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

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Abstract

I study whether competition between broadband providers increases firms' investment in high-speed Internet service. Using survey data on Seattle broadband subscriptions and broadband deployment data from the FCC, I estimate a structural model of the Seattle broadband market to determine the extent to which competitive pressure from cable providers spurred the incumbent DSL provider to deploy fiber. The model allows me to quantify firms' fixed costs of deployment, the effect of competition by cable providers on broadband availability and consumer welfare, as well as the effects of uniform pricing across geographic markets on competition and consumer welfare. I find evidence that the incentive to deploy fiber is weaker under competition from cable providers, however, the main benefit of competition among ISPs to consumers is lower prices, while increased availability of high-speed broadband is of second-order importance.

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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 the current technology that supports high-speed data transmission requires large sunk cost investments. As a result, many American households have few choices of broadband providers, and broadband subscriptions are relatively expensive. 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. because of 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. Furthermore, due to the scale of upfront capital costs necessary to deploy broadband, there may be underprovision of high-speed Internet service not only in rural communities, but even in urban centers where high prices, as a result of a lack of competition, restrict the supply of broadband subscriptions. The current state of the industry begs the following questions: (1) is competition sufficient to ensure widespread access to affordable, high-speed broadband? (2) under what circumstances should the government play a role in increasing the availability of broadband?

In addition to usual concerns about the potential anti-competitiveness of concentrated industries in antitrust, another potential market failure particular to the broadband industry is related to positive externalities associated with the adoption of Internet service. For example, Greenstein and McDevitt (2009) show that increasing adoption of broadband boosts overall economic productivity. More recently, Zho (2021) shows that increased Internet access results in greater employment opportunities and more favorable labor market outcomes in low income communities. Given these positive externalities, understanding the mechanisms that affect the availability of broadband is perhaps even more crucial if underprovision is suspected.

In this paper, I investigate the private incentives of Internet service providers to deploy high-speed Internet to some geographic markets, but not to 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 DSL to fiber in different areas in and around the city.

Initially, I undertake a causal analysis to isolate the effect of competition on broadband providers' deployment decisions. I regress providers' deployment decisions on measures of competition, conditional on market characteristics, to identify competitive effects. However, because providers' deployment decisions are endogenous there is no obvious exogenous variation in market structure, and since we observe that firms tend to enter markets with high demand, taking this reduced-form approach, I find positive correlations between deployment decisions and measures of competition.

In order to address market structure endogeneity, I develop a structural model of the broadband industry in which ISPs' deployment decisions, subscription prices, and household demand for broadband are determined in equilibrium. My estimated model allows me to evaluate the channels through which competition affects consumer surplus, including improved quality and lower prices. I use the model to determine (i) whether CenturyLink's incentives to deploy fiber are stronger with or without competition from its major competitor, Comcast, (ii) the socially optimal number of broadband providers, and (iii) the impact of geographic price dispersion on the level of competition and consumer surplus.

In order to estimate the model, I collect ISP deployment data and data on providers' broadband subscription characteristics from the FCC, as well as micro data on households' broadband subscription choices from a 2018 survey of Seattle households. Estimation follows the two step procedure of Aguirregabiria and Ho (2012). In the first step, I estimate household demand for broadband a la Berry, Levinsohn, and Pakes (1995). In the second step, given the estimates of the demand parameters from step 1, I estimate ISPs' fixed costs of deployment where providers compete in a game of incomplete information. With these estimates I perform counterfactual simulations to address some of the public policy issues raised above.

I find that if the incumbent telephone provider CenturyLink were a monopolist, it would have a greater incentive to deploy DSL and high-speed fiber to some areas. Holding prices constant, this increase in coverage and quality results in consumer welfare gains for households in these areas. However, when CenturyLink prices as a monopolist, on net these gains are erased by price increases—this reduction in consumer welfare is even more acute when the firm engages in price discrimination. Moreover, the loss of service and price competition from Comcast leads to a large net reduction in consumer welfare, which greatly outweighs the gains to select households where new broadband deployment occurs. Overall these results demonstrate the substantial value of competition to consumers in the market for broadband, particularly price competition. Additionally, I find that as a monopolist, CenturyLink has a strong incentive to price discriminate across its service area, therefore, the fact that ISPs engage in uniform pricing under competition suggests that this is a strategy meant to soften competition.

This paper contributes to the broadband literature by developing and estimating an equilibrium model of the industry that can be used to assess important market outcomes and public policy issues. Additionally, I add to the empirical literature in industrial organization evaluating the relationship between competition, market structure, entry, and product quality under oligopolistic competition. Finally, I contribute to the literature analyzing firms' pricing strategies, in particular analyzing the implications of uniform pricing in the broadband industry, in the spirit of DellaVigna and Gentzkow's (2020) investigation of uniform pricing in retail chains.

1.1 Competition and Market Structure

Understanding how competition and industry consolidation affect market outcomes other than price, including entry, product variety, and innovation, has become an increasing focus of antitrust policy and research in industrial organization (see Horizontal Merger Guidelines 2010). The title of this paper is a twist on research that investigates some of these outcomes in the microprocessor industry, Goettler and Gordon's (2011) "Does AMD Spur Intel to Innovate More?" The central question of this paper is, does competition between AMD and Intel generate more consumer welfare greater than if Intel were a monopolist? Because competition between firms generally decreases prices, but the effect of competition on product quality is in theory ambiguous (for a theoretical treatment see Vives 2008), whether consumer welfare is greater under monopoly or duopoly is an empirical question. Goettler and Gordon (2011) estimate a structural model and find that prices are lower under duopoly but the rate of innovation is higher under monopoly; overall, consumer welfare is greater under duopoly. Their research not only demonstrates that the ambiguous relationship between market structure and consumer welfare can be identified empirically, but also demonstrates the importance of industry-specific research in the field of industrial organization. For example, they find that product durability plays a key role in the microprocessor industry, which tempers welfare losses from market power in this context.

Related analyses of the relationship between market structure and competition in the broadband industry are scarce because publicly available data on household demand for broadband is extremely limited. However, studies of industries with similar characteristics, namely those with large fixed costs, small marginal costs, and few firms, do exist, in particular for the cable television and mobile telecommunications industries.

Goolsbee and Petrin (2004) and Chu (2010) examine the impact of the entry of direct broadcast satellite into local television markets on prices, product quality, and consumer welfare. Both find that without competition from satellite television providers cable prices would have been significantly higher and cable quality would have been lower. However, neither study endogenizes television providers' entry decisions. Not accounting for endogenous market structure may lead to an overestimate of consumer welfare, because firms may respond optimally to increased competition either by exiting the market or failing to enter to begin with.

More recently, Elliott, Houngbonon, Ivaldi, and Scott (2021) develop and estimate a model of endogenous infrastructural investment among mobile telephone providers. They find that consolidation generally reduces consumer welfare, however, the physical properties of telecommunications infrastructure generate economies of scale that are a countervailing force, which increases consumer welfare on the margin. Like Gordon and Goettler's (2011) work on microprocessors, the details of the mobile telecommunications industry turn out to matter a great deal for their finding. In this case, synergies in the allocation of spectrum partially offset the anticompetitive effects of consolidation.

I draw on these papers and others in the market structure literature in modeling broadband providers' deployment decisions.

1.2 Previous Broadband Studies

A key component of my analysis is estimating demand for residential broadband. Despite the importance of broadband to modern consumers, there have been relatively few empirical studies that have estimated demand for residential broadband, likely because high-quality publicly available data, and even high-quality proprietary data, is scarce.

Some early studies include, Goolsbee (2006), Dutz, Orszag, and Willig (2009), and Rosston, Savage, and Waldman (2010), all of which estimate aggregate demand for broadband without detailed product-level transaction data. Goolsbee (2006) uses survey data on consumers' stated willingness-to-pay for broadband to estimate aggregate demand for broadband across 69 U.S. cities. Dutz, Orszag, and Willig (2009) use proprietary transaction level data to estimate a discrete choice model of household demand for different internet connections including dial-up cable modem, DSL, satellite, and fiber. Rosston, Savage, and Waldman (2010) use a survey instrument to estimate households' willingness-to-pay for differentiated broadband subscriptions.

More recently, Nevo, Turner, and Williams (2016) use a rich dataset from an unnamed North American ISP to estimate demand for broadband subscriptions differentiated by speed, price, and monthly usage allowance. The authors' primary interest is in how subscribers respond to their monthly usage-allowances, which constrain households' monthly Internet content consumption. They find that subscribers are sensitive to this constraint, and in counterfactual simulations show that the introduction of usage-based pricing would eliminate low-value traffic on the ISPs' network.

Most recently, Goetz (2019) uses publicly available data from the FCC on ISPs' coverage areas, plans and prices, and data from ISPs' annual earnings reports to construct a national dataset on households' choice of ISP with which to estimate households' demand for different broadband providers. Goetz then uses these demand estimates as an input in a bargaining model where ISPs and a streaming content provider negotiate over interconnection fees. Goetz evaluates the effect of ISP mergers on bargaining outcomes and finds that small ISP mergers would reduce the content provider's bargaining surplus, where as larger mergers would have little impact on the distribution of bargaining power.

In this paper, the dataset that I construct to estimate demand most closely resembles Goetz (2019). However, I supplement publicly available data from the FCC with micro data from the city of Seattle on individual households' choice of ISP and subscription, which allows me to estimate a rich micro-BLP style demand model for Seattle households. I compare reported own-price elasticities of demand in the broadband literature to my own estimates and find that they are quite similar.

1.3 Outline

The rest of the paper is organized as follows. Section 2 describes the model of providers' broadband deployment decisions and household demand for broadband. Section 3 describes the dataset I use to estimate the model. In Section 4, I discuss the estimation procedure and present the empirical results. In Section 5, I describe the implementation of the counterfactual simulations I conduct to evaluate the effects of competition on market structure, and I discuss the results. Section 6 concludes.

2 Model

In this section, I describe a model of ISPs' deployment decisions across a geographic market, which depends 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 have been realized, firms set prices with full information about their rivals' products. The structure of information in this model reflects the fact that firms' pricing decisions are more flexible than firms' deployment decisions.

I begin by describing the model of household demand for broadband, followed by the model of ISPs' deployment decisions.

2.1 Household Demand for Broadband

Within a geographic market, Internet service providers offer households a menu of plans or subscriptions 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 $D_{i,m}$, which allows households with different characteristics to have varying preferences for broadband.

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 formula,

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

When we assume that households' preferences for broadband are identical, $\mu_{i,j,m} \equiv 0$, the aggregate market share of product j is given by,

$$S_{j,m} = \frac{\exp\left(\delta_{j,m}\right)}{1 + \sum_k^J \exp\left(\delta_{k,m}\right)}. \tag{5}$$

When we assume that households have heterogenous preferences for broadband that vary with observable demographic characteristics, the aggregate market share of product j is given by,

$$S_{j,m} = \int \frac{\exp\left(\delta_{j,m} + \mu_{i,j,m}\right)}{1 + \sum_k^J \exp\left(\delta_{k,m} + \mu_{i,k,m}\right)} dG_{D_m}(D_{i,m}), \tag{6}$$

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

2.2 Providers' Deployment Decisions

Consider a market with $\mathcal{F}$ potential entrants, where firms or Internet service providers 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.

2.2.1 Total Profits

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

$$\Pi_{f,m,none} = 0 + \sigma\epsilon_{f,m,none}. \tag{7}$$

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

$$\underbrace{\Pi_{f,m,\tau}(a_{-f,m}, z_{f,m}, M_m, \epsilon_{f,m,\tau})}_{\text{Total Profit}} = \underbrace{\pi_{f,m,\tau}(a_{-f,m}, M_m)}_{\text{Variable Profit}} - \underbrace{F_{f,m,\tau}(z_{f,m}, M_m, \epsilon_{f,m,\tau})}_{\text{Fixed Cost}}, \tag{8}$$

where the firm's total profit is made up of its variable profit $\pi_{f,m,\tau}(.)$ minus its fixed cost $F_{f,m,\tau}(.)$, plus $\epsilon_{f,m,\tau}$, the firm's private information, which has variance σ^2.

The variable $z_{f,m}$ represents the state of the firm, which is defined as the firm's deployment decision in the previous year $z_{f,m,t} \equiv a_{f,m,t-1}$. The variable M_m is the size (in number of households) of submarket m. The variables $z_{f,m}$, M_m, and the distribution of $\epsilon_{f,m,\tau}$, $G_\epsilon(\epsilon)$, are common knowledge for all firms.

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

2.2.2 Variable Profits

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

$$\pi_{f,\tau} = 12 \cdot M \sum_{j \in \mathcal{J}_f} S_j(a_{-f}, \mathbf{p})(p_j - c_j), \tag{9}$$

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 $\mathbf{p}$. Finally, 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.

