Does Competition from Cable Providers Spur the Deployment of Fiber?*

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Abstract

Broadband access has become a near necessity, yet many U.S households remain without access or significant choice among Internet service providers. This paper examines whether competition between between broadband providers increases the availability and quality of broadband, as well as the effects of policies that have been proposed to ameliorate the digital divide. Combining data from a survey of Seattle households' broadband subscriptions and broadband deployment data from the FCC, I estimate a structural model of Seattle's broadband market, which allows me to quantify the effect of competition on broadband availability, quality, and price in equilibrium. I find evidence that providers' incentive to increase quality is weaker under competition, however, the benefits of competition to consumers, in terms of increased product choice and lower prices, are substantial. Furthermore, of recent policies proposed to address the digital divide, I find that a demand-side subsidy program for low-income households is significantly more cost effective than a supply-side policy that subsidizes deployment.

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1 Introduction

The current structure of the broadband industry is such that improvements in quality are enormously costly for Internet service providers (ISPs), because state-of-the-art technology that supports high-speed data transmission requires substantial sunk cost investments. As a result, many American households have few choices of broadband providers, and broadband subscriptions are relatively expensive (Nuechterlein and Weiser 2013).[1] While this issue is not exclusive to the United States, limited, expensive, and uneven access to high-speed broadband is particularly acute in the U.S., in part, due to large geographic variation in population density. ISPs choose to collocate in dense urban markets where they can expect to recoup their capital investments, while sparsely populated rural markets have relatively limited access to broadband both in terms of number of providers and quality of service—a problem dubbed the "digital divide" (Greenstein and Prince 2006). However, concern about the digital divide is not only limited to rural communities. Due to the scale of upfront capital necessary to deploy broadband, lack of access to high-speed Internet service may exist even in urban centers where relatively high prices, as a result of a lack of competition, may restrict the supply of broadband subscriptions—particularly for low-income households.

The Federal Communications Commission (FCC) has pursued several different policies to tackle the digital divide including both supply- and demand-side policies. On the supply-side, starting in 2011 the FCC introduced the Connect America Fund,[2] a reverse auction program designed to subsidize the deployment of broadband to particularly high-cost areas. On the demand-side, the FCC has implemented several low-income subsidy programs including the Lifeline Program[3] and, more recently during the COVID-19 pandemic, the Affordable Connectivity Program.[4] Despite these interventions policymakers, industry commentators, and affected consumers continue to be concerned about limited access and choice in the residential broadband market—a concern reflected in the recently passed Investment Infrastructure and Jobs Act (IIJA), which includes a $65 billion carve out for broadband expansion.[5]

The current state of the industry raises the following questions: (1) to what extent is competition alone able to deliver widespread access to affordable, high-speed broadband?; (2) if competition falls short of the socially desired level of broadband access, to what extent is this gap driven by a lack of coverage versus prohibitively high prices?; and (3) which kind of policies, either supply- and demand-side, are likely to be more

[1] "The typical American has a choice of only two fixed-line broadband providers: the local telephone company and the local cable company."

[2] https://www.fcc.gov/general/connect-america-fund-caf

[3] https://www.fcc.gov/general/lifeline-program-low-income-consumers

[4] https://www.fcc.gov/acp

[5] https://www.congress.gov/bill/117th-congress/house-bill/3684/text

effective at achieving widespread and affordable broadband access at the least cost?

In this paper, I investigate the role of competition in determining the equilibrium availability, quality, and price of broadband, as well as the potential effects of policies recently proposed to address the digital divide. On the one hand, increased competition can spur firms to invest in product quality in order to attract customers from rivals, on the other hand, increased competition may reduce the incremental benefit of a quality improvement to the extent that such an investment is no longer profitable (Goettler and Gordon 2011, Vives 2008). Which equilibrium prevails in the broadband industry, as well as how consumers are ultimately affected, is important for determining policies that might address the digital divide.

To that end, I study the private incentives of fixed wireline ISPs operating in Seattle to deploy high-speed Internet in some areas of the city, but not in others, and evaluate the extent to which competition drives this behavior. In particular, I analyze whether competition from cable providers in Seattle spurred the incumbent legacy telephone provider CenturyLink to upgrade its broadband service from lower speed digital subscriber line (DSL) service to higher speed fiber in different areas in and around the city. To do this, I develop a structural model of the broadband industry that endogenizes providers' entry, quality, and pricing decisions along with consumer demand. Then, I estimate the model using broadband deployment data from the FCC and a survey of Seattle households' broadband subscription choices. The structural model allows me to decompose the benefits of broadband competition into those attributable to increased availability, increased product choice, and reduced prices. The model also enables me to perform counterfactual analyses to assess how changes in market structure and policy interventions affect equilibrium outcomes—including those related to the digital divide.

Estimation of the model proceeds in two steps following Aguirregabiria and Ho (2012). In the first step, I estimate demand for broadband for the three main wireline providers in Seattle, CenturyLink, Comcast, and Wave, using a novel dataset that includes rich micro-data on households' broadband subscription choices. Crucially, I observe individual households' choice of broadband provider along with an estimate of their monthly bill, as well as demographic data. This data enables me to link households' choices to information about the menu of subscriptions offered by each broadband provider and allows me to estimate a discrete-choice demand model that includes demographic-characteristic interactions along the lines of Berry et al. (2004), Petrin (2002), and Goolsbee and Petrin (2004). Unlike prior studies that have estimated demand for broadband, I observe individual subscription choices among the primary set of providers offering service in Seattle. Previous studies have relied upon stated-preference data (Goolsbee 2006, Rosston et al. 2010, Varian 2002), national or city-level aggregate data (Dutz et al. 2009, Goetz 2019, Wilson 2021), or individual choice data from a single firm (Lambrecht et al. 2007, Nevo et al. 2016). A key contribution of this paper is that I estimate household demand for broadband under competitive conditions—that is the data allows me to measure substitution both within and across providers at the household-level. This aspect of the data also enables me to model equilibrium price competition among providers.

In the second step, I estimate providers' fixed costs of broadband deployment with deployment data from the FCC using a revealed preference approach. In the data, I observe providers' entry and quality investment decisions in the Seattle area over a two-year period (2017-2018) at the census block level. With estimates from my demand model, I recover marginal costs and predict providers' variable profits in each census block under every possible counterfactual market structure. Then I recover the fixed costs that rationalize providers' observed deployment decisions across census blocks using a nested pseudo-likelihood (NPL) estimator (Aguirregabiria and Mira 2002, 2007).

With empirical estimates of the structural model in hand, I ask and answer the following questions:

(i) Does competition incentivize providers to deploy high-speed broadband service more widely?

(ii) How much do (would) consumers benefit from existing (additional) competition among providers? And what portion of these benefits are attributable to the effect of competition on availability and quality versus the effect of competition on price?

(iii) Are supply- or demand-side subsides likely to be more effective at addressing the digital divide?

I find that:

(i) Competition reduces providers' incentive to deploy high-speed service. Specifically, I find that as a monopolist CenturyLink would deploy slightly more fiber (in place of DSL), increasing available broadband quality for approximately 12,000 households, as compared to its deployment under competition.

(ii) Existing competition among broadband providers is of substantial value to Seattle consumers. Competition from cable providers generates \$302 million in consumer surplus annually or \$209 per household of which \$222 million is attributable to an increase in availability and product choice (\$154 per household) and \$80 million is attributable to reductions in price (\$55 per household).

(iii) A demand-side policy that subsidizes low-income households would be more cost effective than a supply-side policy that subsidizes provider expansion. Specifically, I estimate that it would cost \$6.3 billion for CenturyLink to deploy fiber and \$2.4 billion for Comcast to deploy cable to all unserved households in the market at a cost of about \$5,900 and \$18,300 per household, respectively. Combined this would generate \$35 million in consumer surplus annually, and increase the overall broadband subscription rate from 81.7% to 85.6%. Whereas, I estimate that a broadband subsidy to households with an annual income of less than \$50,000 of \$10/month or \$30/month (the benefits prescribed by the Lifeline and Affordable Connectivity Programs, respectively) would cost \$53 million or \$159 million annually, generate \$26 million or \$131 million annually, and increase the overall subscription rate from 81.7% to 85.2% or 90.3%.

This paper contributes to several existing literatures. First, this paper adds to work analyzing the digital divide. Greenstein and Prince (2006) give an overview of the early literature and describe the economic forces driving the urban, rural digital divide during two distinct waves of Internet diffusion. In the first wave (1995–2000), dial-up service was distributed widely and relatively rapidly partly due to its complementary with the provision of telephone service. As a result, although urban households fared better than rural households, the discrepancy could mainly be attributed to variation in demand. In the second wave (2000–onwards), broadband (DSL and cable service) was, and they predict would continue to be, distributed less evenly and more slowly due to substantial sunk costs generating economies of scale and making highly dense areas more profitable for deployment. As this prediction has more or less come to pass, later work on the digital divide has focused on testing the degree to which high-speed access is unequal given the economics of broadband deployment.

Prieger (2003) investigates whether there is unequal access to broadband across income and minority groups combining census and FCC data. After controlling for cost conditions, demand factors, and local competition, he finds that differences in broadband access across these groups largely disappear. In a similar study, Martin (2019) finds that variation in supply alone is insufficient to explain the digital divide and that correlations with demographic factors point to digital literacy as an important and under-explored determinant of the divide. I add to this work by developing an underlying model of ISPs' deployment decisions, which can not only explain the supply-side of the digital divide but can also be used to investigate which policies would be most effective at closing the divide (including demand-side policies) by predicting market outcomes in equilibrium.

This paper also contributes to the literature examining the relationship between market structure and entry and investment decisions in the broadband industry. Augereau and Greenstein (2001), perhaps the earliest empirical study to model ISPs' technology investment decisions, find that ISPs are more likely to adopt high-speed technologies in urban areas with high levels of infrastructure, placing some but less weight on competitive conditions and demographics, foreshadowing the disparity in broadband access between high- and low-density areas. Building upon this work, Augereau et al. (2006) show how standard setting also played a role in ISPs' early technology adoption decisions. Consistent with economics of broadband deployment, Xiao and Orazem (2011) provide empirical evidence that sunk costs are a major determinant of entry patterns in local markets. Wallsten and Mallahan (2013) and Molnar and Savage (2017) examine the relationship between number of providers and broadband speeds and find that markets with two or more providers have higher speeds than monopoly markets. More recently, Wilson et al. (2021) find that the threat of potential entry delays entry into local markets by an average of two years, leading to an 11% decrease in future download speeds for every year of delay.

Most closely related to this paper, Wilson (2021) investigates whether public provision of broadband induces or crowds out private investment. He estimates a dynamic game in which private and municipal broadband providers make endogenous entry and investment decisions given demand and expected competition and finds that municipal provision increases private investment in fiber through preemption and competition. I build upon his work by endogenizing price competition among providers, which affects their entry and investment decisions, as well as household demand. I find that price competition is an important channel through which consumers benefit from competition among providers, accounting for over a forth of the gains in consumer surplus.

More broadly, this paper is related to studies of entry and investment in other network industries including telecommunications and cable television. Greenstein and Mazzeo (2006), Economedies et al. (2008), Seim and Vivard (2011), Goldfarb and Xiao (2011), and Fan and Xiao (2015) study the consequences of entry into local telephone markets in the wake of the 1996 Telecommunications Act including its effects on product differentiation, market structure, and consumer welfare. Goolsbee and Petrin (2004) and Chu (2010) examine the entry of direct broadcast satellite into local television markets. Both find that without competition from satellite television providers, cable prices would have been significantly higher and cable quality would have been lower. Likewise, I measure the benefits of existing and new competition in the broadband market and find that consumers benefit from lower prices, however, incentives to improve quality decrease. Similar to this paper, Elliott et al. (2021) develop and estimate a model of endogenous infrastructural investment and competition among mobile telephone providers. They find that while consolidation reduces consumer welfare, synergies in the allocation of spectrum are a countervailing force that increases consumer welfare on the margin.

Finally, I contribute to recent work in empirical industrial organization evaluating the relationship between competition, market structure, entry, and product quality under oligopolistic competition. Understanding how competition and industry consolidation affect market outcomes other than price, including entry, product differentiation, and innovation, has become an increasing focus of antitrust policy and research in industrial organization.[6]. The title of this paper is a twist on research that investigates innovation in the microprocessor industry, Goettler and Gordon (2011). Several other papers including Igami (2017) have investigated the effect of competition on a variety of market outcomes besides price in different industries.

2 Industry Background

2.1 The Residential Broadband Industry

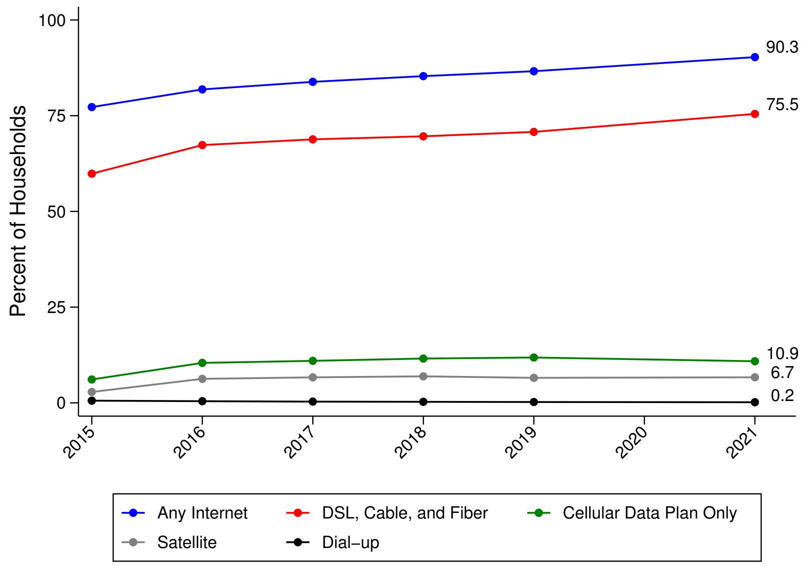
Most U.S. households today access the Internet via fixed wireline broadband providers that deploy DSL, fiber, or cable technologies (see figure 1). Households subscribe to residential ISPs on a monthly basis for Internet plans that are primarily differentiated by downstream and upstream bandwidth (speed) and price, where the maximum bandwidth a provider is capable of delivering to customers is limited by the transmission technology it deploys. The dominant fixed wireline providers today are typically local telephone or cable companies, including AT&T, Charter, Comcast, and Verizon, which began distributing Internet service over their existing network infrastructure (alongside their telephone and television services) as the Internet became widely adopted and digitization eliminated the technological barriers separating the distribution of these services (Nuechterlein and Weiser 2013).

The provision of wireline Internet service can be described relatively simply. ISPs provide customers with access to their networks through a physical connection, which allows users to transmit and receive information (or data) across the network. Information sent at one end is converted into discrete digital packets that traverse separately across the network and are reassembled at the receiving end, for example, to navigate a website, stream video content, or participate in a video conference call. Traditionally, local telephone providers transmit broadband over copper telephone lines, commonly known as digital subscriber line or DSL service, while cable companies transmit broadband over coaxial cables previously used to transmit video services. Because the transmission of video requires more bandwidth than telephone service, coaxial cable is capable of supporting higher capacity service than telephone lines, and therefore cable companies have generally been able to deliver higher speeds. However, increasingly telephone providers have been replacing DSL service with high speed fiber service by deploying

[6]2010 Horizontal Merger Guidelines, U.S. Department of Justice and the Federal Trade Commission, ftc.gov/system/files/documents/public_statements/804291/100819hmg.pdf

fiber-optic cable. Fiber-optic cable is essentially a thin glass tube that transmits light and, unlike copper wire for which bandwidth varies inversely (and increasingly-so) with length, can support very high bandwidths with little degradation over long distances. Fiber technology has dramatically increased the bandwidths providers are able to offer consumers, and as a result, where profitable, ISPs are investing to upgrade portions of their networks with fiber.

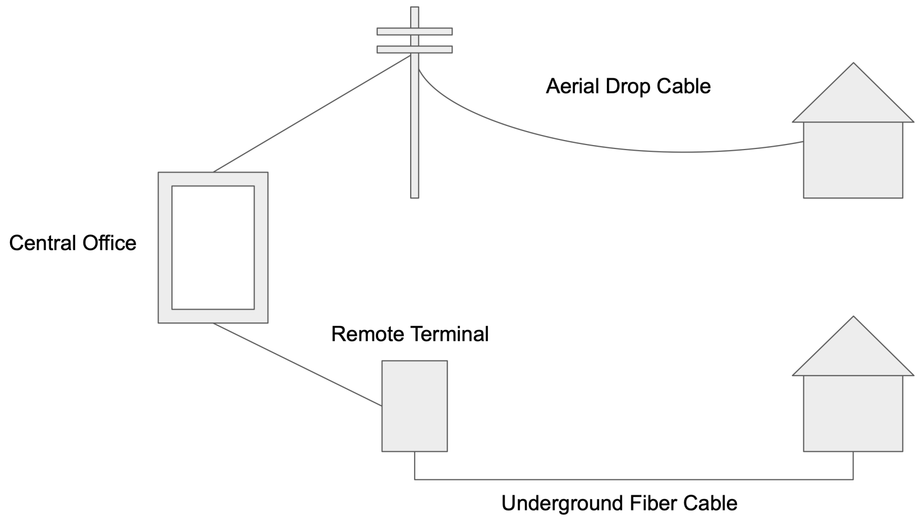
Figure 1. Internet Subscriptions by Technology (return)



Notes: ACS 1-year estimates. Subscriptions broken down by ACS response categories.

While many U.S. households have access to ISPs that deploy other transmission technologies including satellite, and increasingly mobile providers, where available the majority of households continue to rely upon fixed wireline as their primary source of broadband (see figure 1). This is because wireline connections are generally faster and more reliable than wireless alternatives. However, fixed wireline broadband is more costly to deploy, because unlike wireless technologies, fixed wireline requires a direct physical connection to each customer location. In order to deploy new or upgraded service, providers must extend the so-called "last mile" of their existing network infrastructure to reach the premises of new customers. To do so, providers install new cable either underground, by digging trenches, or aerially, by mounting it to utility poles (see figure 2). The last mile is connected to the rest of the network via central offices or data centers, which manage the distribution of data across the network.

