Quality Competition at the Competitive Margin in US Residential Broadband Markets

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New data set incorporating significant corrections to FCC Form 477 data.

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Abstract: This paper investigates the effects of local market structure on residential broadband service quality. Using data from multiple sources, we build a rich panel data set covering all broadband services available, by ISP, technology and maximum advertised download speed for each of approximately six million populated U.S. census blocks between December 2014 and December 2017. In contrast with the previous literature, we utilize highly disaggregated data, control for evolving government subsidies to underserved census blocks, employ individual provider quality measures rather than market-level indexes, and relax strong statistical and economic assumptions maintained in prior work. We estimate causal effects by constructing a novel set of plausibly exogenous instruments exploiting spatial technological variation among incumbent and entrant broadband ISPs. These allow us to identify the effects of entry of new ISPs on service quality for residential customers in spatially disaggregated local markets. Preliminary results suggest that these effects can be substantial, and that intramodal competition (across broadband service technologies) is a primary competitive margin driving improvements in maximum U.S. residential broadband speeds. We find that entry or exit by wireline competitors in census blocks containing only incumbent wireline competitors has essentially no impact on maximum download speeds offered by wireline ISPs. By contrast, entry or exit by wireless competitors in census blocks containing other wireless incumbents is associated with large changes in maximum download speeds offered by wireline ISPs.

Introduction

In markets for differentiated products, quality[1] is likely to be a critical dimension of competition. In addition to price, quality choices allow firms to differentiate product offerings from one another and to target different demand segments. In such circumstances, an analysis of how well a market performs cannot simply rely on the price and quantity observed as market outcomes but must also explicitly consider product quality. Because increases (decreases) in quality are consumer surplus enhancing (diminishing), ceteris paribus, the relationship between market competition and product quality is quite important.

Product quality differences can lessen price competition (Shaked and Sutton, 1982). Similarly, firms in markets with low competitive pricing pressure may choose lower quality levels for their products than firms facing higher levels of competitive pressure in the marketplace (Tirole, 1988, section 2.1).

In this paper, we analyze the effects of local market structure on residential broadband service quality. The links we observe between new entrants and new technology adoption creates a unique opportunity to analyze an interesting and important question: how exactly does increased competition, measured as numbers of competing ISPs in a census block, affect quality of service, measured as the highest speed offered by each provider in a local market (census block)?

The U.S. residential broadband market is an ideal setting for a study of the causal relationship between market structure and quality competition. First, the available data suggest that nominal prices for residential broadband service plans in the U.S. have basically been flat, on average-- unchanged over the last decade. The major dimension for competition among major broadband internet service providers (ISPs) has been improved service quality, particularly upgrades to download speeds. Second, within relatively short time windows, we document evidence of substantial entry and exit by firms within spatially disaggregated local markets. Third, both technological innovation and regulatory policy changes have significantly lowered the costs of quality improvements, so there is substantial variation in quality within a cross-section of spatial locations over time.

Consumer gains due to broadband quality improvements are potentially very large. Internet access has become an essential resource for much of the US population. While in 2000 only 52% of US adults acknowledged that they were internet users, around 90% now do so (Pew Research Center, 2019). Smartphones, music, video, and TV streaming services, and online news sources are now integrated into the rhythm of daily life. For example, Netflix subscribers on average spend more than one hour per day streaming that one source of content (Streaming Observer, 2019). The proportion of US adults who own a smartphone has increased rapidly from

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[1] We think of a higher "quality" product or service in the context of models of vertically differentiated products, with a set of vertically ordered characteristics such that all consumers prefer higher quality to lower quality at a given price, with at least some consumers willing to pay more than others for a higher quality product.

35% in 2012 to 81% in 2018 (Pew Research Center, 2019). These trends in the US are similar across groups with different income, education, and ethnicities, and are mirrored in other countries around our world. For these reasons, improvements in internet service quality have the potential to bring large impacts on household welfare: most people now use the internet, and they use it intensively.[2]

Using data from multiple sources, we build a rich panel data set that covers all broadband services delivered to households by ISP, technology and maximum download speed for each of approximately six million populated U.S. census blocks between December 2014 and December 2017. We describe trends in market structure, quality and technology utilization over this period. Previous empirical analyses examining the effect of market structure on quality provision in the U.S. market (over earlier periods, using more aggregated data) relied on very noisy and sometimes inappropriate measures of quality. Additionally, earlier studies made strong assumptions about the way firms compete in the market, and strong statistical assumptions about explanatory variables.