2.2.3 Fixed Costs of Deployment

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

$$F_{f,\tau} = \phi_{f,\tau} + \underbrace{\mathbb{1}(z_f = none) \cdot [\theta^E_{f,\tau} + M\vartheta^E_{f,\tau}]}_{\text{Entry Cost}} + \underbrace{\mathbb{1}(z_f \neq \tau) \cdot [\theta^A_{f,\tau} + M\vartheta^A_{f,\tau}]}_{\text{Adjustment Cost}} + \sigma\epsilon_{f,\tau}, \tag{10}$$

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 an operating cost ϕ_τ associated with the technology it deploys. If the firm did not operate in the census block previously ($z_f = none$), then it pays a fixed entry cost ($\theta^E_{f,\tau} + M\vartheta^E_{f,\tau}$), which depends on the technology it deploys and on the number of households in the census block. Similarly, if the firm did previously operate in the census block, but chooses to change the technology it deploys there ($z_f \neq \tau$), then it pays a fixed adjustment cost ($\theta^A_{f,\tau} + M\vartheta^A_{f,\tau}$), which again depends on the technology it deploys and the number of households.

2.2.4 Providers' Strategies and Equilibria

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

$$\varphi_f : (z_f, M, \epsilon_f) \rightarrow \{none, dsl, fiber, cable\}.$$

Each firm has uncertainty about the deployment decisions of its competitors, because it does not know $\epsilon_{-f,\tau}$. Therefore, each firm maximizes its expected profits given its private information $\epsilon_{f,\tau}$ 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,

$$\mathbb{E}[\Pi_{f,\tau}(\varphi_{-f}^*, z_f, M, \epsilon_{f,\tau})] \geq \mathbb{E}[\Pi_{f,\tau'}(\varphi_{-f}^*, z_f, M, \epsilon_{f,\tau'})], \forall \tau' \neq \tau.$$

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 $\varphi_f(z_f, M, \epsilon_f)$,

$$P_{f,\tau} = \int \mathbb{1}\big(\varphi_f(z_f, M, \epsilon_f) = \tau\big) dG_{\epsilon_f}(\epsilon_f). \tag{11}$$

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

$$P_{f,\tau} = \frac{\exp\left(\mathbb{E}[\Pi_{f,\tau}(\mathbf{P}_{-f})]\right)}{\sum_{\tau'} \exp\left(\mathbb{E}[\Pi_{f,\tau'}(\mathbf{P}_{-f})]\right)}, \tag{12}$$

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,

$$\mathbb{E}[\Pi_{f,\tau}(\mathbf{P}_{-f})] = \mathbb{E}[\pi_{f,\tau}(\mathbf{P}_{-f})] - F_{f,\tau}, \tag{13}$$

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 $\epsilon_{f,\tau}$.

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

$$\mathbb{E}[\pi_{f,\tau}(\mathbf{P}_{-f})] = \sum_{a_{-f}} \Big(\prod_{r \neq f} P_r(a_r = \tau')\Big) \pi_{f,\tau}(a_{-f}) \tag{14}$$

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,

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

The interpretation of this fixed point is that every provider is choosing the probability distribution over its deployment decisions 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,

$$P^*_{f,\tau}(\Theta) = \Psi_{f,\tau}\big(\mathbf{P}^*_{-f}(\Theta)\big), \forall f, \tau. \tag{16}$$

Given the set of parameters representing providers' fixed costs of deployment $\Theta = \{\theta^E_{f,\tau}, \vartheta^E_{f,\tau}, \theta^A_{f,-\tau}, \vartheta^A_{f,-\tau}, \sigma\}$, this system may have multiple equilibria. 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 (see Aguirregabiria and Mira 2007).

2.2.5 Providers' 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.

$$\mathbf{\Pi}_f = \sum_m \Pi_{f,\tau} = \sum_m \pi_{f,m,\tau} - \sum_m F_{f,m,\tau}. \tag{17}$$

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,

$$\frac{\partial \mathbf{\Pi}_f}{\partial p_j} = \sum_m \frac{\partial \pi_{f,m,\tau}}{\partial p_j} - 0 = 0, \tag{18}$$

where again the firm's variable profit function is,

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

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

$$\frac{\partial \mathbf{\Pi}_f}{\partial p_j} = \sum_m 12 \cdot M_m \cdot S_{j,m} + \sum_m \sum_j 12 \cdot M_m \cdot \frac{\partial S_{j,m}}{\partial p_j}(p_j - c_j) = 0 \tag{19}$$

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,

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

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,

$$\begin{bmatrix} \sum_m S_{1,m} M_m \\ \sum_m S_{2,m} M_m \\ \vdots \\ \sum_m S_{J,m} M_m \end{bmatrix} + \left[\sum_m \Delta_m \right] \begin{bmatrix} p_1 - c_1 \\ p_2 - c_2 \\ \vdots \\ p_J - c_J \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \tag{20}$$

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

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

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

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

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

3 Data

I construct a dataset on households' broadband subscription choices and ISPs' deployment decisions for the city of Seattle and surrounding counties. To construct 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) for additional information about the share of households without broadband subscriptions, as well as to enrich my demand model with demographic data and to estimate the number of households in each census block. 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 data on individual ISPs' broadband subscriptions is not publicly available. Although aggregate sales data is available from broadband providers' public filings, it is difficult to construct a realistic model of demand with these data because ISPs' do not report broadband subscriptions for different geographic markets nor do they report plan-specific subscriptions 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 his/her 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 asked to estimate the monthly cost of the household's Internet subscription (see figure 1). 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.

The data described above allows me to estimate providers' aggregate market shares by zip code, however, ISPs offer households a variety of subscriptions that vary in quality and price. In order to estimate the market share of every plan offered by each broadband provider, I rely upon survey respondents' own estimates of their monthly subscription fees, which I use to identify, or at least approximate, the plan to which each household subscribes. 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. However, measurement error in prices and product characteristics may lead to attenuation bias of my demand estimates.

In order to match households' survey responses to ISPs' plans, I collect data on each provider's menu of subscriptions from the FCC's 2018 Broadband Urban Rate Survey. The Urban Rate Survey is published annually by the FCC to track the change 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), which is collected by web-scraping providers' websites for baseline subscription information. I use plans and prices for the state of Washington 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 according to these bands. In general, I use the following interpolation rule,

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

where $j_i(p_i)$ is household i's choice of subscription, which depends on its estimated monthly subscription fee 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 2, 3, and 4 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.

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. I restrict my sample to only include the major fixed wireline broadband providers that serve Seattle and surrounding areas: CenturyLink, Comcast, Wave, Frontier, and the City of Tacoma's municipal broadband service. While other ISPs, including satellite and wireless providers serve Seattle, as is evident from the 2018 Seattle Technology Access and Adoption Study data, most broadband subscribers purchase service from one of the major fixed wireline providers in Seattle: CenturyLink, Comcast, or Wave.

Figures 5, 6, and 7 show CenturyLink, Comcast, and Wave's coverage areas in the Seattle MSA including maximum downstream speeds and technology deployment decisions in 2018, as well as the difference in firms' deployment decisions from 2017 to 2018.

Figure 8 shows the 2018 coverage areas of CenturyLink, Comcast, Wave, Frontier, and the City of Tacoma's municipal broadband service in 5 major counties surrounding Seattle: King, Kitsap, Mason, Pierce, and Thurston.

3.3 Reduced-form Analysis

The central question of this paper is how does competition affect Internet service providers' deployment decisions? To demonstrate why a structural model is necessary to answer this question, I run a series of reduced-form regressions using data on providers' technology deployment decisions to try and tease out the effect of competition from rivals on firms' deployment decisions. However, as I discuss in more detail, these regressions are not causal, because market structure endogeneity confounds the identification of true competitive effects.

Theoretical and empirical work in industrial organization including Sutton (1991) has shown that market structure endogeneity is a confounding factor which can prevent the identification of competitive effects in empirical studies. Because the number of firms competing in a market is an equilibrium outcome, the causal effect of competition is challenging to identify without modeling firm behavior or without some source of exogenous variation in competition.

For example, to try and quantify the effect of competition on ISPs' deployment decisions in the current setting, one might consider regressing provider's decisions on the presence of competitors, conditional on market characteristics. In theory, controlling for differences across markets, we would expect to see that providers find it more profitable to deploy service in markets with fewer competitors, and so competition should have a negative impact on entry. However, empirical studies have often found an attenuated or even positive effect of competition on firms' entry decisions, because firms tend to concentrate, or collocate, in larger more profitable markets, while avoiding entry into smaller less profitable markets. In other words, the effect of competition on entry is typically attenuated because cross-sectional data shows that firms enter the same markets, despite greater levels of competition.

The theory of endogenous market structure can explain this pattern often seen in data. If each firm decides to enter a market based on the degree of competition it expects to face, then all firms' entry decisions are interlinked and determined simultaneously in equilibrium (the model of broadband deployment I described above is one model of such behavior). On the one hand a firm may want to enter a particularly profitable market with high demand, on the other hand it expects that other firms will also want to enter the same market. As discussed in Seim (2006) this behavior can lead to ex post regret by firms either when too many or too few firms enter a market. As a result, isolating the true effect of competition from such data, without modeling firm behavior, is difficult except in industries where entry is regulated and exogenous variation in market structure may occur as the result of a change in regulation. For example, Vives (2008) suggests studying exogenous changes in the market structure of regulated markets as a potentially fruitful avenue for empirical work. However, this empirical approach significantly limits the set of questions IO economists and policymakers would like to answer about the relationship between market structure and competition in a wide range of industries.

With the caveats above in mind, I run a series of OLS regressions on providers' entry and upgrade decisions in different census blocks on measures of competition, conditional on census block characteristics, to attempt to tease out the effects of competition on ISPs' deployment decisions. To better isolate these competitive effects I match comparable census blocks on the basis of providers' past deployment decisions. In the case of entry decisions I only compare census blocks where the firm either chose not to operate in both 2017 and 2018 or chose to enter in 2018. That is I exclude census blocks where the firm already had a presence in 2017. Similarly, for upgrade decisions I only compare census blocks where the firm operated as a DSL provider in both 2017 and 2018 or chose to upgrade from DSL to fiber in 2018. This allows me to compare outcomes in census blocks where the firm was either choosing to enter for the first time or choosing to upgrade service without mixing in variation from non-comparable census blocks.

For simplicity, I denote census blocks where the provider either entered or upgrade its service ($y_{f,m} = 1$) "treatment" group observations, and the comparable census blocks in each case ($y_{f,m} = 0$) "control" group observations (note that this terminology has no relationship to the usage of treatment and control groups in a randomized control trial or difference-in-differences analysis).

Formally, firm f's entry outcome in census block m is defined as,

$$y_{f,m}^{entry} = \begin{cases} 0, & \text{if No Service in 2017 and 2018 (“Control”)} \\ 1, & \text{if No Service in 2017 and Service in 2018 (“Treatment”)} \end{cases},$$

and the entry regression is specified as the following equation,

$$y_{f,m}^{entry} = \beta_0 + \beta_1 Households_m + \beta_2 LandArea_m + \beta_3 \sum_{r \neq f} d_{r,m} + \epsilon_m. \tag{21}$$

Similarly, firm f's upgrade outcome in census block m is defined as,

$$y_{f,m}^{upgrade} = \begin{cases} 0, & \text{if DSL in 2017 and 2018 (“Control”)} \\ 1, & \text{if DSL 2017 and Fiber in 2018 (“Treatment”)} \end{cases},$$

and the upgrade regression is specified as the following equation,

$$y_{f,m}^{upgrade} = \beta_0 + \beta_1 Households_m + \beta_2 LandArea_m + \beta_3 \sum_{r \neq f} d_{r,m} + \epsilon_m. \tag{22}$$

In both regression equations β_1 and β_2 capture the effects of census block characteristics on firms' decisions, while β_3 captures the effect of competition. I also run a series of regressions that allows the effect of competition to vary over the firm's rivals.

I run these regressions for the two largest broadband providers in the Seattle area: CenturyLink and Comcast. Again, because firms' strategic decisions are endogenous, these regressions show correlations as opposed to causal effects. However, the regressions also demonstrate the variation in the data that allows me to identify the fixed cost parameters associated with entry and upgrade decisions in the estimation of the structural model.

The reduced-form regression results are displayed in table 3. Based on these regressions, I find that the effect of competition on providers' deployment decisions is relatively weak, consistent with the endogeneity problem I described. In fact, the results suggest conditional on market size and density, the number of competing firms has either a near-zero effect or a statistically significant positive effect on providers' entry decisions. Again, these near-zero or positive correlations are due to the fact that firms concentrate in the largest and most profitable markets in equilibrium despite the unambiguously negative impact that competition has on their bottom line.

In regression specifications where I allow for variation in competitive effects across providers some distinct patterns emerge. CenturyLink's entry decisions are positively correlated with cable providers (Comcast and Wave) but negatively correlated with the other major telecom provider in the Seattle area, Frontier. Likewise, Comcast's entry decisions are positively correlated with telecom providers (CenturyLink and Frontier) but negatively correlated with major cable provider Wave. The fact that ISPs operating with the same technologies exhibit less overlap than those operating with different technologies reflects the historical development of the broadband industry, where legacy telephone companies and cable providers operated near monopolies in the provision of wireline telephone service and cable television service before they both began competing in the market for residential broadband.

In any event, this analysis demonstrates the confounding effect of endogenous market structure in attempting to establish the causal effect of competition on providers' deployment decisions without a model of firm behavior or source of exogenous variation in market structure. All else equal, we would expect competition to have an unambiguously negative impact on firms' entry decisions, yet the fact that providers likely choose simultaneously to enter the same profitable markets confounds this effect. These results demonstrate why a structural model of competition that accounts for the fact the providers' deployment decisions are determined in equilibrium might yield more insight about the effects of competition in the broadband industry.