Figure 2. Network Diagram (return)



The cost of broadband deployment varies considerably by the number and density of customer connections, terrain, and local regulatory and labor market conditions. By some estimates, laying fiber-optic cable can cost $60,000-$80,000 per mile. One industry estimate puts the cost of deploying fiber service at $700–$1,500 per household in urban areas and $3,000–$6,000 per household in rural areas (Cartesian 2019). Another estimates that fiber costs $13,900 per household on average (Tarana 2023). The city of Seattle conducted a study to assess the feasibility of stating a municipal broadband provider from scratch. They estimated that it would cost between $440–$850 million to serve 246,635 locations, an implied per location cost of between $1,784–$3,446, which the city ultimately determined was prohibitively expensive.[7] The barrier to entry created by these high sunk cost explains the relative lack of competition and new entry in residential broadband and why, in addition to concerns about basic Internet access, policymakers are concerned about affordability and the potential exercise of market power.

2.2 The Digital Divide

The structural barriers to competition in broadband, and in telecommunications more broadly, has long been recognized, dating back at least to the instantiation of the FCC in 1934. One of the primary objectives of the 1934 Communications Act was to achieve "universal service" in the provision of telephone service "to make available, so far as possible, [...] world-wide wire and radio communication service with adequate facilities at reasonable charges."[8] The 1996 Telecommunications Act extended this principle to

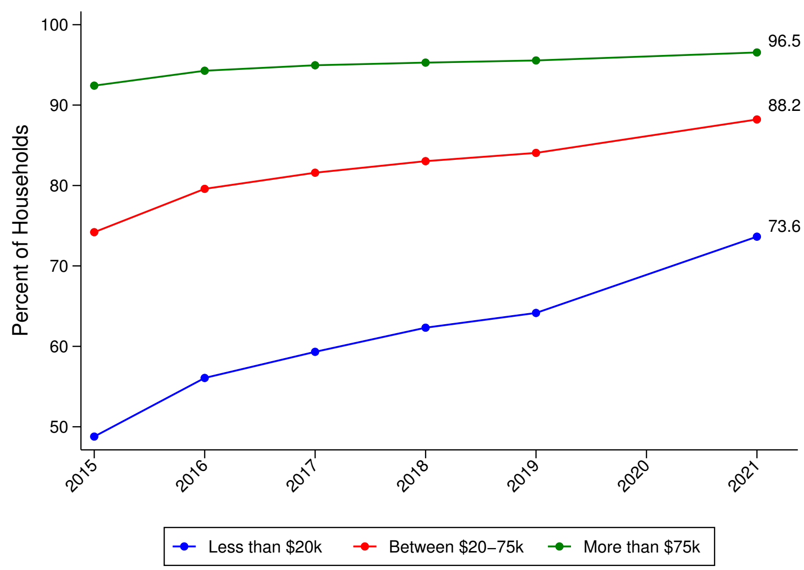
[7] https://www.seattle.gov/tech/initiatives/broadband/studies-and-history

[8] Communications Act of 1934, 47 U.S.C. §151.

other services: "[q]uality services should be available at just, reasonable, and affordable rates" and "[a]ccess to advanced telecommunications and information services should be provided in all regions of the Nation."[9]

With the advent of the Internet, the importance of access to broadband for the success of both individuals and businesses in the modern economy has become increasingly apparent. Despite progress in increasing coverage and subscription rates (see figure 1), however, there is still a substantial gap in broadband subscription rates across income groups (see figure 3) and other demographics groups including minorities and rural and tribal communities.

Figure 3. Broadband Subscriptions by Income (return)



Notes: ACS 1-year estimates. Broadband subscriptions include "DSL, cable, and fiber", "cellular data plans", and "satellite" subscriptions as categorized by ACS.

In recent years, the FCC has made closing the digital divide, particularly in rural and tribal areas, a policy priority. According to the Commission's 2018 broadband deployment report, "[f]ar too many Americans remain unable to access high-speed broadband Internet access, and we have much work to do if we are going to continue to encourage the deployment of broadband to all Americans, including those in rural areas, those on Tribal lands, and those in schools and classrooms."[10]

More recently, the COVID-19 pandemic has highlighted the importance of widespread equal access to broadband and several papers have documented how various inequities stemming from the digital divide were exacerbated during the pandemic. Chiou and Tucker (2020) find that high-speed internet access was a main determinant of individ-

[9] *Id.*, 47 U.S.C. §254.
[10] https://docs.fcc.gov/public/attachments/FCC-18-10A1.pdf

uals' ability to stay at home during the pandemic. Sen and Tucker (2020) find that children from low-income or minority backgrounds were less likely to have internet connections, and therefore, were less prepared to navigate the transition from in-person to online instruction. Barrero et al. (2021) estimate large economic gains from universal broadband access allowing workers to work from home.

Relatedly, an earlier literature has documented various benefits resulting from the diffusion and adoption of broadband in several domains including productivity, labor markets, and education. Greenstein and McDevitt (2009) quantify new economic growth and consumer surplus generated by the diffusion of broadband. LoPiccalo (2021) finds that the adoption of broadband in rural areas increases agricultural productivity. Dettling (2017) finds that internet access increases labor force participation of married women. Zuo (2021) finds that a broadband discount program offered by Comcast to low-income households increased the employment rate and earnings of eligible participants. Dettling et al. (2018) find that broadband access increased students' SAT scores and expanded their set of college applications. Campbell (2022) finds that broadband access improves students' reading and math test scores and employment outcomes.

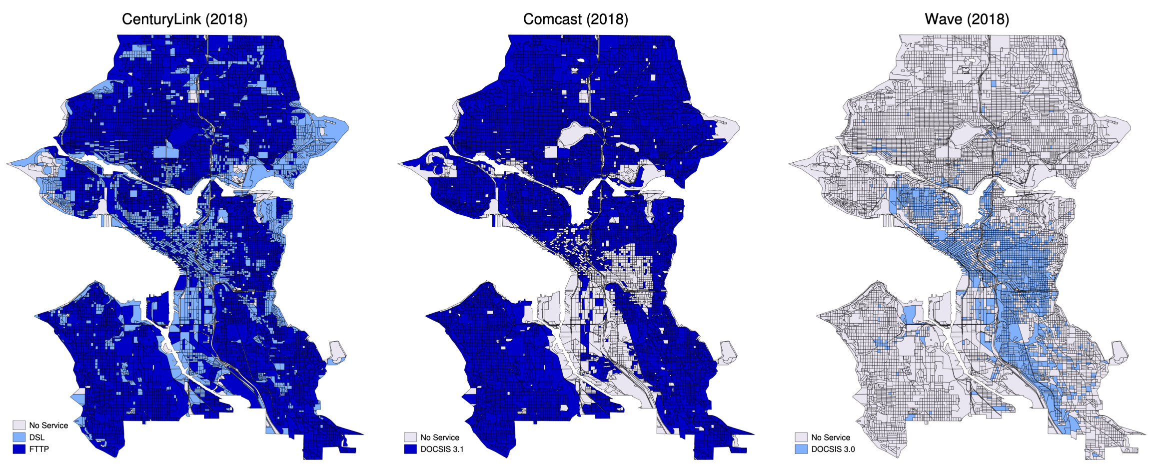
2.3 Seattle's Broadband Market

In this paper, I focus on Seattle's broadband market, an urban market, which is served by three fixed wireline ISPs: (1) CenturyLink, (2) Comcast, and (3) Wave. Although my data come from a single market, Seattle is a representative urban broadband market, primarily dominated by two large providers, therefore, I view my empirical results as more broadly applicable to the broadband industry.

CenturyLink (now Lumen Technologies, previously Century Telephone) is Seattle's legacy local telephone provider. It deploys and operates both DSL and fiber technologies across its coverage area in the city and the broader region (see figure 4 and figure figure A1). Like other national telcos (e.g. AT&T, Frontier, and Verizon), CenturyLink has been gradually upgrading its network from DSL to fiber. Comcast and Wave are both local cable providers also operating in Seattle and broader region. Comcast's coverage area is much larger than Wave's and therefore exerts a greater competitive constraint on CenturyLink. Other wireline providers operating in the region, though not in Seattle, include local telephone provider Frontier and the city of Tacoma's municipal (publicly owned) broadband system. Because I only observe demand for Seattle households, I exclude these other providers from my primary analysis.

Each provider offers households a similar menu of monthly broadband subscriptions, differentiated by downstream and upstream bandwidth, price, and in some instances, usage allowance. One unique feature of the broadband market is that providers set plan prices uniformly across their local coverage areas and perhaps as widely as at the national level. In my empirical model, I assume that providers set uniform prices. I compare this behavior relative to a strategy of geographic price discrimination and assess providers' incentive to price discriminate in an exercise similar to work by Adams and Williams (2019) and DellaVigna and Gentzkow (2020). However, I find little difference between these pricing strategies.

Figure 4. Provider Coverage Areas: Seattle MSA (return)



3 Data

I construct a dataset that combines households' broadband subscription choices and ISPs' deployment decisions in the city of Seattle and surrounding counties. To complie this dataset, I combine data from four different sources.

First, I rely upon survey data from the 2018 Seattle Technology Access and Adoption Study for household-level broadband subscription choices. Second, I use the FCC's Broadband Urban Rate Survey to identify the plans and prices offered by ISPs operating in Seattle. Third, I obtain household demographic data from the American Community Survey (ACS) to estimate the number of households in each census block, for block group level demographic estimates including income, education, and household size, and for information about the share of households with broadband subscriptions. Forth, I use census block level data from FCC Form 477 to identify providers' broadband deployment decisions. I discuss each data source, as well as the integration of these data in more detail below.

3.1 Household Subscription Data

Comprehensive provider-level data on broadband subscriptions is not publicly available. Although highly aggregated subscription data is available from some broadband providers' public filings, it is a challenge to estimate a realistic model of demand with these data, because ISPs' do not report broadband subscriptions for different geographic markets nor do they segment subscriptions by plans in their financials. Ideally a researcher studying the broadband market would rely upon micro-level data reported by providers with detailed information about households' subscription choices including the quality and price of different plans across various geographic markets. In the absence of such data, I rely upon a 2018 survey of Seattle households conducted by Pacific Market Research on behalf of the City of Seattle. This survey provides a unique opportunity to study demand for broadband in a major U.S. city, because it includes information about individual households' broadband subscription choices and demographic characteristics. I use this data to estimate households' probabilities of subscribing to the set of broadband plans offered by the three major fixed wireline ISPs that serve Seattle: CenturyLink, Comcast, and Wave.

The survey data consists of responses from 4,315 households of which 3,153 were used in my analysis after excluding responses with missing data. Each respondent answered 38 questions about their household's internet access and usage, use of other technologies such as computers and mobile phones, as well as about the household's demographics. Most importantly each respondent was asked whether the household had Internet access, whether the household subscribed to a fixed wireline broadband provider, to which provider it subscribed, and was asked to estimate the monthly cost of the household's Internet subscription (see figure A2). Respondents were also asked to report the zip code of their residence, household income, household size, education level, and other demographic information. Table 1 reports the overall number of respondents by ISP including respondents who indicated that they did not subscribe to any of the three fixed wireline providers in Seattle.

While I *do* observe households' choice of provider, I *do not* observe their choice of specific broadband plan. In order to estimate the probability that a household subscribes to a particular broadband plan, I match survey respondents' to broadband plans based on price and respondents' own estimates of their monthly subscription fees. While this method of matching survey responses to broadband subscriptions is imperfect, respondents' estimates of their monthly subscription fees at the very least represent a measure of households' willingness-to-pay for broadband, which is a reasonable approximation of demand (tethered to information about households' actual provider choices, this data is arguably more informative than standard stated-preference data). However,

Table 1. Provider Subscribers and Demographics (return)

Provider	CenturyLink	Comcast	Wave	None	Total
Subscriber Count	816	1,778	203	356	3,153
Income [0k, 50k)	0.233	0.223	0.266	0.713	0.284
Income [50k, 100k)	0.272	0.272	0.251	0.171	0.259
Income [100k, 200k+)	0.495	0.506	0.483	0.115	0.457
Less than HS Grad	0.007	0.006	0.039	0.056	0.014
HS Grad and Some College	0.206	0.200	0.202	0.500	0.235
Bachelor's Degree or Higher	0.787	0.794	0.759	0.444	0.750
Household Size (1)	0.189	0.239	0.350	0.576	0.271
Household Size (2)	0.360	0.386	0.433	0.323	0.376
Household Size (3)	0.176	0.143	0.118	0.031	0.138
Household Size (4+)	0.275	0.231	0.099	0.070	0.216

Notes: Seattle Technology Adoption Survey 2018. This table summarizes the demographic characteristics of households included in my estimation sample by choice of broadband provider including "None". Statistics represent the percent of households in each demographic category.

measurement error in prices and product characteristics may lead to attenuation in my demand estimates.

I match households' survey responses to ISPs' plans based on price information collected from the FCC's 2018 Broadband Urban Rate Survey. The Urban Rate Survey is published annually by the FCC to track changes in Internet subscription prices over time and across geography. The data consists of the prices and attributes of ISPs' plans across different urban areas (aggregated up to the state level). I use plans and prices for Washington state in 2018 as the basis of the subscriptions households choose among in the demand model, reported in table 2.

As discussed above, I match households to broadband plans based on their estimated monthly subscription fees. Because the prices of subscriptions offered by each provider increase monotonically with downstream and upstream bandwidth, I devise price bands for each subscription and assign households to plans according to these bands. In general, I use the following interpolation rule,

$$j_i(\hat{p}_i) = \begin{cases} 1, & \text{if } \hat{p}_i \in [0, \frac{p_1+p_2}{2}) \\ 2, & \text{if } \hat{p}_i \in [\frac{p_1+p_2}{2}, \frac{p_2+p_3}{2}) \\ & \vdots \\ n-1, & \text{if } \hat{p}_i \in [\frac{p_{n-2}+p_{n-1}}{2}, \frac{p_{n-1}+p_n}{2}) \\ n, & \text{if } \hat{p}_i \in [\frac{p_{n-1}+p_n}{2}, \infty) \end{cases},$$

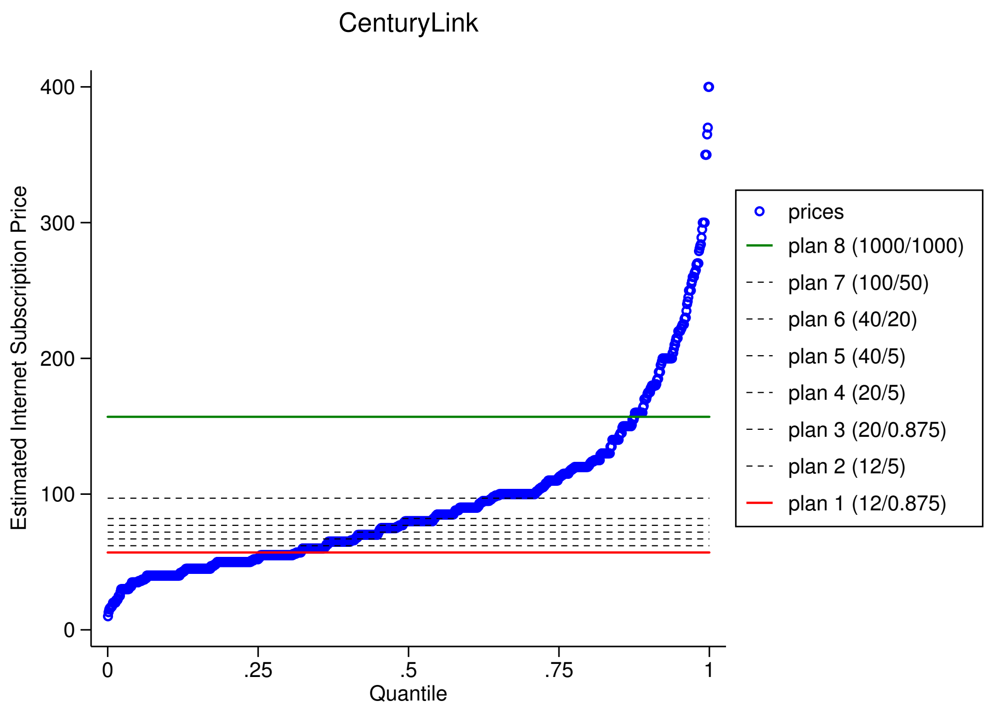
Table 2. Plan Summary Statistics (return)

Plan	Subscriber Count	Monthly Charge	Download Speed (mbps)	Upload Speed (mbps)	Usage Allowance (GB)
CenturyLink: plan 1	310	56.99	12	.875	1,000
CenturyLink: plan 2	41	61.99	12	5	1,000
CenturyLink: plan 3	47	66.99	20	.875	1,000
CenturyLink: plan 4	35	71.99	20	5	1,000
CenturyLink: plan 5	38	76.99	40	5	1,000
CenturyLink: plan 6	87	81.99	40	20	1,000
CenturyLink: plan 7	224	96.99	100	50	1,000
CenturyLink: plan 8	173	156.94	1,000	1,000	.
Comcast: plan 1	357	49.95	10	2	1,024
Comcast: plan 2	247	64.95	55	5	1,024
Comcast: plan 3	232	79.95	100	5	1,024
Comcast: plan 4	340	94.95	200	10	1,024
Comcast: plan 5	244	149.95	250	25	1,024
Comcast: plan 6	705	159.95	987	35	1,024
Wave: plan 1	51	45.10	10	1	100
Wave: plan 2	86	73.45	100	5	400
Wave: plan 3	102	81.55	250	10	500

Notes: Seattle Technology Adoption Survey 2018, FCC Urban Rate Survey 2018. This table summarizes the primary characteristics of providers' broadband plans as reported by the FCC Urban Rate Survey.

where $j_i(\hat{p}_i)$ is household i's choice of subscription, which depends on its estimated monthly subscription fee $\hat{p}_i$. If the household's estimated monthly fee is greater than zero but less than the average of the price of the lowest and second to lowest cost plan, then I assume household i subscribes to the lowest cost plan, and so on. Figures 5, A3, and A4 show the distribution of estimated monthly fees for each provider, as well as the number of subscribers assigned to each plan following the interpolation rule above.

