Regulatory Uncertainty: The Impact of the 2015 Open Internet Order on Broadband Infrastructure Investment

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Abstract

This paper analyzes the impact of the United States Federal Communication's (FCC) March 2015 Open Internet Order (OIO) on broadband infrastructure investment outcomes such as changes in speed of services and market entry. We find that the 2015 OIO appears to have negatively impacted the probability of an internet service provider (ISP) entering a census block for the first time: the odds of a new ISP entering a census block during any six-month time period from June 2015 to December 2016 was 7.17% lower than from June 2010 to December 2014. However, we are unable to make any conclusive statements regarding the 2015 OIO's effect on investments in existing services by existing ISPs, as rates of change of broadband speeds in census blocks seems to have changed after 2015 to varying degrees based on the technology of transmission. Finally, this paper also characterizes the nature of competition amongst incumbent ISPs in geographical units from the time period December 2014 to December 2016, concluding that the greater the number of incumbent ISPs in a census block, the higher the rate of change of speeds.

JEL classification: D21; D25; D42; L20; L50; L96

Keywords: Net neutrality; Telecommunications; Broadband Investment; Policy Uncertainty

Introduction

This paper seeks to explore the impact that the United States Federal Communications Commission's (FCC) 2015 Open Internet Order (OIO) has had on broadband infrastructure investment. From the passage of the Telecommunications Act of 1996 until 2015, the Internet mostly received "light-touch" regulation. However, in March 2015, the FCC increased its regulation of the business practices of Internet Services Providers (ISPs) via the 2015 OIO. The FCC justified the OIO by promoting the theory of the "virtuous cycle".[1] Essentially, if broadband providers act as gatekeepers standing in between edge providers (i.e. online websites and applications, including content service providers (CSPs) like Netflix, that deliver content to customers at the "edge" of the network rather than providing the internet's core infrastructure) and consumers, then the FCC argued that an ISP can unfairly block or limit access to the CSP's services in favor of its own. This could reduce the rate of innovation by CSPs, thereby decreasing the rate of improvements to network infrastructure by ISPs. The FCC hoped that by enforcing net neutrality rules, which would limit the gate-keeping ability of ISPs, the greater level in innovation by CSPs would drive up the need for network improvements and investment in infrastructure by ISPs. This would lead to a positive, "virtuous cycle".[2] Opponents of net neutrality rejected the idea of this virtuous cycle, instead arguing that these regulations would be costly to ISPs and therefore lead them to invest less in broadband infrastructure. This paper seeks to analyze the impacts of the 2015 OIO on broadband investment.

Background

[1] https://apps.fcc.gov/edocs_public/attachmatch/FCC-10-201A1_Rcd.pdf
[2] http://thehill.com/blogs/pundits-blog/technology/333371-fcc-return-to-light-touch-regulation-would-encourage-capital

In 2005, the United States Federal Communications Commission established four open internet principles to preserve and promote the open and interconnected nature of public internet,[3] defined as "…the principle that Internet service providers should enable access to all content and applications regardless of the source, and without favoring or blocking particular products or websites."[4] The standards were put forward in a policy statement without enforceable rules. In December 2010, the FCC sought to solidify these standards in the 2010 Open Internet Order (OIO).[5] However, in 2014, the United States Court of Appeals in D.C. struck down the 2010 OIO, ruling that "… (g)iven that the [FCC] has chosen to classify broadband providers in a manner that exempts them from treatment as common carriers, the Communications Act (1996) expressly prohibits the [FCC] from nonetheless regulating them as such."[6]

In March 2015, the FCC released its 2015 OIO reclassifying broadband internet access service (BIAS) from an "information service" under Title I[7] to a "common carrier service" under Title II of the Communications Act of 1934. This ostensibly gave the FCC regulatory authority over the internet, since Title II falls under FCC regulatory authority. In particular, in addition to reclassifying internet services, the 2015 OIO explicitly banned activities such as content throttling and paid prioritization, where data transfer rates for edge providers are guaranteed by the ISP in exchange for payment.[8] However, in December 2015, the new FCC administration voted to eliminate the 2015 OIO, arguing that it imposed costly regulatory burdens on ISPs and that its repeal would lead to greater investment in broadband investment.[9]

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[3] https://apps.fcc.gov/edocs_public/attachmatch/FCC-05-151A1.pdf
[4] https://en.oxforddictionaries.com/definition/net_neutrality
[5] https://apps.fcc.gov/edocs_public/attachmatch/FCC-10-201A1_Rcd.pdf
[6] https://www.cadc.uscourts.gov/internet/opinions.nsf/3AF8B4D938CDEEA685257C6000532062/$file/11-1355-1474943.pdf
[7] http://transition.fcc.gov/Reports/1934new.pdf
[8] https://whatis.techtarget.com/definition/paid-prioritization
[9] https://www.recode.net/2017/12/14/16777356/full-transcript-ajit-pai-brendan-carr-fcc-statements-net-neutrality-repeal

A few papers have attempted to estimate the impact of the 2015 OIO on investments by considering total capital expenditures by top internet service providers, as well as through simple counterfactual analyses. While previous research has examined industry-specific capital expenditures at the national level, this paper attempts to deepen the empirical analysis by analyzing measurable outcomes of investment within smaller geographic markets within the United States. In this fashion, one can control for market factors which influence incentives for marginal investment.

Every six months, the FCC uses Form 477 to collect data on disaggregated broadband speeds, technology types, and existing service providers at the census block level in the United States (U.S.). We consider two measurements, the rate of change of broadband speeds in the census blocks, and the likelihood of an ISP entering a new census block. These measurements should be positively related to broadband investment at the local level. Form 477 data do not include measures of physical infrastructure or capital expenditures. Hence, additional deployment within a census block by an incumbent firm cannot be directly estimated. Additionally, the most recently released Form 477 data are from December 2016. Therefore, our analysis can at best capture the short run impact of the 2015 OIO. This is particularly limiting given that investment decisions by ISPs may take many years to be fully implemented. Despite these limitations, the data provide insights into changing investment outcomes over time.

Literature Review

Prior research on the impact on broadband investment focuses on two main factors: first, the regulatory uncertainty generated by constantly changing OIO policies and frequent court reversals, and second, particular rules within the 2015 OIO itself which affect overall profit and returns to R&D and physical investment.

There exists a large body of existing research on the impact of uncertainty on investments. Theoretical work by Bernanke (1983) highlights that when investment projects are costly to reverse, high uncertainty about factors such as future prices and interest rates causes firms to delay investment. Once uncertainty decreases, firms will exhibit a spike in the level of investment due to pent-up demand, before returning back to normal levels. Bloom (2009) and Bloom et. al (2012) provide evidence that uncertainty generated by major economic or political shocks, as measured by proxies such as stock market volatility, leads to dramatic falls in investment, followed by a rebound. Baker et. al (2013) and Guleyin and Ion (2015) verify that policy uncertainty has a negative impact on investments for at least four quarters into the future. This seems to suggest that broadband infrastructure investment should be expected to fall in the short term as companies wait until the political and legal uncertainty surrounding the 2015 OIO clears, although the exact timing of this decrease (whether it occurred in the run-up to the 2015 OIO or after its implementation) is unclear.[10]

Various analyses conducted before and after the 2015 Open Internet Order attempted to determine the possible impact of new regulations on broadband investment. For the most part, theoretical papers find that regulations that prohibit ISPs from offering enhanced features such as paid prioritization tend to decrease broadband investment. Choi and Kim (2010) find such

[10] http://www.nera.com/content/dam/nera/publications/2015/016071507K&L_unlocked.pdf

regulation to have ambiguous effects on network investment. Conversely, Bourreau, Kourandi, and Valletti (2015) find that under net neutrality (in which ISPs cannot charge content service providers (CSPs) more to access fast lanes), investments in broadband capacity and content innovation are both lower than otherwise. Economides and Hermalin (2012) find that the ability of ISPs to discriminate results in ISPs installing greater bandwidth capabilities, benefits ISPs through greater profits and potentially benefits CSPs through improved bandwidth capabilities for their content.[11] Similarly, Njoroge and Ozdaglar (2013) find that ISPs invest less in investment under regulations that prohibit “priority lanes”. Without these regulations, ISPs are able to price content provision more appropriately and therefore increase investment, which enhances both consumer surplus and content service providers’ profit. Regiani and Valletti (2016) find that allowing prioritization (such as through fast lanes) increases infrastructure core investment and overall welfare only if it encourages sufficient innovation from large content service providers.

Connolly, Lee, and Tan (2015) provide an overview of how the 2015 OIO would impact Internet prices, accessibility, and content. They suggest that under the 2015 OIO, which prohibits ISPs from charging fees to content service providers, ISPs would need to extract surplus by either raising prices on consumers, lowering the quality of internet service that is provided, restricting service to more profitable clients, or imposing data caps on subscriptions. Connolly et al. (2015) also argue that net neutrality’s constraint of equal bandwidth allocation across all applications leads to allocative inefficiency “if the marginal utility from additional bandwidth for

[11] Economides and Hermalin (2012) find the impact of net neutrality to unambiguously decrease investment in broadband bandwidth. However, they find that the impact of increased bandwidth on overall welfare is ambiguous; particularly, “when household utility is a significantly greater component of welfare than content providers’ profits, then network neutrality can still be the welfare-superior policy even accounting for the ISP’s bandwidth-building incentives.”

the applications differs."[12] The inability to maintain differential prices among CSPs lowers incentives for ISPs to increase investment and coverage, especially for geographic areas with lower returns.[13] Therefore, one would expect that such regulations would lower investment by a greater extent in sparsely-populated rural areas and low-income neighborhoods than their urban and high-income counterparts. Empirical data showing that rural areas continue to lag behind their urban counterparts is consistent with this hypothesis. The FCC's 2016 Broadband Progress Report found that whereas only 4% of Americans in urban areas lack access to 25 Mbps (download) /3 Mbps (upload) broadband speeds, 39% of Americans in rural areas lack access. Likewise, improvement has been slow: the percentage of Americans lacking service to 4 Mbps/1 Mbps and 10 Mbps/1 Mbps broadband speeds in rural areas fell by only 1% and 4%, respectively, between 2011 and 2016.[14]

Several researchers have estimated levels of broadband investment since 2014. Singer (2016) finds that domestic broadband capital expenditures (capex) for 12 major firms declined by $3.6 billion in 2016 relative to 2014 levels, representing a 5.6% decline overall. Eight of the twelve firms experienced a decline in domestic expenditures from 2014 to 2016, with the largest decreases occurring at AT&T and Sprint.[15,16] One of the major arguments used by the FCC when implementing the 2015 OIO was that the 2010 net neutrality order led to a historic increase in

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[12] Connolly, M., Lee, C. and Tan, R. (2017), p. 9

[13] Ibid.

[14] FCC (2016) *2016 Broadband Progress Report*. p. 3

[15] *See* Hal Singer, 2016 Broadband Capex Survey: Tracking Investment in the Title II Era, *available at* http://bit.ly/2reYks0. FCC chairman Ajit Pai cited Singer's analysis in the Restoring Internet Freedom Notice of Proposed Rulemaking in May of 2017, which outlined the FCC's intentions to roll back Title II reclassification for ISPs. See Pai Statement, "Restoring Internet Freedom Notice of Proposed Rulemaking." 23 May 2017.

[16] Singer's analysis received criticism from proponents of the OIO, such as the think-tank Free Press. Free Press found that public ISPs spent 5.3% more on capital investment in the two years following the OIO and that two-thirds of public ISPs reported investment increases. The variance between these two analyses is based on different interpretations of what types of capital expenditures are most relevant; Singer excluded certain capex such as AT&T's acquisition of DirecTV and investments in Mexico to isolate the direct domestic impact of the OIO, whereas Free Press kept these and similar expenditures by other companies in their analysis.

capital expenditures in the 2011-2013 period. Hazlett and Wright (2017) point out that once one adjusts for inflation, this "…asserted result vanishes. Of sixteen data points, rolling three-year averages from 1996-1998 through 2011-2013, 12 values for capex are higher than the 2011-2013 figure, only three values lower (Fig 1)."

In a counterfactual analysis, Horney (2017) finds that total broadband investment was cumulatively $5.6 billion lower in 2015 and 2016 than expected based on the trend of prior twelve years. Horney establishes a trend line of overall national expenditures by broadband providers from 2003 to 2014, then extends it to estimate expected values for 2015 and 2016. This trend suggests that expenditures in 2015 and 2016 should have been $76.6 billion and $78 billion, rather than the observed $76.3 billion and $72.7 billion.[17]

Ford (2017) examines trends in broadband investment after the 2010 OIO. Ford undertakes a counterfactual analysis and suggests that $150-200 billion more would have been invested by the telecommunications industry from 2011 to 2015 had it not been for the threat of Title II reclassification in 2010.[18] The counterfactual is estimated through comparisons with investment in this same time period by manufacturing-based industries, such as machinery manufacturing, computer and electronic products manufacturing, plastic and rubber products manufacturing, and transportation and warehousing. Ford chooses these industries based on high correlation in investment trends between these industries and the telecommunications industry from 1980 to 2010. Ford therefore argues that the telecommunications industry would have continued to experience similar trends as these other industries if not for the 2010 OIO. To the extent that these industries may experience independent economic shocks, it is difficult to know

[17] Horney, M. (2017) Broadband Investment Slowed by $5.6 Billion Since Open Internet Order. The Free State Foundation. http://freestatefoundation.blogspot.com/2017/05/broadband-investment-slowed-by-56.html
[18] Ford, George S. 2017. "Net Neutrality, Reclassification and Investment: A Counterfactual Analysis. Perspectives. Phoenix Center for Advanced Legal & Economic Public Policy Studies. Phoenix Center Perspectives 17-02.

with certainty that the realized differences in investment patterns can be wholly attributed to the 2010 OIO.