4 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 the demand parameters using subscriber data, then using data on providers' deployment decisions and predictions of providers' profits from the demand model, I estimate providers' fixed cost parameters.

I estimate households' demand for broadband using two methods. First, I estimate a baseline logit demand model assuming consumers have homogenous preferences for broadband using zip code level data on households' subscription choices. Then, I estimate a mixed logit demand model which allows households' preferences for broadband to vary over their demographic characteristics using the Generalized Method of Moments (GMM). To do this I use household-level data from the 2018 Seattle Technology Adoption Survey to construct and add micro-moments to the demand model, following Berry, Levinsohn, and Pakes (2004). I discuss both estimation procedures 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 demand parameters to predict providers' expected profits in different census blocks. Then using these estimates of profits and ISPs' deployment data, I estimate providers' fixed costs of deployment corresponding to behavior predicted by the game of incomplete information. I estimate the game using the Nested Pseudo-Likelihood (NPL) estimator of Aguirregabiria and Mira (2002, 2007). Once both pieces of the structural model are estimated, I use the model to make policy-relevant predictions about the effect of competition on both the supply of and demand for broadband in counterfactual simulations.

4.1 Logit Demand Estimation

Recall the model of household demand previously described. First, I estimate a version of the model where I assume households have homogenous preferences for broadband or, $\mu_{i,j,m} = 0$, in which case household i's indirect utility from subscribing to plan j is simply,

$$u_{i,j,m} = x_j'\beta - \alpha p_j + \xi_{j,m} + \epsilon_{i,j,m}, \tag{23}$$

where aggregate market shares are given by,

$$S_{j,m} = \frac{\exp\left(x_j'\beta - \alpha p_j + \xi_{j,m}\right)}{1 + \sum_k^J \exp\left(x_k'\beta - \alpha p_k + \xi_{k,m}\right)}. \tag{24}$$

In order to calculate the empirical analog of these shares, I combine estimates of zip code level product market shares from the 2018 Seattle Survey with zip code level data on the share of households with fixed wireline broadband subscriptions reported in the 2018 ACS. The aggregate market share for plan j in zip code m is given by,

$$S_{j,m} = \underbrace{Pr(\text{Purchase Broadband})_m}_{\text{ACS Data}} \times \underbrace{Pr(\text{Purchase Plan } j|\text{Purchase Broadband})_m}_{\text{Seattle Survey}},$$

where the share of households with broadband subscriptions in zip code m according to ACS data is,

$$Pr(\text{Purchase Broadband})_m = \frac{\text{Households w/ Broadband}_m}{\text{Total Households}_m},$$

and the estimated share of households with plan j in zip code m according to the survey data is,

$$Pr(\text{Purchase Plan } j|\text{Purchase Wireline})_m = \frac{\text{Households w/ Plan } j_m}{\text{Households w/ Broadband}_m}.$$

In this case the estimating equation, which can be estimated with OLS or linear IV, is given by,

$$\log\left(\frac{S_{j,m}}{S_{0m}}\right) = \delta_{j,m} \equiv x_j'\beta - \alpha p_j + \xi_{j,m}. \tag{25}$$

In estimating the model I choose two different parameterizations of the households' mean utility δ_{jm}, a "linear" specification and a "log" specification. Both the linear specification,

$$\delta_{j,m} = \beta^d x_j^d + \beta^u x_j^u + \beta_j^b - \alpha p_j + \xi_{j,m},$$

and the log specification,

$$\delta_{j,m} = \beta^d \log(x_j^d) + \beta^u \log(x_j^u) + \beta_j^b - \alpha \log(p_j) + \xi_{j,m},$$

include downstream bandwidth (in mbps) x_j^d, upstream bandwidth (in mbps) x_j^u, and brand β_j^b as the product characteristics of subscription j.

Like previous empirical work on estimating demand for broadband including Nevo, Turner, and Williams (2016) and Goetz (2019), I find that the results of the log specification make more intuitive economic sense. Nevo, Turner, and Williams (2016) actually estimate a very flexible model of demand for broadband that nests linear and log utility from broadband consumption, of the form,

$$u_i\left(\frac{c^{1-\beta_i}}{1-\beta i}\right)$$

and find that β_i closer to 1 is a good fit for households' consumption of broadband, which is more consistent with a log utility function.

4.2 Mixed Logit Demand Estimation

In order to incorporate heterogenous preferences for broadband and make households' substitution patterns across products more realistic by relaxing the I.I.A. assumption imposed by the baseline logit model, I allow households' preferences to depend on their demographic characteristics.

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,

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

I specify the variance component of demand as,

$$\mu_{i,j} = \sum_{n=2}^{3} \alpha_n \log(p_j) Inc_{n,i} + \sum_{n=2}^{4} \beta_n^d \log(x_j^d) Size_{n,i} + \sum_{n=2}^{4} \beta_n^u \log(x_j^u) Size_{n,i} \tag{26}$$

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

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 the same as before except without variation in aggregate market shares across m, the unobservable demand shocks ξ vary only over products. Based on the results of the baseline logit, I use log product characteristics and price,

$$\delta_j = \beta^d \log(x_j^d) + \beta^u \log(x_j^u) + \beta_j^b - \alpha \log(p_j) + \xi_j. \tag{27}$$

With household heterogeneity the probability that household i subscribes to plan j is given by,

$$s_{i,j} = \frac{\exp(\delta_j + \mu_{ij})}{1 + \sum_k^J \exp(\delta_k + \mu_{i,k})}. \tag{28}$$

In order to estimate the model, I jointly estimate equations (27) and (28) using GMM. First, I derive the log-likelihood function of equation (28),

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

where d_{ij} is dummy variable indicating whether household i subscribes to broadband plan j. This function depends on the mean utilities associated with 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 (28). 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 when prices are assumed to be endogenous.

The model can be estimated in two steps by estimating the parameters of equation (28) $\theta_1 = (\delta_j, \alpha_n, \beta_n, \lambda_n)$ using maximum likelihood (MLE) and then estimating the parameters of equation (27) $\theta_2 = (\alpha, \beta)$ using liner IV. Alternatively, the model can be estimated in one step by estimating equations (27) and (28) jointly using GMM. Point estimates are the same whether the equations are estimated separately or together, however, standard errors are correct when the equations are estimated jointly using GMM.

To form moments for equation (28), 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 (see Train 2003). The moment conditions associated with equation (27) 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 (28), and the second block contains weights for the macro-moments associated with equation (27), is given by,

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

I minimize the weighted distance of the stacked moments to find the optimal vector of parameters $\hat{\theta}^*$.

4.2.1 Estimating Aggregate Market Shares Across Markets

With parameter estimates from the mixed logit demand model, it is possible 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 realistic approximation would account for covariation in these characteristics among households. I report summary statistics for the demographic data underlying the market-specific demographic weights ω_{im} in table 4.

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

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

In practice, I use the mixed logit demand estimates to predict aggregate market shares for broadband subscriptions in different census blocks, which are used as an input in the estimation of providers' fixed costs.

4.3 Identification and Instrumental Variables for Price

The price of broadband subscriptions is endogenous in the demand model, 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, Levinsohn, and Pakes (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, Levinsohn, and Pakes (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, Stern, and Trajtenberg (1997) use a variation on these instruments where, rather than summing over product characteristics, they average over product characteristics.

In my application, because product characteristics are invariant over markets, 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, following Bresnahan, Stern, and Trajtenberg (1997) I use mean own-product characteristics as instruments for price.

Unfortunately, because my demand specification includes brand dummy variables, which are invariant over firms, the second set of instruments proposed by Berry, Levinsohn, and Pakes (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,

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

In specifications where demand is a function of log price, I use the instruments, $\log(z_j^d), \log(z_j^u)$, instead.

The vector of instruments that is interacted with the demand shocks ξ in the both the simple logit and mixed logit demand models is,

$$\mathbf{Z} = [z_j^d, z_j^u, x_j'].$$

4.4 Demand Results

Table 5 displays the results of the baseline logit model. All specifications of the baseline logit include market (zip-code) fixed effects. In the first two specifications, household utility is a linear function of product characteristics and price. Notice that instrumenting for price increases the magnitude of the price coefficient and the mean own-price elasticity increases in magnitude from -0.915 to -1.337. However, the price coefficient is not statistically significant in the linear specifications, and unexpectedly, households are less sensitive to increases in downstream bandwidth than upstream bandwidth.

In the third and fourth specifications, household utility is a function of log product characteristics and price. In these specifications, the magnitude of the price coefficient is greater and statistically significant. Again, instrumenting for price increases the magnitude of the price coefficient substantially, and the mean own-price elasticity increases in absolute terms from -6.840 to -22.820. The coefficient on log download speed is statistically significant and larger than the coefficient on log upload speed, which is consistent with how one would expect households to prioritize plan characteristics, as well as consistent with how ISPs generally differentiate their plans.

An overidentification test of the instruments included in both IV regressions shows that exogeneity of the instruments for price cannot be rejected.

Based on the results of the baseline logit model, the specifications with log product characteristics and price seem to make more intuitive economic sense, given the relative importance of download and upload speeds, as well as larger own-price elasticities.

Table 6 displays the results of the mixed logit model. 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 mean that the main price coefficient is no longer statistically significant, the own-price elasticities by income bracket (approximately -3.741, -3.169, and -2.944 for low, middle, and high income households, respectively) are more elastic and in line 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, Orsang, and Willig (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. Roston, Savage, and Waldman (2010) find more inelastic demand (-0.44) using a survey instrument to estimate demand. Finally, using the most comparable data to my own, and a BLP-style demand model, Goetz (2019) reports a mean-own price elasticity of -5.901.

The own-price elasticities of the mixed logit 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, Sun, and Verboven (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 of the mixed logit model make economic sense too. 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).

4.5 Fixed Cost Estimation

In this section, I estimate the game of incomplete information described in section 2 to recover providers' fixed costs of deployment in and around the city of Seattle.

I estimate the model using deployment data for CenturyLink and Comcast only.

This is because I observe household demand for CenturyLink, Comcast, and Wave but not for either Frontier or the city of Tacoma's municipal broadband service. Additionally, Wave's deployment decisions vary very little between 2017 and 2018, which prevents me from identifying its fixed costs of deployment. However, the deployment data from FCC's Form 477 shows that CenturyLink and Comcast are the dominant ISPs in Seattle and in the surrounding counties (see Figure 8).

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 7, 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.

4.5.1 Variable Profits

In order to estimate the model, I use the mixed logit demand parameters to predict CenturyLink and Comcast's variable profits in each census block,

$$\hat{\pi}_{f,m,\tau} = 12 \cdot M_m \sum_{j \in \mathcal{J}_f} \hat{S}_{j,m}(a_{-f,m}, \mathbf{p})(p_j - \hat{c}_j),$$

under different potential deployment scenarios. With 3 deployment choices for CenturyLink and 2 deployment choices for Comcast, there are 6 possible scenarios in each census block:

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

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

I calculate the market shares of each provider's plan $\hat{S}_{j,m}$ under these scenarios based on the mixed logit demand parameters. Then I combine these with estimates of providers' marginal costs $\hat{c}_j$, which I get by "backing out" the implied marginal cost of each subscription assuming uniform Nash-Bertrand pricing behavior. I describe this in greater detail below.

4.5.2 Marginal Costs

Based on my demand estimates and given that providers engage in uniform Nash-Bertrand pricing across their coverage areas, as previously outlined, following Nevo

(2000) I use the set of providers' FOCs to "back out" marginal costs for CenturyLink and Comcast's subscriptions.

In the data, I observe census blocks where CenturyLink deploys DSL and fiber, as well as where Comcast deploys cable. To estimate the marginal costs using the mixed logit estimates, I calculate: (1) the predicted shares of each plan in each census block, $S_{j,m}$, and (2) the predicted price effects in each census block Δ_m. With these estimates, I sum over all census blocks in each provider's coverage area to obtain marginal costs with the following equation,

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

I present these estimates in table 8.

4.5.3 Fixed Cost Specifications

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

$$F_{\ell,m,dsl} = \phi_{dsl} + \mathbb{1}(z_{\ell,m} = none) \cdot [\theta^E_{dsl} + M_m \vartheta^E_{dsl}] + \mathbb{1}(z_{\ell,m} = fiber) \cdot [\theta^D_{dsl} + M_m \vartheta^D_{dsl}] + \sigma \epsilon_{\ell,m,dsl},$$

$$F_{\ell,m,fiber} = \phi_{fiber} + \mathbb{1}(z_{\ell,m} = none) \cdot [\theta^E_{fiber} + M_m \vartheta^E_{fiber}] + \mathbb{1}(z_{\ell,m} = dsl) \cdot [\theta^U_{fiber} + M_m \vartheta^U_{fiber}] + \sigma \epsilon_{\ell,m,fiber},$$

and I specify Comcast's fixed cost function as,

$$F_{f,m,cable} = \phi_{cable} + \mathbb{1}(z_{c,m} = none) \cdot [\theta^E_{cable} + M_m \vartheta^E_{cable}] + \sigma \epsilon_{f,m,cable}.$$

Recall that ϕ_τ is a fixed operating cost, θ^E_τ and ϑ^E_τ are fixed entry costs, and $\theta^D_\tau, \vartheta^D_\tau, \theta^U_\tau$ and ϑ^U_τ are fixed adjustment costs associated with a provider's deployment of technology τ.