Given the richness of the data set and a novel empirical identification strategy, we are able to address many of the limitations of previous studies. Identification of the causal effects of market structure on service quality must account for the potential endogeneity of market structure measures. We construct a novel set of plausibly exogenous instruments exploiting spatial variation in the impact of technological change on incumbent and entrant broadband ISPs. We are thus able to identify the effects of entry of new ISPs on service quality for residential customers in spatially disaggregated local markets. Our results suggest that these effects can be substantial, and that intramodal competition (across broadband service technologies) is a primary competitive margin driving improvements in quality-adjusted U.S. residential broadband service prices. We conclude by identifying how our results have potential policy implications.

We have in mind a reduced form model of the intensive competitive margin, as firms choose the quality of their service offerings in the short to medium run, while facing fixed numbers of competitors.[3] Firms using any broadband delivery technology face a tradeoff between number of users served by their existing network, and speeds that can be offered to those users. Given market structure (the number of competitors in the market), how does the extent of competition from other ISPs affect the maximum service quality (maximum download speed) offered to consumers? We explicitly recognize that in the long run, entry and exit into a market is also endogenous—that is, the same factors that lead a firm to offer higher quality

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[2] We note, however, that it is plausibly argued that the typical U.S. household would make little use of broadband bandwidth over about 100 megabits per second. See for example S. Ramachandran, T. Gryta, K. Dapena, and P. Thomas, "The Truth About Faster Internet: It's Not Worth It," *Wall Street Journal*, August 20, 2019.

[3] The canonical model of vertical product differentiation is "a three stage game in which a number of firms choose firstly, whether to entry an industry; secondly, the quality of their respective products, and thirdly, their prices." A. Shaked and J. Sutton, "Relaxing Price Competition Through Product Differentiation," *Review of Economic Studies*, vol. 49, no. 1, January 1982, p. 12. In the abstract, we can think of the sequential stages of this game as the long, medium, and short runs.

service may also lead others to enter (or exit) the market. We defer a model of entry and exit to follow-on research. Instead, we are interested in what can we learn about how market quality outcomes—in this case, the maximum quality/speed for broadband—, conditioning on economically relevant demand and cost shifters, vary with market structure, i.e., the numbers of different types of competitors?

The remainder of the paper is organized as follows. Section II describes related literature; section III provides background and stylized facts about the US broadband service industry; section IV discuss the FCC's Connect America Fund subsidy program, which affected rural, high cost service areas in our sample during the time period we are analyzing; section V describes data sources and how we built our analytical dataset; section VI discuss our identification strategy and empirical model results; section VII presents conclusions.[4]

II. Literature review

There is a broad economic literature studying the effects of market competition on equilibrium outcomes, such as price and quality. The starting point is that firms in oligopoly markets can exploit their market power by either reducing quality or increasing price (Tirole, 1988). In theoretical models of imperfect competition, the predicted effect of a new entrant on equilibrium prices is clearer than its effect on equilibrium quality (Abbott, 1955). In these models, as the number of firms in the market increases, equilibrium prices tend to decrease and approach competitive price levels.

In contrast, the effect of greater competition on product quality is more ambiguous. Early theoretical work such as Allen (1984) and Shapiro (1983) found that firms have incentives to provide high quality products as a way to assure high prices. Nevertheless, later works, such as Kranton (2003), show that under some conditions high quality perfect equilibria do not necessarily exist in competitive environments.

Empirical papers have provided additional insights on this topic by addressing the relationship between market structure and market outcomes. One of the first empirical papers to address this the effect of market structure on prices was Bresnahan and Reiss (1991). They measure the effects of entry on incumbents' competitive conduct, with firms pricing closer to marginal costs as a metric for more competitive conduct. They find that almost all changes in competitive conduct happen after a second or third competitor enter the market. Some papers where researchers measure price and also have some plausibly exogenous variation in market structure find a strong relationship between market structure and prices. Some recent examples are Basker and Noel (2009), Atkin et al. (2018), and Busso and Galiani (2017). All of them find significant and economically relevant price drops after the entry of new competitors.