A major issue with the above-mentioned literature is that analyses are based on aggregate annual expenditures by companies and across the telecommunications industry. This is to be expected, as telecommunications companies report overall capital expenditures in their public financial statements without designating between investments in specific geographic areas or across different types of expenditures. This aggregated data does not distinguish between investments in new technology, such as fiber, versus deployment to new markets. Likewise, expenditures at the national level do not take into account variations in factors such as income or population density, which affect incentives for investment. Therefore, it would be helpful to examine data at smaller geographic measurements while controlling for these factors. Our goal is to address this gap in the literature. Analysis of more granular data will help identify the changes in investment in broadband infrastructure, and whether these changes might be attributable to the 2015 OIO. Since more granular data on research and development (R&D) or infrastructure spending are not publicly available, we instead consider the Form 477 data in the hopes of capturing the output, or results, of these inputs; namely by measuring speeds and the likelihood of an ISP entering new markets.

Theoretical Framework

A. Improving Quality: Undertaking Investment Projects by an Existing Firm

Consider a firm currently established in a market. In examining a firm's decision to invest, one can assume that a firm seeks to maximize profits

$$\mathbf{\Pi}^i(q,s) = q\ P(q,s) - C(q,s)$$

where q is the quantity of the good, s is the quality of the good, $P(q,s)$ is the price that generates a demand for q units of the good at the quality s, and $C(q,s)$ is the total cost of producing q units of the good at quality s.

The resulting first-order conditions are

$$P(q,s) + \ q\ P_q(q,s) = C_q(q,s)$$

and

$$q\ P_s(q,s) = C_s(q,s).$$

In the context of an ISP, an ISP that seeks to meet the first-order conditions will need to engage in investments on two fronts: 1) improving quality of broadband service as a form of product innovation in order to increase P_s, and 2) expanding broadband coverage to improve market penetration or to contest for market share, which increases q. An investment project in product innovation, such as by replacing copper wiring with fiber in the case of ISPs, can produce a higher quality product relative to a firm's prior product or other competitors. The difference in quality can allow a firm to charge a premium for a product, in this case by increasing the price $P_s(q,s)$, or capture a greater market share (increasing quantity) if price remains unchanged. An investment project which results in more extensive goods provision (in a market with a penetration rate smaller than 100%), such as by building new internet towers in an area to improve connectivity, can capture more market share or increase the market penetration rate, thereby increasing the quantity supplied.

When examining the likelihood of production innovation and the ability to set higher prices, it is crucial to consider the degree of competition within an industry. Consider a monopoly in an industry with a high cost of entry. If the monopolist has not fully penetrated the industry yet, it can undertake an investment project to engage in either production innovation or increasing market penetration or both. However, in the case of product innovation, Arrow (1962) theorizes that a new product would cannibalize the existing excess profits of the monopolist, and the monopolist would thus find taking on an investment project less worthwhile. Nonetheless, it is not to say a monopolist will not engage in product innovation; the threat of a new entrant with a better product will still drive a monopolist to engage in product innovation. In contrast, in competitive industries with two or more firms engaged in Bertrand price competition, Arrow (1962) finds that the degree of innovation would be higher than in a monopoly, as innovation would be the only way for a firm to make (short-term) positive profits.

For ISPs in different geographic markets, the degree of innovation is influenced by the number of existing ISPs and potential entrants in the geographic market

$$P_s(q, s) = F(n, n^*)$$

where n is the number of ISPs in the market, and n^* the number of potential entrants.

When examining the likelihood of an existing firm increasing goods provision, it is crucial to consider the existing market penetration rate. According to Arrow, for a market with 100% market penetration rate already serviced by 1 or more firms, an investment project to increase provision will only be rational for firms fighting over market share, and only if the expected marginal profit is at least zero. For an ISP, each geographical market will have a different broadband penetration rate, and the decision to engage in an investment to increase broadband provision depends on the geographic broadband penetration rate and the expected marginal profit.

B. Expanding Coverage: Entering a Market by a Firm

Before a firm decides to enter a new geographic market, the underlying question it faces is: does the firm expect to be able to make at least zero marginal profits from entering this new market? To determine the firm's expected profits, a firm considers whether the market can support an additional firm and whether the firm can capture sufficient market share from a competitor and/or capture the unpenetrated sections of the market. Consider the case of a monopoly with 100% market penetration charging prices *p* for quantity *q* with cost *c* per unit of production, and fixed cost *f*. Using a standard profit model, as presented by Tirole (1988), the monopoly profit is

$$\mathbf{\Pi}^m = p\,q - q\,c - f.$$

Now consider the entrance of a new homogenous firm with an identical, non-differentiated good which managed to capture some market share. It is clear that the overall profits in the market will decrease with the entry of a new firm due to rising overall fixed costs:

$$\mathbf{\Pi}^1 + \mathbf{\Pi}^2 = p\,q - q\,c - 2f.$$

Regardless of whether one assumes Bertrand or Cournot competition, the entrance of a new identical firm would result in each firm splitting the profits equally between each other. [19] Generalizing to *n* firms, it is possible that the addition of a *n+1* firm will result in

$$\sum_i^{n+1} \mathbf{\Pi}^i < 0.$$

[19] This assumes that there is no possibility of one firm acting as a Stackleberg leader under Cournot competition.

whereby at this point the market cannot support an additional firm, and at least one firm is making negative profits. For simplicity, assuming the $n+1^{th}$ firm is the only firm expected to make negative profits, the firm will not enter the new market.

However, in the case of heterogeneous firms, if one firm's product is of significantly higher quality, it could potentially capture all of the market share and replace the monopolist, while making at least zero profits. The same argument can be extended for a market with more than one incumbent firm: if the quality of the new firm's product is comparatively higher than one or more incumbent (heterogeneous) firms, the entry of the new firm into that geographic market is more likely to occur.

In the case of a market with current market penetration rate below 100%, with the number of firms greater than 1, a firm could seek to enter the market to capture the unpenetrated market segment, as well as potentially capture market share away from current firms.

In the context of broadband markets, the likelihood that an ISP enters a new geographic market can be modeled as:

$$\boldsymbol{L}(Entry) = V(pq, n, s, bp),$$

where *pq* denotes the total possible market revenue, *n* is the number of ISPs in the target geographic market, *s* is measure of the quality of the existing broadband services, and *bp* is the broadband penetration rate.

Empirical Model

In 2015 the FCC argued that enforcing open internet rules would lead to a "virtuous cycle", in which good business practices and consumer trust would encourage edge provider innovation and broadband infrastructure investments, and lead to network improvements. While there exists little disaggregated information on capital expenditures by the telecommunications industry, there has been even less analysis examining the profit functions of firms in individual geographic markets. Ideally, it would be useful to directly examine R&D expenditures by firms in order to represent those firms' motivations and optimism for future investment projects. However, of the ten largest telecommunications in the U.S., only AT&T lists R&D as an individual line-item on their public financial documents. Likewise, R&D expenditures only capture the earliest steps of innovation and do not provide information on deployment or infrastructure upgrade expenditures.

We therefore attempt to directly measure network improvements by observing individual geographic market changes in 1) download and upload speeds across time and 2) deployment (i.e. entrance of a new firm into a given market). Changes in broadband quality across time and between different geographic regions will serve as a proxy for broad changes in broadband infrastructure investment.

Specifically, we consider changes in broadband quality across time periods, with a specific focus on the changes after the years: 1) 2014, when the FCC voted on a new set of network neutrality rules; and 2) 2015, when the 2015 OIO passed. Any changes in trends will potentially reflect the impact that the 2015 OIO has had on broadband infrastructure investment.

The uncertainty due to the possible changes in the OIO from 2010 to 2015 may have resulted in a temporary fall in investments; for example, if the ISPs were not certain how much regulation they would be subjected to, and when such regulations would be imposed on them, ISPs might delay planned investments. Hence, there is a possibility that ISPs' investments would fall during this window of regulatory uncertainty.

However, the level of investments by ISPs could also be affected by the 2015 OIO regulations themselves. In line with Connolly et al.'s (2015) suggestion that banning paid prioritization would lower incentives for ISP to invest, it would be possible to observe investments increasing or decreasing in different geographic markets based on the geographic-specific rates of return. For example, if the 2015 OIO did indeed make it more expensive for ISPs to increase network investments, then ISPs might be less likely to invest generally, and this may be even more visible in rural areas or lower socioeconomic areas, all else equal. This would increase the so-called "digital divide", which represents the disparity in access to and use of digital technology based on urban vs. rural and rich vs. poor areas, relative to what it would've been without the 2015 OIO. Although this paper does not analyze the distinction between urban and rural areas, it does examine the role that household income levels within geographical markets play in a firm's decision process.

A. Estimating Changes in Speed of Existing Services

Every six months, the FCC releases Broadband Deployment data. From June 2010 to June 2014, this broadband deployment data was collected as part of the National Broadband Map effort. From December 2014 to December 2016, the data was sourced from Form 477, which is filled biannually by all firms providing facilities-based broadband. On this form, ISPs are required to report a list of all census blocks where the ISPs provides at least one broadband connection to end-user premises, type of transmission technology, maximum advertised upload and download speeds, and a distinction between consumer and business/government service. [20]

While there is a lack of information on broadband penetration rates and quantity of services provided by an ISP at the census block level, the rate at which an ISP engages in investments to improve broadband quality between each time period, as a form of product innovation, can be proxied using the rate of change of broadband speeds. Given that different technology types will require different levels of investments to achieve a certain improvement in broadband speeds, the model will examine the changes in broadband speed for each technology type and any upgrades to new transmission technologies. To account for the changes in broadband speeds due to the impact of regulation uncertainty and the 2015 OIO directly, the marginal impact will be examined for the treatment years 2014 and 2015 respectively, using a time-series regression. Competition within the census block will be accounted for by the number of ISPs and also the entry and exit of ISPs. The model used is:

$$\Delta S_{ivt_{j\to k}} = \beta_0 + \beta_1 N_{it_j} + \beta_2 \Delta(-N)_{it_{j\to k}} + \beta_3 \Delta(+N)_{it_{j\to k}} + \varepsilon_{it}$$

where $\Delta S_{ijt_{j\to k}}$ refers to the rate of change of an ISP's offered consumer download speeds for each census block i, technology type v, and from time period t_j to t_k,[21] N_{it_j} refers to the number of ISPs in the starting time period, $\Delta(-N)_{it_{j\to k}}$ refers to the number of ISPs that left the

[20] A census block is the smallest geographic unit delineated by the United States Census Bureau and used by the Census Bureau for 100-percent data tabulation. Census blocks are grouped into Census Block Groups, which are then grouped into Census Tracts. Census blocks are numbered uniquely with a 4-digit number ranging from 0000 to 9999, with the first digit identifying the Census Block Group.

[21] Rate of change of an ISP's consumer download speeds will be examined for the same technology type and/or upgrades to, or provision of new transmission technologies. It is likely that an ISP can have multiple services with different broadband technology, per census block.

block in that time period, $\Delta(+N)_{it_{j\to k}}$refers to the number of ISPs that entered the block in that time period, and ε_{it} refers to the error term.

While it is not possible to identify the number of potential entrants eyeing a market, based on the assumption that the broadband investment project for market entry requires a period of time thereby alerting incumbent ISPs of an upcoming competitor, it is necessary to control for any responses by incumbent ISPs to materializing competition.

B. Estimating Changes in Market Entry

The likelihood function of an ISP entering a market can be estimated using a logit regression. Comparing the broadband deployment data over time periods reveals which census blocks welcomed a new ISP provider. The logit model allows us to find the relationship between a binary outcome, such as entering or not entering, and various predictor variables. The model used is:

$$\ln\left(\frac{L}{1-L}\right) = \beta_0 + \beta_1 P_{it}Y_{it} + \beta_2 N_{i(t-1)} + \beta_3 Q_{max>avg} + \beta_4 OIO_{2015} + \beta_5 OIO_{2015}P_{it}Y_{it} + \beta_6 OIO_{2015}N_{i(t-1)}$$

where L refers to the probability of any ISP entering a census block, P_{it} refers to population, and Y_{it} refers to income. $P_{it}Y_{it}$ represents a proxy for the maximum attractiveness of a market. $N_{i(t-1)}$ refers to the number of ISPs in market i in the previous time period, $Q_{max>avg}$ is a dummy for whether or not the maximum speed of the census block is equal to or greater than national average, OIO_{2015} is a dummy for whether or not the time period begins June 2015 or after (since the 2015 OIO was enacted in March), $OIO_{2015}P_{it}Y_{it}$ is an interaction term that describes how the OIO changed the likelihood of entry based on Maximum Market Attractiveness, and $OIO_{2015}N_{i(t-1)}$. While there are no disaggregated data for broadband penetration and prices charged by ISPs in every market, the attractiveness of a potential new market can be proxied using population and income data from the ACS. The quality of existing broadband service in a market can be determined based on median available broadband speeds for a given year.[22] The coefficients of this regression can then be transformed into odds ratios for easier interpretation.