Figure 5. CenturyLink Subscriber Estimates and Plans (return)



Notes: Seattle Technology Adoption Survey 2018, FCC Urban Rate Survey 2018. This figure shows the distribution of CenturyLink subscribers' estimated subscription price with CenturyLink's menu of plans overlayed. The lowest priced plan (in red) is 12/0.875 mpbs upload/download speed. The highest priced plan (in green) is 1000/1000 mpbs upload/download speed.

3.2 Provider Deployment Data

I collect data on providers' deployment decisions across census blocks in the Seattle MSA and the surrounding counties where CenturyLink, Comcast, and Wave operate during the years 2017 and 2018 from the FCC's Form 477 broadband deployment data. FCC Form 477 requires broadband providers to report information about their broadband deployment including transmission technology and maximum download and upload speeds at the census block-level every six months. I collect deployment data for the major fixed wireline broadband providers that serve Seattle and surrounding areas.

While other ISPs, including satellite and wireless providers serve Seattle, as is evident from the 2018 Seattle Technology Access and Adoption Study data, most Seattle subscribers purchase service from one of the major fixed wireline providers.

Figure 4 shows CenturyLink, Comcast, and Wave's coverage areas in the Seattle MSA. Figure A1 shows the 2018 coverage areas of CenturyLink, Comcast, Wave, Frontier, and the City of Tacoma's municipal broadband service in five major counties surrounding Seattle: King, Kitsap, Mason, Pierce, and Thurston.

4 Empirical Model

I model ISPs' deployment decisions within a geographic market, which depend upon households' demand for broadband, the fixed costs of deploying different broadband transmission technologies, and the strategic behavior of competing firms.

In the model, given households' demand for broadband in different geographic submarkets (in this case census blocks), each broadband provider chooses whether to deploy service in each census block, and chooses which transmission technology to deploy, given its expectations of its rivals' deployment decisions. After all providers' deployment decisions have been realized, each firm sets the prices of its products to maximize its profits given full information about its rivals' products. In other words, firms make deployment decisions with full information about consumer demand but incomplete information about their rivals' decisions; however, once deployment decisions are realized, firms set prices with full information about their rivals' products. The structure of information in the model reflects the fact that firms' pricing decisions are more flexible than firms' deployment decisions.

I begin by describing households' demand followed by ISPs' deployment.

4.1 Household Demand for Broadband

Within a geographic market, ISPs offer households a menu of plans that vary in quality and price, and each subscribing household pays a monthly subscription fee to its broadband provider.

I model households' demand for broadband using a discrete choice model of demand, where each household i in census block $m = \{1, .., \mathcal{M}\}$ chooses between $j = \{1, ..., J_m\}$ broadband plans offered by the firms that serve census block m. The outside option $j = 0$ represents the household's decision not to subscribe to fixed wireline broadband (the outside option therefore encompasses several alternative choices including choosing no form of Internet access, as well as Internet access via satellite or mobile providers or via public institutions such as schools and libraries).

Household i's monthly indirect utility from subscribing to plan j is,

$$u_{i,j,m} = \delta_{j,m} + \mu_{i,j,m} + \epsilon_{i,j,m}, \tag{1}$$

where, as in Berry (1994), $\delta_{j,m}$ represents households' mean utility from plan j, $\mu_{i,j,m}$ represents a component of utility which varies across households, and $\epsilon_{i,j,m}$ is the household's idiosyncratic taste for product j, which is assumed to be i.i.d. extreme value type 1. I normalize households' indirect utility from the outside option to zero, $u_{i,0,m} = 0 + \epsilon_{i,0,m}$.

The mean component of utility,

$$\delta_{j,m} \equiv x_j'\beta - \alpha p_j + \xi_{j,m}, \tag{2}$$

depends on plan characteristics x_j (in this case downstream upstream, upstream bandwidth, and provider dummies) and prices p_j, as well as an unobservable plan characteristic $\xi_{j,m}$. Notice here that plan characteristics and prices are invariant across m, because ISPs engage in uniform pricing across geographic markets.

The variance component of utility,

$$\mu_{i,j,m} \equiv (x_j', p_j)'(\Omega D_{i,m}), \tag{3}$$

is a function of plan characteristics and prices interacted with a set of households' demographic characteristics $D_{i,m}$, capturing heterogeneous preferences for broadband across households with different demographics.

Because of the distributional assumption on $\epsilon_{i,j,m}$, the probability that household i subscribes to plan j is given by the multinomial logit function,

$$s_{i,j,m} = \frac{\exp\left(\delta_{j,m} + \mu_{i,j,m}\right)}{1 + \sum_k^J \exp\left(\delta_{k,m} + \mu_{i,k,m}\right)}. \tag{4}$$

It follows that the aggregate market share of product j in submarket m is given by,

$$S_{j,m} = \int \frac{\exp\left(\delta_{j,m} + \mu_{i,j,m}\right)}{1 + \sum_k^J \exp\left(\delta_{k,m} + \mu_{i,k,m}\right)} dG_{D_m}(D_{i,m}), \tag{5}$$

where $G_{D_m}(D_{i,m})$ is the distribution of demographic characteristics over households.

4.2 Providers' Deployment Decisions

Consider a market with $\mathcal{F}$ potential entrants, where firms or ISPs are indexed by $f \in \{1, 2, ..., \mathcal{F}\}$ and submarkets (census blocks) are indexed by $m \in \{1, 2, ..., \mathcal{M}\}$. The set of technologies that can be deployed by a provider is indexed by $\tau \in \{none, dsl, fiber, cable\}$. Let $a_{f,m} = \tau$ represent the deployment decision of firm f in census block m.

If providers' deployment decisions are interdependent across locations, the combination of possible deployment configurations is *enormous*. For example, in a game where CenturyLink chooses among technologies $\{none, dsl, fiber\}$ and Comcast chooses among technologies $\{none, cable\}$, the space of possible market outcomes is $(3 \times 2)^{\mathcal{M}}$. In my empirical application $\mathcal{M} = 59,705$, which makes providers' problem intractable. Following Aguirregabiria and Ho (2012), I simplify providers' problem and instead assume that a provider's deployment decision in one location is independent of its decisions in all other locations. This assumption significantly shrinks the space of outcomes that providers' consider (3×2 in each location) and is also econometrically convenient in that it allows for a likelihood-based approach to estimation.

4.2.1 Total Profits

If firm f does not operate in census block m ($a_{f,m} = none$), then its total profit is,

$$\Pi_{f,m,none} = 0 + \sigma\eta_{f,m,none}. \tag{6}$$

If instead the firm does operate in census block m ($a_{f,m} \neq none$), then its total profit from deploying technology τ is,

$$\underbrace{\Pi_{f,m,\tau}(a_{-f,m}, z_{f,m}, H_m, A_m, \eta_{f,m,\tau})}_{\text{Total Profit}} = \underbrace{\pi_{f,m,\tau}(a_{-f,m}, H_m)}_{\text{Variable Profit}} - \underbrace{F_{f,m,\tau}(z_{f,m}, H_m, A_m, \eta_{f,m,\tau})}_{\text{Fixed Cost}}, \tag{7}$$

where the firm's total profit is made up of its variable profit $\pi_{f,m,\tau}(.)$ minus its fixed cost $F_{f,m,\tau}(.)$, including $\eta_{f,m,\tau}$, the firm's private information, which has scale σ.

The variable $z_{f,m}$ represents the state of the firm, which is defined as the firm's deployment decision in the previous year $z_{f,m,t} \equiv a_{f,m,t-1}$. H_m and A_m are the number of households and land area (in square miles), respectively, of submarket m. $z_{f,m}$, H_m, A_m, and the distribution of $\eta_{f,m,\tau}$, $G_\eta(\eta)$, are common knowledge for all firms.

To simplify notation going forward, I drop the submarket subscript m.

4.2.2 Variable Profits

Each provider's annual variable profit from deploying technology τ is,

$$\pi_{f,\tau} = 12 \cdot H \cdot \sum_{j \in \mathcal{J}_f} S_j(a_{-f}, \mathbf{p})(p_j - c_j), \tag{8}$$

where $\mathcal{J}_f$ is firm f's set of broadband plans given its deployment decision ($\mathcal{J}_f$ is a subset of all plans J), and S_j, p_j, and c_j are the market share, price, and marginal cost of plan j respectively. The market shares of the firm's products depend upon the deployment decision of its competitors a_{-f} and the prices of all plans $\mathbf{p}$. I multiply variable profit by 12 to convert monthly variable profit into annual profit, because I observe monthly broadband subscription prices. Later on I describe firms' pricing behavior.

4.2.3 Fixed Costs of Deployment

Each provider's annual fixed costs from deploying technology τ are,

$$F_{f,\tau} = \phi_{f,\tau} + \underbrace{\mathbb{1}(z_f = none) \cdot [\theta_{f,\tau} + H\theta^H_{f,\tau} + A\theta^A_{f,\tau}]}_{\text{Entry Cost}} + \underbrace{\mathbb{1}(z_f \neq \tau) \cdot [\vartheta_{f,\tau} + H\vartheta^H_{f,\tau} + A\vartheta^A_{f,\tau}]}_{\text{Adjustment Cost}} + \sigma\eta_{f,\tau}, \tag{9}$$

where the fixed costs associated with its deployment decision depend on its state z_f, which again, can be thought of as its deployment decision in the previous year $a_{f,t-1}$.

If the firm operates in the census block at all, it pays a technology-specific operating cost $\phi_{f,\tau}$. If the firm did not operate in the census block previously ($z_f = none$), then it pays a technology-specific entry cost ($\theta_{f,\tau} + H\theta^H_{f,\tau} + A\theta^A_{f,\tau}$) that depends on census block characteristics. Similarly, if the firm did previously operate in the census block, but chooses to deploy a different technology there ($z_f \neq \tau$), then it pays a technology-specific adjustment cost ($\vartheta_{f,\tau} + H\vartheta^H_{f,\tau} + A\vartheta^A_{f,\tau}$) that depends on block characteristics.

4.2.4 Providers' Strategies and Equilibria

Each provider's strategy depends on its information set. Let firm f's strategy $\varphi_f(z_f, H, A, \eta_f)$ be a mapping from state variables to actions,

$$\varphi_f : (z_f, H, A, \eta_f) \rightarrow \{none, dsl, fiber, cable\}.$$

Each firm has uncertainty about the deployment decisions of its competitors, because it does not know $\eta_{-f,\tau}$. Therefore, each firm maximizes its expected profits given its private information $\eta_{f,\tau}$ and its expectations of its rivals' strategies. A Bayesian Nash equilibrium in this game of incomplete information is a set of strategies $\{\varphi^*_f : f = 1, 2, ..., \mathcal{F}\}$ such that every firm maximizes its expected profit,

$$\mathbb{E}[\Pi_{f,\tau}(\varphi^*_{-f}, z_f, H, A, \eta_{f,\tau})] \geq \mathbb{E}[\Pi_{f,\tau'}(\varphi^*_{-f}, z_f, H, A, \eta_{f,\tau'})], \forall \tau' \neq \tau.$$

The strategy of firm f can be represented as a probability distribution,

$$P_f = \{P_{f,\tau} : \tau = none, dsl, fiber, cable\},$$

where $P_{f,\tau}$ is the probability that firm f deploys technology τ when following its strategy $\varphi_f(z_f, H, A, \eta_f)$,

$$P_{f,\tau} = \int \mathbb{1}\big(\varphi_f(z_f, H, A, \eta_f) = \tau\big) dG_{\eta_f}(\eta_f). \tag{10}$$

Assuming that $G_{\eta_f}(\eta_f)$ is extreme value type 1, the probability that firm f deploys technology τ is,

$$P_{f,\tau} = \frac{\exp\left(\mathbb{E}[\Pi_{f,\tau}(\mathbf{P}_{-f})]\right)}{\sum_{\tau'} \exp\left(\mathbb{E}[\Pi_{f,\tau'}(\mathbf{P}_{-f})]\right)}, \tag{11}$$

where the expected profit $\mathbb{E}[\Pi_{f,\tau}(\mathbf{P}_{-f})]$ the firm gets from τ, depends on the joint likelihood that other firms compete in the market $\mathbf{P}_{-f}$.

The total expected profit that firm f gets from deploying technology τ,

$$\mathbb{E}[\Pi_{f,\tau}(\mathbf{P}_{-f})] = \mathbb{E}[\pi_{f,\tau}(\mathbf{P}_{-f})] - F_{f,\tau}, \tag{12}$$

is made up of its expected variable profit $\mathbb{E}[\pi_{f,\tau}(\mathbf{P}_{-f})]$ and fixed cost $F_{f,\tau}$, which is deterministic apart from $\eta_{f,\tau}$.

The firm's expected variable profit from deploying technology τ,

$$\mathbb{E}[\pi_{f,\tau}(\mathbf{P}_{-f})] = \sum_{a_{-f}} \Big(\prod_{r \neq f} P_r(a_r = \tau')\Big) \pi_{f,\tau}(a_{-f}) \tag{13}$$

depends on the joint probabilities of its competitors' deployment decisions, and known variable profits $\pi_{f,\tau}(a_{-f})$ when its rivals choose actions a_{-f}.

Defining $\Psi_{f,\tau}(.)$ as the best response probability function of firm f, a Bayesian Nash equilibrium in this game is a fixed point,

$$P^*_{f,\tau} = \Psi_{f,\tau}(\mathbf{P}^*_{-f}), \forall f, \tau. \tag{14}$$

The interpretation of this fixed point is that every provider is choosing the deployment decision that maximizes its expected profit, given that all of its competitors are doing the same, thus, no firm wants to change its strategy.

Finding an equilibrium in this game consists of finding a fixed point, or equivalently a solution to the system of nonlinear equations,

$$P^*_{f,\tau}(\Theta) = \Psi_{f,\tau}\big(\mathbf{P}^*_{-f}(\Theta)\big), \forall f, \tau. \tag{15}$$

Given the set of parameters representing providers' fixed costs of deployment Θ, this system may have multiple equilibria.[11] In estimation, I deal with the potential for multiple equilibria by using a nested-pseudo likelihood (NPL) estimator (Aguirregabiria and Mira 2002, 2007).

5 Estimation

In this section, I estimate households' demand for broadband and providers' fixed costs of deployment. Following Aguirregabiria and Ho (2012), I estimate the model in two steps. First, I estimate households' demand for broadband. Second, I estimate providers' fixed costs given the demand parameters from the first step.

I estimate a mixed logit demand model which allows households' preferences for broadband to vary over their demographic characteristics using a generalized method of moments (GMM) estimator. I discuss the estimation procedure, which follows Berry et al. (2004), Petrin (2002), and Goolsbee and Petrin (2004), in more detail below, as well as outline the instruments I include to deal with price endogeneity.

Once I've estimated demand, I use the mixed logit parameters to predict providers' variable profits in each census block under all possible counterfactual market structures. Then using these estimates of variable profits and data on ISPs' deployment decisions, I estimate providers' fixed costs of deployment corresponding to behavior predicted by the game of incomplete information using a nested pseudo-likelihood (NPL) estimator (Aguirregabiria and Mira 2002, 2007). Once both pieces of the structural model are estimated, I perform counterfactual simulations.

5.1 Demand Estimation

The demand model I estimate is a mixed logit that allows households to have heterogenous preferences for broadband, which is important in order to produce realistic substitution across products. To do this, I use data on individual households' broadband subscription choices and demographic characteristics in the 2018 Seattle Technology Adoption Survey to include interactions between subscription characteristics and demographic characteristics in the model,

$$\mu_{i,j} \equiv (x_j', p_j)'(\Omega D_i).$$

[11] Whether one or more solutions exist depends upon the magnitude of the spectral radius of the Jacobian matrix of the system with respect to the parameters (Aguirregabiria and Mira 2007).

I specify the variance component of demand as,

$$\mu_{i,j} = \sum_{n=2}^{3} \alpha_n \log(p_j) Inc_{n,i} + \sum_{n=2}^{4} \beta_n^d \log(x_j^d) Size_{n,i} + \sum_{n=2}^{4} \beta_n^u \log(x_j^u) Size_{n,i} \tag{16}$$

$$+ \sum_{n=2}^{3} \lambda_n^{Inc} Inc_{n,i} + \sum_{n=2}^{4} \lambda_n^{Size} Size_{n,i} + \sum_{n=2}^{3} \lambda_n^{Educ} Educ_{n,i},$$

where the set of dummy variables $(Inc_{n,i})$ denote household i's income bracket, $(Size_{n,i})$ denote the size of household i, and $(Educ_{n,i})$ denote the head of household i's education level. The three income brackets are defined as [0k, 50k), [50k, 100k), and [100k, 200k+); the household size categories are defined as 1, 2, 3 and 4+ individuals; and the head of household education categories are defined as "less than high school," "high school grad and some college," and "bachelor's degree or higher."

I interact subscription prices with household income to allow for different price elasticities across income brackets with the expectation that higher income households are less price sensitive. I interact downstream and upstream bandwidth with household size to capture the fact that larger households require subscriptions with more bandwidth to keep Internet performance constant across users. Lastly, I include the entire set of demographic dummies as demand shifters to allow take up of the outside option to vary among households.