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

$$\mathbf{\Theta} = \{\phi_{dsl}, \theta^E_{dsl}, \vartheta^E_{dsl}, \phi_{fiber}, \theta^E_{fiber}, \vartheta^E_{fiber}, \phi_{cable}, \theta^E_{cable}, \vartheta^E_{cable}, \sigma\},$$

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

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

$$\mathbf{\Theta} = \left\{\frac{\phi_{dsl}}{\sigma}, \frac{\theta^E_{dsl}}{\sigma}, \frac{\vartheta^E_{dsl}}{\sigma}, \frac{\phi_{fiber}}{\sigma}, \frac{\theta^E_{fiber}}{\sigma}, \frac{\vartheta^E_{fiber}}{\sigma}, \frac{\phi_{cable}}{\sigma}, \frac{\theta^E_{cable}}{\sigma}, \frac{\vartheta^E_{cable}}{\sigma}, \frac{1}{\sigma}\right\},$$

then, with these estimates, I can recover the fixed cost estimates in dollar terms by multiplying $\mathbf{\Theta}$ by σ (or equivalently by dividing by $\frac{1}{\sigma}$).

I denote the fixed cost estimates in dollar terms (which I scale to be in thousands of dollars) as,

$$\tilde{\mathbf{\Theta}} = \{\tilde{\phi}_{dsl}, \tilde{\theta}^E_{dsl}, \tilde{\vartheta}^E_{dsl}, \tilde{\phi}_{fiber}, \tilde{\theta}^E_{fiber}, \tilde{\vartheta}^E_{fiber}, \tilde{\phi}_{cable}, \tilde{\theta}^E_{cable}, \tilde{\vartheta}^E_{cable}\}.$$

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

4.5.4 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,

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

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

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

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

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

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

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

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

4.5.5 NPL Estimation

I estimate the game using the Nested Pseudo Likelihood (NPL) estimator based on Agguirregabiria and Mira (2002, 2007), which is robust to the presence of multiple equilibria given that the system of players' best-responses is stable. Specifically, I define a pseudo likelihood function where players' choice probabilities are best responses to an arbitrary $\mathbf{P}$; "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,

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

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 $\hat{\mathbf{\Theta}}$.

Agguirregabiria 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 the number of households (market size) and land area as the relevant census block characteristics in this step.

4.6 Fixed Cost Results

Tables 9 and 10 display the fixed cost estimates. Table 9 displays the raw parameter estimates $\mathbf{\Theta}$, and Table 10 displays the scaled parameter estimates $\tilde{\mathbf{\Theta}}$, which can be interpreted in units of thousands of dollars.

The fixed cost estimates follow the same pattern for different broadband technologies, and are generally of the expected sign and relative magnitude except for providers' operating costs. In terms of absolute magnitude, however, on a per census block basis, the fixed costs I estimate seem quite high compared to engineering estimates ($30,000-$50,000 per square mile). Operating costs ϕ_τ are negative and large, entry costs θ^E_τ are positive and larger than operating costs, adjustment costs $\theta^D_{dsl}, \theta^U_{fiber}$ are smaller than entry costs but still large and positive, and per household fixed costs ϑ_τ are very small.

One explanation for the negative estimates of providers' operating costs is that ISPs' deployment decisions are long-term capital investments, from which they expect to earn net profits over a certain time horizon, greater than one year. However, the model I estimate is essentially a one-shot game where providers' make their deployment decisions based on the previous year's decisions and earn variable profits for one year only. Because in reality providers' expect to earn a stream of variable profits over a longer time horizon, the negative operating cost parameters I obtain likely reflect the fact that providers' variable profits must be larger than I've estimated to reconcile the deployment decisions I observe in the data.

CenturyLink's annual operating costs per census block for DSL and fiber are -$126,000 and -$205,000, respectively. Given the explanation above, it makes sense that the operating cost parameter for fiber is larger in magnitude, because CenturyLink earns more variable profit from fiber. CenturyLink's fixed entry cost for DSL is $231,000 and close to double for the deployment of fiber at $407,000. Its per household entry costs make intuitive economic sense at $16 per household for DSL and $69 per household for fiber, however, these estimates are imprecise. CenturyLink's fixed adjustment costs for DSL and fiber are also intuitive. Upgrading from DSL to fiber costs $177,000, while downgrading from fiber to DSL is less expensive at $69,000. The per household adjustment costs are relatively small and likely of the wrong sign but suggest that providers' are more likely to make technology changes in census blocks with more households (-$274 DSL, -$138 fiber).

Like CenturyLink's annual operating costs, Comcast's operating costs are relatively large and of the wrong sign -$136,000. Its fixed cost of entry is greater than CenturyLink's cost of deploying of DSL but less than CenturyLink's cost of deploying fiber at $258,000. However, Comcast's per household cost of deployment is much higher than CenturyLink's at $869 per household.

5 Counterfactuals

In order to address some of the public policy raised in the introduction of this paper, in particular, to what extent does competition incentivize ISPs to invest in network quality?, I use my estimated model of the broadband industry to quantify the impact that competition from Comcast has on CenturyLink's broadband deployment decisions and subscription prices.

Specifically, I conduct three counterfactual simulations in which I predict CenturyLink's deployment decisions in the absence of Comcast, or in other words, if CenturyLink behaved as a monopolist. In the first simulation, I make the assumption that CenturyLink holds its broadband subscription prices constant. In the second simulation, I allow CenturyLink to adjust its prices given that without competition from Comcast the firm wields more market power. In the third simulation, I allow CenturyLink to price discriminate across geographic markets by setting prices in each census block group that make up its coverage area. Because demand varies across observable demographic characteristics, CenturyLink's optimal pricing and deployment decisions will differ according to variation in households' demographics across geography when it price discriminates.

Then, in each counterfactual scenario, I quantify the impact of changes in deployment and prices on consumer welfare to determine whether consumers are better off with or without competition from Comcast. This is a non-trivial policy question, because it is possible that without competition from Comcast, CenturyLink may be incentivized to increase its investment in fiber, making high-speed broadband more widely available and increasing consumer welfare. On the other hand, because CenturyLink will increase its prices in the absence of competition, consumers may be worse off. From a policy perspective, one might think of these counterfactuals as a test of whether the Seattle broadband market is a natural monopoly. Additionally, analyzing the strength of CenturyLink's incentive to price discriminate across geography can shed light on whether the uniform pricing we observe in the broadband industry is a strategy that firms use to soften price competition. If, as a monopolist, CenturyLink has a strong incentive to price discriminate, then this outcome suggests that broadband providers may choose to uniform price under competition in order to compete less vigorously on price.

5.1 Implementation

In the first counterfactual, to predict the change in CenturyLink's deployment decisions without competition from Comcast, I simply use the fixed cost estimates to determine which census blocks CenturyLink will choose to enter and with which technology, given that it is a monopolist. I predict the probabilities that it deploys each technology to each census block,

$$\hat{P}_{\ell,m,\tau} = \frac{\exp\left(\hat{\Pi}_{\ell,m,\tau}\right)}{\sum_{\tau'} \exp\left(\hat{\Pi}_{\ell,m,\tau'}\right)},$$

where CenturyLink's predicted profits from decision τ, $\hat{\Pi}_{\ell,m,\tau}$, no longer depend on the actions of Comcast. Then, I assume that the decision CenturyLink makes is the one with the highest estimated probability,

$$(\hat{a}_{\ell,m} = \tau) = \max_{\tau}\{\hat{P}_{\ell,m,none}, \hat{P}_{\ell,m,dsl}, \hat{P}_{\ell,m,fiber}\}.$$

which is the same of the decision associated with highest profit.

The second counterfactual in which CenturyLink can adjust its subscription prices is slightly more complicated. To predict the change in broadband deployment when prices change, I assume that CenturyLink first plans where it will deploy in the absence of Comcast, holding prices constant. Then, once it has determined the census blocks in which it plans to deploy, I assume the firm adjusts its subscription prices based on Nash-Bertrand uniform pricing behavior, where it chooses its prices $\hat{\mathbf{p}}$ to maximize its total profits over its coverage area based on,

$$\begin{bmatrix} \sum_m S_{1,m}(\hat{\mathbf{p}})M_m \\ \sum_m S_{2,m}(\hat{\mathbf{p}})M_m \\ \vdots \\ \sum_m S_{J,m}(\hat{\mathbf{p}})M_m \end{bmatrix} + \left[\sum_m \Delta_m(\hat{\mathbf{p}})\right] \begin{bmatrix} \hat{p}_1 - c_1 \\ \hat{p}_2 - c_2 \\ \vdots \\ \hat{p}_J - c_J \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

Finally, once the firm has updated its prices, I assume it re-updates it deployment decisions, given the new optimal prices $\hat{\mathbf{p}}$. This process captures the fact that higher prices may lead CenturyLink to change its deployment decisions (presumably it is possible to continue to iterate this process until both prices and deployment decisions are stable, however, as a first approximation and to reduce computational complexity I do not iterate here).

In the third counterfactual, rather than setting uniform prices across geographic markets CenturyLink sets optimal prices in each census block group within its coverage area. To predict the change in prices and deployment in this case, I assume CenturyLink plays a two-stage game. In the first stage the firm chooses which census blocks to enter and with which technology, and in the second stage, the firm chooses the prices of its products in each census block group to maximize variable profits. The firm maximizes total profits by backward induction, first choosing the Nash-Bertrand prices it will set in each census block if it chooses to deploy there, then choosing which technology to deploy given its variable profits and fixed costs of deployment.

5.2 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,

$$\Delta CS = \frac{1}{\alpha}\Big[\log\big(1+\sum_{j\in J'}\exp(u_{i,j})\big) - \log\big(1+\sum_{j\in J}\exp(u_{i,j})\big)\Big] \tag{29}$$

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 (29) 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 (29) 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, which enters (29), 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,

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

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,

$$\Delta CS = 12 \cdot M_m \sum_{i=1}^{36} \frac{p_j^{\text{min}}}{\alpha_i}\Big[\log\big(1 + \sum_{j \in J'} \exp(u_{i,j})\big) - \log\big(1 + \sum_{j \in J} \exp(u_{i,j})\big)\Big] \cdot \omega_{i,m}, \quad (30)$$

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

5.3 CenturyLink Monopoly without Price Changes

Table 11 reports the change CenturyLink's broadband deployment decisions, and change in consumer surplus based on (30), when CenturyLink makes its broadband deployment decisions without competition from Comcast, but holding its subscription prices constant. I separate the change in consumer surplus into what I call the "partial effects," just due to the change in CenturyLink's behavior, and the "total effects," due to the change in CenturyLink's behavior in addition to the loss of Comcast from the market.

Table 11 shows that without adjusting its prices, CenturyLink chooses to deploy DSL service in a small number of populated census blocks (8) and upgrade its service from DSL to fiber in a slightly larger number of populated census blocks (53). The average annual value of the deployment of DSL to these households is about \$31, and the average annual value of the increase in broadband quality from DSL to fiber is about \$15.

However, on net, the decrease in consumer surplus due to the exit of Comcast from the market greatly outweighs the increase due to changes in CenturyLink's deployment decisions. The net change in average consumer surplus, accounting for the loss of Comcast in census blocks where CenturyLink chooses to deploy new DSL service is -\$288 per household, while the net change in average consumer surplus in census blocks where CenturyLink chooses to upgrade its service to Fiber is -\$164 per household. In aggregate, the change in CenturyLink's deployment decisions and the loss of Comcast's broadband service in the market reduces consumer surplus by approximately \$312,500,000 or by \$216 on average across all households in the market.

5.4 CenturyLink Monopoly with Price Changes

Table 12 displays the change in CenturyLink's subscription prices under Nash-Bertrand uniform pricing when the firm acts as a monopolist. All of CenturyLink's prices increase substantially. The price increase in its DSL subscriptions range from 37% to 44%, while the price increase in its fiber plans range from 52% to 72%.

Table 13 reports the change CenturyLink's broadband deployment decisions, and change in consumer surplus, when CenturyLink makes its broadband deployment decisions without competition from Comcast, given the increase in the price of its subscriptions. Again, I separate the change in consumer surplus into the "partial effects" and "total effects" of the change in broadband deployment in the market. When CenturyLink raises its prices, it increases quality even more than the case where prices are held constant, and it increases deployment. CenturyLink upgrades from DSL to fiber in 152 census blocks (covering over 56,000 households), deploys DSL in 23 census blocks (covering over 9,000 households), and deploys fiber in 2 census blocks (covering 800 households). However, overall the benefit of increased quality and deployment is outweighed by the increase in prices as a result of monopoly pricing. In areas where CenturyLink deploys new service households benefit on net, however, in areas where the firm upgrades its service from DSL to fiber consumers, consumers are worse off on net due to increases in prices. This shows that the gains in consumer welfare from increased quality is more the offset by the loss of consumer welfare from increased prices, which is an important result in terms of how policymakers should think about the tradeoff between the benefits competition and firms' incentive to improve product quality in this industry.