Although this model measures the probability of *any* ISP entering a block, rather than a specific ISP, the theoretical framework of profit functions for individual firms (as described above) still holds. Ideally, our model would also include proxies for existing regulation or geographic constraints in order to account for barriers to entry, but since we do not have appropriate data for these measures, they are not included in the regressions.

[22] The quarterly values for the national average internet connection speeds came from Akamai Technologies and were presented by the statistics website Statista at https://www.statista.com/statistics/616210/average-internet-connection-speed-in-the-us/

Methodology

A. Data Cleaning

Using the biannual data from the National Broadband Map and the FCC Form 477 Fixed Broadband Deployment data, data entries irrelevant to the analysis were removed. A trimmed dataset was generated for each biannual data, containing *hoconum* (the Holding Company Number assigned to a Holding Company by the FCC, which remained unchanged across the years), *stateabbr* (2-letter state abbreviation used by the US Postal Service), *blockcode* or *fullfipsid* (a 15-digit census block code used in the 2010 US Census), *techcode* or *transtech* (a 2-digit code indicating the Technology of Transmission[23] used to offer broadband service), *maxaddown* or *maxdown* (the maximum advertised downstream speed offered by the provider in the block for consumer service). Biannual data from the FCC Form 477 Fixed Broadband Deployment data, across December 2014 to December 2016, provided *maxaddown* in disaggregated speed values; biannual data from the National Broadband Map, across June 2010 to June 2014, provided *maxdown* in speed bands.[24] For data entries recorded in speed bands, the lower bound speed value of the speed band was assigned as a means of approximation. The lower bound speed values had on average a 45% match with the disaggregated speed values from Form 477, compared to the average or median speed value within a speed band, with an average of 20% match, and hence the lower bound speed values were chosen.

From June 2010 to June 2014, publicly available broadband data was collected by the National Telecommunications and Information Administration's (NTIA) State Broadband Initiative (SBI) for the National Broadband Map (NBM). Data collected from telecommunication

[23] See Appendix A1 for a full list of *techcodes* and associated Technology of Transmission.
[24] See Appendix A2 for a full list of speed bands.

companies was on a voluntary basis, and hence is not fully comprehensive. However, starting from December 2014, Form 477 Broadband Data was used as the source for publicly available broadband data. Reporting for Form 477 was mandatory for all telecommunication companies, with every provider that fit into one of four categories[25] required to submit data to the FCC. Data starting from December 2014 also contained entries by satellite providers too, and these data entries were removed to ensure consistent comparison from June 2010 to December 2016.

For population and income data, the 2016 American Community Survey (ACS) 5-Year Estimates of household income data at the census block group level, from the years 2013 to 2016, and the 2012 American Community Survey (ACS) 5-Year Estimates of household income data at the census tract level, from the years 2010 to 2012, were used. The ACS data outlined the number of households in various income ranges[26], and the income values from 2010 to 2012 were converted from 2012 dollars to 2016 dollars based on an inflation rate of 1.12% per year. The maximum market attractiveness for each tract or block was generated by finding the sum of all the products of the lower-bound of the income range and the number of households in that range. For the income range "less than $10,000", the population was multiplied by $5,000 rather than $0. A new dataset was generated per year, containing *census_tract* or *census_block_group*, and the *total_max_revenue* (the maximum market attractiveness for the census tract for the years 2010 to 2012 and block group from 2013 to 2016). The *total_max_revenue* values were then averaged to census block values by comparing the number of census tracts or block groups to the total number of census blocks in each state.[27] Entries with a value of 0 for the maximum market

[25] Facilities-based Providers of Broadband Connections to End Users, Providers of Wired or Fixed Wireless Local Exchange Telephone Service, Providers of Interconnected Voice over Internet Protocol (VoIP) Service, and Facilities-based Providers of Mobile Telephony (Mobile Voice) Service.
[26] See Appendix A3 for a full list of income ranges.
[27] Based on 2010 census data found at https://www.census.gov/geo/maps-data/data/tallies/tractblock.html.

attractiveness were dropped, and the averaged *max_revenue* values were then associated with the census block code. The variable *max_revenue* was then normalized by a factor of 100,000 to produce *norm_max_revenue*[28].

Overall, 96.2% of the census block entries in Form 477 were associated with ACS demographic data. A summary of the data is shown below in Figure 1:

Figure 1: Number of Observations per Data Set

Month	*Form 477 (biannual; multiple firms per block)*	*ACS (annual; same values used for Jun and Dec)*	*ACS Equivalent # of Blocks (approx.)*
Jun 2010	11,602,116	74,003 (tracts)	11,146,604
Dec 2010	13,749,059	74,003 (tracts)	11,146,604
Jun 2011	17,942,330	74,002 (tracts)	11,146,454
Dec 2011	18,579,924	74,002 (tracts)	11,146,454
Jun 2012	20,388,437	74,002 (tracts)	11,146,454
Dec 2012	21,352,406	74,002 (tracts)	11,146,454
Jun 2013	18,981,921	218,408 (block groups)	11,048,270
Dec 2013	19,308,420	218,408 (block groups)	11,048,270
Jun 2014	19,447,808	218,413 (block groups)	11,048,522
Dec 2014	20,094,059	218,413 (block groups)	11,048,522
Jun 2015	21,234,100	218,370 (block groups)	11,046,347
Dec 2015	22,199,865	218,370 (block groups)	11,046,347
Jun 2016	22,976,813	218,370 (block groups)	11,046,347
Dec 2016	23,442,649	218,370 (block groups)	11,046,347
Total	271,299,907		155,257,996

[28] Only 3.06% of the *max_revenue* values are less than 100,000, so we decided this was a reasonable number to use to normalize *max_revenue*.

B. Generating Variables for Changes in Speed

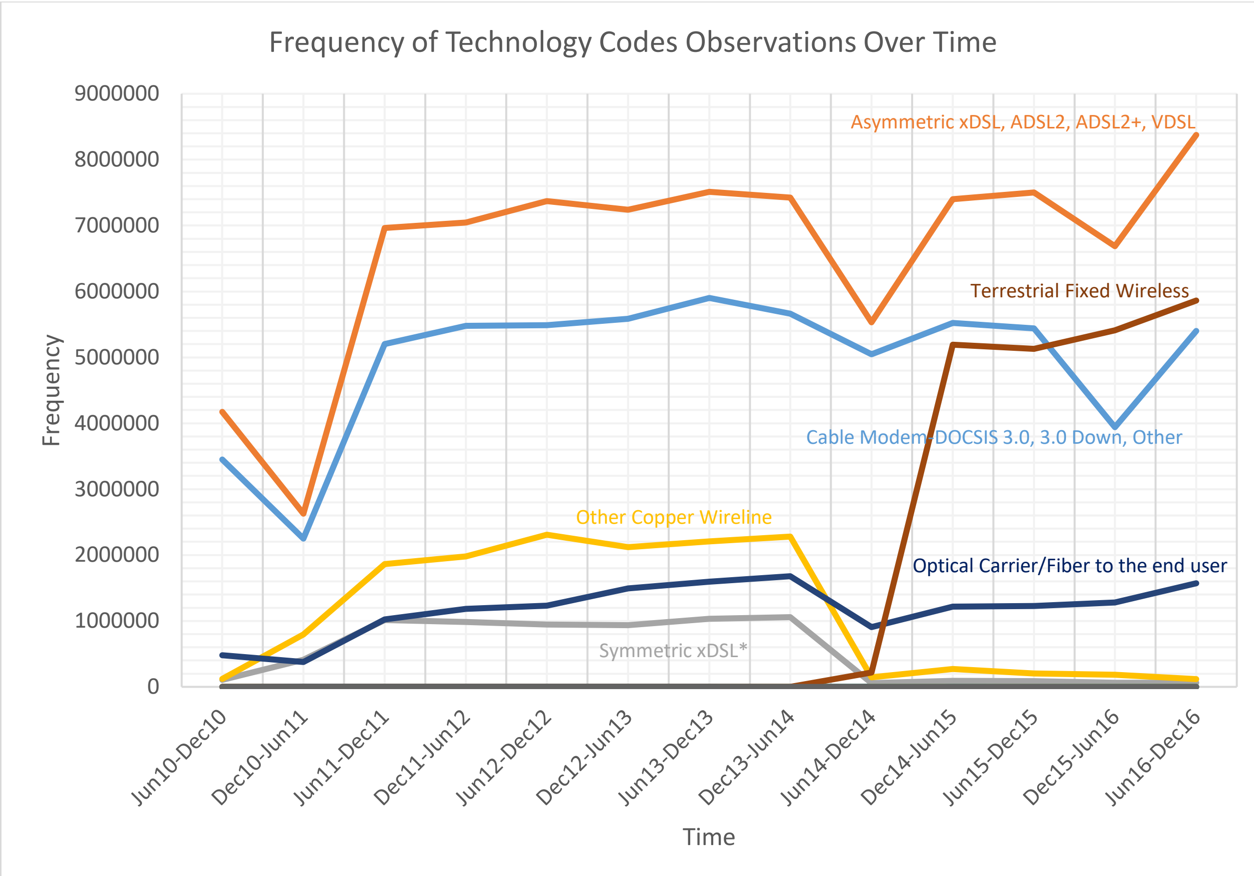
With the broadband speeds data, data from two consecutive time periods were examined (e.g. June 2010 and December 2016). For each census block, the unique ISPs, determined by the unique *hoconum*, were compared across both time periods, with N_{it_j} (or *n*) as the number of unique ISPs in the preceding time period. $\Delta(-N)_{it_{j\to k}}$ (or *delta_neg)* was generated by finding the difference between the number of original unique ISPs (from the preceding time period) that still remained in the census block in the following time period and the original number. $\Delta(+N)_{it_{j\to k}}$ (*delta_pos*) was generated by determining the number of new unique ISPs in the following time period vis-à-vis the original unique ISPs in the preceding time period. $\Delta S_{ivt_{j\to k}}$ (or *delta_s_rate*) was generated by taking the natural log of the advertised broadband speeds for the matching data entries of pre-existing ISPs, with the same unique *hoconum* and same *techcode/transtech*, in the two time-periods, and taking the difference of the natural logs. The rate of change of speed was used instead of nominal values as broadband speeds rose exponentially. In the occurrence of a negative change in speed, these observations (accounting for around 4% of the total observations) were dropped, with the assumption that ISPs might have falsely advertised speeds in the preceding time period. This is also in line with changes in broadband speeds as a proxy for broadband infrastructure – aside from depreciation, which is not measured, zero infrastructure investment should produce no changes in offered broadband speeds.

For ISPs that upgraded their transmission technology but kept the same base technology (e.g. upgrading from Cable Modem – DOCSIS 3.0 to DOCSIS 3.1), the data entries were associated together, and $\Delta S_{ivt_{j\to k}}$ was calculated vis-à-vis these entries. For ISPs that upgraded their transmission technology and switched to an entirely different technology, these data entries were treated as pre-existing ISPs providing new broadband services. Although no such data entry for the different transmission technology existed in the preceding time period, and thereby calculating the rate of change would not be possible, a value of one was added these *maxaddown* values. $\Delta S_{ivt_{j \rightarrow k}}$ was then calculated by taking the difference between the natural log of the new *maxaddown* value in the following time period and the natural log of one. Figure 2A provides a summary of the observed data entries by existing ISPs across time periods for each technology code, which is then graphed in Figure 2B. As visible in Figure 2A and Appendix 1A, observations for technology codes 10 and 40 are disaggregated into 10, 11, 12 and 40, 41, 42 starting December 2014, and these observations were aggregated. We also observed that there is a significant loss of data entries in the period Jun 2014 – Dec 2014, which most likely resulted from the switch from National Broadband Map to the FCC Form 477 Fixed Broadband Deployment data.