Empirical work on quality competition supports the claim that the effect of competition on product quality is ambiguous. Mazzeo (2002) and Seim (2006), in studying the motel and video

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[4] Appendix A briefly reviews the history and limitations of the FCC Form 477 data we are using to measure both market structure and service quality.

game markets respectively, find that as competition (i.e., number of competitors) increases, firms have greater incentives to differentiate through quality choices. Matsa (2011) studies the effect of competition on service quality in the supermarket industry. He finds that supermarkets in more competitive markets tend to have fewer inventory shortfalls. On the other hand, Katz (2013), after surveying the literature on competition and quality in the healthcare industry, shows that conditional on prices, an increase in competition may result in a decrease of healthcare provider quality. Lin (2015) studies the nursing home market. A key result of her paper is the heterogeneous effect of market structure on quality; firms of similar quality compete more intensively than firms of dissimilar quality.

Our paper contributes to the literature on competition and equilibrium quality by measuring the impacts of entry when firms mainly compete in product quality and not in prices. The previous empirical literature has largely not engaged with the effects of entry on dimensions of competition other than prices. In addition, a feature of the broadband industry, and the data we utilize, is that there are objective and directly observed measures of quality: advertised maximum download and upload speeds, which providers and consumers contract for, and we directly observe in the data.[5]

Turning to empirical studies of the US broadband industry, several papers seek to assess the service availability across markets. Beede (2014) describes broadband service availability in December 2013 across the US. A novelty is that raw data (restricted and non-public) from the FCC's Form 477 (at the census tract level) is used in the analysis, so it provides a unique overview of the whole industry. One main finding was that 98 percent of the population had a choice of at least two ISPS with speed of 3 Mbps or higher. Additionally, 37 percent of the population had a choice of at least two providers at speeds of 25 Mbps or greater, but only 9 percent had three or more choices. Gadiraju et al. (2018) study the deployment of broadband in the US during the period 2014 and 2016. They also use Form 477 census tract data from the FCC to describe service availability and speed, and how they are related to demographic characteristics. Their main finding is that around 3/4 of households have access to two or more internet providers.

Neither of those papers considers the evolution of the market, limiting their analysis to the market state at a given point of time. One of the goals of this paper is to assess the impact of changes in market structure and concentration on broadband quality outcomes over the period from 2014 and 2017. Furthermore, one of the principal conclusions of our previous study (Flamm and Varas, 2018) is that census tract level data significantly overstate the number of broadband providers from which an individual residential household in that census tract may be able to purchase service. That is why we construct our analysis at the census block level.

This paper is also related to a previous literature that studies competition and market structure in the broadband service industry, and its effects on quality. Previous papers have found a positive relationship between market structure and download speeds. Reed and Watts (2017) show that access to high speed internet increases as the number of providers increases in

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[5] Published data on the relationship between advertised speeds and delivered speed, by ISP, based on a small national sample of households, has been reported publicly by the Federal Communications Commission since 2011. See https://www.fcc.gov/general/measuring-broadband-america .

a county. Prieger et al. (2015) study how broadband firms respond to the entry and quality decisions of their rivals. Estimating a discrete choice game of entry and quality, their preliminary results show that firms actually respond to quality choices of rival broadband providers, and firms' responses are heterogeneous with respect to type of provider and quality. Wallsten and Mallahan (2013) is one of the few papers that analyze the effect of market structure on prices. Using non-public versions of older FCC data, they find a strong correlation of number of providers with housing density, penetration with income, and show how different wireline technologies are more or less prevalent in areas with differing housing density. A key result is that lower prices, attributed to competition, are observed in markets with three providers, compared to markets with just two providers. Molnar and Savage (2017) use field measures of download speed to analyze the effect of entry and market structure on product quality. Their results show that wireline speeds tend to be higher in markets with two or more wireline providers than with a single wireline provider. An important limitation in their analysis is their very limited sample of households. For instance, in many of their markets (defined as census block groups), they use an observed speed measurement derived from only a single volunteer household's purchase of internet services, and their data is available only in a single period. In addition, their statistical model relies on parametric assumptions and exclusion restrictions that seem unrealistic.