5.5 CenturyLink Monopoly with Price Discrimination

Figure 9 displays the change in the distribution of prices across CenturyLink's coverage area when the firm price discriminates across geography based upon demographic differences.

Table 14 reports the change CenturyLink's broadband deployment decisions, and change in consumer surplus, when CenturyLink price discriminates and makes its broadband deployment decisions without competition from Comcast. Notice that CenturyLink's deployment of DSL and fiber increases relative to the case where it sets uniform prices, which is driven by the fact that variable profits are higher across census blocks when the firm can set prices more flexibly. Under price discrimination, CenturyLink upgrades from DSL to fiber in 163 census blocks (covering over 59,000 households), deploys DSL in 23 census blocks (covering over 9,000 households), and deploys fiber in 4 census blocks (covering over 1,500 households). In this case we see that when CenturyLink price discriminates it extracts more consumer surplus from households, as a result overall consumer welfare is reduced even further than under uniform pricing. Additionally, based on the substantial decrease in consumer surplus under under price discrimination relative to uniform pricing, we can infer that CenturyLink has a strong incentive to price discriminate in order to maximize profits as a monopolist. This is consistent with the idea that broadband providers choose to set uniform prices as a strategy to soften price competition.

6 Conclusion

Based on the results of my counterfactual simulations, I conclude that competition from Comcast has a small negative impact on CenturyLink's incentive to deploy fiber. In the absence of price effects, I find that CenturyLink chooses to upgrade service in a small number of census blocks, which increases consumer welfare in these areas. However, accounting for price changes, I find that consumer welfare decreases. These results highlight the importance of simultaneously accounting for changes in market structure and prices when modeling equilibrium outcomes for purposes of analyzing policies that affect market structure.

From a policy perspective, these results highlight the benefits of competition in the broadband industry. Consumer surplus decreases substantially under a monopoly market structure due to increases in price, even though the monopolist's incentive to deploy high-speed broadband service increases (although marginally). Overall, I find the benefits of competition from Comcast are highly valued by Seattle consumers. These results demonstrate the value of competition in the broadband market.

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Appendices

A Tables

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
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
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
Bachelors Degree or Higher	0.787	0.794	0.759	0.444	0.750

Table 2. Plan Summary Statistics (return)

Plan	Share	Monthly Charge	Download Speed (mbps)	Upload Speed (mbps)	Usage Allowance (GB)
CenturyLink: plan 1	0.0675	56.99	12	.875	1,000
CenturyLink: plan 2	0.0098	61.99	12	5	1,000
CenturyLink: plan 3	0.0126	66.99	20	.875	1,000
CenturyLink: plan 4	0.0067	71.99	20	5	1,000
CenturyLink: plan 5	0.0078	76.99	40	5	1,000
CenturyLink: plan 6	0.0184	81.99	40	20	1,000
CenturyLink: plan 7	0.0514	96.99	100	50	1,000
CenturyLink: plan 8	0.0391	156.94	1,000	1,000	.
Comcast: plan 1	0.0782	49.95	10	2	1,024
Comcast: plan 2	0.0608	64.95	55	5	1,024
Comcast: plan 3	0.0596	79.95	100	5	1,024
Comcast: plan 4	0.0759	94.95	200	10	1,024
Comcast: plan 5	0.0597	149.95	250	25	1,024
Comcast: plan 6	0.1817	159.95	987	35	1,024
Wave: plan 1	0.0330	45.10	10	1	100
Wave: plan 2	0.0667	73.45	100	5	400
Wave: plan 3	0.0642	81.55	250	10	500

Table 3. Reduced-form Deployment Decision Regressions (return)

	CenturyLink						Comcast	
	Entry: DSL		Entry: Fiber		Upgrade		Entry	
Households	0.000124***	0.000135***	0.00000380	0.00000469	0.000594***	0.000562***	-0.0000542	0.00000419
	(0.0000337)	(0.0000328)	(0.00000720)	(0.00000713)	(0.0000422)	(0.0000423)	(0.0000373)	(0.0000378)
Land Area (Miles^2)	-0.000336***	-0.000261**	-0.0000149	-0.0000129	-0.00303***	-0.00289**	-0.000118	-0.000229**
	(0.0000830)	(0.000124)	(0.00000992)	(0.0000104)	(0.00115)	(0.00113)	(0.0000820)	(0.0000892)
Number of Competitors (CenturyLink)	-0.00242*		0.000171		0.0112***			
	(0.00125)		(0.000216)		(0.00221)			
Number of Competitors (Comcast)							0.00747***	
							(0.00121)	
Comcast		0.0428***		0.00209**		0.0259***		
		(0.00428)		(0.000912)		(0.00300)		
Wave		0.0609***		0.00482*		0.0445***		-0.0185***
		(0.00949)		(0.00280)		(0.00617)		(0.00302)
Frontier		-0.0643***		-0.00275***		0.0133		0.0272***
		(0.00373)		(0.000914)		(0.0260)		(0.00564)
Tacoma		-0.000530		0.000294		-0.0138***		-0.00278
		(0.00586)		(0.00124)		(0.00300)		(0.00342)
CenturyLink								0.0199***
								(0.00239)
Constant	0.0248***	0.0224***	0.000676***	0.000583***	0.00969***	-0.00119	0.00956***	0.00750***
	(0.00127)	(0.00126)	(0.000204)	(0.000197)	(0.00227)	(0.00255)	(0.000806)	(0.000812)
R^2	0.000456	0.0225	0.0000564	0.00181	0.0305	0.0345	0.00198	0.00831
Control Group Obs.	18639	18639	18639	18639	27950	27950	20146	20146
Treatment Group Obs.	470	470	15	15	1148	1148	272	272
Observations	19109	19109	18654	18654	29098	29098	20418	20418

Note (a): * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note (b): Robust standard errors in parentheses.

Table 4. 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

Table 5. Logit Demand Estimates (return)

	Linear Specification		Log Specification	
	OLS	GMM	OLS	GMM
Monthly Charge	-0.0110	-0.0161		
	(0.0128)	(0.0129)		
Download Speed (mbps)	0.00258*	0.00285*		
	(0.00144)	(0.00147)		
Upload Speed (mbps)	0.00320***	0.00338***		
	(0.00103)	(0.000968)		
Log Monthly Charge			-7.217***	-24.08***
			(2.010)	(7.289)
Log Download Speed (mbps)			2.250***	6.049***
			(0.687)	(1.771)
Log Upload Speed (mbps)			0.169	0.383
			(0.340)	(0.297)
Comcast	4.762***	4.844***	3.164***	1.499
	(0.612)	(0.586)	(0.755)	(1.074)
Wave	1.263	1.861	-1.331	-6.380**
	(1.490)	(1.333)	(1.700)	(2.760)
Constant	-5.988***	-5.777***	16.75**	76.02***
	(1.902)	(1.797)	(6.858)	(25.54)
Mean Own-price Elasticity	-0.915	-1.337	-6.840	-22.82
Zip Code Fixed Effects	Yes	Yes	Yes	Yes
Price IV	No	Yes	No	Yes
Hansen's J (p-value)		0.187		0.690
R^2	0.280	0.278	0.283	0.210
Observations	400	400	400	400

Note (a): * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note (b): Robust standard errors in parentheses.

Table 6. Mixed Logit Demand Estimates (return)

Parameters	No Price IVs			Price IVs	
	MLE 2-Step	GMM Joint	Standard Errors	GMM Joint	Standard Errors
Linear Parameters					
Log Price	-1.8531	-1.8531	(0.6837)	-3.7411	(4.1748)
Log Download Speed	0.4881	0.4881	(0.2710)	0.9505	(0.9933)
Log Upload Speed	-0.0294	-0.0293	(0.2455)	-0.0359	(0.2145)
Comcast	1.0450	1.0450	(0.4543)	0.8687	(0.6593)
Wave	-0.5383	-0.5383	(0.5530)	-1.0814	(1.4306)
Constant	2.2022	2.2022	(3.5948)	8.4739	(15.1116)
Log Price × Income					
Income [50k, 100k)	0.5931	0.5931	(0.2885)	0.5718	(0.2876)
Income [100k, 200k+)	0.8153	0.8153	(0.2599)	0.7971	(0.2588)
Log Download Speed × Household Size					
Household Size (2)	0.0023	0.0023	(0.1425)	-0.0159	(0.1465)
Household Size (3)	-0.0932	-0.0932	(0.1466)	-0.1110	(0.1505)
Household Size (4+)	-0.0630	-0.0630	(0.1436)	-0.0784	(0.1471)
Log Upload Speed × Household Size					
Household Size (2)	0.0017	0.0017	(0.1551)	0.0153	(0.1573)
Household Size (3)	0.1087	0.1087	(0.1618)	0.1208	(0.1636)
Household Size (4+)	0.1762	0.1762	(0.1574)	0.1845	(0.1590)
Demographics					
Income [50k, 100k)	-1.5283	-1.5283	(1.2807)	-1.4338	(1.2778)
Income [100k, 200k+)	-1.8934	-1.8934	(1.1655)	-1.8187	(1.1608)
HS Grad and Some College	0.7864	0.7863	(2.4205)	1.0247	(2.4469)
Bachelor's Degree or Higher	1.5501	1.5501	(2.4187)	1.7881	(2.4437)
Household Size (2)	0.6105	0.6105	(0.4708)	0.6867	(0.4915)
Household Size (3)	2.0528	2.0528	(0.5568)	2.1323	(0.5815)
Household Size (4+)	1.0976	1.0976	(0.4953)	1.1729	(0.5173)
Price Coefficients					
Income [0k, 50k)	-1.8531	-1.8531		-3.7411	
Income [50k, 100k)	-1.2600	-1.2600		-3.1693	
Income [100k, 200k+)	-1.0378	-1.0378		-2.9440	
Objective Value	-7,866.77	0.0000		0.1085	
Individuals (Micro Moments)	3,153	3,153		3,153	
Products (Macro Moments)	17	17		17	

Table 7. 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
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	.

Table 8. Marginal Costs Estimates (return)

Plan	Plan Characteristics			Logit		Mixed Logit	
	Download Speed (mbps)	Upload Speed (mbps)	Price	Marginal Cost	Margin	Marginal Cost	Margin
CenturyLink, DSL: plan 1	1.5	.875	46.99	40.45	0.1392	27.10	0.4233
CenturyLink, DSL: plan 2	7	.875	51.99	44.75	0.1392	29.95	0.4239
CenturyLink, DSL: plan 3	12	.875	56.99	49.05	0.1392	32.76	0.4251
CenturyLink, DSL: plan 4	20	.875	66.99	57.66	0.1392	38.35	0.4276
CenturyLink, DSL: plan 5	20	2	71.99	61.97	0.1392	41.07	0.4295
CenturyLink, DSL: plan 6	40	5	76.99	66.27	0.1392	43.81	0.4309
CenturyLink, DSL: plan 7	60	5	101.98	87.78	0.1392	57.60	0.4352
CenturyLink, DSL: plan 8	100	12	126.98	109.30	0.1392	71.24	0.4389
CenturyLink, Fiber: plan 1	12	.875	56.99	48.85	0.1428	33.30	0.4157
CenturyLink, Fiber: plan 2	12	5	61.99	53.14	0.1428	36.04	0.4187
CenturyLink, Fiber: plan 3	20	.875	66.99	57.42	0.1428	38.99	0.4180
CenturyLink, Fiber: plan 4	20	5	71.99	61.71	0.1428	41.70	0.4207
CenturyLink, Fiber: plan 5	40	5	76.99	65.99	0.1428	44.55	0.4213
CenturyLink, Fiber: plan 6	40	20	81.99	70.28	0.1428	47.26	0.4236
CenturyLink, Fiber: plan 7	100	50	96.99	83.14	0.1428	55.63	0.4264
CenturyLink, Fiber: plan 8	1,000	1,000	156.94	134.53	0.1428	88.73	0.4346
Comcast: plan 1	10	2	49.95	24.71	0.5053	-3.87	1.0775
Comcast: plan 2	55	5	64.95	32.13	0.5053	-5.68	1.0875
Comcast: plan 3	100	5	79.95	39.55	0.5053	-7.56	1.0945
Comcast: plan 4	200	10	94.95	46.97	0.5053	-9.67	1.1019
Comcast: plan 5	250	25	149.95	74.17	0.5053	-18.03	1.1203
Comcast: plan 6	987	35	159.95	79.12	0.5053	-19.33	1.1209

Table 9. k-NPL Fixed Cost Estimates (Mixed Logit Demand) (return)