Figure 2A: Number of Data Entries across Time Periods and Technology Codes

Tech Code	***Jun10-Dec10***	***Dec10-Jun11***	***Jun11-Dec11***	***Dec11-Jun12***	***Jun12-Dec12***	***Dec12-Jun13***	***Jun13-Dec13***	***Dec13-Jun14***	***Jun14-Dec14***	***Dec14-Jun15***	***Jun15-Dec15***	***Dec15-Jun16***	***Jun16-Dec16***	***Total***
0	527	0	0	0	0	0	0	0	2784	1952	0	4747	1076	11086
10	4174059	2628055	6965572	7044187	7370950	7240801	7513389	7427011	1742870	3535596	3713952	3204867	3859124	66320433
11	0	0	0	0	0	0	0	0	1637497	1722988	2309148	2031863	2879175	10580671
12	0	0	0	0	0	0	0	0	2151741	2142628	1477201	1450353	1636715	8858638
10-12	4174059	2628055	6965572	7044187	7370950	7240801	7513389	7427011	5532108	7401212	7500301	6687083	8375014	10580671
20	105809	413720	1014032	982842	946471	936179	1035184	1057626	57191	92130	88588	64133	62114	6856019
30	121227	792787	1864205	1979269	2308255	2117823	2205123	2278003	143087	273067	203498	185529	116941	14588814
40	1147091	1500254	3866661	4334612	4570767	4806015	5179449	5026506	49497	72237	61099	66737	80037	30760962
41	2302742	749222	1333585	1141560	916458	780874	721819	637615	349325	187630	120714	126618	107969	9476131
42	0	0	0	0	0	0	0	0	4647700	5261244	5258916	3745958	5210341	24124159
40-42	3449833	2249476	5200246	5476172	5487225	5586889	5901268	5664121	5056522	5521111	5440729	3939313	5398347	64361252
43	0	0	0	0	0	0	0	0	0	0	0	0	1042	1042
50	478799	376828	1020729	1183705	1229562	1495920	1593924	1678714	908395	1215679	1224712	1281168	1571562	15259697
70	0	0	0	0	0	0	0	0	215947	5191191	5130427	5408845	5862149	21808559
90	1158	1564	2219	2219	2219	2219	2219	376	0	0	0	0	0	14193
Total	**8331412**	**6462430**	**16067003**	**16668394**	**17344682**	**17379831**	**18251107**	**18105851**	**11906034**	**19596342**	**19588255**	**17570818**	**21388245**	**208660404**

Figure 2B: Graph of Data Entries across Time Periods and Technology Codes



Tech Codes that are not visible: Cable Modem-DOCSIS 3.1, Electric Powerline, All Other

C. Generating Variables for Market Entry

To establish a measure of quality of the existing broadband services provided in each census block, the maximum offered speed in the preceding time period is determined and compared against the national average broadband speed for that time period. The indicator $Q_{max>avg}$ (or *max_prev_quality*) is assigned a value of 1 when the maximum offered speed is equal or higher than the national average, and 0 otherwise. The indicator *Entry* is assigned a value of 1 whenever a census block has one or more new ISPs entering the census block, and 0 otherwise. The dummy variable for the enactment of the 2015 OIO, *oioindicator15*, is assigned a value of 1, if the time period occurs after March 2015, and 0 if before. *oioindicator15* is interacted with *norm_max_revenue* and *n* to produce *oio15_norm_max_revenue* and *oio15_n.* A summary of the frequency of new entrants is outlined in Figure 3. The vast majority (84.16%) of six-month periods per census block saw no new entrants, while 15.84% of the 102 million observations across the 13 time-periods experienced the entrance of at least one new firm.

Figure 3: Frequency of Entrants into Census Blocks

Number of New Entrants	*Frequency*	*Percent*	*Cumulative*
0	86,041,780	84.16	84.16
1	13,486,423	13.19	97.35
2	2,175,457	2.13	99.48
3	454,922	0.44	99.93
4	64,762	0.06	99.99
5	8,044	0.01	100.00
6	1,248	0.00	100.00
7	41	0.00	100.00
8	2	0.00	100.00
9	1	0.00	100.00
19	1	0.00	100.00
Total	102,232,681	100.0	

Results

A. Estimating Changes in Speed of Existing Services

Our paper tests for the change in the rate of broadband speeds across 13 time periods (Jun 2010 – Dec 2010, Dec 2010 – Jun 2010, …, Dec 2015 – Jun 2016, Jun 2016 – Dec 2016) as a proxy for determining the impact that the 2015 OIO had on broadband infrastructure investments:

$$\Delta S_{ivt_{j\to k}} = \beta_0 + \beta_1 N_{it_j} + \beta_2 \Delta(-N)_{t_{j\to k}} + \beta_3 \Delta(+N)_{t_{j\to k}} + \sum\nolimits_{t_{j\to k}\in\mathbb{T}} \gamma_{j\to k} \cdot TimePeriod_{t_{j\to k}}$$

$$+ \sum\nolimits_{c\in\mathbb{C}} \delta_c \cdot State_c + \sum\nolimits_{v\in\mathbb{V}} \lambda_v \cdot TechCode_v$$

$$+ \sum\nolimits_{t_{j\to k}\in\mathbb{T},\ v\in\mathbb{V}} \alpha_n \cdot TimePeriod_{t_{j\to k}} \cdot TechCode_v + \varepsilon_{it}$$

The results of the effect of each time period on the rate of change of speeds for each transmission technology are outlined in Figure 4A. For consistency across time periods, data entries from the time period Jun 2014 – Dec 2014 are dropped, and data entries after Dec 2014 with technology codes 11, 12 and 41, 42 are aggregated with technology codes 10 and 40 respectively[29], as the switch to Form 477 data also expanded the technology code categories for Asymmetric xDSL (introduction of technology code 11 and 12) and Cable Modem (introduction of technology code 41, 42 and 43).[30,31]

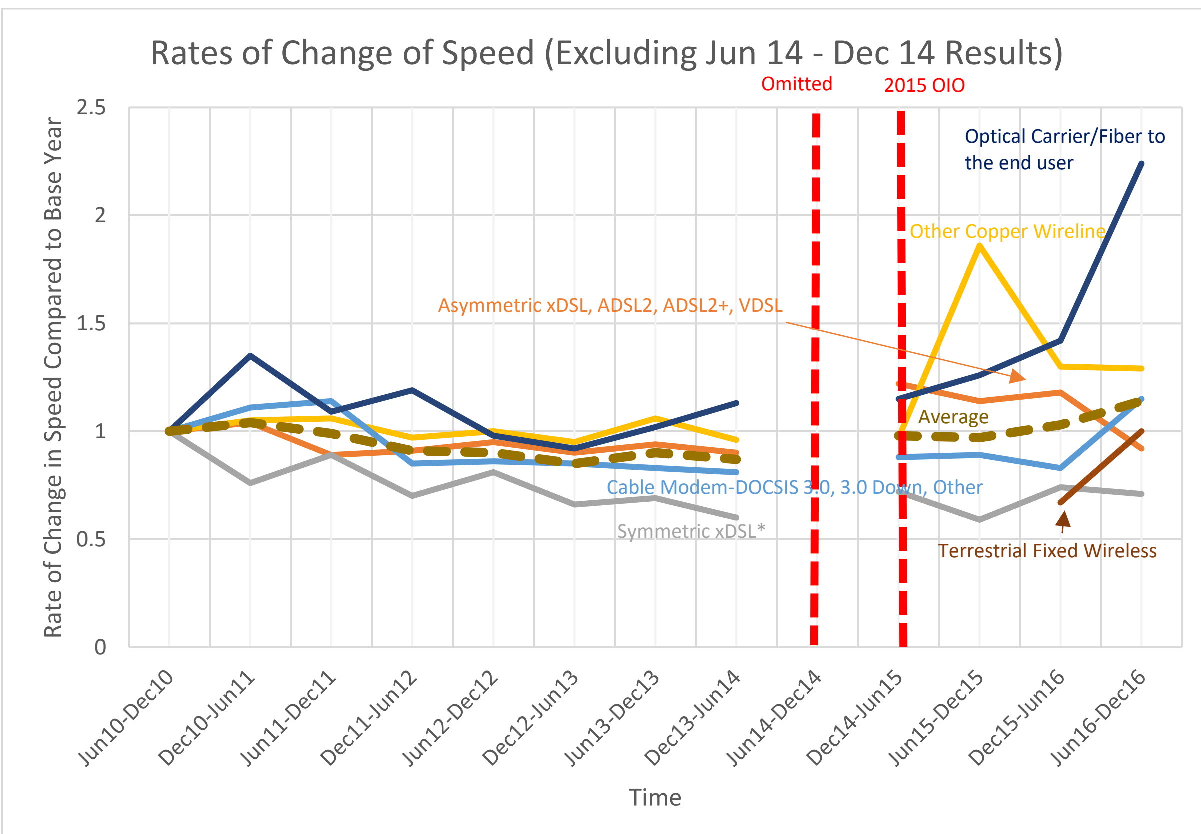
[29] Refer to Appendix B1(2) for full regression results with disaggregated technology code entries, and (1) for results without the dropped time period.
[30] Refer to Appendix A1.
[31] The first instance of technology code 43 was observed in June 2016 – December 2016.

Figure 4A: Rate of Change of Speeds from Jun 2010 to Dec 2016[32]

Tech Code	*Jun10-Dec10*	*Dec10-Jun11*	*Jun11-Dec11*	*Dec11-Jun12*	*Jun12-Dec12*	*Dec12-Jun13*	*Jun13-Dec13*	*Dec13-Jun14*	*Jun14-Dec15*****	*Dec14-Jun15***	*Jun15-Dec15*	*Dec15-Jun16*	*Jun16-Dec16*	*Avg ****
0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10-12	1.00	1.04	0.89	0.91	0.95	0.90	0.94	0.9	-	1.22	1.14	1.18	0.92	1.00
20	1.00	0.76	0.89	0.70	0.81	0.66	0.69	0.60	-	0.72	0.59	0.74	0.71	0.72
30	1.00	1.05	1.06	0.97	1.00	0.95	1.06	0.96	-	0.97	1.86	1.30	1.29	1.14
40-42	1.00	1.11	1.14	0.85	0.86	0.85	0.83	0.81	-	0.88	0.89	0.83	1.15	0.93
43	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50	1.00	1.35	1.09	1.19	0.98	0.92	1.02	1.13	-	1.15	1.26	1.42	2.24	1.25
70	-	-	-	-	-	-	-	-	-	0.66	-	0.67	1.00	0.67
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Avg	1.00	1.04	0.99	0.91	0.90	0.85	0.90	0.87		0.98	0.97	1.03	1.14	

******Note: Results highlighted in blue are base-levels.*
***OIO was enacted in March 2015.*
****Average rate of change of speeds across time periods taken with respect to base-levels.*
*****Data omitted due to inconsistency*

Figure 4B: Rates of Change of Speed from Jun 2010 to Dec 2016



[32] The full regression results can be found in Appendix B1(3).

The average rate of change of speeds for each technology before the Form 477 data is also compared with the average rate of change post- Dec 2014 (when Form 477 data became available) and post-June 2015 (since the 2015 OIO was enacted in March 2015), as seen in Figure 5.

Figure 5: Comparing Average Rates of Change Before and After Implementation of Form 477, and the 2015 OIO

Tech Code	*Avg. Pre-Dec 2014*	*Avg. Post-Dec 2014 (Form 477)*	*Avg. Post-Jun 2015 (OIO)*
0	-	-	-
10-12	0.934	1.112	1.078
20	0.731	0.691	0.680
30	1.009	1.357	1.484
40-42	0.920	0.935	0.954
43	-	-	-
50	1.097	1.516	1.639
70	-	0.777	0.836
90	-	-	-
Average	0.938	1.065	1.112

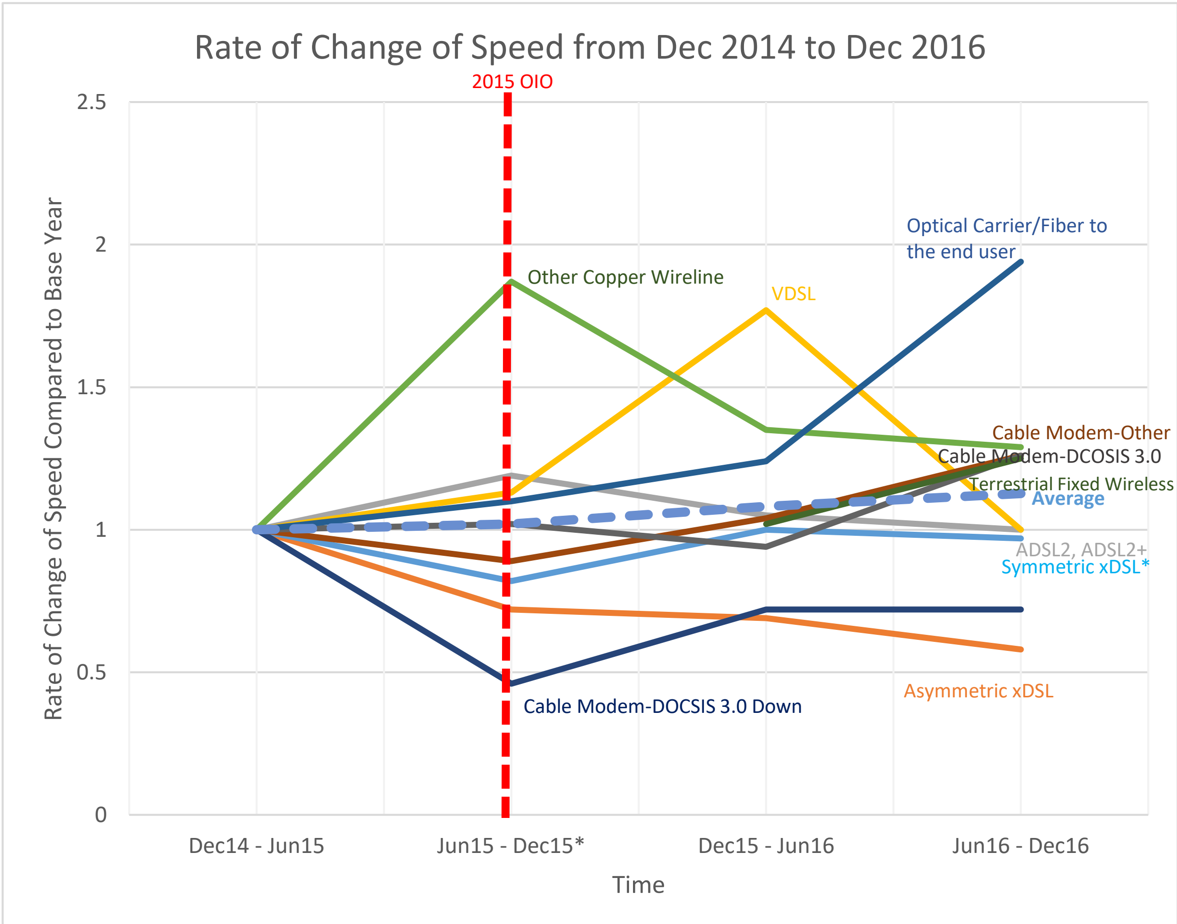
To account for the loss of accuracy switching from speed-band speed approximations to disaggregated speed values, the rates of change of speeds can be examined more accurately using only the disaggregated speed values (starting from the time period Dec 2014 to Jun 2015). The results of the rate of change of speeds across the subset of time periods and for each transmission are outlined in Figure 6A and graphed in Figure 6B.

