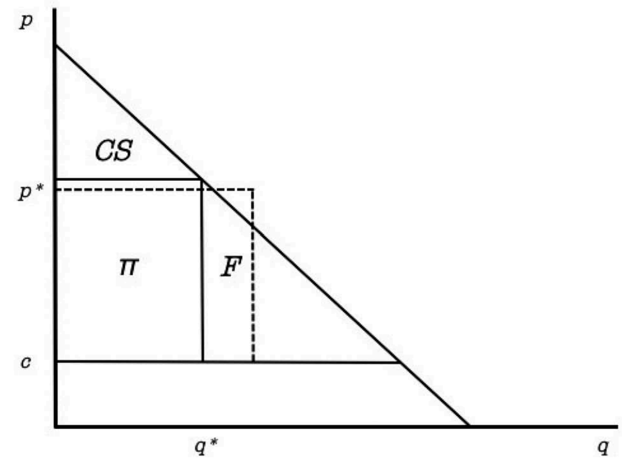

Figure 2. Fixed costs and market entry.

NOTES. c is marginal cost. CS is consumer surplus. F is fixed cost. p is price. q is quantity. π is a variable profit.

SOURCE. Boik (2017).

also increase housing values and property tax revenue, some local government jurisdictions without high-speed Internet may also favor some public support for the fixed costs of private broadband infrastructure. Alternatively, they may be more willing to let the market price of broadband service rise rather than capitalizing it into housing values. We now use our hedonic housing price estimates below to conduct a simple cost-benefit exercise that evaluates the rural broadband deployment of 25 Mbps. To be clear, absent a structural model, we do not provide counterfactual equilibrium welfare calculations in this exercise. Our intention is to use existing cost estimates and our demand results to help shed light on the policy discussion around the merits of a widely discussed infrastructure investment.

The FCC (2010) estimate there were seven million housing units in 2010 without access to a 4 Mbps connection. For our cost-benefit analysis, we assume that these same housing units do not have access to a broadband connection under the new definition of 25 Mbps. FCC data also indicates it would cost about $9,484 per household to build a Greenfield cable or telephone (i.e., digital subscriber line or 'DSL') network capable of supplying a 25 Mbps broadband connection to these unserved, largely rural, areas of the United States.[7] Our hedonic estimate of the

[7]We calculate $9,484 from the weighted-average cost per household of building two alternative six Mbps DSL networks (each with different average local loop lengths), and a 50 Mbps cable network. The cost of a six Mbps DSL network is a reasonable proxy for 25 Mbps because the greater portion of costs is for outside plant, which is largely the same regardless of capacity. Higher capacity DSLAMs are needed to provide 25 Mbps, but recent technology change has seen their prices fall to levels comparable to lower capacity DSLAMs from a few years ago.

expected benefit of rural broadband access to the typical household is about $5,099, which implies a revenue gap of about $4,385 per home. This suggests demand in many rural communities is insufficient to directly support private infrastructure investment through private revenue. This gap may be accentuated by the costs of connecting the local network to the national backbone, making private infrastructure investment even more marginal.

Our cost analysis does not account for some rural areas having legacy cable and telephone networks in place that can be upgraded to broadband at a lower incremental investment cost. Discussion with industry players and several engineering studies indicate it is about 30 to 50% cheaper to upgrade to broadband, rather than build a new network (FCC 2013; Emmendorfer 2015). When assuming a 40% cost discount at the mid-point of this range, the revenue gap becomes much more manageable at about $592 per home, and the total subsidy for providing broadband to the seven million unserved rural households is about $4.14 billion. Even under less generous cost and demand assumptions, the total subsidy cost only increases to about $10.8 billion, which is less than 4% of the total federal spending suggested in President Trump's Infrastructure Plan discussed in his 2018 State of the Union address.[8] The USF also has almost $10 billion available annually to companies and institutions to make universal broadband service possible, and has been subsidizing high-cost rural ISPs with about $4.5 billion per year in recent times.[9] Furthermore, since 1995 the USF, Rural Utility Service (RUS) and NTIA together have spent over $90 billion subsidizing rural ISP with subsidies, grants and loans (Eisenach and Caves 2011; Wallsten 2017). Although our exercise examines the average, rather than the marginal rural network, the reported total benefits and costs indicate that much of the rural digital divide could be bridged with a 25 Mbps connection supplied under an appropriate public-private arrangement with existing public subsidies.

V. Conclusions

We estimated a hedonic model that related house values to high-speed Internet access while controlling for the endogeneity of Internet access. Results show that single-family homes in neighborhoods with access to a 25 Mbps broadband connection have a transaction price that is about $5,977, or 3%, more than similar homes in neighborhoods with a one Mbps connection. This result is strikingly similar to Ahlfeldt, Koutroumpis, and Valletti (2014) who find that upgrading from dial-up to eight Mbps increases English home prices by 2.8%. The rural premium is lower. For example, homes with access to a 25 Mbps have a price that is about $5,099, or 2.5 percent, more than similar homes in neighborhoods with 1 Mbps.

We used our hedonic model estimates to perform a simple cost-benefit analysis of the viability of broadband deployment to unserved rural households. While our analysis shows that residential demand will generally not support this type of private infrastructure investment, the revenue gap from upgrading legacy networks to broadband is relatively low at about five to ten billion dollars and could be readily covered by entry subsidies from the USF, RUS, and NTIA. However, given they have spent over $90 billion since 1995 subsidizing rural ISPs, one must question the effectiveness of these programs in delivering universal broadband service of 25 Mbps. Eisenach and Caves (2011) argue that RUS programs are not cost-effective, and often funded duplicative coverage in areas already served by existing providers. Wallsten (2017) notes that about 60% of high-cost subsidies went to rural ISP's overhead rather than investment and that 'a cost-effective program should provide funds first where they will yield the largest bang for the buck.' One way to improve efficiency is to have policy makers clearly state the speed and reach of their broadband objective and distribute the subsidies through a transparent government procurement program, as advocated by a group of 71 economists in 2009.

[8]When assuming a 30% cost discount, the revenue gap increases to $1,540 per home, and the total subsidy for providing broadband to the seven million unserved rural households is about $10.78 billion. When assuming the 15% demand valuation discount estimated by Rosston, Savage, and Waldman (2010), the revenue gap increases to $1,356 per home, and the total broadband subsidy is about $9.49 billion.

[9]See http://www.usac.org/default.aspx.

We assume that homeowners are rational and fully capitalize the benefits from broadband into their home. When this assumption does not hold, valuations of the high-speed Internet would be larger than predicted by our empirical model and the case for rural broadband investment would be stronger. The number of rural households in our sample will slow speeds (i.e., 10 Mbps or fewer) is also relatively small and the findings from our cost-benefit exercise should be viewed with this qualification. Our study also uses baseline cost data from 2010. Recent industry reports suggest that deployment costs are decreasing, although the assumptions underlying these reports are not always clear. A useful avenue of future research would be to transparently estimate a contemporary cost model of broadband deployment and repeat our cost-benefit analysis with more recent real estate transaction data. Finally, there has been some discussion in the industry and among policy makers about 1,024 Mbps universal broadband service. Boik (2017) showed that this speed does not reach an acceptable welfare standard in rural markets and our cost-benefit analysis suggests that 25 Mbps is a more realistic short- to medium-run policy objective.

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