A key element in any analysis of competition is market definition. Equilibrium outcomes, such as number of firms in each market or quality, may vary greatly depending on how markets are defined. Previous papers have used widely varying spatial definitions of fixed broadband service markets, driven primarily by the data availability. For instance, Reed and Watts (2017) use counties as markets; Flamm (2015), Xiao and Orazem (2011), and Grubesic and Murray (2004) use zip codes as markets; Molnar and Savage (2017) use census block groups, and Wallsten and Mallahan (2013), Prieger et al. (2015), and Denni and Gruber (2007) use census tracts. Certainly (and particularly for wireline networks), it seems clear that there is zero substitution possible on the demand side between broadband services providers whose networks pass a particular block, and service providers whose networks do not reach that particular block, even if both blocks lie in the same census tract or block group. A novel contribution of this paper is to study how, when the definition of the residential broadband market is drawn spatially at the block level, observed numbers of competitors offering services to a residential household actually affects highest quality service availability.

III. Empirical Context: Stylized Facts About US Residential Broadband Service

We first review some simple, stylized facts about US residential broadband service. The goal of this narrative is to establish that broadband is an important and significant expenditure for most US households in the wired America of the 21st century, that historically there has been limited competition in the provision of fixed broadband service to US households, that nominal service prices have been relatively flat, that competition has primarily taken the form of improved quality (in the form of download speeds), and finally, that recent technological improvements in fixed wireless broadband service appear to be directly associated with recently observed increases in competition in US residential broadband service markets.

***Broadband service is a significant expenditure for US households*.** The weighted average (by numbers of households choosing different service speed tiers) monthly standalone broadband service plan price in US urban areas was estimated by the FCC to be $61.65 in 2017. (FCC, 2018) This monthly price tag varied across speed tiers, averaging $47.08 for .2 to 10 Mbps download speeds, $52.29 in the 10 to 25 Mbps tier, $61.78 for 25-100 Mbps, and $104 for speeds at or above 100 Mbps. By most measures, US broadband prices are relatively costly in comparison to other countries.[6] The data in the FCC report support the authors' experiential observation that "low-end" broadband service plans available in most US cities run about $40 to $50/month, and have not varied greatly in nominal price in recent years.

***In the majority of US markets, there has been limited competition in provision of residential broadband services*.** Flamm and Varas (2018) show that in 60% of US urban census blocks and 85% of rural census blocks, in December 2014, there were two or less fixed terrestrial broadband providers offering residential service to households.[7] By December 2016, the share of duopoly and monopoly census blocks in the distribution of numbers of competing providers across census blocks had shrunk somewhat—to about 55% in urban areas and to under 80% in rural areas—but this was still extraordinarily high. For populated census blocks in the United States overall, 63% had only 1 or 2 ISPs offering service in 2014, declining to 52% by 2017. Terrestial broadband service markets saw some new entry over the 2014-17 period, but effectively remained a duopoly or monopoly in the majority of US census blocks.[8]

Broadband service plan prices have been flat in most US markets. Prices for broadband service as portrayed in official price indexes look more like the price of cheese than the price of chips (the silicon kind). The Bureau of Labor Statistics collects and publishes data on fixed internet service prices in its consumer (CPI) and producer (PPI) price indexes. (See Figure 1.) Until 2017, for the most part, these indexes appear to behave like conventional matched model

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[6] At purchasing power parity exchange rates in an international comparison using the US distribution of households across speed tiers to weight fixed standalone broadband plan prices, the FCC found that its index of US prices--$61.65-- ranked 21 out of 29 countries (where Chile, country 29, is the most expensive--$80.71, and Finland, country 1, at $35.11, was the least expensive. Controlling for factors affecting demand (like income) and cost (like population density), a hedonic price index still puts the US in the top to middle of the price band. Only by adding quantity of broadband data consumed or country language as hedonic characteristics (which raise conceptual and econometric issues) does the US move into the bottom quartile of an international price comparison. See FCC, *International Broadband Data Report, Sixth Report*, Docket GN Docket No. 17-199, 2018, Appendix C.