Mean utility is defined as a function of log product characteristics and price,

$$\delta_j = \beta^d \log(x_j^d) + \beta^u \log(x_j^u) + \beta_j^b - \alpha \log(p_j) + \xi_j. \tag{17}$$

And the probability that household i subscribes to plan j depends on both δ_j and μ_{ij},

$$s_{i,j} = \frac{\exp(\delta_j + \mu_{ij})}{1 + \sum_k^J \exp(\delta_k + \mu_{i,k})}. \tag{18}$$

To estimate the model, I jointly estimate equations (17) and (18) using GMM. First, I derive the log-likelihood function of equation (18),

$$\log[\mathcal{L}(\delta_j, \alpha_n, \beta_n, \lambda_n)] = \sum_i^I \sum_j^J [d_{i,j} \log(s_{i,j})],$$

where d_{ij} is dummy variable indicating whether household i subscribes to broadband plan j. This function depends upon the mean utility of each plan δ_j and the parameters that capture variation in utility across households' demographic characteristics $(\alpha_n, \beta_n, \lambda_n)$.

The set of δ_j's are parameters to be estimated in equation (18). Then, in order to recover the parameters associated with mean utility for product characteristics and price (α, β), I project the matrix of product characteristics onto the estimates of δ_j,

$$\hat{\delta}_j = \beta^d \log(x_j^d) + \beta^u \log(x_j^u) + \beta_j^b - \alpha \log(p_j) + \xi_j.$$

This equation can be estimated using OLS if prices are thought to be exogenous or using linear IV if prices are thought to be endogenous.

The model can be estimated in two steps by estimating the parameters of equation (18) $\theta_1 = (\delta_j, \alpha_n, \beta_n, \lambda_n)$ using maximum likelihood (MLE) and then estimating the parameters of equation (17) $\theta_2 = (\alpha, \beta)$ using liner IV. Alternatively, the model can be estimated in one step by estimating the equations jointly using GMM. Point estimates are the same whether the equations are estimated separately or together, however, standard errors are correct when the model is estimated jointly using GMM.

To form moments for equation (18), I derive the first-order conditions (or scores) of the log-likelihood function with respect to the parameters; these are micro-moments since they are sampled from household-level data. In a GMM framework, setting the expected scores of the log-likelihood function equal to zero is equivalent to MLE (Train 2009). The moment conditions associated with equation (17) are formed as usual by interacting a set of instruments $\mathbf{Z}$ with the error term ξ; these are macro-moments since they are sampled from aggregate market-level data.

Stacking the moment conditions together,

$$\mathbf{g}(\theta) = \begin{bmatrix} \frac{\partial \log[\mathcal{L}(\theta_1)]}{\partial \theta_1} \\ \mathbf{Z}'\xi(\delta, \theta_2) \end{bmatrix},$$

the GMM objective function, where the weight matrix $\mathbf{W}$ is a block diagonal matrix, in which the first block contains weights for the micro-moments associated with equation (18), and the second block contains weights for the macro-moments associated with equation (17), is given by,

$$\hat{\theta}^* = \arg\min_{\theta} \mathbf{g}(\theta)'\mathbf{W}\mathbf{g}(\theta).$$

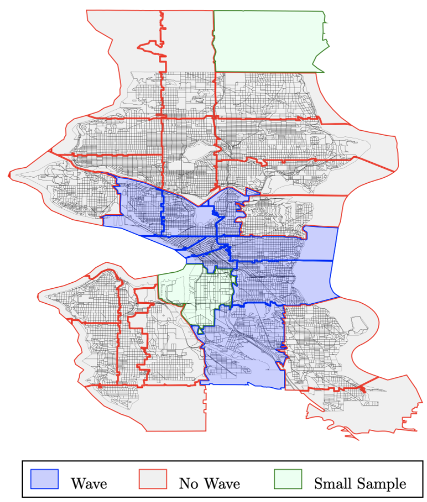
I use quasi-Newton methods to find the optimal values of θ that minimizes the weighted distance of the stacked moments.

5.2 Identification

The demand parameters are identified by several sources of variation in my data. First, the alternative-specific constants (or mean utilities) δ_j and product characteristic-demographic interactions α_n, β_n and λ_n are identified by variation in households' demographics correlated with their broadband subscription choices. For example, higher income households generally purchase higher quality, more expensive subscriptions, which is reflected in the estimates of α_n.

Second, mean product characteristic parameters α, β are identified by variation in characteristics x_j and prices p_j across products, which vary widely because providers offer households wide ranging menus of plans in terms of bandwidth and price.

Figure 6. Households' Choice Sets (return)



Notes: This figure overlays Seattle zip codes onto census blocks. Wave is available in the blue shaded areas. Wave is unavailable in grey shaded areas. Green shaded areas do not have enough survey respondents to determine which providers are available.

Third, differences in households' choice sets across the Seattle MSA helps pin down the parameters—specifically Wave's coverage area is more limited than CenturyLink and Comcast's as shown in figure 4. To take advantage of this variation in product availability, I partition zip codes (observed in the household survey data) into two groups—(1) those with access to all three providers and (2) those without access to Wave—based on my analysis of survey responses and the FCC 477 deployment data. Figure 6 overlays zip codes within the Seattle MSA onto census blocks and identifies zip codes that fall into these two groups.

5.3 Price Endogeneity

As is standard in the literature, I treat the price of broadband subscriptions as endogenous. Because demand for product j depends upon price and quality, and any unobserved quality will be correlated with price, $\mathbb{E}[p_j, \xi_j] \neq 0$. As a result estimation of the demand parameters without instrumenting for price will yield an inconsistent estimate of the price coefficient α, usually implying that demand is less elastic than in reality. To identify the price coefficient, following Berry et al. (1995), I assume that the characteristics of other products in the market are correlated with prices but uncorrelated with ξ and include the mean of each firm's other product characteristics as instruments, assuming $\mathbb{E}[\xi|\mathbf{Z}] = 0$. I discuss this choice of instruments in greater detail below.

Berry et al. (1995) suggest and use two sets of instruments for price in their empirical study of demand for new cars. First, one set of possible instruments for the price of product j is the sum of product characteristics (other than price) of the firm's products, excluding product j. The second set of possible instruments for the price of product j is the sum of product characteristics (other than price) of all rival firms' products,

$$z_{j,1} = \sum_{k \neq j} x_k, z_{j,2} = \sum_{r \notin f} x_r.$$

Assuming that product characteristics are determined exogenously and that firms compete on price, these sets of instruments are valid because they should be independent with product j's unobservable demand shock, ξ_j, but should be correlated with price. This is because a firm with higher overall quality will be able to set higher prices for all its products, including product j, under the assumption of oligopoly pricing. Bresnahan et al. (1997) use a variation on these instruments where, rather than summing over product characteristics, they average over product characteristics.

In my application, because the set of available product characteristics are essentially invariant across census blocks, the sum of product characteristic x over the firm's own-products, other than j, is a linear combination of x_j, and thus perfectly collinear with x_j. As a result, this variable cannot be used as an instrument for price. However, the *mean* of product characteristic x over the firm's own-products, other than j, is not perfectly collinear with x_j, therefore, like Bresnahan et al. (1997) I use mean own-product characteristics as instruments for price.

Because my demand specification includes brand dummy variables, which are invariant over firms, unfortunately the second set of instruments proposed by Berry et al. (1995) is perfectly collinear with these dummies, regardless of whether I sum or average over the product characteristics of each firm's rival. As a result, I cannot use variation in rival's product characteristics as instruments for price. However, the first set of instruments is still valid with the inclusion of brand dummies. With two continuous product characteristics, download and upload speed, I have two valid IVs for price,

$$z_j^d = \frac{1}{K-1} \sum_{k \neq j} x_k^d, z_j^u = \frac{1}{K-1} \sum_{k \neq j} x_k^u.$$

To match my demand specification, I use $\log(z_j^d), \log(z_j^u)$ as the excluded instruments.

5.4 Demand Results

Table 3 displays the demand results. The first two columns show the parameter estimates without instrumenting for price using both two-step estimation and joint estimation. Notice that the point estimates are identical, however, joint estimation is necessary to obtain correct standard errors. Column (4) displays parameter estimates where instruments are included to identify the price coefficient. The major difference between the results in columns (2) and (4) is an increase in the magnitude of the primary price coefficient when instruments are included, as well as an increase in its standard error.

While the inclusion of instruments for price leads to a price coefficient that is no longer statistically significant, the own-price elasticities by income bracket (approximately -4.73, -4.46, and -4.19 for low, middle, and high income households, respectively) are more elastic and are comparable with prior estimates in the empirical literature. For example, in an early study of demand for broadband Goolsbee (2006) found an average own-price elasticity for Internet service of roughly -2.75 estimating a simple quadratic inverse demand curve. Using discrete choice demand estimation, Dutz et al. (2009) report the following average own-price elasticities for different broadband services: broadband (overall) -0.69, cable -5.21, DSL -4.04, satellite -9.94, and fiber -8.11. Rosston et al. (2010) find more inelastic demand (-0.44) using a survey instrument to estimate demand. Finally, in more recent studies, Goetz (2019) reports a mean-own price elasticity of -5.901, and Wilson (2021) reports price elasticities for different broadband technologies: cable -0.512, DSL -0.530, and fiber -0.746.

The own-price elasticities are also comparable with empirical estimates reported in the literature for services similar to broadband including cable television and mobile telecommunications. Goolsbee and Petrin (2004) estimate demand for cable television subscriptions in the U.S. and find the following own-price elasticities for different services: basic cable -1.5, premium cable -3.2, and satellite -2.4. Bourreau et al. (2021) estimate demand for mobile phone subscriptions in France and find an average own-price elasticity of -3.0.

In addition to the price coefficients, most of the other parameters are economically intuitive. More educated households and larger households are more likely to purchase any broadband plan, and larger households are more likely to purchase plans with higher upstream speeds (although not higher downstream speeds).

Table 3. Demand Estimates (return)

Parameters	No Price IVs			Price IVs	
	MLE	Joint GMM	Standard Errors	Joint GMM	Standard Errors
Linear Parameters					
Log Price	-2.0155	-2.0155	(0.5911)	-4.7254	(3.6211)
Log Download Speed	0.4884	0.4884	(0.2300)	1.1502	(0.9101)
Log Upload Speed	0.0040	0.0040	(0.2075)	0.0267	(0.1831)
Comcast	1.0144	1.0144	(0.3491)	0.6977	(0.5672)
Wave	0.5039	0.5039	(0.4272)	-0.4490	(1.2785)
Constant	2.8255	2.8257	(3.3689)	12.1909	(12.9641)
Log Price $\times$ Income					
Income [50k, 100k)	0.5662	0.5662	(0.2882)	0.2681	(0.5085)
Income [100k, 200k+)	0.8073	0.8073	(0.2588)	0.5403	(0.5099)
Log Download Speed $\times$ Household Size					
Household Size (2)	0.0135	0.0135	(0.1440)	0.0360	(0.1342)
Household Size (3)	-0.0777	-0.0777	(0.1484)	-0.0502	(0.1395)
Household Size (4+)	-0.0515	-0.0515	(0.1466)	-0.0216	(0.1384)
Log Upload Speed $\times$ Household Size					
Household Size (2)	-0.0118	-0.0118	(0.1543)	-0.0187	(0.1413)
Household Size (3)	0.0846	0.0846	(0.1618)	0.0777	(0.1482)
Household Size (4+)	0.1436	0.1436	(0.1590)	0.1367	(0.1443)
Demographics					
Income [50k, 100k)	-1.4242	-1.4243	(1.2787)	-0.0975	(2.2682)
Income [100k, 200k+)	-1.8514	-1.8514	(1.1603)	-0.6628	(2.2825)
HS Grad and Some College	0.7001	0.6999	(2.4223)	0.7000	(2.4235)
Bachelor's Degree or Higher	1.4514	1.4512	(2.4244)	1.4508	(2.4255)
Household Size (2)	0.5831	0.5830	(0.4774)	0.4966	(0.4676)
Household Size (3)	2.0344	2.0343	(0.5635)	1.9271	(0.5599)
Household Size (4+)	1.0933	1.0933	(0.5069)	0.9707	(0.5085)
Price Coefficients					
Income [0k, 50k)	-2.0155	-2.0155		-4.7254	
Income [50k, 100k)	-1.4493	-1.4493		-4.4573	
Income [100k, 200k+)	-1.2082	-1.2082		-4.1852	
Objective Value	-7,499.58	0.0000		0.0286	
Individuals	3,129	3,129		3,129	
Products	17	17		17	

Notes: Observations are individual-product combinations. MLE estimates are two-step estimates, which yield incorrect standard errors. Joint GMM estimates without IVs yield the same point estimates as MLE, however, standard errors are correct. "Price coefficients" are simply linear combinations of the price coefficient and price $\times$ income interactions for each income group. Heteroskedasticity-consistent standard errors reported in parentheses.

5.5 External Validity

As a test of the external validity of my demand model, I compute aggregate market shares for each plan/provider in census block groups across the Seattle area and compare these estimates to the overall share of households subscribing to wireline broadband reported in the ACS. I also show that the model is capable of matching other moments in the ACS data such as the share of broadband subscriptions by demographic groups, which are relevant to the issue of the digital divide.

With parameter estimates from the mixed logit, I am able to predict aggregate market shares for plans in different geographic markets m that are correlated with market demographics using aggregate demographic data. To do this I specify a discrete distribution for $G_{D_m}(D_{i,m})$ with 36 household "types" (based on the set of demographic dummies included in the model: $3 \times 4 \times 3$) each with weight $\omega_{i,m}$, which I calculate using demographic data from the ACS.

I construct these weights by multiplying the share of households that fall into each demographic category (reported in the ACS) to approximate the joint probability that a household falls into each possible combination of demographic categories,

$$\omega_{i,m} \approx \omega_m^{Inc} \cdot \omega_m^{Size} \cdot \omega_m^{Educ},$$

where ω_m^{Inc}, ω_m^{Size}, and ω_m^{Educ} are the shares of households in each demographic category, respectively. Notice that this approximation assumes these demographic characteristics are independent of one another, where a more accurate approximation would account for covariation in these characteristics among households.[12] I report summary statistics for the demographic data underlying the market-specific demographic weights ω_{im} in table A1.

Using these weights, the aggregate market share of plan j in market m can be approximated as,

$$S_{j,m} \approx \sum_{i=1}^{36} \frac{\exp\left(\delta_j + \mu_{i,j}\right)}{1 + \sum_k^J \exp\left(\delta_k + \mu_{i,k}\right)} \cdot \omega_{i,m}.$$

From the ACS data, I observe the share of households, at the census block group level (2,352 CBGs in my sample), that have a wireline broadband subscription of any kind (i.e. DSL, fiber, cable). The complement of these shares are the share of households without a broadband subscription, which corresponds to the share of households choosing the outside option in my demand model. From the FCC 477 data, I observe the broadband providers' deployment at the census block level. Using the estimates of the demand parameters $\hat{\theta}$, I predict the share of households who subscribe to each

[12] I obtain similar results in robustness checks using alternative weights.

provider at the census block level, which I then sum over to predict the share households subscribing to each provider at the census block group level,

$$\hat{\mathcal{S}}_{f,g}(\hat{\theta}) = \frac{\sum_{m \in g} H_m \cdot \hat{\mathcal{S}}_{dsl,m}(\hat{\theta})}{\sum_{m \in g} H_m}.$$

The predicted share of households that do not subscribe to a high speed broadband provider in census block group g is then,

$$\hat{\mathcal{S}}_{0,g}(\hat{\theta}) = 1 - \hat{\mathcal{S}}_{dsl,g}(\hat{\theta}) - \hat{\mathcal{S}}_{fiber,g}(\hat{\theta}) - \hat{\mathcal{S}}_{comcast,g}(\hat{\theta}) - \hat{\mathcal{S}}_{wave,g}(\hat{\theta}).$$

Table 4 displays the overall share of households with and without broadband in my sample according to the ACS and the predicted shares from the demand model. The overall share of households with broadband predicted by the model (0.82) compares favorably with the ACS data (0.80). Figure 7 shows the correlation between the fitted shares of the outside option and the ACS data across census block groups.

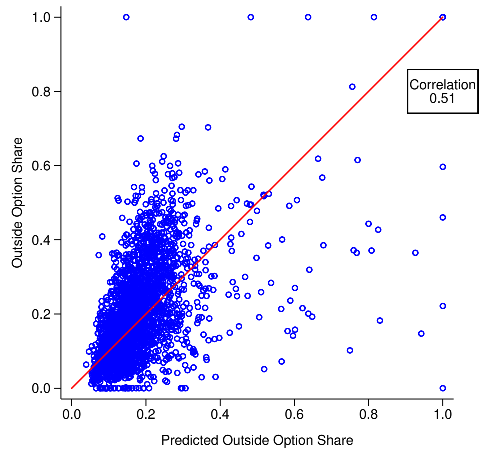
Figure 8 bins census block groups based on demographic characteristics of interest—namely poverty and race—and compares the share of households with broadband subscriptions based on ACS data and the predictions of the model. The predicted shares match the correlations in the ACS data relatively well without any of these demographic variables being included in the underlying demand model.