Figure 6A: Rate of Change of Speeds from Dec 2014 to Dec 2016

Tech Code	*Dec14 - Jun15*	*Jun15 - Dec15**	*Dec15 - Jun16*	*Jun16 - Dec16*
0	-	-	-	-
10	1.00	0.72	0.69	0.58
11	1.00	1.19	1.05	1.00
12	1.00	1.13	1.77	1.00
20	1.00	0.82	1.00	0.97
30	1.00	1.87	1.35	1.29
40	1.00	0.46	0.72	0.72
41	1.00	0.89	1.04	1.26
42	1.00	1.02	0.94	1.26
43	-	-	-	-
50	1.00	1.10	1.24	1.94
70	1.00	-	1.02	1.25
Average	1	1.02	2.19	1.10

Note: Results highlighted in blue are base-levels.
**OIO enacted in March 2015*

Figure 6B: Rates of Change of Speed from Dec 2014 to Dec 2016



Using the accurate data from December 2014 to December 2016, one can generalize the impact of various factors on changes in speed. These measures of competition -- *N*, *Exit*, and *Entry* -- can be found in Figure 7.

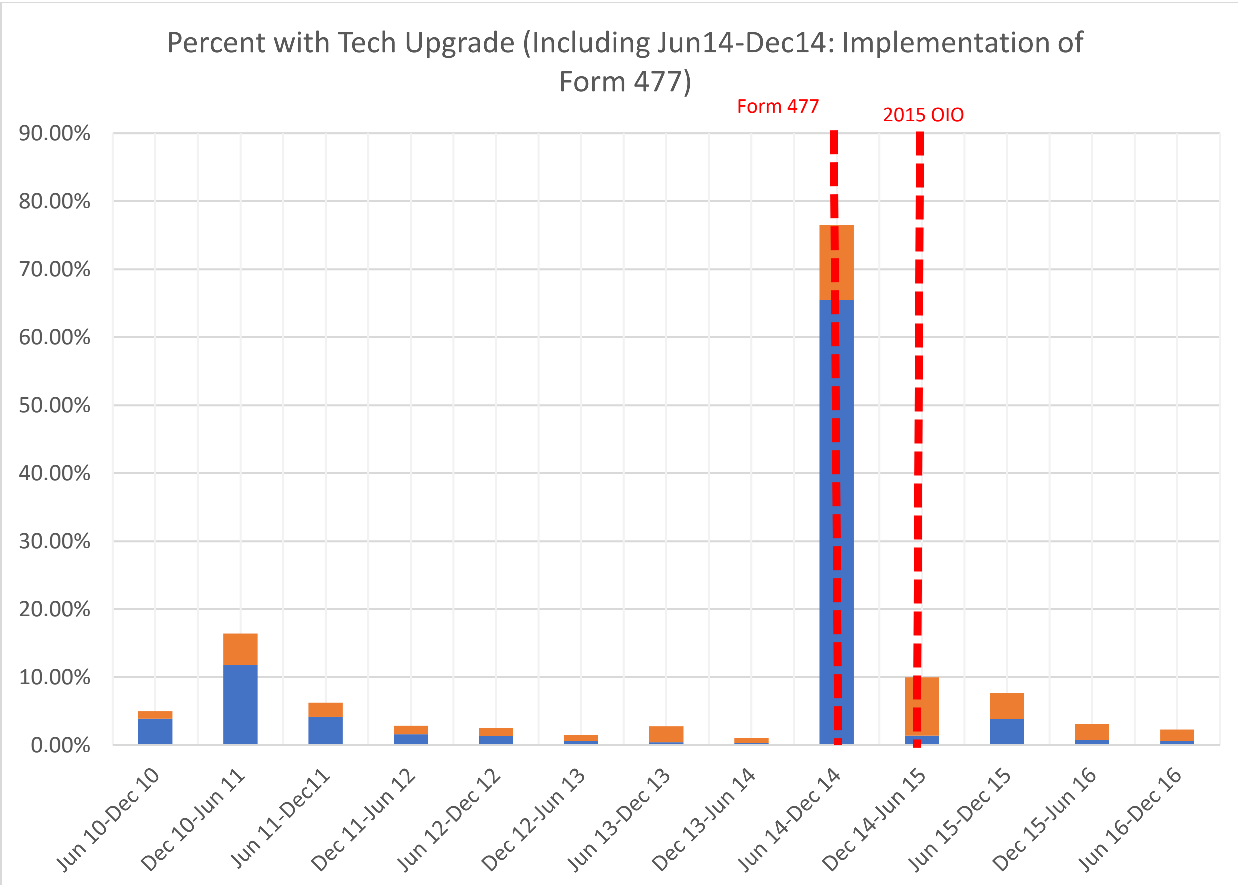
Figure 7: Impact of Competition on Rates of Change of Speed (Dec 2014 - Dec 2016 data)[33]

	N	*Exit*	*Entry*
Coefficient	0.00616	0.0281	-0.00332

[33] The full regression results can be found in Appendix B1(4).

Finally, the overall frequency of network improvements occurring in all census blocks during a time period is shown in Figure 8A. Network improvements can take the form of either a technology upgrade or a new service. A technology upgrade is defined as an instance in which an existing ISP replaces one of its existing technologies of transmission with a higher-coded technology of transmission in the latter part of the time period, whereas a new service is defined as an instance in which an ISP provides an all-together new technology of transmission, in addition to what it already provides. Both of these measures represent an investment in upgrading or building new broadband infrastructure, which may not always be captured by the changes in speed.

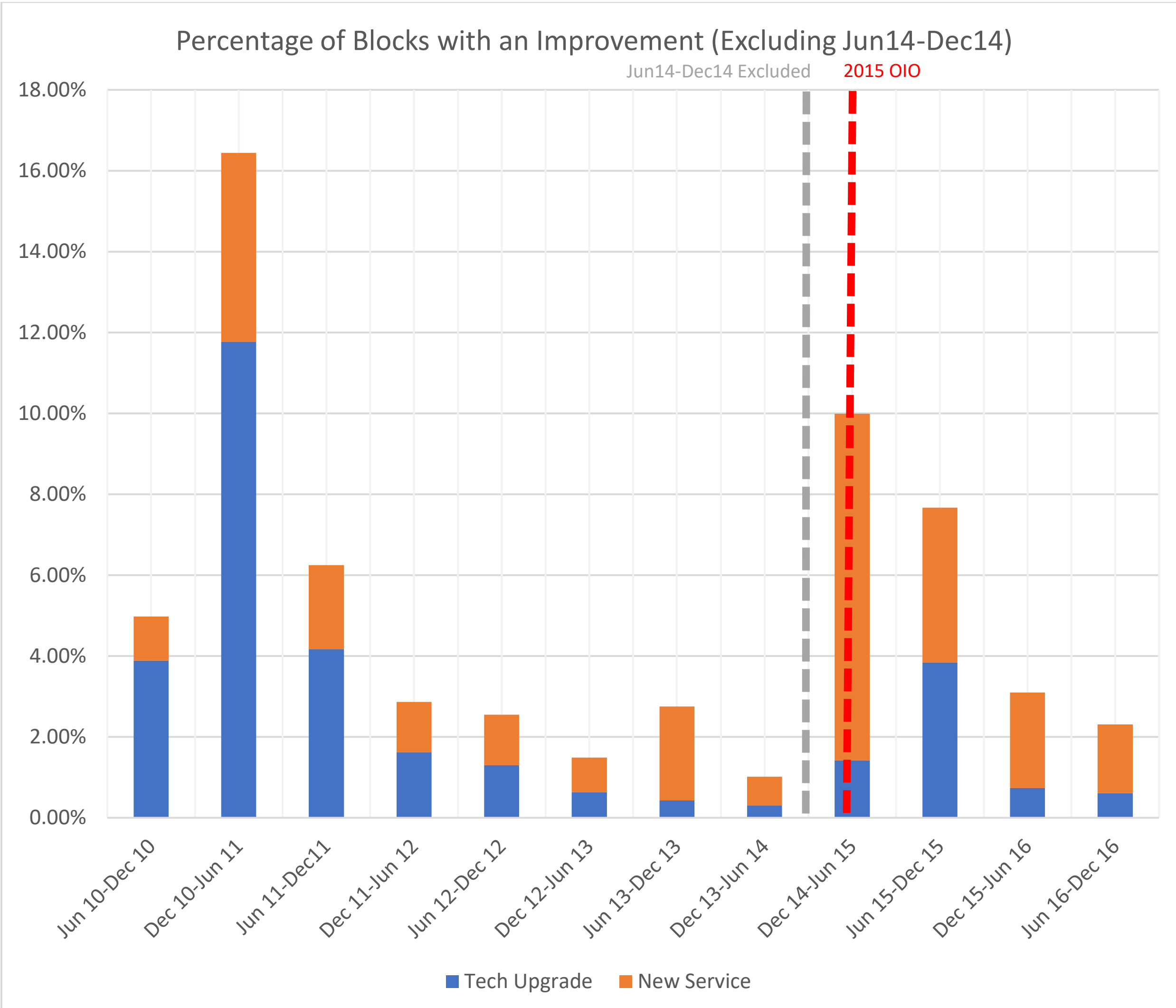
Figure 8A: Frequency of Network Improvements across All Census Blocks



The huge increase in network improvements by existing providers during the June 2014-December 2014 period can be attributed to the switch to Form 477 data again – the expansion of technology codes or perhaps an accurate reclassification of transmission technology by ISPs. Figure 8B illustrates the frequency of network investments by existing providers without data from June 2014 – December 2014.

Figure 8B: Frequency of Network Improvements across All Census Blocks

(Excluding Jun14 - Dec14 Results)



B. Estimating Changes in Market Entry

Our paper examines the impact that the 2015 OIO had on entry by new ISPs into new markets with the model:

$$\ln\left(\frac{L}{1-L}\right) = \beta_0 + \beta_1 P_{it} Y_{it} + \beta_2 N_{i(t-1)} + \beta_3 Q_{max>avg} + \beta_4 OIO_{2015} + \beta_5 OIO_{2015} P_{it} Y_{it} + \beta_6 OIO_{2015} N_{i(t-1)}$$

Figure 9 outlines the marginal impact of the 2015 OIO on the probability of market entry by a new ISP(s). The odds ratio was determined by taking the coefficient with the natural exponential function. This means that holding everything else constant, the odds of market entry are 7.17% lower (1.0000 - 0.9283 = 0.0717) after June 2015 than they are before December 2014.

Figure 9: Coefficients as Odds Ratios

Variable	*Coefficient*	*Odds Ratio*	*"Odds of market entry with an increase by one unit of this variable are..."*
norm_max_revenue	-0.0018253	0.9981763	0.18% lower
n	0.1269166	1.1353223	13.53% higher
max_prev_quality	-0.1334891	0.8750370	12.50% lower
oioindicator15	-0.0743597	0.9283377	7.17% lower
oio15_norm_max_revenue	0.0067032	1.0067257	0.67% higher
oio15_n	-0.0258392	0.9744917	2.55% lower

The correlations between each of the three market variables (*norm_max_revenue, n, and max_prev_quality*) are shown in Figure 10.

Figure 10: Correlations Between Market Factors

	Norm_max_revenue	*N*	*Max_prev_quality*
Norm_max_revenue	1	-	-
N	0.1059	1	-
Max_prev_quality	0.1361	0.3645	1

Discussion

A. Estimating Changes in Speed of Existing Services

In our first attempt to examine the change in rate of speeds across all time periods for each transmission technology, we noticed a huge spike in the change in rate for the time period Jun 2014 – Dec 2014[34]. This is due to the shift from speed estimations using speed-bands to disaggregated speed values. This discrepancy between pre-2014 and post-2014 data is also evident in Figure 8A, in which there was a large increase between June 2014 and December 2014 in the frequency of tech upgrades.