[7] Flamm and Varas, 2018, Figure 6c. Note that we are excluding satellite-based providers from this count.

[8] In 2002, a report from the National Research Council used the following taxonomy of U.S. broadband geographies: type 0 (no terrestrial providers of broadband; satellite only), type 1 (one terrestrial provider), type 2 (two terrestrial providers—either the incumbent cable and telephone service providers, or one of the incumbents and a new entrant [overbuilder]), and type 3 (more than two providers; overbuilders plus the incumbent cable or telephone companies). Types one 1 and 2 above correspond to what we refer to as "monopoly or duopoly" blocks. "The financial viability of type 3 competition—and prospects for competition beyond that offered by the incumbent telephone and cable companies—will be tested over the next few years." See National Research Council, *Broadband: Bringing Home the Bits*, Washington, DC: The National Academies Press, 2002, pp. 21-22.

price indexes,[9] covering some fixed bundle of low and high end service plans. Changes in plan quality (like speed upgrades) in low and high end plans do not generally appear to have been systematically reflected in adjustments to these price indexes.[10]

The new hedonically-adjusted PPI has only a brief history, but even with the BLS' hedonic price methodology, quality-adjusted internet service prices have not declined very much over the last couple of years. From December 2016 to December 2017, the newly quality-adjusted PPI for wireline internet services fell at a respectable annual rate of -3.9 percent. From December 2017 to December 2018, however, the annual decline rate for quality-adjusted broadband service price was a paltry -.32%.

By and large, the price indexes published by the BLS paint a picture of basically flat internet service prices. Our working hypothesis is that (at least until recently), government price indexes effectively tracked the nominal price of high, medium, and low end service plans, and that the weighted average price (i.e., a price index) of nominal monthly broadband service plan prices, at the bottom, middle, and top tiers for service, has simply not changed very much over the last decade.

The pancake-flat monotony in the PPI history is broken by occasional episodes of low-single-digit annual declines. We see such an episode over 2017, and earlier, around 2010. It is interesting (though possibly coincidental) that the 2010 decline in the broadband PPI occurs around the time that 4G LTE mobile broadband service is being rolled out into the US market.[11]

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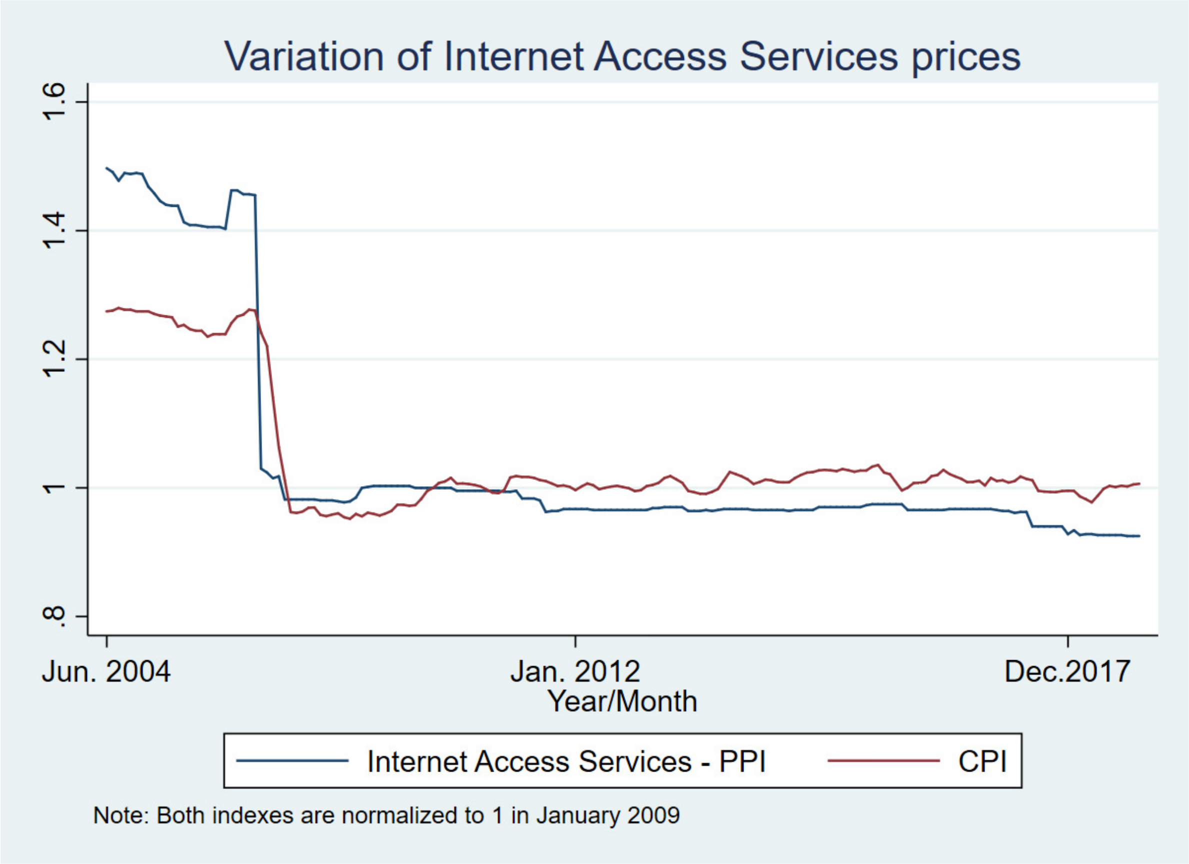
[9] That is, index behavior is consistent with use of item substitution, without any hedonically valued adjustment for quality, as service plan characteristics change over time.