Table 4. Model Fit (return)

	Actual		Predicted					
	Outside Option	Inside Options	Outside Option	Inside Options	DSL	Fiber	Comcast	Wave
Model Fit	0.1981	0.8019	0.1789	0.8211	0.0912	0.0680	0.6215	0.0404

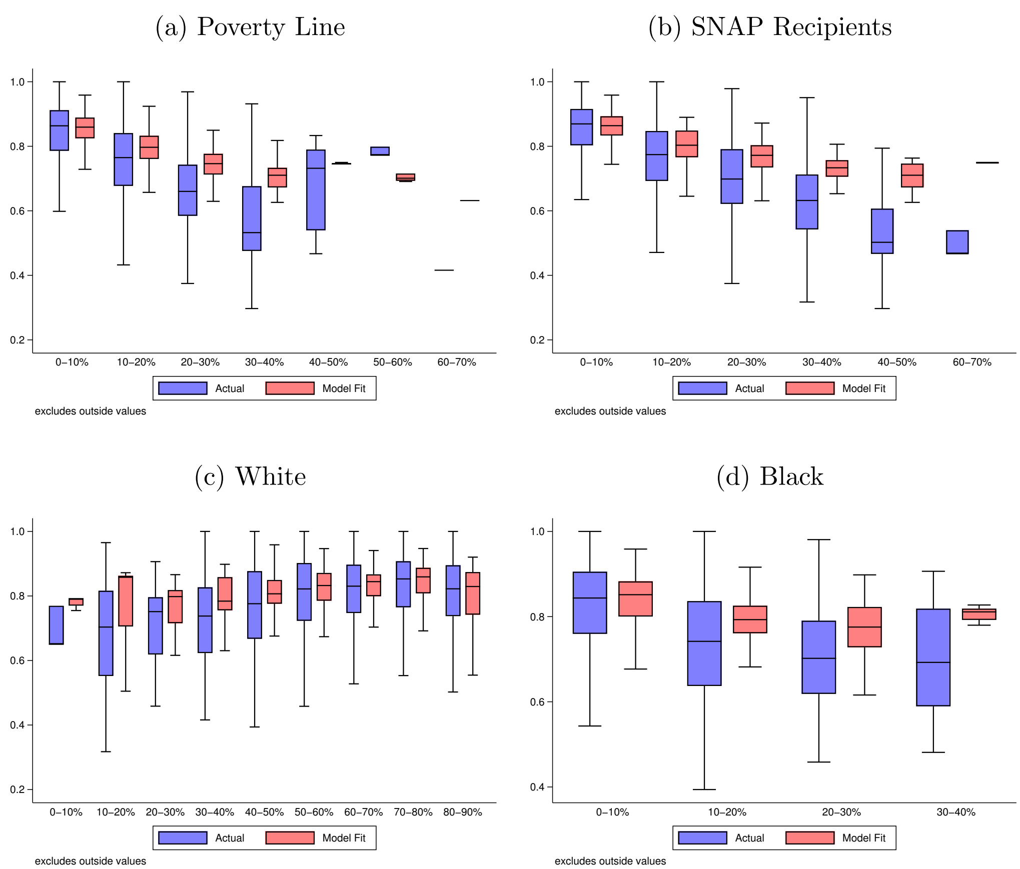
Notes: This table summarizes overall actual and predicted broadband shares in estimated for 2,352 census block groups in the Seattle region. "Actual" shares are computed using ACS estimates. "Predicted" shares are computed using demand estimates. "Outside option" is the share of households that don't purchase wireline broadband. "Inside options" is the share of households that purchase any type of broadband, as calculated by ACS, or the share of households that subscribe to either CenturyLink, Comcast, or Wave, as predicted by the demand model. "DSL" and "Fiber" refer to the share of CenturyLink's DSL and fiber services.

Figure 7. Model Fit (return)



Notes: This figure plots the "Actual" against the "Predicted" share of households that don't subscribe broadband. The red line is a 45 degree line.

Figure 8. Distribution of Broadband Shares by Demographics (return)



Notes: This figure plots distributions of the share of households subscribing to broadband across census block groups, binned by the share of households that (a) fall below the poverty line, (b) are SNAP recipients, (c) are white, (d) are black.

5.6 Fixed Cost Estimation

In this section, I estimate the model outlined in section 4 to recover CenturyLink and Comcast's fixed costs of deployment. While I observe household demand for CenturyLink, Comcast, and Wave, Wave's deployment decisions vary very little between 2017 and 2018, which prevents me from identifying its fixed costs of deployment. However, I *do* include Wave as a non-active player in the game—that is the presence of Wave impacts CenturyLink and Comcast's profits and deployment decisions, but Wave's deployment is held fixed in the model.

In my implementation of the model, two potential entrants, CenturyLink and Comcast, $f \in \{\ell, c\}$, choose whether to deploy broadband in census blocks $m \in \{1, 2, , .., \mathcal{M}\}$. CenturyLink chooses among the technologies $\tau \in \{none, dsl, fiber\}$ and Comcast chooses among the technologies $\tau \in \{none, cable\}$. When CenturyLink deploys either dsl or $fiber$ in a census block, it offers households a menu of plans associated with each technology, reported in table A2, which come from the FCC Urban Survey data. When Comcast deploys *cable* in a census block, it offers households the same menu of plans which I used for purposes of estimating demand, reported in table 2.

With 3 deployment choices for CenturyLink and 2 deployment choices for Comcast, there are 6 possible outcomes in each census block:

$$(a_{\ell,m}, a_{c,m}) = \{(none, none), (dsl, none), (fiber, none),$$

$$(none, cable), (dsl, cable), (fiber, cable)\}.$$

I compute providers' predicted variable profits $\hat{\pi}_{f,\tau,m}$ for each of these outcomes for all census block in my sample. To do this, I calculate the market shares of each provider's plan $\hat{S}_{j,m}$ based on the demand parameters. Then I estimate providers' marginal costs $\hat{c}_j$, which I obtain by "backing out" the implied marginal cost of each subscription assuming uniform Nash-Bertrand pricing behavior (see table A3). I describe this in greater detail in the appendix. With predicted market shares and marginal costs I can estimate providers' variable profits, which serve as the main input into my empirical model.

5.6.1 Fixed Cost Specifications

I specify the fixed cost functions associated with CenturyLink's deployment of DSL and fiber, respectively as,

$$F_{\ell,m,dsl} = \phi_{dsl} + \mathbb{1}(z_{\ell,m} = none) \cdot [\theta^E_{dsl} + H_m\theta^H_{dsl} + A_m\theta^A_{dsl}]$$

$$+\mathbb{1}(z_{\ell,m} = fiber) \cdot [\vartheta^D_{dsl} + H_m \vartheta^H_{dsl} + A_m \vartheta^A_{dsl}] + \sigma \eta_{\ell,m,dsl},$$

$$F_{\ell,m,fiber} = \phi_{fiber} + \mathbb{1}(z_{\ell,m} = none) \cdot [\theta^E_{fiber} + H_m \theta^H_{fiber} + A_m \theta^A_{fiber}]$$

$$+\mathbb{1}(z_{\ell,m} = dsl) \cdot [\vartheta^U_{fiber} + H_m \vartheta^H_{fiber} + A_m \vartheta^A_{fiber}] + \sigma \eta_{\ell,m,fiber},$$

and I specify Comcast's fixed cost function as,

$$F_{c,m,cable} = \phi_{cable} + \mathbb{1}(z_{c,m} = none) \cdot [\theta^E_{cable} + H_m \theta^H_{cable} + A_m \theta^A_{cable}] + \sigma \eta_{c,m,cable}.$$

Recall that ϕ_τ's are fixed operating costs, θ_τ's are fixed entry costs, and ϑ_τ's are fixed adjustment costs associated with providers' deployment of technology τ.

Given these specifications, the set of fixed cost parameters to be estimated are,

$$\mathbf{\Theta} = \{\phi_\tau, \theta_\tau, \vartheta_\tau, \sigma\},$$

where σ represents the scale of the extreme value errors $\eta_{f,m,\tau}$.

In practice, the parameters that I estimate are normalized by the scale of the errors $\eta_{f,m,\tau}$,

$$\mathbf{\Theta} = \left\{\frac{\phi_\tau}{\sigma}, \frac{\theta_\tau}{\sigma}, \frac{\vartheta_\tau}{\sigma}, \frac{1}{\sigma}\right\},$$

then, with these estimates, I recover the fixed cost estimates in dollar terms by multiplying $\mathbf{\Theta}$ by σ. I denote the fixed cost estimates in dollar terms (which I scale to be in thousands of dollars) as,

$$\tilde{\mathbf{\Theta}} = \{\tilde{\phi}_\tau, \tilde{\theta}_\tau, \tilde{\vartheta}_\tau\}.$$

Because recovering $\tilde{\mathbf{\Theta}}$ involves a nonlinear operation on $\mathbf{\Theta}$, I obtain standard errors for the parameter estimates by nonparametric bootstrap.

5.6.2 Expected Total Profits

With providers' fixed cost functions specified, for a given set of parameters $\mathbf{\Theta}$ and probabilities of providers' deployment decisions $(\mathbf{P}_{\ell,m}, \mathbf{P}_{c,m})$, I can calculate firms' expected total profits. CenturyLink's total expected profits from deploying DSL and fiber in census block m, respectively, are,

$$\mathbb{E}[\Pi_{\ell,m,dsl}(\mathbf{P}_{c,m})] = \frac{1}{\sigma}\big[P(a_{c,m} = none) \cdot \hat{\pi}^{mon}_{\ell,ml,dsl} + P(a_{c,m} = cable) \cdot \hat{\pi}^{duo}_{\ell,m,dsl}\big] - \frac{1}{\sigma} F_{\ell,m,dsl},$$

$$\mathbb{E}[\Pi_{\ell,m,fiber}(\mathbf{P}_{c,m})] = \frac{1}{\sigma}\big[P(a_{c,m} = none) \cdot \hat{\pi}^{mon}_{\ell,m,fiber} + P(a_{c,m} = cable) \cdot \hat{\pi}^{duo}_{\ell,m,fiber}\big] - \frac{1}{\sigma} F_{\ell,m,fiber},$$

and Comcast's total expected profit from deploying cable in census block m is,

$$\mathbb{E}[\Pi_{c,m,cable}(\mathbf{P}_{\ell,m})] = \frac{1}{\sigma}\big[P(a_{\ell,m} = none) \cdot \hat{\pi}^{mon}_{c,m,cable} + P(a_{\ell,m} = dsl) \cdot \hat{\pi}^{duo}_{c,m,cable}$$

$$+P(a_{\ell,m} = fiber) \cdot \hat{\pi}^{duo}_{c,m,cable}\big] - \frac{1}{\sigma}F_{c,m,cable}.$$

Given expected total profits, each firms' probabilities of deploying technology τ in census block m are given by,

$$P_{\ell,m,\tau} = \frac{\exp\big(\mathbb{E}[\Pi_{\ell,m,\tau}(\mathbf{P}_{c,m})]\big)}{\sum_{\tau'}\exp\big(\mathbb{E}[\Pi_{\ell,m,\tau'}(\mathbf{P}_{c,m})]\big)},\ P_{c,m,\tau} = \frac{\exp\big(\mathbb{E}[\Pi_{c,m,\tau}(\mathbf{P}_{\ell,m})]\big)}{\sum_{\tau'}\exp\big(\mathbb{E}[\Pi_{c,m,\tau'}(\mathbf{P}_{\ell,m})]\big)},$$

which are used to formulate a likelihood function for estimation.

5.6.3 NPL Estimation

To estimate the model I use a nested pseudo-likelihood (NPL) estimator based on Aguirregabiria and Mira (2002, 2007), which is robust to the presence of multiple equilibria given that the system of equations governing players' best-responses is stable. Specifically, I define a pseudo likelihood function where players' choice probabilities are best responses to an arbitrary $\mathbf{P}$. These are called "pseudo" because $\mathbf{P}$ does not represent players' equilibrium probabilities but can be interpreted as players' beliefs about the actions of other players. The pseudo likelihood function (pseudo log-likelihood function here) is the joint probability of firms' deployment decisions,

$$Q(\mathbf{\Theta}, \mathbf{P}) = \sum_{m}^{\mathcal{M}}\sum_{f}^{\mathcal{F}}\sum_{\tau}^{T} \mathbb{1}(a_{f,m} = \tau) \cdot \log\big(\Psi_{f,m,\tau}(\mathbf{P}_{-f}, \mathbf{\Theta})\big).$$

The NPL estimator is defined as the vector of parameters and beliefs $(\hat{\mathbf{P}}, \hat{\mathbf{\Theta}})$ that satisfy the conditions,

$$\hat{\mathbf{\Theta}} = \arg\max_{\mathbf{\Theta}} Q(\mathbf{\Theta}, \hat{\mathbf{P}}),$$

$$\hat{\mathbf{P}} = \mathbf{\Psi}(\hat{\mathbf{P}}, \hat{\mathbf{\Theta}}),$$

where $\hat{\mathbf{\Theta}}$ maximizes the pseudo likelihood function, given beliefs $\hat{\mathbf{P}}$, and $\hat{\mathbf{P}}$ is a fixed point, given parameters $\hat{\mathbf{\Theta}}$.

Aguirregabiria and Mira (2007) propose an algorithm to obtain the NPL estimator, which I follow. First, start with an initial guess for firms' beliefs $\hat{\mathbf{P}}^0$. Then, at iteration $k \geq 1$ estimate the parameters, given $\hat{\mathbf{P}}^{k-1}$, using maximum likelihood, $\hat{\mathbf{\Theta}}^k = \arg\max_{\mathbf{\Theta}} Q(\mathbf{\Theta}, \hat{\mathbf{P}}^{k-1})$. Then, update firms' beliefs using the estimated parameters, $\hat{\mathbf{P}}^k = \mathbf{\Psi}(\hat{\mathbf{P}}^{k-1}, \hat{\mathbf{\Theta}}^k)$. Continuing iterating until convergence, $\|\hat{\mathbf{\Theta}}^k - \hat{\mathbf{\Theta}}^{k-1}\| < \varepsilon$.

In practice, to obtain an initial guess of firms' beliefs $\hat{\mathbf{P}}^0$ I use a simple frequency estimator,

$$\hat{P}^0_{f,m,\tau} = \frac{\sum_m \mathbb{1}(a_{f,m} = \tau) \cdot \mathbb{1}(X_m = X^b)}{\sum_m \mathbb{1}(X_m = X^b)},$$

where $\mathbb{1}(X_m = X^b)$ is an indicator function that denotes whether the vector of census block characteristics in census block m falls within a certain bin. I use number of households and land area $X_m \equiv (H_m, A_m)$ as the relevant census block characteristics.

5.7 Fixed Cost Results

Table 4 displays the fixed cost estimates scaled in thousands of dollars. Table A4 displays the raw, unscaled parameter estimates. The entry cost intercepts indicate that per census block, it costs approximately \$404,000, \$464,000, and \$710,000 to deploy DSL, cable, and fiber, respectively. CenturyLink's fiber upgrade cost intercept is of a similar magnitude, \$306,000, but less than half of the fiber entry cost and less than either the DSL or cable entry costs indicating that upgrading existing infrastructure is cheaper than de novo entry. Conditional on block characteristics, number of households and land area, for the average census block (weighted by households) in my sample it costs \$13,750, \$16,366, and \$24,259 per household to deploy DSL, cable, and fiber, respectively. Similarly, on average it costs \$10,428 per household for CenturyLink to upgrade from DSL to fiber. While these average fixed cost estimates are higher than industry estimates, as I demonstrate below, my deployment costs estimates vary dramatically by household density—note that entry costs are generally decreasing in number of households and increasing in land area. Additionally, as Wilson (2021) points out these estimates also reflect firms' opportunity costs and other implicit costs such as regulatory barriers, which would also explain why they exceed industry estimates.

Relatedly, the operating cost parameters, $\phi_{f,\tau}$'s, are large and (unexpectedly) negative. One explanation for this result is that broadband deployment is a long-term capital investment, from which providers expect to earn revenues over a long time horizon. However, I model providers' behavior as the result of a one-shot game in which firms make their deployment decisions based on the previous year's decisions and earn profits for one year only. In reality, since providers expect to earn a stream of variable profits over a longer time horizon, the negative operating cost parameters I obtain may reflect the fact that providers' variable profits are larger than I estimate. As a result, in order to reconcile the deployment decisions I observe in the data, the model needs to fit negative operating cost parameters. Another potential explanation is that providers earn revenue from other lines of business including television and phone service, which I do not account for. Regardless, the model is still useful for estimating providers' deployment costs, because providers' operating costs don't factor into these calculations.

Table 4. Fixed Cost Estimates (return)

Parameters		Point Estimates	Standard Errors	5th Pct.	95th Pct.
CenturyLink, DSL					
Operating Cost	ϕ_{dsl}	-222.202	(152.045)	-448.578	-123.283
Entry Cost	θ_{dsl}	404.286	(274.525)	226.520	815.975
Entry Cost × Households	θ^H_{dsl}	-0.099	(0.088)	-0.244	-0.020
Entry Cost × Land Area	θ^A_{dsl}	1.948	(1.405)	0.747	4.631
Downgrade Cost	ϑ_{dsl}	118.746	(76.777)	50.625	226.268
Downgrade Cost × Households	ϑ^H_{dsl}	-0.406	(0.252)	-0.752	-0.223
Downgrade Cost × Land Area	ϑ^A_{dsl}	-53.211	(41.607)	-129.597	-23.687
CenturyLink, Fiber					
Operating Cost	ϕ_{fiber}	-359.222	(256.675)	-760.608	-202.690
Entry Cost	θ_{fiber}	710.632	(492.534)	400.723	1,442.014
Entry Cost × Households	θ^H_{fiber}	-0.135	(0.974)	-0.517	1.175
Entry Cost × Land Area	θ^A_{fiber}	18.161	(460.741)	1.816	726.988
Upgrade Cost	ϑ_{fiber}	306.630	(219.870)	171.983	656.579
Upgrade Cost × Households	ϑ^H_{fiber}	-0.339	(0.262)	-0.725	-0.165
Upgrade Cost × Land Area	ϑ^A_{fiber}	78.485	(48.506)	41.304	163.441
Comcast					
Operating Cost	ϕ_{cable}	-252.855	(182.542)	-524.958	-135.453
Entry Cost	θ_{cable}	464.226	(324.717)	254.409	946.014
Entry Cost × Households	θ^H_{cable}	0.438	(0.143)	0.167	0.601
Entry Cost × Land Area	θ^A_{cable}	9.415	(43.080)	1.095	116.766
Scaling Factor					
	σ	49.074	(33.358)	27.718	98.690
Pseudo Log-likelihood		-11,618.410			
Census Blocks		59,705			

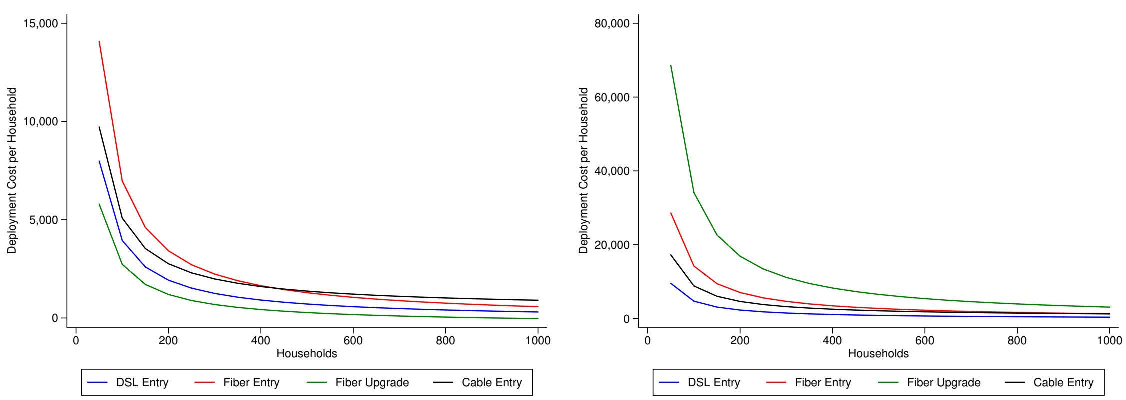
Notes: Observations are census blocks. Model estimated using k-step NPL algorithm. Standard errors in parentheses and confidence intervals are estimated by nonparametric bootstrap (250 replications). The scaling factor σ coverts unscaled parameter values Θ into thousands of dollars $\tilde{\Theta}$.