In spite of the inaccuracy shown by going from speed-bands to disaggregated speed values, we attempted to estimate the change in the rate of speeds across time periods by dropping the anomalous time period and also aggregating the post-Dec 2014 expanded technology categories. It is important to note that in the time periods between Jun 2010 and Jun 2014, the usage of speed bands imply that small speed changes will not be captured: a slight change in speed that is not significant enough to raise the service to the next speed band will not be captured by the regression. This will likely add downward pressure to the rate of change; however, effects of positive rates of change of speeds will still be captured, albeit with some diminished accuracy. It is highly likely that the positive changes in speed not captured prior to Jun 2014 were captured by the effect of transition in data during Jun 2014 – Dec 2014.

We find that for most of the transmission technologies, as seen in Figure 5, the average rate of change of speed was higher post-Dec 2014 and post-2015 OIO compared to pre-Dec 2014 rates, at Jun 2010 – Dec 2010 base levels, except for technology code 20. Unfortunately, it is difficult to conclude whether the rate of change of speed was truly higher than pre-Dec 2014 levels due to

[34] Refer to full regression results in Appendix B1(1).

the speed band inaccuracies, and also difficult to attribute any effects to the rate of change of speed to the 2015 OIO.

B. Estimating Changes in Technology Upgrades and New Services

Another way to determine network improvements is to measure the frequency of technology upgrades or new services by existing providers, as shown above in Figure 8 and Figure 8B. Clearly, the transition from National Broadband Data to Form 477 data makes it difficult to accurately examine trends over time. However, as Figure 8B shows, the two time-periods during and after the 2015 OIO (Dec 2014 – Jun 2015, and Jun 2015 – Dec 2015) seemed to have higher levels of network improvements by existing ISPs. This then decreased in the two subsequent time periods, but unfortunately this effect cannot be easily tied to the 2015 OIO. A further examination of this might provide insight if this is truly a direct effect of the 2015 OIO – might this have been a phenomenon of specific improvements to a transmission technology making it more appealing for investment, or did incumbent ISPs provide technology upgrades and new services to high-income geographic markets?

C. Characterizing the Nature of Fixed Broadband Markets

Using disaggregated speed data, we are able to characterize the competition within a geographical market. The coefficients in Figure 7 correspond to theory that more competitors in a market would drive more innovation. The positive coefficient on N_{it_j} highlights the upward pressure on the rate of change of speed caused by existing providers in a geographical market. Given that $\Delta(+N)_{t_{j\to k}}$ is calculated across the time period, a negative coefficient illustrates that potential entrants are more likely to enter a geographical market when existing providers' investment in broadband infrastructure are lacking and the rate of change of speeds is lower. A positive coefficient on $\Delta(-N)_{t_{j\to k}}$ could suggest that existing ISPs in the preceding time period leave the geographical market when existing ISPs, who are still present in the following time period, have higher rate of change of speeds. Another postulation could be that this is a result of survivorship bias – the broadband services provided by exiting ISPs are now excluded, and only the change in speeds of surviving ISPs is captured. Nonetheless, the results seem to suggest that from the period of Dec 2014 to Dec 2016, a higher rate of change of speed, and as such, a proxy for a higher level of broadband investment, does deter potential entrants and may also weed out the competition amongst existing ISPs.

D. Lower Probability of Market Entry Post-2015 OIO

All coefficients were found to be statistically significant in this logit regression. The coefficient on *oioindicator15* in Figure 5, with a value of -0.074, indicates that the odds of a census block witnessing market entry by at least one new ISP within a six-month time frame decreased after the 2015 OIO was enacted. This illustrates that the probability of market entry into a census block after March 2015 to December 2016 fell by 7.17%, as compared to the probability before December 2014. This supports the hypothesis that the 2015 OIO had a negative effect on fixed broadband infrastructure investment by lowering the probability of market entry into a census block by new ISPs, and thereby lowering the occurrence of new investment to support the provision of new broadband services by potential a new ISP(s).

The interaction between the OIO dummy and *norm_max_revenue* term also provides an important insight into the marginal impact the 2015 OIO had on revenue-seeking behavior. The positive value of the interaction coefficient illustrates that post-enactment of the 2015 OIO, new

ISPs had a higher probability of entry into census blocks with greater total max revenue. Given that theory suggests that the 2015 OIO would have a negative impact on ISPs' profits, this result corroborates with the hypothesis that ISPs were more likely to enter a more attractive, higher-income market after the 2015 OIO was put into place and less inclined to enter lower-income markets.

Interpreting the coefficient value on *max_prev_quality*, firms are less likely to enter a market if the broadband service provided in that geographical market is of a certain quality (in this case, the maximum speed provided by an ISP in the census block is higher than the national average). However, the negative coefficient on *norm_max_revenue* and the positive coefficient on *n* are more difficult to interpret. One would intuitively guess that an ISP is more likely to enter a higher-income market or a market with fewer existing competitors; however, the regression result suggests that there may be uncaptured effects. There is a possibility that the position(s) of incumbent ISP(s) in high-income markets are deeply entrenched and hence pose a high barrier of entry to potential entrants. Another postulation, supported by the positive correlation value of *n* – the odds of entry into a geographical market are higher for a market with a greater number of incumbents – could be that markets may be more contestable as the number of incumbents increases. While having a larger number of incumbent firms in a market might also raise the likelihood of the geographical market providing higher quality services, as demonstrated by the correlation value of 0.3645 between *n* and *max_prev_quality*, the weak relationship and the fairly similar value of both coefficients could suggest that the market contestability may depend more heavily on the number of incumbents. The negative coefficient on *oio15_n* may suggest that the contestability of a market might have fallen post-2015.

Conclusion

We are unable to make any conclusive statements regarding the 2015 OIO's effect on investments on existing services by existing ISPs. Rates of change of broadband speeds in census blocks seems to have changed after 2015 to varying degrees based on the technology of transmission. Likewise, the fact that the 2015 OIO coincided with the switch from the National Broadband Map to the FCC's Form 477 data makes it difficult to conclude the degree to which the 2015 OIO had a part to play in the decision of incumbent firms to improve their existing broadband services or invest in the provision of new services, and as a proxy, to change broadband infrastructure investment behavior.

This paper successfully characterizes the nature of competition amongst incumbent ISPs in geographical units from the time period Dec 2014 to Dec 2016.The greater the number of incumbent ISPs in a census block, the higher the rate of change of speeds. We can also draw conclusions regarding the 2015 OIO's impact on the likelihood of entering new markets. The 2015 OIO appears to have negatively impacted the probability of an internet service provider (ISP) entering a census block for the first time: namely, the odds of a new ISP entering a census block during any six-month time period from June 2015 to December 2016 was 7.17% lower than from June 2010 to December 2014.

Future research on this matter should further analyze changes over time across different types of geographic areas; for example, it would be interesting to determine how rates of change of speeds and likelihood of entry differed between urban and rural areas. Likewise, further research should be conducted into the frequency of technology upgrades and new services by existing providers. Finally, one should control for the length of time an ISP has been in a census block; the decisions of a long-term incumbent might be very different from those of a recent entrant.

Appendix A: List of Technology Codes and Income Ranges

Figure A1: Tech Codes

Tech Code	*Technology of transmission*
10	Asymmetric xDSL
11(Post-Dec 2014)	ADSL2, ADSL2+
12 (Post-Dec 2014)	VDSL
20	Symmetric xDSL*
30	Other Copper Wireline (all copper-wire based technologies other than xDSL; Ethernet over copper and T-1 are examples)
40 (Pre-Dec 2014)	Cable Modem - DOCSIS 3.0 Down
40 (Post-Dec 2014)	Cable Modem - DOCSIS 1, 1.1, 2.0, 3.0, or 3.1
41 (Pre-Dec 2014)	Cable Model - Other
40 (Post-Dec 2014)	Cable Modem - DOCSIS 1, 1.1 or 2.0
42 (Post-Dec 2014)	Cable Modem - DOCSIS 3.0
43 (Post-Dec 2014)	Cable Modem - DOCSIS 3.1
50	Optical Carrier / Fiber to the end user (Fiber to the home or business end user, does not include "fiber to the curb")
60	Satellite
70	Terrestrial Fixed Wireless
71	Terrestrial Fixed - Licensed
80	Terrestrial Mobile Wireless
90	Electric Power Line
0	All Other

Figure A2: Speed Bands

Code	*Description*	*Speed Used in Analysis*
2	Greater than 200 kbps and less than 768 kbps	200 kbps
3	Greater than 768 kbps and less than 1.5 mbps	768 kbps
4	Greater than 1.5 mbps and less than 3 mbps	1.5 mbps
5	Greater than 3 mbps and less than 6 mbps	3 mbps
6	Greater than 6 mbps and less than 10 mbps	6 mbps
7	Greater than 10 mbps and less than 25 mbps	10 mbps
8	Greater than 25 mbps and less than 50 mbps	25 mbps
9	Greater than 50 mbps and less than 100 mbps	50 mbps
10	Greater than 100 mbps and less than 1 gbps	100 mbps
11	Greater than 1 gbps	1 gbps

Figure A3: List of Income Ranges

Household Income Range (2016 dollars)	*Income Used in Calculation*
Less than $10,000	$5,000
$10,000-$14,999	$10,000
$15,000-$19,999	$15,000
$20,000-$24,999	$20,000
$25,000-$29,999	$25,000
$30,000-$34,999	$30,000
$35,000-$39,999	$35,000
$40,000-$44,999	$40,000
$45,000-$49,999	$45,000
$50,000-$59,999	$50,000
$60,000-$74,999	$60,000
$75,000-$99,999	$75,000
$100,000-$124,999	$100,000
$125,000-$149,999	$125,000
$150,000-$199,999	$150,000
$200,000 or more	$200,000

Figure A4: List of States and Respective State_id

State/Region	***State Abbreviation***	***State_id***	***State/Region***	***State Abbreviation***	***State_id***
Alaska	AK	1	Mississippi	MS	29
Alabama	AL	2	Montana	MT	30
Arkansas	AR	3	North Carolina	NC	31
America Samoa	AS	4	North Dakota	ND	32
Arizona	AZ	5	Nebraska	NE	33
California	CA	6	New Hampshire	NH	34
Colorado	CO	7	New Jersey	NJ	35
Connecticut	CT	8	New Mexico	NM	36
Washington D.C.	DC	9	Nevada	NV	37
Delware	DE	10	New York	NY	38
Florida	FL	11	Ohio	OH	39
Georgia	GA	12	Oklahoma	OK	40
Guam	GU	13	Oregon	OR	41
Hawaii	HI	14	Pennsylvania	PA	42
Iowa	IA	15	Puerto Rico	PR	43
Idaho	ID	16	Rhode Island	RI	44
Illinois	IL	17	South Carolina	SC	45
Indiana	IN	18	South Dakota	SD	46
Kansas	KS	19	Tennessee	TN	47
Kentucky	KY	20	Texas	TX	48
Louisiana	LA	21	Utah	UT	49

Massachusetts	MA	22	Virginia	VA	50
Maryland	MD	23	U.S. Virgin Islands	VI	51
Maine	ME	24	Vermont	VT	52
Michigan	MI	25	Washington	WA	53
Minnesota	MN	26	Wisconsin	WI	54
Missouri	MO	27	West Virginia	WV	55
Northern Mariana Islands	MP	28	Wyoming	WY	56

Figure A5: Time Periods Regression Codes

Time Period Regression Code	*Time Period*
T1	June 2010 – December 2010
T2	December 2010 – June 2011
T3	June 2011 – December 2011
T4	December 2011 – June 2012
T5	June 2012 – December 2012
T6	December 2012 – June 2013
T7	June 2013 – December 2013
T8	December 2013 – June 2014
T9	June 2014 – December 2014
T10	December 2014 – June 2015
T11	June 2015 – December 2015
T12	December 2015 – June 2016
T13	June 2016 – December 2016

Appendix B: Full Regression Results for Rate of Change of Speeds

Figure B1: Rates of Change of Speed (June 2010 – December 2016)

Refer to Appendix A5 for time period codes in the regression results
Regression (1) was run across all time periods.
Regression (2) was run across all time periods except for T9 (Jun 2014 – Dec 2014)
Regression (3) was run across all time periods, except for T9, and with aggregated technology codes (10, 11, 12 and 40, 41, 42)
Regression (4) was run across time periods T10 to T13 (Dec 2014 to Dec 2016), with post-Dec 2014 technology codes