[10] In the case of the PPI, beginning in December 2016 the BLS began to employ a hedonic quality adjustment to its wireline internet service price PPI, reporting a quality-adjusted (constant quality) price index that reflected market valuation of speed improvements. (For the official description of the PPI, see https://www.bls.gov/ppi/broadbandhedonicmodel.htm .) Prior to that date, there apparently was no sustained effort to adjust these indexes hedonically, and report a quality-adjusted price index that reflected significant improvements to download speeds in both higher and lower end service tiers. The CPI, by contrast, published an experimental methodology for hedonic quality adjustment back in 2008 (https://www.bls.gov/opub/mlr/2008/07/art3full.pdf) and the CPI description on the BLS website makes reference to substitution of similar new products for old products in price indexes, subject to the occasional hedonic quality adjustment.(For the CPI, see https://www.bls.gov/cpi/factsheets/telecommunications.htm .) But the trend over time in the CPI generally matches the flat prices found in the PPI prior to the beginning of the PPI hedonic quality adjustments in 2017.

[11] The earlier sharp drop in 2006 in the BLS consumer price index likely is an artifact produced by the switch of AOL (at the time the largest ISP in the US) from a paid to free, ad-supported dial-up Internet service business model. See Greenstein and McDevitt, 2009.

Figure 1 BLS Fixed Internet Access Service Price Indexes

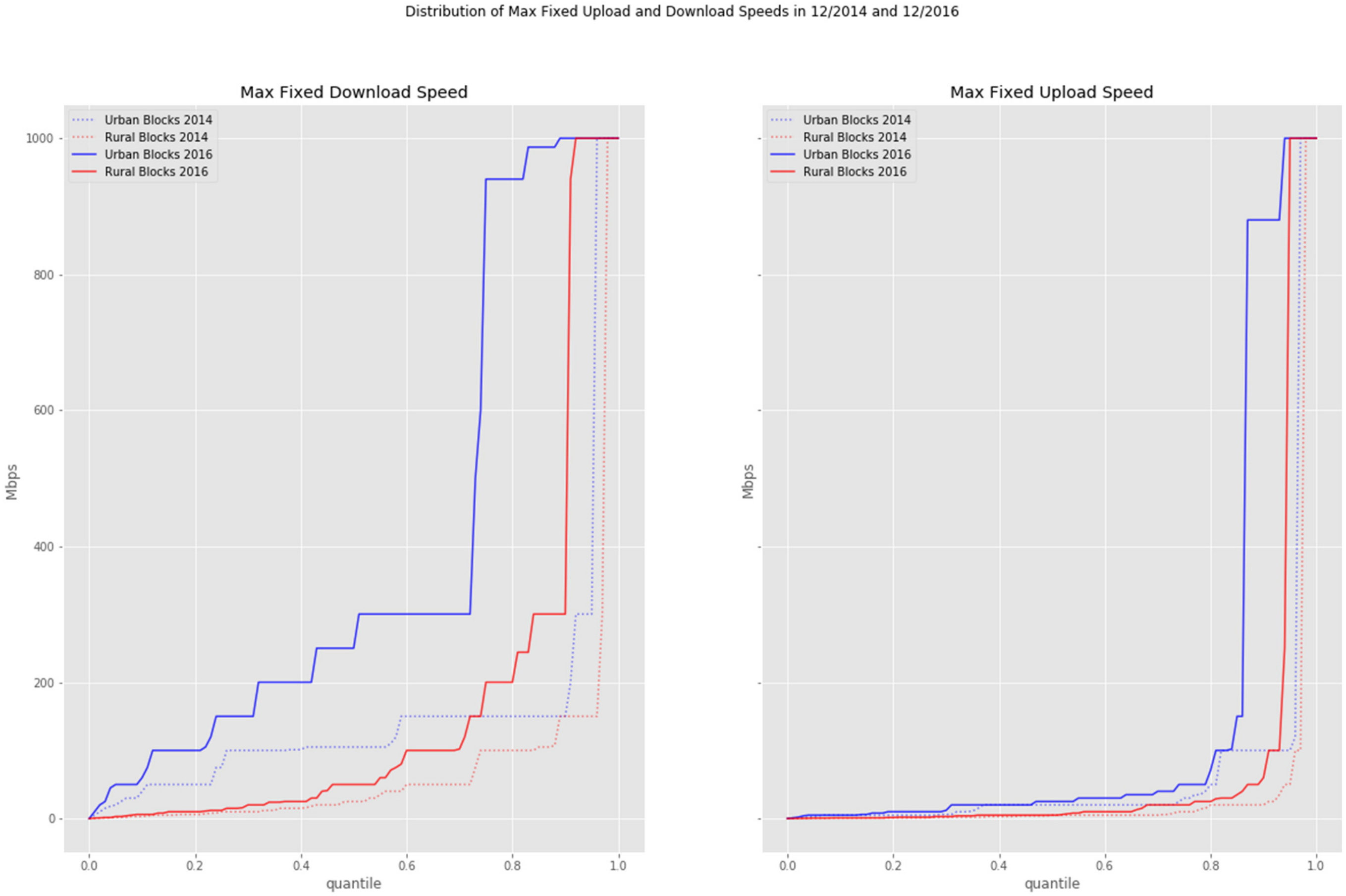


Note: Both indexes are normalized to 1 in January 2009