CenturyLink's entry and upgrade costs are decreasing in the number of households and increasing in land area. Comcast's entry costs are increasing in both households and land area. For more insight into the estimated deployment cost relationships, I plot providers' fixed cost functions on a per household basis in figures 9 and 10. Figure 10 plots per household deployment costs as a function of households, holding land area fixed at 0 square miles and 40 square miles (the maximum value in my sample). These plots show that providers' deployment costs exhibit significant economies of scale over the space of block characteristics in my sample. Also, notice that the ranking from least to most expensive entry cost by technology is generally DSL, cable, fiber, except that fiber becomes cheaper than cable at some threshold of households. Additionally, the per household cost of upgrading from DSL to fiber is cheapest in the smallest blocks but most expensive in the largest blocks, reflecting the fact that CenturyLink's opportunity cost of forgoing an upgrade of service in dense areas is much greater than in sparely populated areas.

Figure 10 presents contour maps of providers' fixed cost functions on a per household basis, separately for each technology. These plots show that deployment costs decline as household density increases, moving northwest. In each subfigure, the lightest grey region indicates census blocks for which implied deployment costs range from $0-1,000 per household. Collectively these figures show that the relatively parsimonious fixed cost functions I estimate are able to capture well-known economic characteristics of broadband deployment, namely economies of scale and density. Additionally, the cost of deployment on a per household basis is not dissimilar from industry sources.

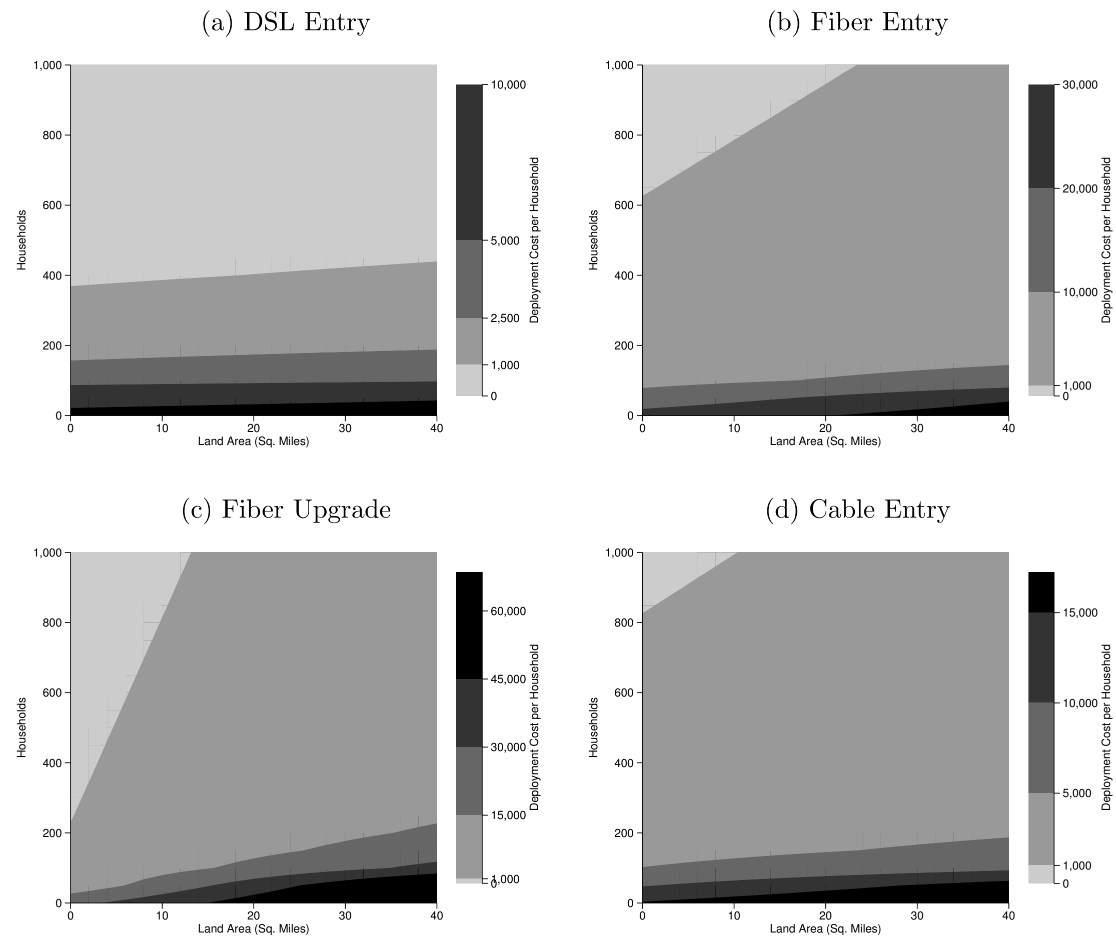
Figure 9. Economies of Scale (return)

(e) Land Area = 0 (Sq. Miles) (f) Land Area = 40 (Sq. Miles)



Notes: Using the estimated fixed cost parameters, this figure plots the implied deployment cost per household for each technology as a function of households. Panel (a) holds land area fixed at 0 square miles. Panel (b) holds land area fixed at 40 square miles.

Figure 10. Economies of Density (return)



Notes: Using the estimated fixed cost parameters, this figure plots the implied deployment cost per household for each technology as a function of households and land area. Deployment costs per household increase from light to dark.

6 Counterfactuals

In this section, I use the estimates of the structural model to perform counterfactuals to address the following policy questions:

(i) Does competition incentivize providers to deploy high-speed broadband service more widely?

(ii) How much do (would) consumers benefit from existing (additional) competition among broadband providers?

(iii) Are supply- or demand-side subsides likely to be more effective at addressing the digital divide?

To determine changes in equilibrium broadband deployment under each counterfactual scenario, I compute providers' subscription prices, household demand for broadband given subscription prices, and providers' deployment decisions given household demand using the supply and demand parameters of my structural model. In some counterfactuals I hold providers' prices fixed, in others I let providers adjust their prices. I describe these scenarios briefly below.

In "Fixed Price" scenarios, I assume each provider holds its subscription prices constant at pre-counterfactual levels. In "Uniform Price" scenarios, I assume that each provider sets uniform prices Nash-Bertrand, where it chooses subscription prices to maximize its total profits over its entire pre-counterfactual coverage area, then I assume it re-updates it deployment decisions, given its new optimal prices. This process captures the fact that higher prices may lead providers to change their deployment decisions.[13] In the "Price Discrimination" scenarios, I assume providers price discriminate across geographic markets by setting prices Nash-Bertrand in each census block group that comprise its coverage area, then after setting prices make their deployment decisions. Because demand varies by demographic characteristics, providers' optimal pricing and deployment decisions will differ according to variation in households' demographics across geography. I describe providers price setting behavior in more detail in appendix A.

As part of my counterfactual analysis I compute the change in consumer welfare under each scenario. Based on my demand specification, I derive lower and upper bounds for consumer welfare, which I describe in more detail in appendix B.

6.1 Competition and Broadband Deployment

In counterfactual (i), I analyze whether competition incentivizes providers to deploy broadband service more widely. I compare providers' deployment predicted by the structural model under competitive conditions to providers' deployment in counterfactuals where CenturyLink and Comcast behave as monopolists. Table 5 summarizes the results. Panel A shows that, holding prices fixed, a monopolist CenturyLink would upgrade its service from DSL to fiber in a small number of census blocks covering approximately 12,000 households relative to the model's baseline prediction under competition. When CenturyLink is also able to adjust its prices, its incentive to upgrade from DSL to fiber is stronger resulting in upgraded service for about 19,500 households. This suggests that broadband providers' incentive to increase high speed deployment is weaker under competition. Panel B displays results for Comcast, which shows that Comcast's deployment decisions are unaffected by competition whether regardless of whether or not it is able to adjust its prices. Overall, these results suggest that the effect of competition on CenturyLink and Comcast's deployment decisions is relatively

[13] Presumably it is possible to iterate this process, however, convergence may not be guaranteed.

weak.

Table 5. Counterfactual (i): Effect of Competition on Broadband Deployment (return)

Panel A. CenturyLink Monopoly

	Census Blocks Covered				Households Covered			
Counterfactual	DSL	Fiber	Comcast	Wave	DSL	Fiber	Comcast	Wave
Baseline	29,335	11,246	39,287	4,481	888,168	372,985	1,314,345	191,341
Fixed Prices	29,308	11,273			876,363	384,790		
Uniform Prices	29,289	11,292			868,608	392,545		
Price Discrimination	29,289	11,292			868,608	392,545		

Panel B. Comcast Monopoly

	Census Blocks Covered				Households Covered			
Counterfactual	DSL	Fiber	Comcast	Wave	DSL	Fiber	Comcast	Wave
Baseline	29,335	11,246	39,287	4,481	888,168	372,985	1,314,345	191,341
Fixed Prices			39,287				1,314,345	
Uniform Prices			39,287				1,314,345	
Price Discrimination			39,287				1,314,345	

Notes: This table displays the number of census blocks and households covered by CenturyLink, Comcast, and Wave under different counterfactual scenarios. Panel A shows results where CenturyLink is a monopolist. Panel B shows results where Comcast is a monopolist. “DSL” and “Fiber” refer to census blocks/households where CenturyLink deploys DSL and fiber, respectively.

6.2 Benefits of Broadband Competition

In counterfactual (iia), I analyze how much consumers benefit from existing competition among providers, and what portion of their gains are attributable to changes in availability and quality versus changes in price. Like counterfactual (i), counterfactual (iia) simulates broadband deployment in scenarios where CenturyLink and Comcast behave as monopolists. Table 6 displays the change in consumer surplus when either CenturyLink or Comcast is a monopolist relative to the baseline in which they compete. In the case where CenturyLink is a monopolist, total annual consumer surplus decreases by \$222 million (lower bound), holding prices fixed, and \$302 million accounting for CenturyLink’s incentive to raise prices—on average CenturyLink raises its DSL prices by about 25% and its fiber prices by about 35% (observe that there is little difference between uniform pricing and geographic price discrimination, see table A5). These overall reductions in consumer surplus translate into a loss of \$154 and \$209 per household annually. These results indicate that the benefit of existing broadband competition from Comcast is substantial. Furthermore, approximately 2/3 of this benefit ($222 million) comes from increased availability and product choices and 1/3 ($80 million) is attributable to price competition. Because competition actually decreases CenturyLink's incentive to deploy fiber there are no benefits attributable to competition derived from increased product quality or deployment.

The results of the Comcast monopoly counterfactual are similar but the loss of CenturyLink has a smaller, though still substantial, overall impact on consumer welfare. However, CenturyLink constrains Comcast's incentive to raise prices substantially. In the absence of competition from CenturyLink, I estimate that Comcast's prices would increase by approximately 25% (see table A6).

Similar to the previous analysis, in counterfactual (iib) I analyze the benefit of broadband competition to consumers. However, unlike counterfactual (iia), here I estimate the gain in consumer surplus from additional competition by simulating an expansion of CenturyLink and Comcast's service areas to all census blocks in my sample, holding prices fixed.[14] Table 7 displays these results. I find an overall increase in consumer surplus of $35 million (lower bound), $24 per household, as a result of CenturyLink deploying fiber and Comcast deploying cable to all census blocks in the market. As might be expected, when compared with the results of counterfactual (iia), the marginal benefit of increased competition/coverage is decreasing.

6.3 Digital Divide Policy: Supply- and Demand-side Subsidies

In counterfactual (iii), I compare the relative costs and benefits of supply- and demand-side subsides in the broadband market. First, I estimate the costs and benefits of a "broadband expansion" policy in which CenturyLink deploys fiber and Comcast deploys cable to every unserved census block with households in the market. Second, I estimate the costs and benefits of a broadband subsidy program that reduces the cost of broadband for low-income households.

For the supply-side subsidy, I calculate providers' costs of deployment based on the fixed cost parameter estimates in table 4, and I calculate the benefits of the policy as the change in consumer surplus attributable to this new deployment. Specifically, I calculate the minimum subsidy providers would find profitable to deploy service in each unserved, populated census block. Table 8 displays these results. CenturyLink's overall cost of deploying fiber to 1,072,426 households is $6.3 billion or $5,898 per household. Comcast's overall cost of deploying cable to 131,066 households is $2.4 billion or $18,281

[14] In principle, it is possible to simulate changes in prices here as well, however, issues with multiplicity are preventing me from doing so currently.

Table 6. Counterfactual (iia): Benefits of Existing Competition (return)

Panel A. CenturyLink Monopoly

Counterfactual	Households Covered				Δ Consumer Welfare ($M)		Av. Δ Consumer Welfare	
	DSL	Fiber	Comcast	Wave	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Baseline	888,168	372,985	1,314,345	191,341				
Fixed Prices	876,363	384,790			-222	-789	-154	-546
Uniform Prices	868,608	392,545			-302	-1,074	-209	-743
Price Discrimination	868,608	392,545			-302	-1,072	-209	-742

Panel B. Comcast Monopoly

Counterfactual	Households Covered				Δ Consumer Welfare ($M)		Av. Δ Consumer Welfare	
	DSL	Fiber	Comcast	Wave	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Baseline	888,168	372,985	1,314,345	191,341				
Fixed Prices			1,314,345		-46	-164	-32	-113
Uniform Prices			1,314,345		-171	-609	-119	-421
Price Discrimination			1,314,345		-172	-610	-119	-422

Notes: This table displays the number of households covered by CenturyLink, Comcast, and Wave under different counterfactual scenarios, as well as corresponding changes in consumer welfare. Panel A shows results where CenturyLink is a monopolist. Panel B shows results where Comcast is a monopolist. "DSL" and "Fiber" refer to census blocks/households where CenturyLink deploys DSL and fiber, respectively.

Table 7. Counterfactual (iib): Benefits of Additional Competition (return)

Counterfactual	Households Covered				Δ Consumer Welfare ($M)		Av. Δ Consumer Welfare	
	DSL	Fiber	Comcast	Wave	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Baseline	888,168	372,985	1,314,345	191,341				
Expansion (Fixed Prices)		1,445,411	1,445,411	191,341	35	125	24	87

Notes: This table displays the number of households covered by CenturyLink, Comcast, and Wave under broadband expansion, as well as the corresponding change in consumer welfare. "DSL" and "Fiber" refer to census blocks/households where CenturyLink deploys DSL and fiber, respectively.

per household. Comcast's relatively high per household cost of deployment reflects the fact that the unserved areas to which it deploys new service are few and presumably the most high cost areas, whereas CenturyLink deploys some new service and upgrades its service from DSL to fiber in many more areas. Combined this policy generates $35 million in consumer surplus annually and increases the overall broadband subscription rate from 81.7% to 85.6% (see table A7). Based on these estimates, the cost of a policy that completely compensates providers for broadband expansion significantly outweighs the benefits.

To compare the costs and benefits of the broadband subsidy program I calculate the cost of distributing subsidies to low-income households, which I compare to the consumer surplus generated by the program. Specifically, I estimate demand for broadband using my demand model, where households with household income less than $50,000 receive either a $10 or $30 credit towards whichever subscription they choose on a monthly basis. I specify these credits to match the subsides distributed to low-income households under the FCC's Lifeline Program and Affordable Connectivity Program (ACP), respectively. Then I multiply the cost of each subsidy by the number of eligible households to calculate the total program costs. I estimate that a broadband subsidy of $10 would cost $53 million on an annual basis, generate $26 million in consumer welfare, and raise the overall broadband subscription rate by 3.5 percentage points to 85.2%. A $30 subsidy program would cost $159 million annually, generate $131 million in consumer welfare, and raise the overall broadband subscription rate by 8.6 percentage points to 90.3%.

Comparatively, I find that a broadband subsidy program for low-income households is much more efficient than supply-side subsidies to providers. However, some limitations of my analysis deserve discussion. First, these programs benefit different constituents. Underserved households are not necessarily low-income households, and in fact many low-income households may live in dense urban areas that have access but may struggle to afford broadband subscriptions. Second, deployment is a one-time lump sum investment, whereas demand-side subsidies must continue to be paid out annually. Third, to the extent that providers respond to demand-side subsidies by raising their prices, the benefits of a low-income subsidy program would be partially offset by such increases. Despite these caveats, however, the overall cost of a broadband expansion policy is significantly higher than the cost of a low-income subsidy program, and so, even subject to sensitivity analysis, a reversal in the ranking of the cost effectiveness of these policies is unlikely.