	(1) Rate of ΔS	(2) Rate of ΔS	(3) Rate of ΔS	(2) Rate of ΔS
Incumbents	0.00355***	0.00406***	0.00526***	0.00616***
	(73.89)	(84.97)	(109.75)	(87.88)
Exit	-0.00123***	0.00515***	0.00626***	0.0281***
	(-8.50)	(34.94)	(42.17)	(112.81)
Entry	0.00693***	0.00801***	0.0103***	-0.00332***
	(59.56)	(68.38)	(87.14)	(-17.05)
AL	-0.0988***	-0.0751***	-0.0516***	-0.0432***
	(-83.24)	(-67.28)	(-45.34)	(-25.03)
AR	0.0176***	0.0289***	0.0495***	0.188***
	(14.03)	(24.31)	(41.02)	(97.94)
AS	-0.191***	-0.175***	-0.181***	-0.166***
	(-139.71)	(-134.26)	(-120.32)	(-49.92)
AZ	-0.0737***	-0.0659***	-0.0375***	-0.00719***
	(-61.68)	(-58.52)	(-32.73)	(-4.14)
CA	-0.0503***	-0.0361***	-0.00309**	-0.0434***
	(-43.25)	(-33.14)	(-2.78)	(-26.13)
CO	-0.0189***	-0.00759***	0.0144***	0.0560***
	(-15.76)	(-6.72)	(12.53)	(31.64)
CT	-0.0591***	-0.0376***	-0.000477	0.260***
	(-47.03)	(-31.44)	(-0.39)	(122.48)
DC	-0.0497***	-0.0765***	-0.0443***	-0.0765***
	(-29.59)	(-49.76)	(-28.59)	(-24.41)
DE	-0.203***	-0.185***	-0.143***	-0.202***
	(-157.97)	(-153.06)	(-117.29)	(-104.46)
FL	-0.0907***	-0.0778***	-0.0390***	-0.00969***
	(-77.42)	(-70.79)	(-34.88)	(-5.74)
GA	-0.0810***	-0.0609***	-0.0255***	0.0924***
	(-68.41)	(-54.63)	(-22.51)	(51.83)
GU	-0.135***	-0.144***	-0.149***	-0.0715***
	(-88.62)	(-100.94)	(-102.23)	(-13.21)
HI	-0.133***	-0.105***	-0.0824***	-0.0956***
	(-77.09)	(-61.05)	(-46.97)	(-40.61)
IA	0.0317***	0.0366***	0.0467***	0.139***
	(26.11)	(31.97)	(40.11)	(78.57)
ID	-0.0236***	-0.0112***	0.0140***	0.0960***
	(-18.70)	(-9.40)	(11.58)	(52.17)
IL	-0.0267***	0.00149	0.0288***	0.0878***
	(-22.86)	(1.36)	(25.79)	(52.61)
IN	-0.0753***	-0.0577***	-0.0256***	0.00490**
	(-64.25)	(-52.47)	(-22.85)	(2.92)
KS	-0.0965***	-0.0808***	-0.0551***	-0.0264***
	(-81.36)	(-72.57)	(-48.56)	(-15.62)
KY	-0.0670***	-0.0576***	-0.0382***	0.00153
	(-54.99)	(-50.15)	(-32.63)	(0.85)
LA	-0.123***	-0.0950***	-0.0635***	-0.0602***
	(-103.63)	(-84.84)	(-55.62)	(-34.68)
MA	-0.168***	-0.154***	-0.114***	-0.186***
	(-141.50)	(-138.92)	(-101.43)	(-109.10)

MD	-0.179***	-0.159***	-0.124***	-0.174***
	(-151.83)	(-143.90)	(-110.43)	(-101.49)
ME	-0.123***	-0.0981***	-0.0923***	-0.133***
	(-101.13)	(-85.46)	(-78.95)	(-72.56)
MI	-0.112***	-0.0831***	-0.0550***	0.000827
	(-95.66)	(-75.82)	(-49.23)	(0.49)
MN	-0.0337***	-0.0199***	0.00606***	0.0106***
	(-28.06)	(-17.63)	(5.27)	(6.14)
MO	-0.0937***	-0.0725***	-0.0448***	-0.0560***
	(-79.86)	(-65.82)	(-39.92)	(-33.43)
MP	0.290***	0.306***	0.291***	1.288***
	(36.20)	(38.18)	(35.62)	(55.38)
MS	-0.0989***	-0.0665***	-0.0368***	0.0650***
	(-81.67)	(-58.07)	(-31.53)	(35.05)
MT	-0.0489***	-0.0160***	-0.00339**	-0.0480***
	(-37.85)	(-13.02)	(-2.73)	(-26.59)
NC	-0.0884***	-0.0705***	-0.0426***	-0.0258***
	(-74.94)	(-63.81)	(-37.87)	(-15.03)
ND	0.0815***	0.0640***	0.0942***	-0.0249***
	(57.83)	(47.26)	(68.63)	(-11.52)
NE	-0.0903***	-0.0769***	-0.0523***	-0.0407***
	(-75.22)	(-68.02)	(-45.51)	(-23.87)
NH	-0.0955***	-0.139***	-0.127***	-0.134***
	(-73.45)	(-117.64)	(-105.82)	(-67.91)
NJ	-0.180***	-0.153***	-0.113***	-0.149***
	(-153.85)	(-139.27)	(-100.85)	(-86.93)
NM	-0.115***	-0.104***	-0.0851***	-0.0770***
	(-95.21)	(-91.53)	(-73.66)	(-45.09)
NV	-0.0139***	-0.0197***	0.00690***	0.0847***
	(-10.29)	(-15.64)	(5.39)	(39.77)
NY	-0.183***	-0.161***	-0.126***	-0.121***
	(-156.63)	(-146.90)	(-113.22)	(-71.95)
OH	-0.0835***	-0.0668***	-0.0415***	-0.0274***
	(-71.44)	(-60.93)	(-37.14)	(-16.35)
OK	-0.0337***	-0.00857***	0.0227***	0.0850***
	(-28.05)	(-7.57)	(19.66)	(48.98)
OR	-0.0137***	-0.00285*	0.0224***	-0.00128
	(-11.10)	(-2.44)	(18.91)	(-0.70)
PA	-0.126***	-0.134***	-0.106***	-0.166***
	(-107.53)	(-122.85)	(-95.20)	(-99.04)
PR	0.0907***	0.0159***	0.0286***	0.0479***
	(67.74)	(13.30)	(23.46)	(25.23)
RI	-0.283***	-0.254***	-0.211***	-0.173***
	(-219.15)	(-208.75)	(-172.13)	(-86.79)
SC	-0.0664***	-0.0351***	-0.00769***	-0.0171***
	(-55.28)	(-30.98)	(-6.65)	(-9.68)
SD	0.0254***	0.0252***	0.0524***	0.00261
	(18.44)	(19.35)	(39.54)	(1.32)
TN	-0.0877***	-0.0560***	-0.0216***	0.0238***
	(-73.64)	(-49.91)	(-18.91)	(13.55)
TX	-0.0605***	-0.0418***	-0.0239***	0.0701***
	(-52.05)	(-38.38)	(-21.49)	(42.03)
UT	-0.0252***	-0.0177***	0.0107***	0.0293***
	(-19.51)	(-14.40)	(8.62)	(15.66)
VA	-0.0779***	-0.0555***	-0.0209***	0.00985***
	(-65.55)	(-49.66)	(-18.40)	(5.65)
VI	0.669***	0.735***	0.770***	0.797***
	(127.22)	(136.80)	(144.54)	(142.94)
VT	0.0400***	-0.0322***	-0.0340***	-0.0754***
	(25.50)	(-23.39)	(-24.37)	(-37.86)
WA	-0.0752***	-0.0680***	-0.0412***	-0.0119***

	(-62.99)	(-60.54)	(-36.07)	(-6.86)
WI	-0.0972***	-0.0756***	-0.0482***	-0.0609***
	(-82.37)	(-68.26)	(-42.75)	(-36.20)
WV	-0.00701***	-0.00330**	0.00996***	-0.00238
	(-5.70)	(-2.85)	(8.44)	(-1.36)
WY	-0.193***	-0.169***	-0.161***	-0.192***
	(-149.57)	(-139.12)	(-130.40)	(-106.13)
T2	0.306***	0.307***	0.302***	
	(36.36)	(36.10)	(35.88)	
T3	-0.0143***	-0.00950***	-0.0125***	
	(-13.88)	(-8.39)	(-10.52)	
T4	-0.0157***	-0.0104***	-0.0137***	
	(-14.78)	(-9.00)	(-11.23)	
T5	-0.0162***	-0.0110***	-0.0145***	
	(-15.09)	(-9.42)	(-11.71)	
T6	-0.0156***	-0.0103***	-0.0136***	
	(-14.75)	(-8.95)	(-11.19)	
T7	-0.0156***	-0.0103***	-0.0135***	
	(-14.73)	(-8.93)	(-11.16)	
T8	-0.0685***	-0.0738***	-0.0807***	
	(-73.28)	(-74.65)	(-77.26)	
T9	3.391***			
	(137.49)			
T10	1.029***	1.027***	1.055***	
	(26.84)	(26.79)	(27.51)	
T11	-0.481***	-0.440***	-0.427***	-0.0109***
	(-26.99)	(-24.68)	(-23.99)	(-59.85)
T12	3.654***	3.678***	3.694***	2.586***
	(124.39)	(124.72)	(125.35)	(61.88)
T13	-0.248***	-0.206***	-0.194***	-1.201***
	(-13.92)	(-11.56)	(-10.90)	(-35.29)
Tech Code 10	0.0566**	0.0699***	0.0816***	-0.582***
	(3.19)	(3.93)	(4.59)	(-17.13)
Tech Code 11	0.208***	0.181***		-1.092***
	(128.97)	(143.20)		(-32.11)
Tech Code 12	0.262***	0.233***		-1.069***
	(157.55)	(175.43)		(-31.42)
Tech Code 20	0.402***	0.423***	0.437***	-0.977***
	(22.27)	(23.44)	(24.20)	(-28.63)
Tech Code 30	-0.0217	-0.0159	-0.0104	-1.138***
	(-1.21)	(-0.89)	(-0.58)	(-33.46)
Tech Code 40	0.295***	0.309***	0.184***	-0.464***
	(16.61)	(17.40)	(10.34)	(-13.39)
Tech Code 41	0.0951***	0.107***		-1.075***
	(5.36)	(6.02)		(-31.58)
Tech Code 42	0.546***	0.519***		-1.073***
	(336.56)	(406.16)		(-31.55)
Tech Code 43	6.305***	6.277***	6.276***	6.145***
	(147.37)	(146.92)	(147.34)	(142.33)
Tech Code 50	0.145***	0.159***	0.167***	-0.793***
	(8.16)	(8.94)	(9.36)	(-23.31)
Tech Code 70	0.404***	0.376***	0.377***	-1.171***
	(248.79)	(294.13)	(285.17)	(-34.43)
Tech Code 90	-0.111***	-0.104***	-0.0879***	
	(-6.23)	(-5.85)	(-4.94)	
T2 * Tech Code 10	-0.268***	-0.270***	-0.267***	
	(-31.80)	(-31.76)	(-31.70)	
T2 * Tech Code 11	0	0		
	(.)	(.)		

T2 * Tech Code 12	0	0		
	(.)	(.)		
T2 * Tech Code 20	-0.563***	-0.572***	-0.575***	
	(-62.27)	(-62.59)	(-63.47)	
T2 * Tech Code 30	-0.266***	-0.260***	-0.255***	
	(-30.77)	(-29.84)	(-29.58)	
T2 * Tech Code 40	-0.157***	-0.160***	-0.198***	
	(-18.60)	(-18.76)	(-23.51)	
T2 * Tech Code 41	-0.497***	-0.494***		
	(-58.86)	(-58.02)		
T2 * Tech Code 42	0	0		
	(.)	(.)		
T2 * Tech Code 43	0	0	0	
	(.)	(.)	(.)	
T2 * Tech Code 50	-0.00506	-0.00601	-0.00194	
	(-0.58)	(-0.68)	(-0.22)	
T2 * Tech Code 70	0	0	0	
	(.)	(.)	(.)	
T2 * Tech Code 90	0	0	0	
	(.)	(.)	(.)	
T3 * Tech Code 10	-0.104***	-0.107***	-0.104***	
	(-98.02)	(-91.83)	(-85.30)	
T3 * Tech Code 11	0	0		
	(.)	(.)		
T3 * Tech Code 12	0	0		
	(.)	(.)		
T3 * Tech Code 20	-0.0920***	-0.104***	-0.106***	
	(-26.67)	(-29.31)	(-29.79)	
T3 * Tech Code 30	0.0625***	0.0669***	0.0718***	
	(29.44)	(30.72)	(32.60)	
T3 * Tech Code 40	0.138***	0.133***	0.139***	
	(109.97)	(98.84)	(110.17)	
T3 * Tech Code 41	-0.183***	-0.183***		
	(-167.37)	(-153.24)		
T3 * Tech Code 42	0	0		
	(.)	(.)		
T3 * Tech Code 43	0	0	0	
	(.)	(.)	(.)	
T3 * Tech Code 50	0.0952***	0.0937***	0.0974***	
	(52.96)	(50.46)	(51.45)	
T3 * Tech Code 70	0	0	0	
	(.)	(.)	(.)	
T3 * Tech Code	0	0	0	