Parameters	Point Estimates	Standard Errors	5th and 95th Percentiles
CenturyLink, DSL			
ϕ_{dsl}: Operating Cost	-4.484	(0.058)	[-4.593, -4.402]
θ^E_{dsl}: Entry Cost	8.195	(0.078)	[8.075, 8.314]
ϑ^E_{dsl}: Entry Cost per Household	0.001	(0.002)	[-0.002, 0.004]
θ^D_{dsl}: Downgrade Cost	2.430	(0.399)	[1.676, 2.929]
ϑ^D_{dsl}: Downgrade Cost per Household	-0.010	(0.001)	[-0.012, -0.008]
CenturyLink, Fiber			
ϕ_{fiber}: Operating Cost	-7.253	(0.353)	[-7.865, -6.889]
θ^E_{fiber}: Entry Cost	14.421	(0.508)	[13.856, 15.304]
ϑ^E_{fiber}: Entry Cost per Household	0.002	(0.022)	[-0.001, 0.055]
θ^U_{fiber}: Upgrade Cost	6.276	(0.362)	[5.907, 6.866]
ϑ^U_{fiber}: Upgrade Cost per Household	-0.005	(0.001)	[-0.006, -0.003]
Comcast			
ϕ_{cable}: Operating Cost	-4.819	(0.189)	[-5.051, -4.444]
θ^E_{cable}: Entry Cost	9.135	(0.196)	[8.736, 9.353]
ϑ^E_{cable}: Entry Cost per Household	0.031	(0.014)	[0.016, 0.058]
Scaling Factor			
σ	28.198	(10.987)	[15.286, 53.105]
Pseudo Log-likelihood	-11,629.861		
Markets	59,705		

Table 10. k-NPL Fixed Cost Estimates in $1,000s (Mixed Logit Demand) (return)

Parameters	Point Estimates	Standard Errors	5th and 95th Percentiles
CenturyLink, DSL			
$\tilde{\phi}_{dsl}$: Operating Cost	-126.432	(49.709)	[-244.155, -70.091]
$\tilde{\theta}^{E}_{dsl}$: Entry Cost	231.080	(90.288)	[128.209, 436.931]
$\tilde{\vartheta}^{E}_{dsl}$: Entry Cost per Household	0.016	(0.046)	[-0.082, 0.075]
$\tilde{\theta}^{D}_{dsl}$: Downgrade Cost	68.508	(28.973)	[31.754, 119.392]
$\tilde{\vartheta}^{D}_{dsl}$: Downgrade Cost per Household	-0.274	(0.090)	[-0.476, -0.168]
CenturyLink, Fiber			
$\tilde{\phi}_{fiber}$: Operating Cost	-204.530	(79.864)	[-405.294, -111.189]
$\tilde{\theta}^{E}_{fiber}$: Entry Cost	406.637	(157.382)	[220.956, 776.665]
$\tilde{\vartheta}^{E}_{fiber}$: Entry Cost per Household	0.069	(0.791)	[-0.048, 1.393]
$\tilde{\theta}^{U}_{fiber}$: Upgrade Cost	176.957	(68.317)	[96.335, 346.050]
$\tilde{\vartheta}^{U}_{fiber}$: Upgrade Cost per Household	-0.138	(0.074)	[-0.313, -0.051]
Comcast			
$\tilde{\phi}_{cable}$: Operating Cost	-135.881	(57.946)	[-268.122, -68.012]
$\tilde{\theta}^{E}_{cable}$: Entry Cost	257.588	(104.846)	[133.466, 495.959]
$\tilde{\vartheta}^{E}_{cable}$: Entry Cost per Household	0.869	(0.054)	[0.793, 0.972]
Scaling Factor			
σ	28.198	(10.987)	[15.286, 53.105]
Pseudo Log-likelihood	-11,629.861		
Markets	59,705		

Table 11. Counterfactual Change in Consumer Surplus ($), Holding Prices Fixed (Mixed Logit Demand) (return)

Scenario	Census Blocks	Households	Total ΔCS	Average ΔCS
Partial Effects				
CenturyLink, DSL Entry (With Comcast)	8	3,746	116,512	31
CenturyLink, Quality Increase (With Comcast)	53	24,323	359,942	15
Total Effects				
CenturyLink, DSL Entry (Comcast Exit)	8	3,746	-852,275	-228
CenturyLink, Quality Increase (Comcast Exit)	53	24,323	-3,983,798	-164
CenturyLink, DSL (No Comcast)	5,833	82,517	0	0
CenturyLink, DSL (Comcast Exit)	23,457	785,565	-175,785,583	-224
CenturyLink, Fiber (No Comcast)	594	14,310	0	0
CenturyLink, Fiber (Comcast Exit)	10,645	355,031	-66,490,346	-187
No CenturyLink (Comcast Exit)	5,124	145,680	-65,344,593	-449
No Change (No CenturyLink or Comcast)	13,991	34,239	0	0
Total	59,705	1,445,411	-312,456,595	-216

Table 12. Counterfactual Prices (return)

Plan	Plan Characteristics		Price Difference		
	Download Speed (mbps)	Upload Speed (mbps)	Price	Monopoly Price	% Δ in Price
CenturyLink, DSL: plan 1	1.5	.875	46.99	64.28	36.79
CenturyLink, DSL: plan 2	7	.875	51.99	70.80	36.18
CenturyLink, DSL: plan 3	12	.875	56.99	77.75	36.43
CenturyLink, DSL: plan 4	20	.875	66.99	91.94	37.24
CenturyLink, DSL: plan 5	20	2	71.99	99.94	38.82
CenturyLink, DSL: plan 6	40	5	76.99	107.64	39.81
CenturyLink, DSL: plan 7	60	5	101.98	144.35	41.55
CenturyLink, DSL: plan 8	100	12	126.98	182.56	43.77
CenturyLink, Fiber: plan 1	12	.875	56.99	86.48	51.75
CenturyLink, Fiber: plan 2	12	5	61.99	96.85	56.23
CenturyLink, Fiber: plan 3	20	.875	66.99	102.40	52.86
CenturyLink, Fiber: plan 4	20	5	71.99	113.21	57.25
CenturyLink, Fiber: plan 5	40	5	76.99	120.81	56.92
CenturyLink, Fiber: plan 6	40	20	81.99	131.77	60.71
CenturyLink, Fiber: plan 7	100	50	96.99	158.34	63.25
CenturyLink, Fiber: plan 8	1,000	1,000	156.94	269.99	72.04

Table 13. Counterfactual Change in Consumer Surplus ($), Uniform Pricing (Mixed Logit Demand) (return)

Scenario	Census Blocks	Households	Total ΔCS	Average ΔCS
Partial Effects				
CenturyLink, DSL Deployment and Price Increase (No Comcast)	1	462	40,466	88
CenturyLink, DSL Deployment and Price Increase (With Comcast)	22	8,886	104,006	12
CenturyLink, Quality Increase and Price Increase (No Comcast)	2	940	-82,562	-88
CenturyLink, Quality Increase and Price Increase (With Comcast)	150	55,592	-995,146	-18
CenturyLink, Fiber Deployment and Price Increase (With Comcast)	2	826	11,676	14
Total Effects				
CenturyLink, DSL Deployment and Price Increase (No Comcast)	1	462	40,466	88
CenturyLink, DSL Deployment and Price Increase (Comcast Exit)	22	8,886	-2,897,447	-326
CenturyLink, Quality Increase and Price Increase (No Comcast)	2	940	-82,562	-88
CenturyLink, Quality Increase and Price Increase (Comcast Exit)	150	55,592	-17,592,791	-316
CenturyLink, Fiber Deployment and Price Increase (Comcast Exit)	2	826	-306,421	-371
CenturyLink, DSL Price Increase (No Comcast)	5,831	81,578	-6,446,773	-79
CenturyLink, DSL Price Increase (Comcast Exit)	23,360	754,295	-233,125,613	-309
CenturyLink, Fiber Price Increase (No Comcast)	594	14,310	-1,866,479	-130
CenturyLink, Fiber Price Increase (Comcast Exit)	10,645	355,031	-115,840,672	-326
No CenturyLink (Comcast Exit)	5,108	139,714	-62,569,237	-448
No Change (No CenturyLink or Comcast)	13,990	33,778	0	0
Total	59,705	1,445,411	-440,687,530	-305

Table 14. Counterfactual Change in Consumer Surplus ($), Price Discrimination (Mixed Logit Demand) (return)

Scenario	Census Blocks	Households	Total ΔCS	Average ΔCS
Partial Effects				
CenturyLink, DSL Deployment and Price Increase (No Comcast)	1	462	-57,311	-124
CenturyLink, DSL Deployment and Price Increase (With Comcast)	22	8,717	82,297	9
CenturyLink, Quality Increase and Price Increase (No Comcast)	2	940	-191,544	-204
CenturyLink, Quality Increase and Price Increase (With Comcast)	161	58,846	-1,241,508	-21
CenturyLink, Fiber Deployment and Price Increase (With Comcast)	4	1,582	12,129	8
Total Effects				
CenturyLink, DSL Deployment and Price Increase (No Comcast)	1	462	-57,311	-124
CenturyLink, DSL Deployment and Price Increase (Comcast Exit)	22	8,717	-4,600,280	-528
CenturyLink, Quality Increase and Price Increase (No Comcast)	2	940	-191,544	-204
CenturyLink, Quality Increase and Price Increase (Comcast Exit)	161	58,846	-29,103,654	-495
CenturyLink, Fiber Deployment and Price Increase (Comcast Exit)	4	1,582	-930,994	-589
CenturyLink, DSL Price Increase (No Comcast)	5,831	81,578	-13,421,341	-165
CenturyLink, DSL Price Increase (Comcast Exit)	23,349	751,042	-368,216,906	-490
CenturyLink, Fiber Price Increase (No Comcast)	594	14,310	-3,571,142	-250
CenturyLink, Fiber Price Increase (Comcast Exit)	10,645	355,031	-179,687,172	-506
No CenturyLink (Comcast Exit)	5,106	139,127	-58,716,208	-422
No Change (No CenturyLink or Comcast)	13,990	33,778	0	0
Total	59,705	1,445,411	-658,496,553	-456

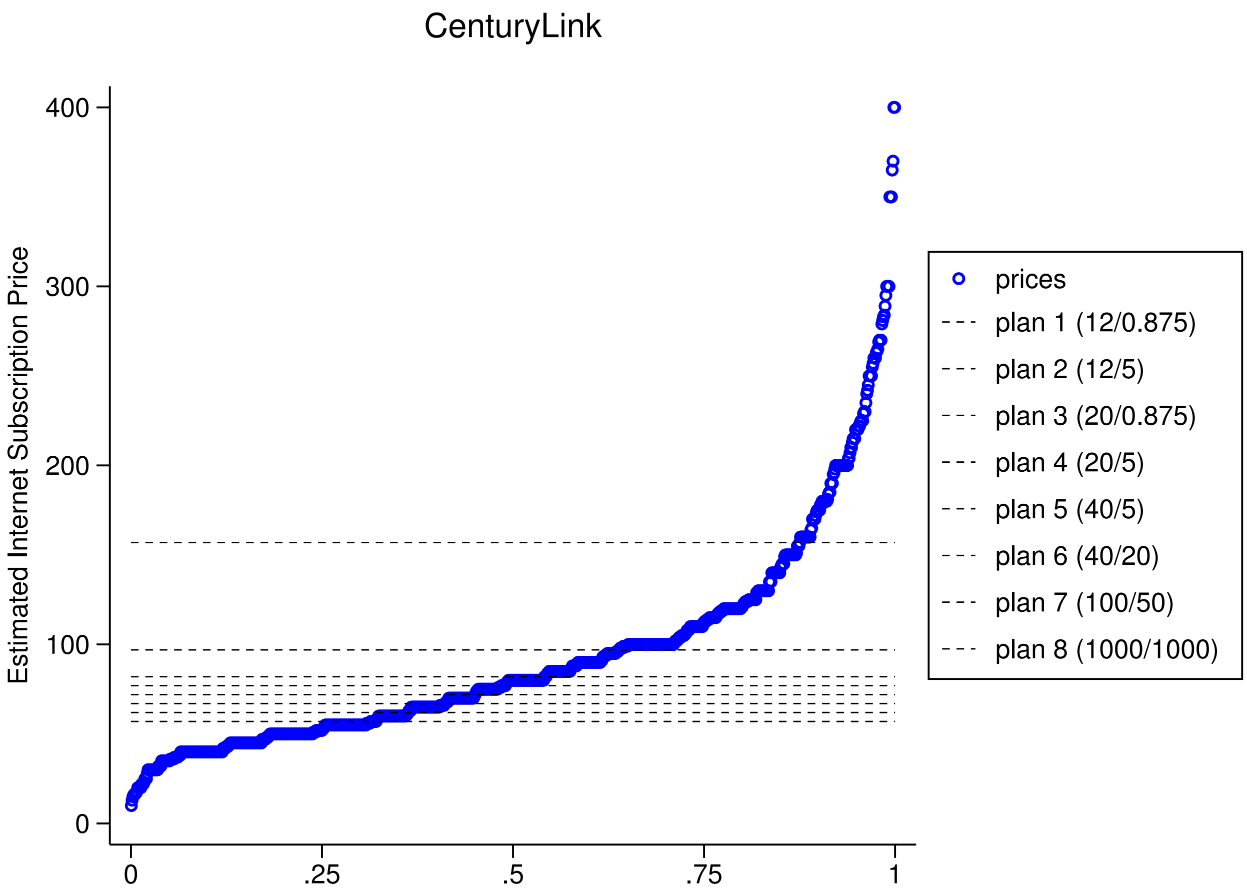
B Figures

Figure 1. 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: ________________	❑	❑	❑	$______	❑	$______