Table 8. Counterfactual (iii): Supply- vs. Demand-side Subsidies (return)

Counterfactual	Households Covered				Δ Consumer Welfare ($M)		Av. Δ Consumer Welfare		Cost ($M)
	DSL	Fiber	Comcast	Wave	Lower Bound	Upper Bound	Lower Bound	Upper Bound	
Baseline	888,168	372,985	1,314,345	191,341					
Expansion (Fixed Prices)		1,445,411	1,445,411	191,341	35	125	24	87	8,722
Household Subsidy ($10)	888,168	372,985	1,314,345	191,341	26	92	18	63	53
Household Subsidy ($30)	888,168	372,985	1,314,345	191,341	131	464	90	321	159

Notes: This table displays the number of households covered by CenturyLink, Comcast, and Wave under different counterfactual scenarios, as well as corresponding changes in consumer welfare. "DSL" and "Fiber" refer to census blocks/households where CenturyLink deploys DSL and fiber, respectively.

7 Conclusion

This paper analyzes the relationship between competition and broadband availability in equilibrium through the lens of a structural model. The model enables me to quantify the effect of competition on Internet service providers' incentives to deploy high-speed service, as well as assess the impact of policy prescriptions for the digital divide.

With empirical estimates from Seattle, I find that providers' incentive to invest in high-speed broadband is weaker under competition. Despite this negative effect on providers' investment incentive, however, I show that consumers reap substantial benefits from competition between providers both from increases in product availability and choice, as well as from lower prices. Unlike the existing literature, I model price competition between providers and find that price competition accounts for over a third of these benefits. Overall, I find that Comcast's competition with CenturyLink generates $300 million in consumer welfare annually. From a competition policy perspective, these results suggest that the impact of competition on providers' investment incentives is of second-order importance in the broadband market relative to price competition and product choice.

In terms of digital divide policy, in a cost-benefit analysis that compares supply- and demand-side subsidies to increase broadband subscriber-ship, I find that a program that reduces the price of broadband for low-income households is considerably more cost effective than a broadband expansion policy that compensates providers for building out their coverage areas. These results are potentially useful for policymakers that face a tradeoff between implementing policies that either increase broadband availability or increase broadband affordability.

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A Appendix: Pricing Behavior

Providers engage in Nash-Bertrand uniform pricing over the census blocks that made up their coverage areas.

Firm f chooses the set of prices p_j to maximize its profits across all census blocks in its coverage area.

$$\mathbf{\Pi}_f = \sum_m \Pi_{f,\tau} = \sum_m \pi_{f,m,\tau} - \sum_m F_{f,m,\tau}. \tag{19}$$

The firm's first order condition is the sum of the derivative of its variable profit function across all census blocks in its coverage area,

$$\frac{\partial \mathbf{\Pi}_f}{\partial p_j} = \sum_m \frac{\partial \pi_{f,m,\tau}}{\partial p_j} - 0 = 0, \tag{20}$$

where again the firm's variable profit function is,

$$\pi_{f,m,\tau} = \sum_j 12 \cdot M_m \cdot S_{j,m}(p_j - c_j).$$

$$\frac{\partial \pi_{f,m,\tau}}{\partial p_j} = 12 \cdot M_m \cdot S_{j,m} + 12 \cdot M_m \cdot \sum_j \frac{\partial S_{j,m}}{\partial p_j}(p_j - c_j) = 0$$

$$\frac{\partial \mathbf{\Pi}_f}{\partial p_j} = \sum_m 12 \cdot M_m \cdot S_{j,m} + \sum_m \sum_j 12 \cdot M_m \cdot \frac{\partial S_{j,m}}{\partial p_j}(p_j - c_j) = 0 \tag{21}$$

Stacking all firms' first order conditions, we can represent uniform pricing behavior in the market as,

$$\begin{bmatrix} \sum_m S_{1,m}M_m \\ \sum_m S_{2,m}M_m \\ \vdots \\ \sum_m S_{J,m}M_m \end{bmatrix} + \sum_m \left(\mathcal{O}_{f,m} * \begin{bmatrix} \frac{\partial S_{1,m}}{\partial p_1}M_m & \frac{\partial S_{2,m}}{\partial p_1}M_m & \dots & \frac{\partial S_{J,m}}{\partial p_1}M_m \\ \frac{\partial S_{1,m}}{\partial p_2}M_m & \frac{\partial S_{2,m}}{\partial p_2}M_m & \dots & \frac{\partial S_{J,m}}{\partial p_2}M_m \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial S_{1,m}}{\partial p_J}M_m & \frac{\partial S_{2,m}}{\partial p_J}M_m & \dots & \frac{\partial S_{J,m}}{\partial p_J}M_m \end{bmatrix} \right) \begin{bmatrix} p_1 - c_1 \\ p_2 - c_2 \\ \vdots \\ p_J - c_J \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix},$$

where $\mathcal{O}_{f,m}$ represents the "ownership" matrix as in Nevo (2000).

To simplify the representation of the first-order conditions, I define Δ_m as the matrix product of the ownership matrix and market-size weighted derivatives of market shares with respect to prices,

$$\Delta_m \equiv \mathcal{O}_{f,m} * \begin{bmatrix} \frac{\partial S_{1,m}}{\partial p_1} H_m & \frac{\partial S_{2,m}}{\partial p_1} H_m & \dots & \frac{\partial S_{J,m}}{\partial p_1} H_m \\ \frac{\partial S_{1,m}}{\partial p_2} H_m & \frac{\partial S_{2,m}}{\partial p_2} H_m & \dots & \frac{\partial S_{J,m}}{\partial p_2} H_m \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial S_{1,m}}{\partial p_J} H_m & \frac{\partial S_{2,m}}{\partial p_J} H_m & \dots & \frac{\partial S_{J,m}}{\partial p_J} H_m \end{bmatrix},$$

The final equation resembles the "classic" FOC matrix in Nevo (2000), except with uniform prices across census blocks, the firms' FOCs are essentially weighted by census blocks size,

$$\begin{bmatrix} \sum_m S_{1,m} H_m \\ \sum_m S_{2,m} H_m \\ \vdots \\ \sum_m S_{J,m} H_m \end{bmatrix} + \left[\sum_m \Delta_m\right] \begin{bmatrix} p_1 - c_1 \\ p_2 - c_2 \\ \vdots \\ p_J - c_J \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \tag{22}$$

Given firms' price setting behavior, one can use these FOCs to "back out" the marginal cost of each product,

$$\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_J \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_J \end{bmatrix} + \left[\sum_m \Delta_m\right]^{-1} \begin{bmatrix} \sum_m S_{1,m} H_m \\ \sum_m S_{2,m} H_m \\ \vdots \\ \sum_m S_{J,m} H_m \end{bmatrix},$$

Given marginal costs, one can also use these FOCs to predict prices in counterfactual scenarios,

$$\begin{bmatrix} \sum_m S_{1,m}(\mathbf{p}) H_m \\ \sum_m S_{2,m}(\mathbf{p}) H_m \\ \vdots \\ \sum_m S_{J,m}(\mathbf{p}) H_m \end{bmatrix} + \left[\sum_m \Delta_m(\mathbf{p})\right] \begin{bmatrix} p_1 - c_1 \\ p_2 - c_2 \\ \vdots \\ p_J - c_J \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix},$$

where predicted prices given a change in the market are the new set of prices that satisfy the set of FOCs.

A.1 Uniform Pricing vs. Price Discrimination

Table. Counterfactual (iv): Uniform Pricing vs. Price Discrimination

	Variable Profits ($M)		
Provider	Uniform Pricing	Price Discrimination	Percent Difference
CenturyLink	265.70	268.74	1.15%
Comcast	950.89	982.54	3.33%

B Appendix: Consumer Welfare

To quantify the change in consumer welfare resulting from changes in the market, I follow Small and Rosen (1981) to calculate the change in consumer surplus in a discrete choice model. However, because price enters non-linearly into households' indirect utility function in my demand model, I cannot use the standard formula derived by Small and Rosen (1981) to quantify changes in consumer surplus. Small and Rosen (1981) note that price must enter linearly into the indirect utility function in order for their formula to hold. McFadden (1995) shows that it is possible to numerically approximate changes in consumer surplus when price enters non-linearly into the indirect utility function. However, I show that when price enters the indirect utility function as a logarithmic function, it should be possible to calculate a lower bound of the change in consumer surplus using a modification of Small and Rosen (1981).

The standard formula, derived in Small and Rosen (1981), generally used to calculate a change in consumer surplus when a representative consumer's indirect utility function is a linear function of price is,

$$\Delta CS = \frac{1}{\alpha}\Big[\log\big(1+\sum_{j\in J'}\exp(u_{i,j})\big) - \log\big(1+\sum_{j\in J}\exp(u_{i,j})\big)\Big] \tag{23}$$

where consumer i's indirect utility from good j is,

$$u_{i,j} = x_j'\beta - \alpha p_j + \epsilon_{i,j},$$

and $\epsilon_{i,j}$ is i.i.d. extreme value type 1.

More generally, equation (23) is made up of three components: (1) the marginal utility of income, (2) the expected utility of the bundle of goods J', and (3) the expected utility of the bundle of goods J.

The marginal utility of income comes from differentiating $u_{i,j}$ with respect to p_j,

$$-\frac{\partial u_{i,j,m}}{\partial p_j} = \alpha,$$

and, the expected utility of bundle J when $\epsilon_{i,j}$ is i.i.d. extreme value type 1 is,

$$\mathbb{E}\max\{u_{i,0}, u_{i,1}, ..., u_{i,J}\} = \log\big(1 + \sum_{j\in J}\exp(u_{i,j})\big),$$

and the expected utility of bundle J' is analogous.

When price enters consumer i's indirect utility function as a logarithmic function,

$$u_{i,j} = x_j'\beta - \alpha\log(p_j) + \epsilon_{i,j},$$

the only change in the above is the marginal utility of income, which now becomes,

$$-\frac{\partial u_{i,j}}{\partial p_j} = \frac{\alpha}{p_j}.$$

The result is that the marginal utility of income now depends on the price of each good j.

However, we know that the inverse marginal utility of income will be greatest for the highest priced good,

$$-\frac{\partial p_j^{max}}{\partial u_{i,j}} = \frac{p_j^{max}}{\alpha},$$

and smallest for the least expensive good,

$$-\frac{\partial p_j^{min}}{\partial u_{i,j}} = \frac{p_j^{min}}{\alpha}.$$

In which case, a lower bound of the change in consumer surplus when indirect utility is a function of log price is,

$$\Delta CS^{lb} = \frac{p_j^{min}}{\alpha}\Big[\log\big(1 + \sum_{j\in J'}\exp(u_{i,j})\big) - \log\big(1 + \sum_{j\in J}\exp(u_{i,j})\big)\Big].$$

and an upper bound is,

$$\Delta CS^{ub} = \frac{p_j^{max}}{\alpha}\Big[\log\big(1 + \sum_{j\in J'}\exp(u_{i,j})\big) - \log\big(1 + \sum_{j\in J}\exp(u_{i,j})\big)\Big].$$

To calculate the lower bound of the change in consumer surplus in census block m using the estimates of my mixed logit demand model when there is change in the market, I use the following formula,

$$\Delta CS_m = 12 \cdot H_m \sum_{i=1}^{36} \frac{p_j^{\min}}{\alpha_i} \Big[\log \big(1 + \sum_{j \in J'} \exp(u_{i,j})\big) - \log \big(1 + \sum_{j \in J} \exp(u_{i,j})\big) \Big] \cdot \omega_{i,m}, \quad (24)$$

where $p_j^{\min}$ is the lowest priced plan offered by CenturyLink.

C Appendix: Tables

Table A1. Census Tract Demographic Weights (ACS Data) (return)

Statistics	Mean	Stdv	Minimum	Median	Maximum	N
Income [0k, 50k)	0.3071	0.1362	.043	.284	.974	686
Income [50k, 100k)	0.3009	0.0800	0	.305	.6	686
Income [100k, 200k+)	0.3920	0.1684	0	.388	.845	686
Less than HS Grad	0.0557	0.0519	0	.041	.411	686
HS Grad and Some College	0.4893	0.1876	.082	.516	.863	686
Bachelor's Degree or Higher	0.4550	0.2152	.039	.421	.911	686
Household Size (1)	0.2798	0.1270	0	.26	.778	686
Household Size (2)	0.3484	0.0641	0	.35	.658	686
Household Size (3)	0.1569	0.0524	0	.161	.5	686
Household Size (4+)	0.2149	0.0939	0	.216	.667	686

Notes: ACS 5-year estimates 2018. This table displays summary statistics for the demographic weights used to predict households' demand for broadband in areas extending beyond the Seattle MSA.

Table A2. CenturyLink Plans by Technology (return)

Plan	Monthly Charge	Download Speed (mbps)	Upload Speed (mbps)	Usage Allowance (GB)
CenturyLink (DSL): plan 1	46.99	1.5	.875	1,000
CenturyLink (DSL): plan 2	51.99	7	.875	1,000
CenturyLink (DSL): plan 3	56.99	12	.875	1,000
CenturyLink (DSL): plan 4	66.99	20	.875	1,000
CenturyLink (DSL): plan 5	71.99	20	2	1,000
CenturyLink (DSL): plan 6	76.99	40	5	1,000
CenturyLink (DSL): plan 7	101.98	60	5	1,000
CenturyLink (DSL): plan 8	126.98	100	12	1,000
Plan	Monthly Charge	Download Speed (mbps)	Upload Speed (mbps)	Usage Allowance (GB)
CenturyLink (FTTH): plan 1	56.99	12	.875	1,000
CenturyLink (FTTH): plan 2	61.99	12	5	1,000
CenturyLink (FTTH): plan 3	66.99	20	.875	1,000
CenturyLink (FTTH): plan 4	71.99	20	5	1,000
CenturyLink (FTTH): plan 5	76.99	40	5	1,000
CenturyLink (FTTH): plan 6	81.99	40	20	1,000
CenturyLink (FTTH): plan 7	96.99	100	50	1,000
CenturyLink (FTTH): plan 8	156.94	1,000	1,000	.

Notes: FCC Urban Rate Survey 2018. This table summarizes the product portfolios or subscription menus of CenturyLink, DSL and CenturyLink, Fiber as reported for Washington state in the FCC Urban Rate Survey. These sets of plans correspond to CenturyLink's technology choice in my deployment model.

Table A3. Marginal Costs Estimates (return)

Plan	Plan Characteristics: Download Speed (mbps)	Plan Characteristics: Upload Speed (mbps)	Plan Characteristics: Price	Mixed Logit: Marginal Cost	Mixed Logit: Margin
CenturyLink, DSL: plan 1	1.5	.875	46.99	33.75	0.2818
CenturyLink, DSL: plan 2	7	.875	51.99	37.33	0.2820
CenturyLink, DSL: plan 3	12	.875	56.99	40.90	0.2823
CenturyLink, DSL: plan 4	20	.875	66.99	48.04	0.2829
CenturyLink, DSL: plan 5	20	2	71.99	51.59	0.2834
CenturyLink, DSL: plan 6	40	5	76.99	55.15	0.2837
CenturyLink, DSL: plan 7	60	5	101.98	72.94	0.2848
CenturyLink, DSL: plan 8	100	12	126.98	90.70	0.2858
CenturyLink, Fiber: plan 1	12	.875	56.99	40.16	0.2953
CenturyLink, Fiber: plan 2	12	5	61.99	43.62	0.2964
CenturyLink, Fiber: plan 3	20	.875	66.99	47.17	0.2959
CenturyLink, Fiber: plan 4	20	5	71.99	50.61	0.2970
CenturyLink, Fiber: plan 5	40	5	76.99	54.12	0.2971
CenturyLink, Fiber: plan 6	40	20	81.99	57.55	0.2980
CenturyLink, Fiber: plan 7	100	50	96.99	67.99	0.2990
CenturyLink, Fiber: plan 8	1,000	1,000	156.94	109.53	0.3021
Comcast: plan 1	10	2	49.95	11.92	0.7614
Comcast: plan 2	55	5	64.95	15.21	0.7658
Comcast: plan 3	100	5	79.95	18.50	0.7685
Comcast: plan 4	200	10	94.95	21.67	0.7718
Comcast: plan 5	250	25	149.95	33.03	0.7797
Comcast: plan 6	987	35	159.95	35.13	0.7803
Wave: plan 1	10	1	45.10	28.80	0.3613
Wave: plan 2	100	5	73.45	46.59	0.3658
Wave: plan 3	250	10	81.55	51.63	0.3669

Notes: Marginal costs are estimated with the parameters of the mixed logit demand model using firms' pricing FOCs under the assumption of uniform pricing across geographic markets.

Table A4. Fixed Cost Estimates (return)

Parameters		Point Estimates	Standard Errors	5th Pct.	95th Pct.
CenturyLink, DSL					
Operating Cost	ϕ_{dsl}	-4.528	(0.057)	-4.627	-4.437
Entry Cost	θ_{dsl}	8.238	(0.077)	8.115	8.372
Entry Cost × Households	θ^H_{dsl}	-0.002	(0.001)	-0.003	-0.001
Entry Cost × Land Area	θ^A_{dsl}	0.040	(0.022)	0.017	0.087
Downgrade Cost	ϑ_{dsl}	2.420	(0.481)	1.497	3.005
Downgrade Cost × Households	ϑ^H_{dsl}	-0.008	(0.001)	-0.010	-0.006
Downgrade Cost × Land Area	ϑ^A_{dsl}	-1.084	(0.474)	-2.202	-0.678
CenturyLink, Fiber					
Operating Cost	ϕ_{fiber}	-7.320	(0.458)	-8.182	-6.782
Entry Cost	θ_{fiber}	14.481	(0.517)	13.806	15.452
Entry Cost × Households	θ^H_{fiber}	-0.003	(0.016)	-0.007	0.030
Entry Cost × Land Area	θ^A_{fiber}	0.370	(9.289)	0.043	11.941
Upgrade Cost	ϑ_{fiber}	6.248	(0.456)	5.680	7.135
Upgrade Cost × Households	ϑ^H_{fiber}	-0.007	(0.001)	-0.008	-0.006
Upgrade Cost × Land Area	ϑ^A_{fiber}	1.599	(0.390)	1.098	2.403
Comcast					
Operating Cost	ϕ_{cable}	-5.153	(0.127)	-5.357	-4.941
Entry Cost	θ_{cable}	9.460	(0.138)	9.189	9.655
Entry Cost × Households	θ^H_{cable}	0.009	(0.005)	0.002	0.019
Entry Cost × Land Area	θ^A_{cable}	0.192	(0.710)	0.021	2.051
Scaling Factor					
	σ	49.074	(33.358)	27.718	98.690
Pseudo Log-likelihood	-11,618.410				
Markets	59,705				

Notes: Observations are census blocks. Model estimated using k-step NPL algorithm. Standard errors in parentheses and confidence intervals are estimated by nonparametric bootstrap (250 replications). The scaling factor σ coverts unscaled parameter values Θ into thousands of dollars $\tilde{\Theta}$.