90				
	(.)	(.)	(.)	
T4 * Tech Code 10	-0.0772***	-0.0801***	-0.0770***	
	(-70.43)	(-67.38)	(-61.55)	
T4 * Tech Code 11	0	0		
	(.)	(.)		
T4 * Tech Code 12	0	0		
	(.)	(.)		
T4 * Tech Code 20	-0.328***	-0.339***	-0.341***	
	(-96.01)	(-96.57)	(-96.15)	
T4 * Tech Code 30	-0.0283***	-0.0231***	-0.0178***	
	(-13.36)	(-10.63)	(-8.09)	
T4 * Tech Code 40	-0.262***	-0.266***	-0.146***	
	(-211.02)	(-201.38)	(-114.84)	
T4 * Tech Code 41	-0.155***	-0.154***		
	(-134.97)	(-124.27)		
T4 * Tech Code 42	0	0		
	(.)	(.)		
T4 * Tech Code 43	0	0	0	
	(.)	(.)	(.)	
T4 * Tech Code 50	0.186***	0.185***	0.189***	
	(95.95)	(92.67)	(92.81)	
T4 * Tech Code 70	0	0	0	
	(.)	(.)	(.)	
T4 * Tech Code 90	0	0	0	
	(.)	(.)	(.)	
T5 * Tech Code 10	-0.0366***	-0.0406***	-0.0376***	
	(-32.75)	(-33.47)	(-29.35)	
T5 * Tech Code 11	0	0		
	(.)	(.)		
T5 * Tech Code 12	0	0		
	(.)	(.)		
T5 * Tech Code 20	-0.187***	-0.200***	-0.201***	
	(-52.36)	(-54.62)	(-54.40)	
T5 * Tech Code 30	0.00850***	0.0124***	0.0193***	
	(3.90)	(5.56)	(8.52)	
T5 * Tech Code 40	-0.254***	-0.260***	-0.136***	
	(-202.35)	(-193.53)	(-105.57)	
T5 * Tech Code 41	-0.158***	-0.157***		
	(-135.31)	(-125.11)		
T5 * Tech Code 42	0	0		
	(.)	(.)		
T5 * Tech Code 43	0	0	0	

	(.)	(.)	(.)
T5 * Tech Code 50	-0.00632***	-0.00729***	-0.00270
	(-3.55)	(-3.95)	(-1.43)
T5 * Tech Code 70	0	0	0
	(.)	(.)	(.)
T5 * Tech Code 90	0	0	0
	(.)	(.)	(.)
T6 * Tech Code 10	-0.0905***	-0.0939***	-0.0906***
	(-82.97)	(-79.45)	(-72.91)
T6 * Tech Code 11	0	0	
	(.)	(.)	
T6 * Tech Code 12	0	0	
	(.)	(.)	
T6 * Tech Code 20	-0.381***	-0.394***	-0.394***
	(-111.87)	(-112.63)	(-111.74)
T6 * Tech Code 30	-0.0440***	-0.0400***	-0.0329***
	(-20.81)	(-18.47)	(-15.01)
T6 * Tech Code 40	-0.280***	-0.284***	-0.155***
	(-227.25)	(-216.30)	(-122.80)
T6 * Tech Code 41	-0.155***	-0.156***	
	(-135.68)	(-126.70)	
T6 * Tech Code 42	0	0	
	(.)	(.)	
T6 * Tech Code 43	0	0	0
	(.)	(.)	(.)
T6 * Tech Code 50	-0.0704***	-0.0712***	-0.0673***
	(-41.24)	(-40.30)	(-37.20)
T6 * Tech Code 70	0	0	0
	(.)	(.)	(.)
T6 * Tech Code 90	0	0	0
	(.)	(.)	(.)
T7 * Tech Code 10	-0.0464***	-0.0494***	-0.0461***
	(-42.42)	(-41.67)	(-36.99)
T7 * Tech Code 11	0	0	
	(.)	(.)	
T7 * Tech Code 12	0	0	
	(.)	(.)	
T7 * Tech Code 20	-0.341***	-0.353***	-0.353***
	(-99.49)	(-100.30)	(-99.46)
T7 * Tech Code 30	0.0592***	0.0640***	0.0713***
	(27.49)	(29.06)	(31.94)
T7 * Tech Code 40	-0.300***	-0.305***	-0.170***

	(-243.81)	(-231.92)	(-135.35)
T7 * Tech Code 41	-0.147***	-0.148***	
	(-128.02)	(-119.36)	
T7 * Tech Code 42	0	0	
	(.)	(.)	
T7 * Tech Code 43	0	0	0
	(.)	(.)	(.)
T7 * Tech Code 50	0.0306***	0.0291***	0.0340***
	(17.26)	(15.89)	(18.19)
T7 * Tech Code 70	0	0	0
	(.)	(.)	(.)
T7 * Tech Code 90	0	0	0
	(.)	(.)	(.)
T8 * Tech Code 10	-0.0319***	-0.0244***	-0.0175***
	(-32.80)	(-23.77)	(-16.18)
T8 * Tech Code 11	0	0	
	(.)	(.)	
T8 * Tech Code 12	0	0	
	(.)	(.)	
T8 * Tech Code 20	-0.432***	-0.433***	-0.430***
	(-128.73)	(-126.19)	(-124.19)
T8 * Tech Code 30	0.0172***	0.0325***	0.0433***
	(8.30)	(15.47)	(20.37)
T8 * Tech Code 40	-0.286***	-0.280***	-0.136***
	(-254.16)	(-239.15)	(-123.71)
T8 * Tech Code 41	-0.0794***	-0.0685***	
	(-74.27)	(-61.33)	
T8 * Tech Code 42	0	0	
	(.)	(.)	
T8 * Tech Code 43	0	0	0
	(.)	(.)	(.)
T8 * Tech Code 50	0.182***	0.191***	0.199***
	(109.97)	(113.23)	(115.56)
T8 * Tech Code 70	0	0	0
	(.)	(.)	(.)
T8 * Tech Code 90	0	0	0
	(.)	(.)	(.)
T9 * Tech Code 10	-2.809***		
	(-113.83)		
T9 * Tech Code 11	-2.703***		
	(-157.11)		
T9 * Tech Code 12	-3.047***		
	(-177.22)		

T9 * Tech Code 20	-1.598***			
	(-61.62)			
T9 * Tech Code 30	-0.716***			
	(-28.93)			
T9 * Tech Code 40	-3.110***			
	(-124.40)			
T9 * Tech Code 41	-2.479***			
	(-100.22)			
T9 * Tech Code 42	-3.691***			
	(-214.80)			
T9 * Tech Code 43	0			
	(.)			
T9 * Tech Code 50	-2.436***			
	(-98.31)			
T9 * Tech Code 70	-2.316***			
	(-134.01)			
T9 * Tech Code 90	0			
	(.)			
T10 * Tech Code 10	-0.574***	-0.573***	-0.859***	
	(-14.97)	(-14.94)	(-22.40)	
T10 * Tech Code 11	-1.237***	-1.191***		
	(-36.35)	(-35.01)		
T10 * Tech Code 12	-1.250***	-1.207***		
	(-36.75)	(-35.49)		
T10 * Tech Code 20	-1.345***	-1.351***	-1.377***	
	(-34.87)	(-35.01)	(-35.68)	
T10 * Tech Code 30	-1.073***	-1.067***	-1.082***	
	(-27.96)	(-27.79)	(-28.17)	
T10 * Tech Code 40	-0.690***	-0.682***	-1.184***	
	(-17.75)	(-17.54)	(-30.88)	
T10 * Tech Code 41	-1.120***	-1.107***		
	(-29.19)	(-28.84)		
T10 * Tech Code 42	-1.554***	-1.510***		
	(-45.69)	(-44.42)		
T10 * Tech Code 43	0	0	0	
	(.)	(.)	(.)	
T10 * Tech Code 50	-0.900***	-0.894***	-0.919***	
	(-23.47)	(-23.30)	(-23.94)	
T10 * Tech Code 70	-1.500***	-1.456***	-1.471***	
	(-44.10)	(-42.82)	(-43.26)	
T10 * Tech Code 90	0	0	0	
	(.)	(.)	(.)	
T11 * Tech	0.619***	0.577***	0.555***	-0.312***

Code 10				
	(34.68)	(32.38)	(31.14)	(-561.05)
T11 * Tech Code 11	0.455***	0.455***		0.183***
	(739.26)	(740.41)		(279.21)
T11 * Tech Code 12	0.380***	0.380***		0.134***
	(426.68)	(427.27)		(168.20)
T11 * Tech Code 20	-0.0406*	-0.0891***	-0.0992***	-0.193***
	(-2.24)	(-4.92)	(-5.47)	(-68.09)
T11 * Tech Code 30	1.086***	1.048***	1.049***	0.638***
	(59.39)	(57.35)	(57.41)	(193.15)
T11 * Tech Code 40	0.0803***	0.0379*	0.306***	-0.774***
	(4.49)	(2.12)	(17.15)	(-115.40)
T11 * Tech Code 41	0.275***	0.236***		-0.108***
	(15.39)	(13.25)		(-62.59)
T11 * Tech Code 42	-0.0230***	-0.0229***		0.0328***
	(-50.29)	(-50.10)		(100.07)
T11 * Tech Code 43	0	0	0	0
	(.)	(.)	(.)	(.)
T11 * Tech Code 50	0.702***	0.665***	0.656***	0.105***
	(39.16)	(37.14)	(36.63)	(60.19)
T11 * Tech Code 70	0	0	0	0
	(.)	(.)	(.)	(.)
T11 * Tech Code 90	0	0	0	
	(.)	(.)	(.)	
T12 * Tech Code 10	-3.566***	-3.591***	-3.532***	-2.954***
	(-121.38)	(-121.76)	(-119.86)	(-70.67)
T12 * Tech Code 11	-3.808***	-3.790***		-2.539***
	(-162.24)	(-160.64)		(-60.75)
T12 * Tech Code 12	-3.302***	-3.286***		-2.013***
	(-140.64)	(-139.20)		(-48.15)
T12 * Tech Code 20	-3.956***	-3.991***	-4.002***	-2.590***
	(-133.25)	(-133.88)	(-134.33)	(-61.68)
T12 * Tech Code 30	-3.409***	-3.431***	-3.432***	-2.289***
	(-115.53)	(-115.81)	(-115.92)	(-54.69)
T12 * Tech Code 40	-3.605***	-3.630***	-3.885***	-2.919***
	(-121.37)	(-121.74)	(-131.82)	(-68.62)
T12 * Tech Code 41	-3.703***	-3.723***		-2.543***
	(-125.90)	(-126.09)		(-60.77)
T12 * Tech Code 42	-4.241***	-4.223***		-2.646***
	(-180.73)	(-179.02)		(-63.31)
T12 * Tech Code 43	0	0	0	0
	(.)	(.)	(.)	(.)
T12 * Tech Code 50	-3.309***	-3.330***	-3.343***	-2.372***

	(-112.46)	(-112.73)	(-113.25)	(-56.71)
T12 * Tech Code 70	-4.104***	-4.088***	-4.092***	-2.570***
	(-174.90)	(-173.28)	(-173.67)	(-61.48)
T12 * Tech Code 90	0	0	0	
	(.)	(.)	(.)	
T13 * Tech Code 10	0.159***	0.117***	0.112***	0.652***
	(8.93)	(6.57)	(6.30)	(19.15)
T13 * Tech Code 11	0	0		1.153***
	(.)	(.)		(33.87)
T13 * Tech Code 12	0	0		1.178***
	(.)	(.)		(34.62)
T13 * Tech Code 20	-0.0879***	-0.138***	-0.144***	1.166***
	(-4.80)	(-7.57)	(-7.87)	(34.04)
T13 * Tech Code 30	0.493***	0.455***	0.450***	1.457***
	(27.19)	(25.14)	(24.85)	(42.69)
T13 * Tech Code 40	0.257***	0.221***	0.333***	0.876***
	(14.25)	(12.29)	(18.70)	(25.22)
T13 * Tech Code 41	0.405***	0.365***		1.435***
	(22.40)	(20.23)		(41.99)
T13 * Tech Code 42	0	0		1.479***
	(.)	(.)		(43.46)
T13 * Tech Code 43	0	0	0	0
	(.)	(.)	(.)	(.)
T13 * Tech Code 50	1.049***	1.010***	1.001***	1.865***
	(58.53)	(56.45)	(55.96)	(54.73)
T13 * Tech Code 70	0	0	0	1.422***
	(.)	(.)	(.)	(41.80)
T13 * Tech Code 90	0	0	0	
	(.)	(.)	(.)	
Constant	0.188***	0.156***	0.114***	1.211***
	(10.58)	(8.76)	(6.38)	(35.56)
Observations	208660404	196754370	196754370	78143660

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Appendix C: Full Regression Results for Market Entry

Figure C1: Results of the Marginal Impact of the 2015 OIO on Entry by New ISPs

	(1) Entry
Normalized Max Revenue	-0.00183***
	(-39.93)
Number of Incumbents	0.127***
	(364.63)
High Quality	-0.133***
	(-171.31)
2015 OIO Dummy	-0.0744***
	(-54.61)
OIO Interaction with Max Revenue	0.00670***
	(102.30)
OIO Interaction with Number of Incumbents	-0.0258***
	(-47.01)
Constant	-1.775***
	(-1978.73)
Observations	98298232

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