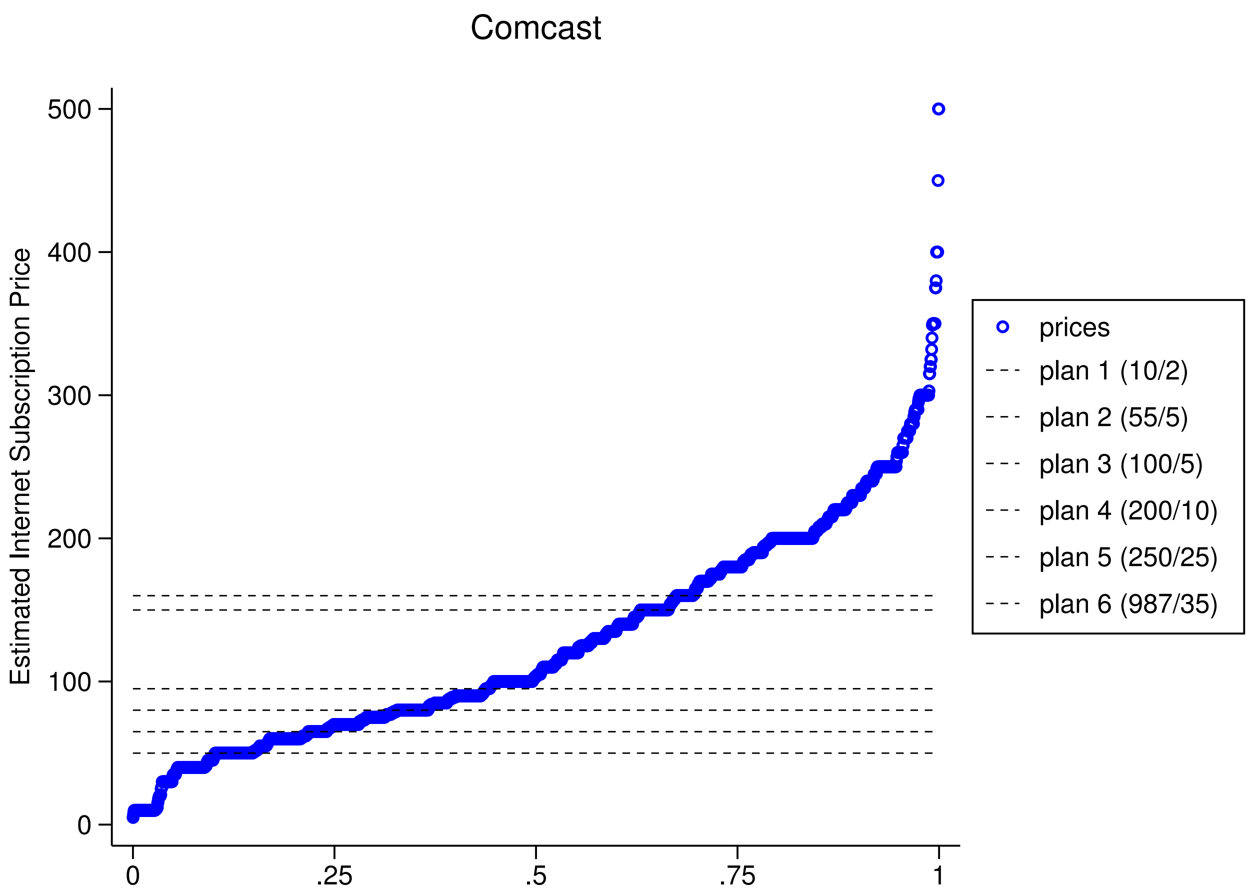
Figure 2. CenturyLink (return)



CenturyLink Subscriptions

Plans	Subscribers	Percent
plan 1: 12/0.875	310	32.46
plan 2: 12/5	41	4.29
plan 3: 20/0.875	47	4.92
plan 4: 20/5	35	3.66
plan 5: 40/5	38	3.98
plan 6: 40/20	87	9.11
plan 7: 100/50	224	23.46
plan 8: 1000/1000	173	18.12
Total	955	100.00

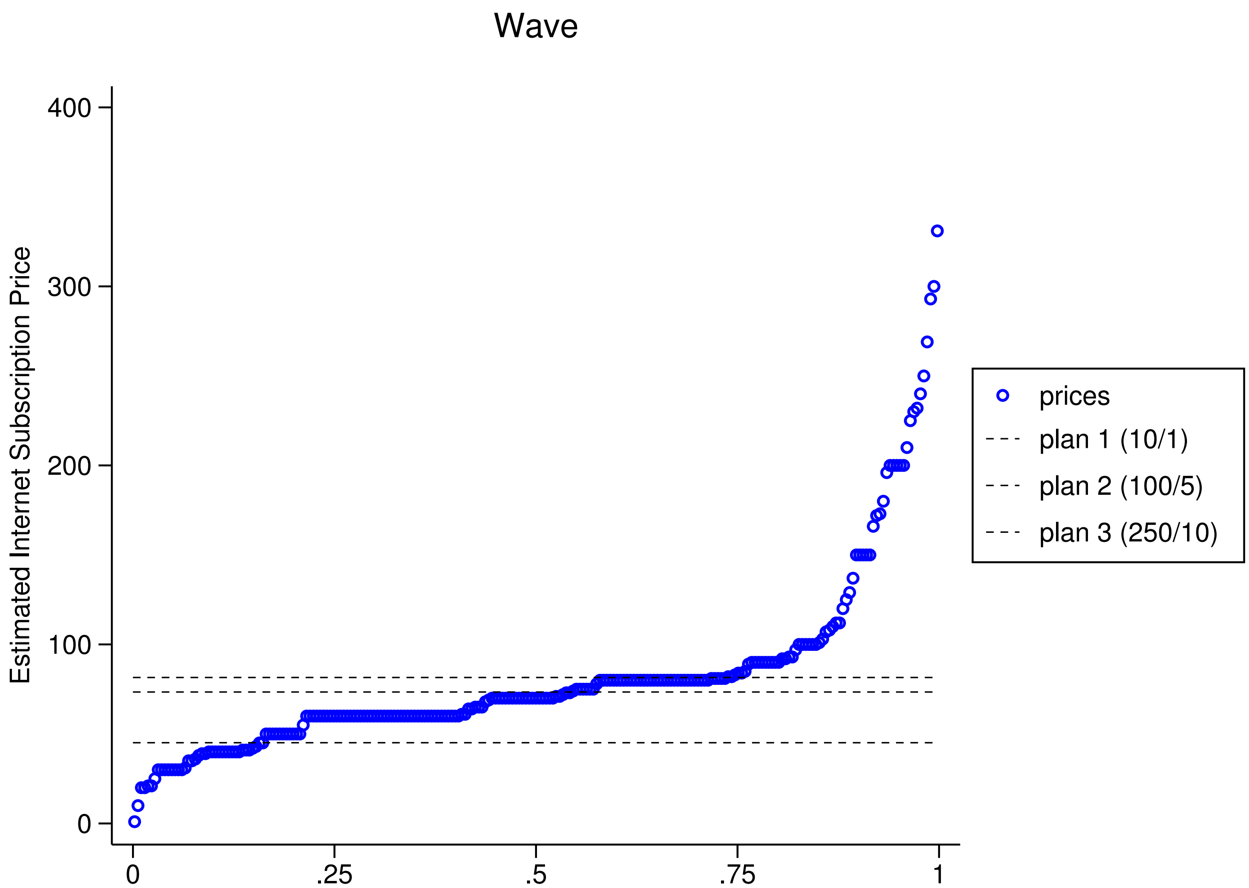
Figure 3. Comcast (return)



Comcast Subscriptions

Plans	Subscribers	Percent
plan 1: 10/2	357	16.80
plan 2: 55/2	247	11.62
plan 3: 100/5	232	10.92
plan 4: 200/10	340	16.00
plan 5: 250/25	244	11.48
plan 6: 987/35	705	33.18
Total	2125	100.00

Figure 4. Wave (return)



Wave Subscriptions

Plans	Subscribers	Percent
plan 1: 10/1	51	21.34
plan 2: 100/5	86	35.98
plan 3: 250/10	102	42.68
Total	239	100.00

Figure 5. CenturyLink Coverage Area (return)

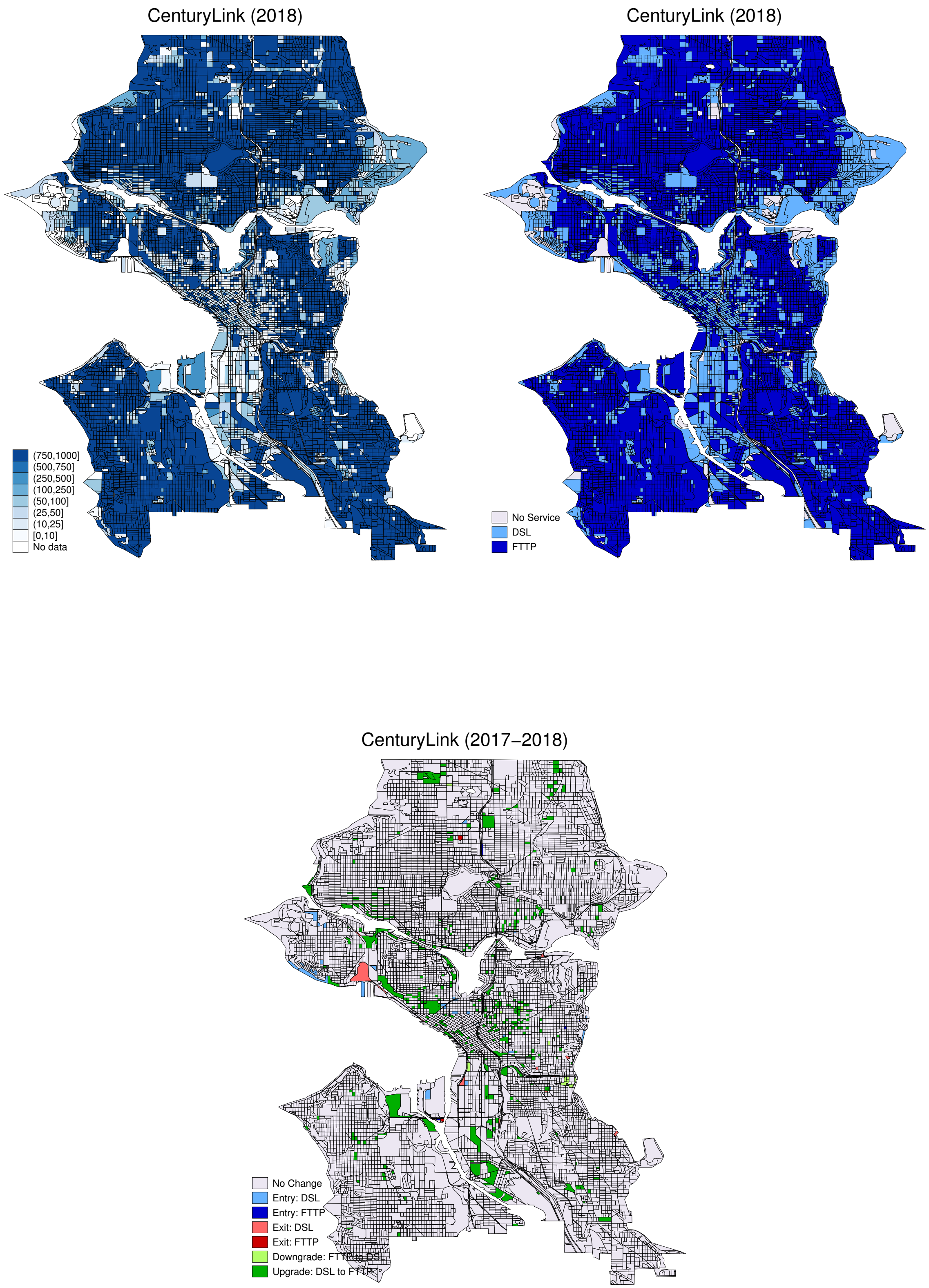


Figure 6. Comcast Coverage Area (return)