Table A5. CenturyLink Monopoly: Counterfactual Prices (return)

Plan	Plan Characteristics			Uniform Prices		Price Discrimination	
	Download Speed (mbps)	Upload Speed (mbps)	Price	Uniform	% Change	PD	% Change
CenturyLink, DSL: plan 1	2	1	46.99	58.58	24.67	58.48	24.46
CenturyLink, DSL: plan 2	7	1	51.99	64.72	24.48	64.58	24.22
CenturyLink, DSL: plan 3	12	1	56.99	70.97	24.53	70.80	24.23
CenturyLink, DSL: plan 4	20	1	66.99	83.56	24.73	83.30	24.35
CenturyLink, DSL: plan 5	20	2	71.99	90.13	25.19	89.81	24.76
CenturyLink, DSL: plan 6	40	5	76.99	96.62	25.50	96.24	25.01
CenturyLink, DSL: plan 7	60	5	101.98	128.45	25.95	127.81	25.33
CenturyLink, DSL: plan 8	100	12	126.98	160.73	26.58	159.78	25.83
CenturyLink, Fiber: plan 1	12	1	56.99	75.74	32.90	75.04	31.67
CenturyLink, Fiber: plan 2	12	5	61.99	83.20	34.22	82.39	32.91
CenturyLink, Fiber: plan 3	20	1	66.99	89.25	33.23	88.34	31.87
CenturyLink, Fiber: plan 4	20	5	71.99	96.84	34.51	95.81	33.09
CenturyLink, Fiber: plan 5	40	5	76.99	103.53	34.47	102.39	32.99
CenturyLink, Fiber: plan 6	40	20	81.99	111.12	35.53	109.84	33.97
CenturyLink, Fiber: plan 7	100	50	96.99	132.20	36.30	130.53	34.58
CenturyLink, Fiber: plan 8	1,000	1,000	156.94	217.95	38.87	214.50	36.67

Table A6. Comcast Monopoly: Counterfactual Prices (return)

Plan	Plan Characteristics			Uniform Prices		Price Discrimination	
	Download Speed (mbps)	Upload Speed (mbps)	Price	Uniform	% Change	PD	% Change
Comcast: plan 1	10	2	49.95	60.87	21.85	61.41	22.95
Comcast: plan 2	55	5	64.95	80.70	24.25	80.72	24.28
Comcast: plan 3	100	5	79.95	100.63	25.87	100.00	25.08
Comcast: plan 4	200	10	94.95	121.57	28.03	120.08	26.47
Comcast: plan 5	250	25	149.95	201.24	34.20	195.69	30.51
Comcast: plan 6	987	35	159.95	214.65	34.20	208.21	30.17

Table A7. Counterfactuals: Coverage and Market Shares (return)

Panel A. CenturyLink Monopoly

	Percent of Households Covered				Market Shares					
Models	DSL	Fiber	Comcast	Wave	Outside Option	Inside Options	DSL	Fiber	Comcast	Wave
(0) Baseline	0.6145	0.2580	0.9093	0.1324	0.1835	0.8165	0.0976	0.0583	0.6218	0.0389
(1) Fixed Prices	0.6063	0.2662	.	.	0.4980	0.5020	0.3286	0.1735	.	.
(2) Uniform Prices	0.6009	0.2716	.	.	0.6845	0.3155	0.2083	0.1072	.	.
(3) Price Discrimination	0.6009	0.2716	.	.	0.6785	0.3215	0.2121	0.1094	.	.

Panel B. Comcast Monopoly

	Percent of Households Covered				Market Shares					
Models	DSL	Fiber	Comcast	Wave	Outside Option	Inside Options	DSL	Fiber	Comcast	Wave
(0) Baseline	0.6145	0.2580	0.9093	0.1324	0.1835	0.8165	0.0976	0.0583	0.6218	0.0389
(1) Fixed Prices	.	.	0.9093	.	0.2548	0.7452	.	.	0.7452	.
(2) Uniform Prices	.	.	0.9093	.	0.4040	0.5960	.	.	0.5960	.
(3) Price Discrimination	.	.	0.9093	.	0.3927	0.6073	.	.	0.6073	.

Panel C. Broadband Expansion or Subsidy

	Percent of Households Covered				Market Shares					
Models	DSL	Fiber	Comcast	Wave	Outside Option	Inside Options	DSL	Fiber	Comcast	Wave
(0) Baseline	0.6145	0.2580	0.9093	0.1324	0.1835	0.8165	0.0976	0.0583	0.6218	0.0389
(1) Expansion (Fixed Prices)	.	1.0000	1.0000	0.1324	0.1443	0.8557	.	0.2203	0.6128	0.0226
(2) Household Subsidy ($10)	0.6145	0.2580	0.9093	0.1324	0.1482	0.8518	0.1055	0.0598	0.6450	0.0415
(3) Household Subsidy ($30)	0.6145	0.2580	0.9093	0.1324	0.0968	0.9032	0.1210	0.0574	0.6743	0.0505

Notes: This table displays the number of households covered by CenturyLink, Comcast, and Wave under different counterfactual scenarios, as well as counterfactual market shares. Panel A shows results where CenturyLink is a monopolist. Panel B shows results where Comcast is a monopolist. Panel C shows results for supply- and demand-side subsidies. “DSL” and “Fiber” refer to census blocks/households where CenturyLink deploys DSL and fiber, respectively.

D Appendix: Figures

Figure A1. ISPs' Coverage Areas (return)

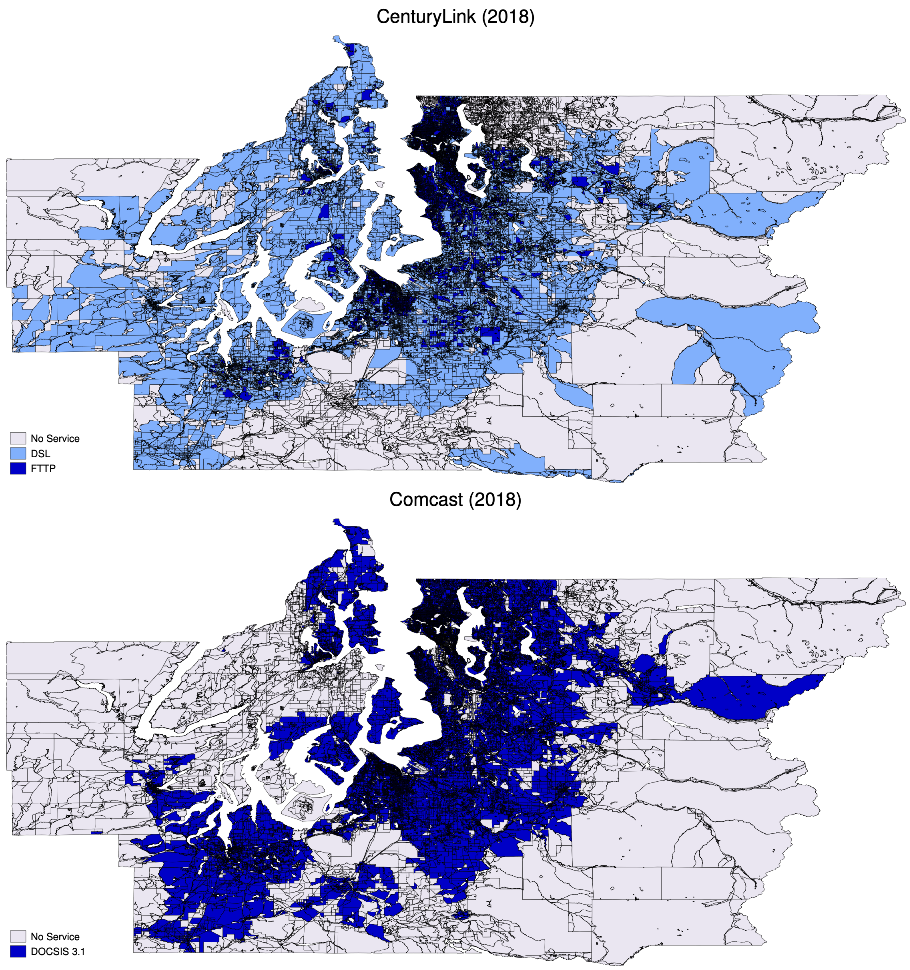
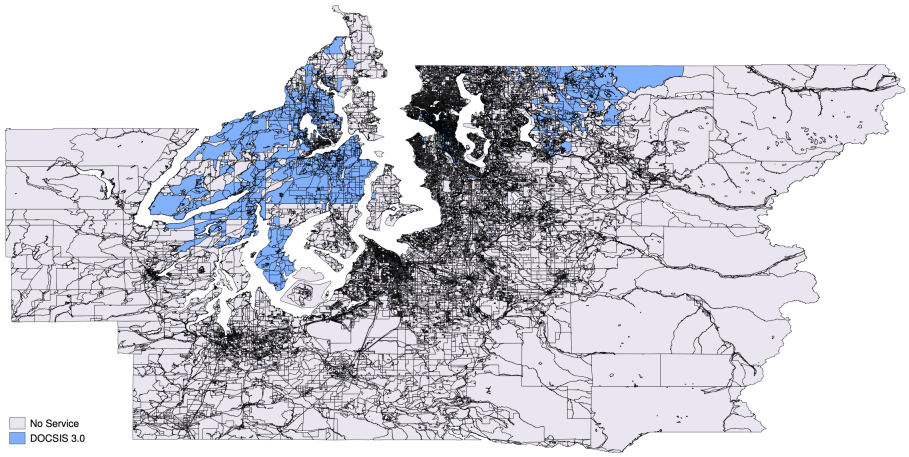
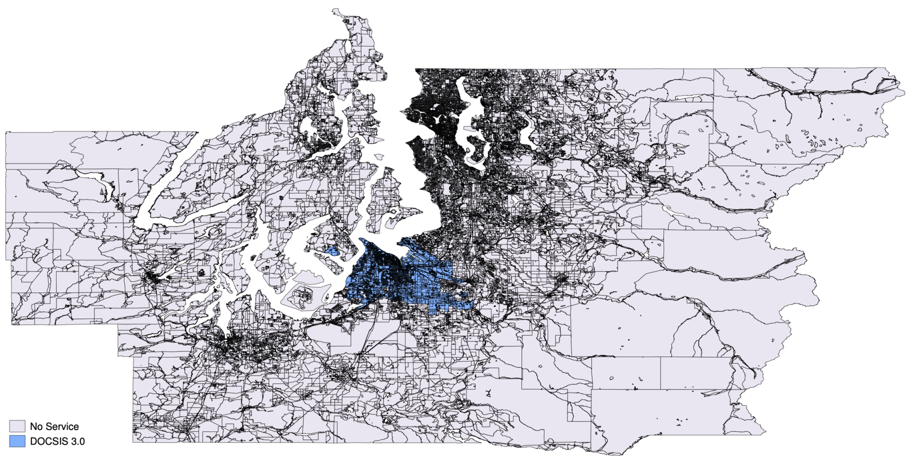


Figure A1 (Cont.). ISPs' Coverage Areas (return)

Wave (2018)



City of Tacoma (2018)



Frontier (2018)

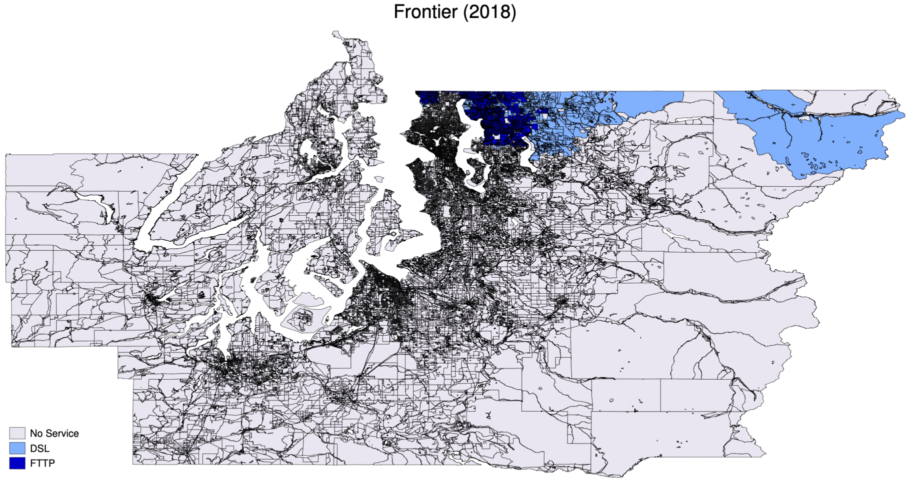


Figure A2. Seattle Technology Access and Adoption Survey (return)

Q5. **For each of the ways you get internet where you live, please tell us approximately how much each internet service costs per month to your household. If the cost is included as part of your rent or homeowner's dues, please check the box provided. If it is part of a bundled service that also includes other services (such as cable TV, calling and/or text, home security, etc.) please tell us the total cost per month for all bundled services:**
Please check all that apply.

		Answer for Separately Charged Services			Answer for Bundled Services	
	Have This Service Where I Live	**Included with My Rent or Homeowner Dues**	**Pay for Each Service Individually**	**Approx. Monthly Cost for Each Service**	**Pay as Part of Bundled Service**	**Approx. Monthly Cost for Bundled Services**
Century Link (DSL or fiber internet)	☐	☐	☐	$______	☐	$______
Wave cable internet	☐	☐	☐	$______	☐	$______
Comcast cable internet	☐	☐	☐	$______	☐	$______
Cellular data plan	☐		☐	$______	☐	$______
Other specify: ________________	☐	☐	☐	$______	☐	$______

Figure A3. Comcast (return)

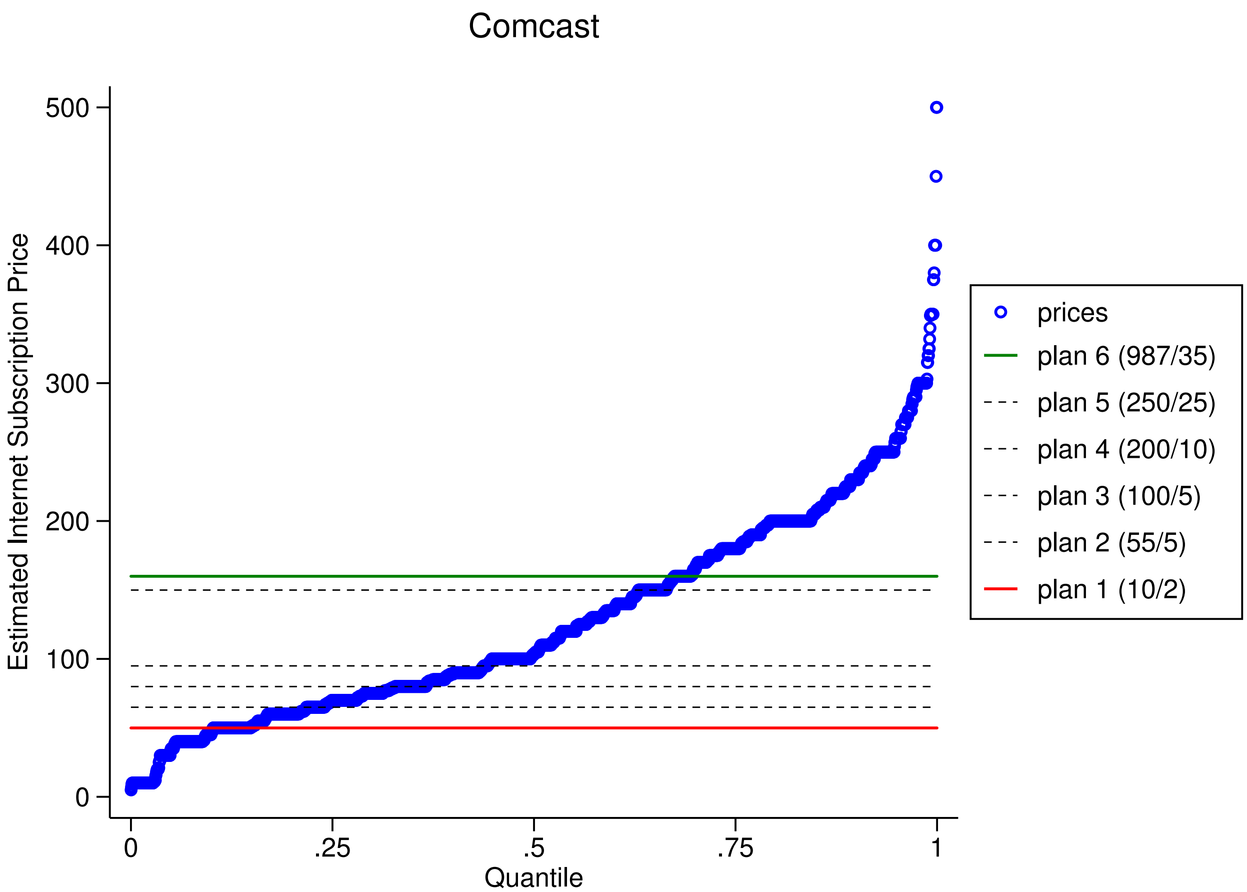


Figure A4. Wave (return)