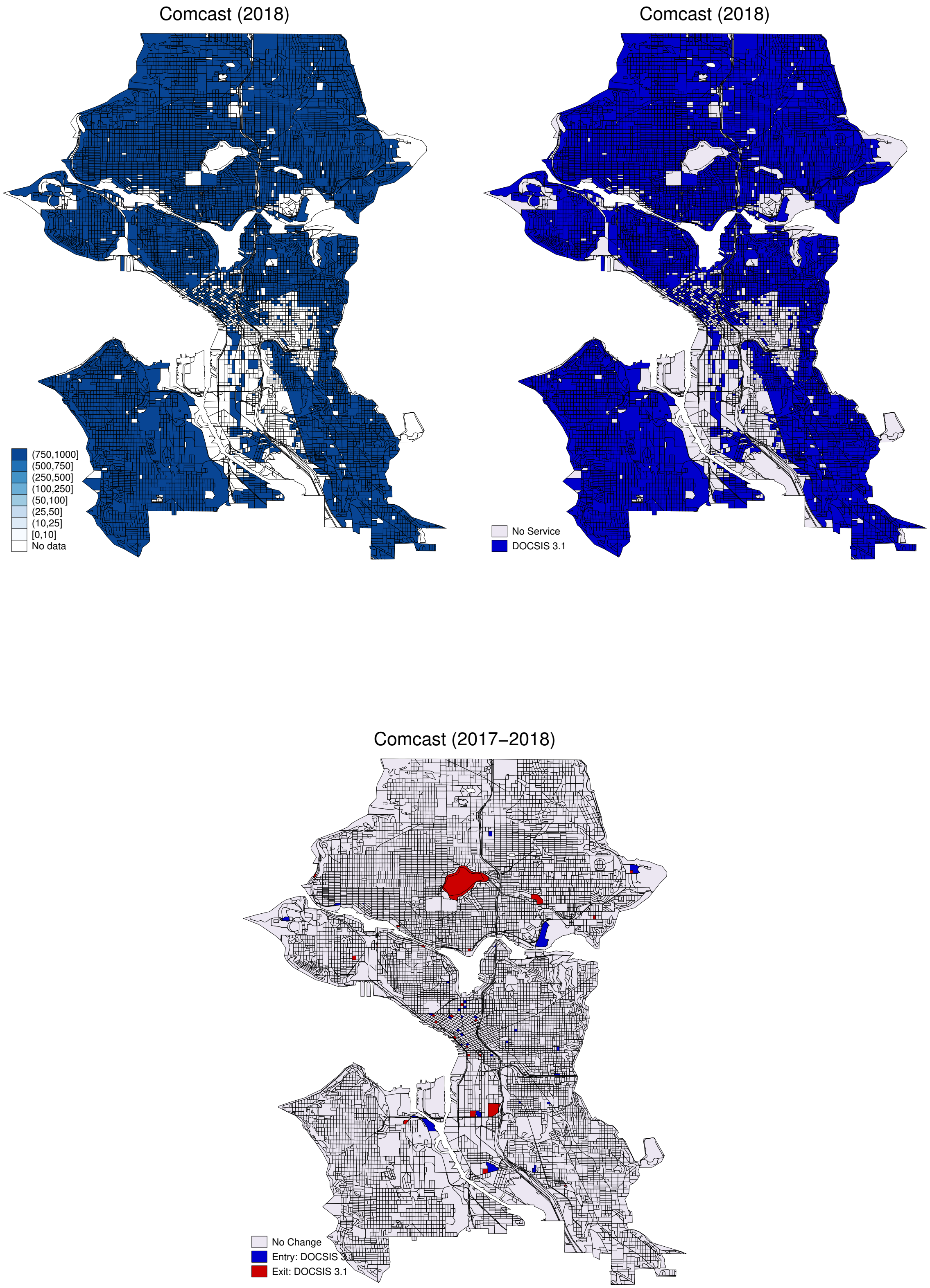


Figure 7. Wave Coverage Area (return)

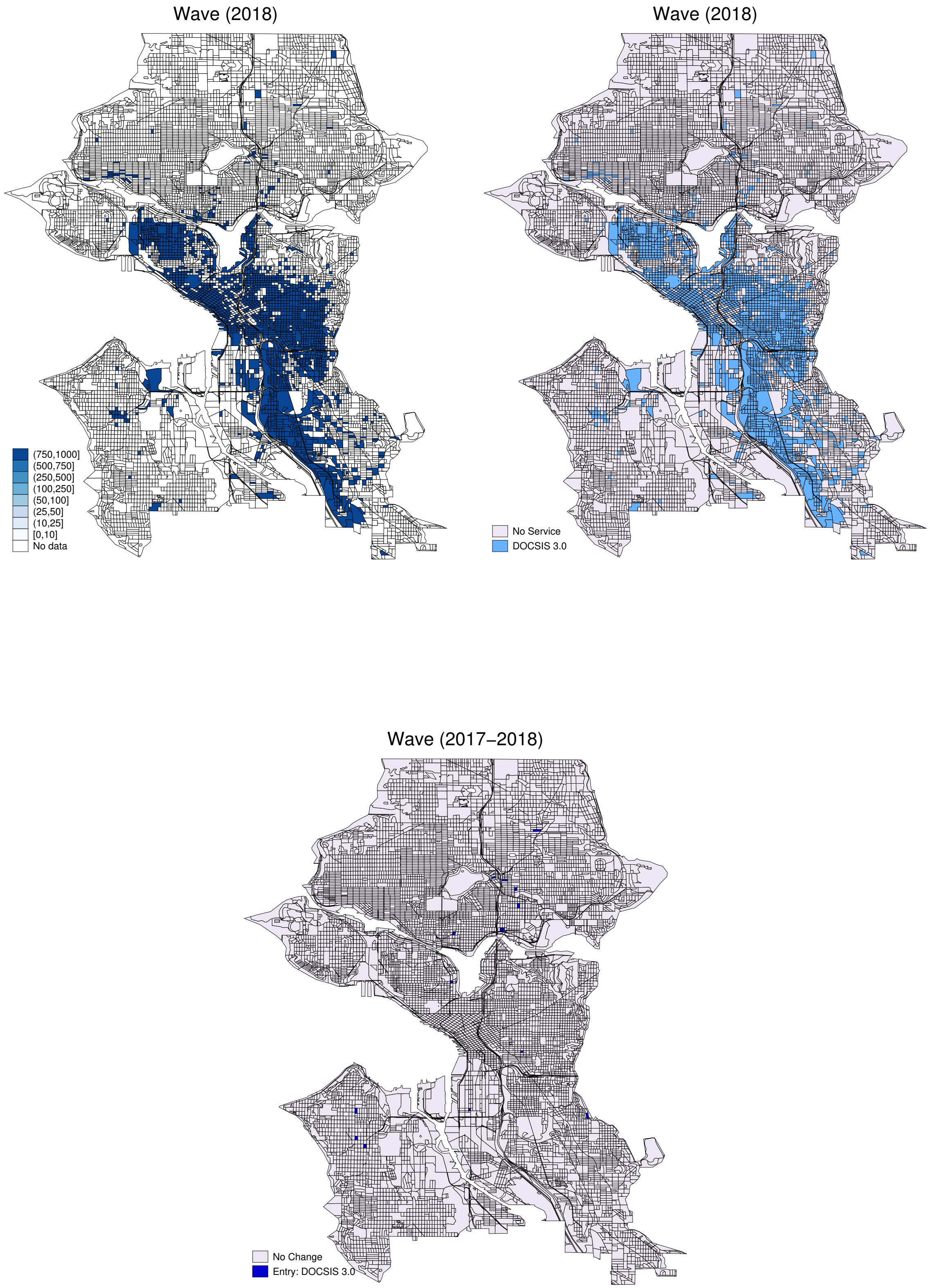


Figure 8. ISPs' Coverage Areas (return)

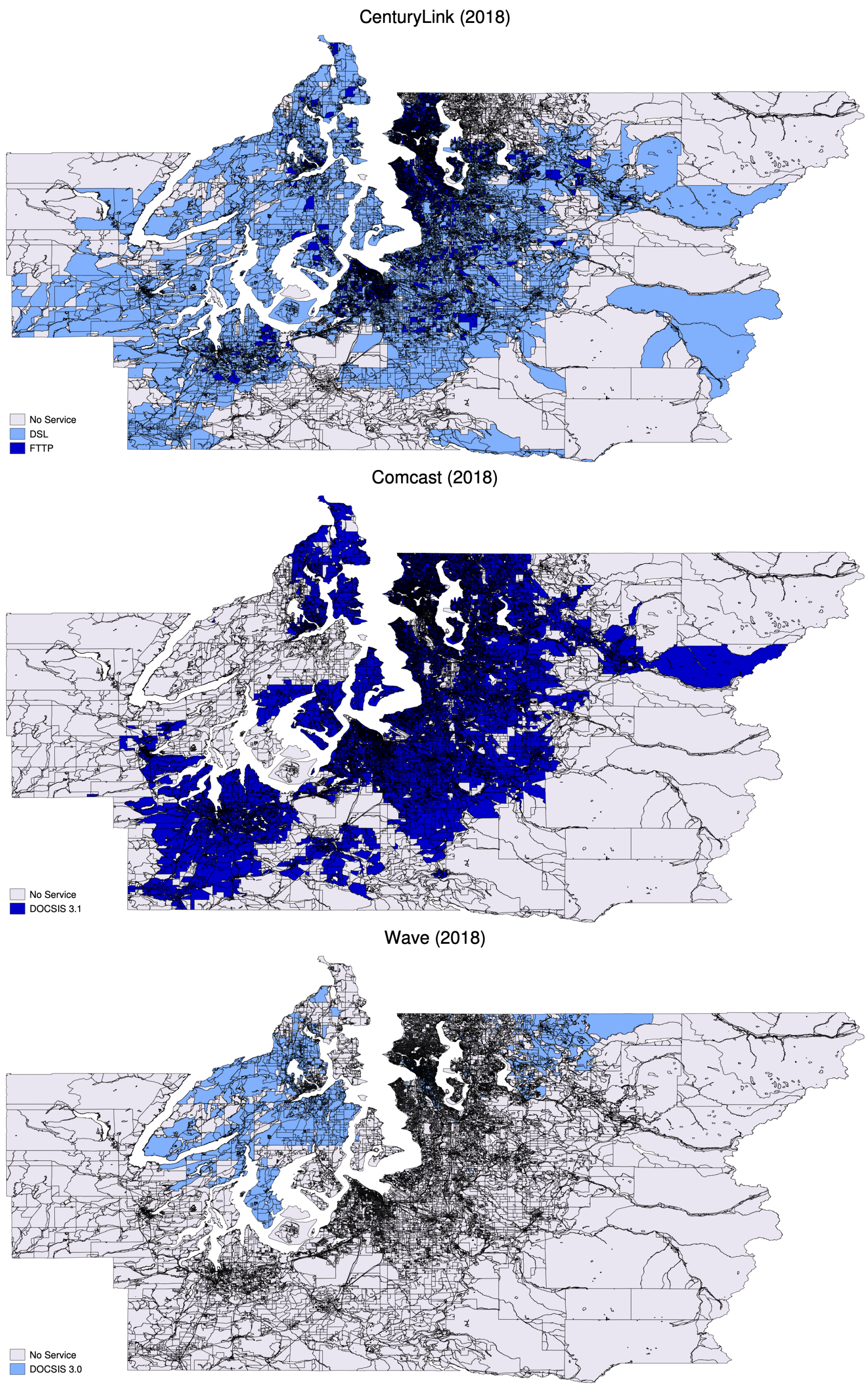
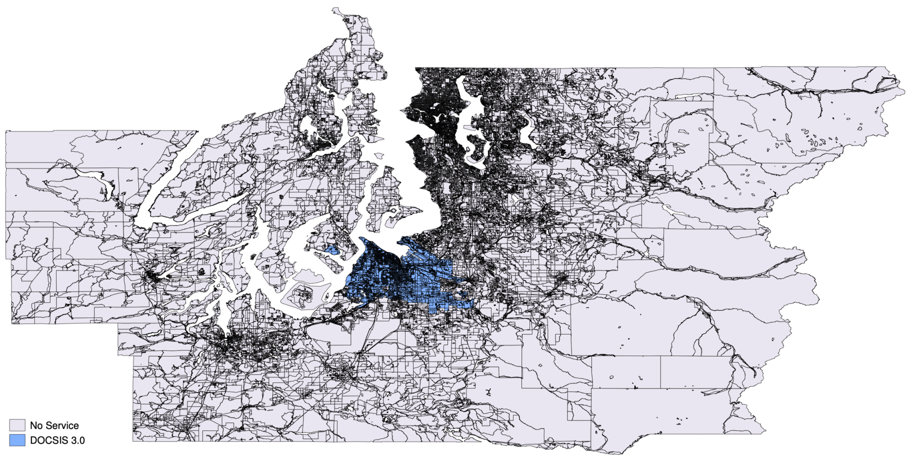


Figure 8 (Cont.). ISPs' Coverage Areas (return)

City of Tacoma (2018)



Frontier (2018)

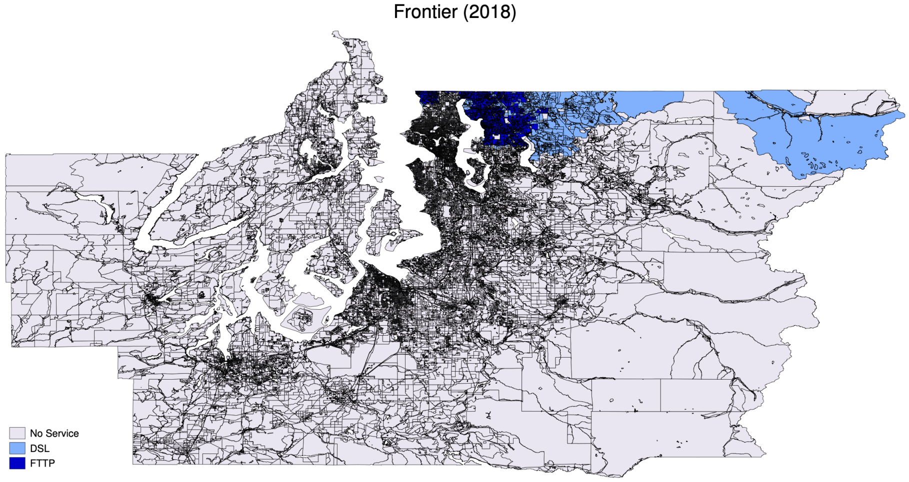


Figure 9. CenturyLink: Uniform Pricing vs. Price Discrimination (return)