Competition between incumbent broadband service providers primarily seems to involve quality upgrades. Flat nominal service plan prices may be related to the duopoly market structure observed in the majority of local US markets, but this does not mean there is no competition. There is substantial evidence of continuing quality improvement in broadband services across local US markets, evidence that suggests that the primary dimension for residential broadband competition is not service plan price, but service plan quality (primarily download and upload speeds).

This can be seen in Figure 2, which shows the distribution US census blocks by maximum available download speed from any ISP, in December of 2014 and 2016. There is a dramatic increase in the availability of higher speeds across the entire distribution of census blocks.

Figure 2 Evolution of Distribution of Max Broadband Speed in US Census Blocks, 2014-16



Source: Flamm and Varas (2018)

Figure 3 and Figure 4 show the distribution of maximum advertised speed in December 2014 and December 2017 for all ISP/census block combinations reported in the FCC's public data, and the maximum of these maxima (across ISPs) by census block. Both figures show a significant increase in maximum available service speed. In fact, the median in the distribution of maximum speed offered by ISPs per census block, across all ISP/census block combinations, increased from 20 Mbps in 2014, to 24 in 2015, to 45 in 2016 and 80 Mbps in 2017. The median maximum speed available per census block (across all ISPs) increased from 101 Mbps in 2014, to 150 in 2015, 200 in 2016, and 900 Mbps in 2017. The very large increase from 2016 to 2017 in median maximum census block speed (350%) is particularly notable.

Figure 3. Distribution of Maximum Available Download Speed by ISP/Census Block

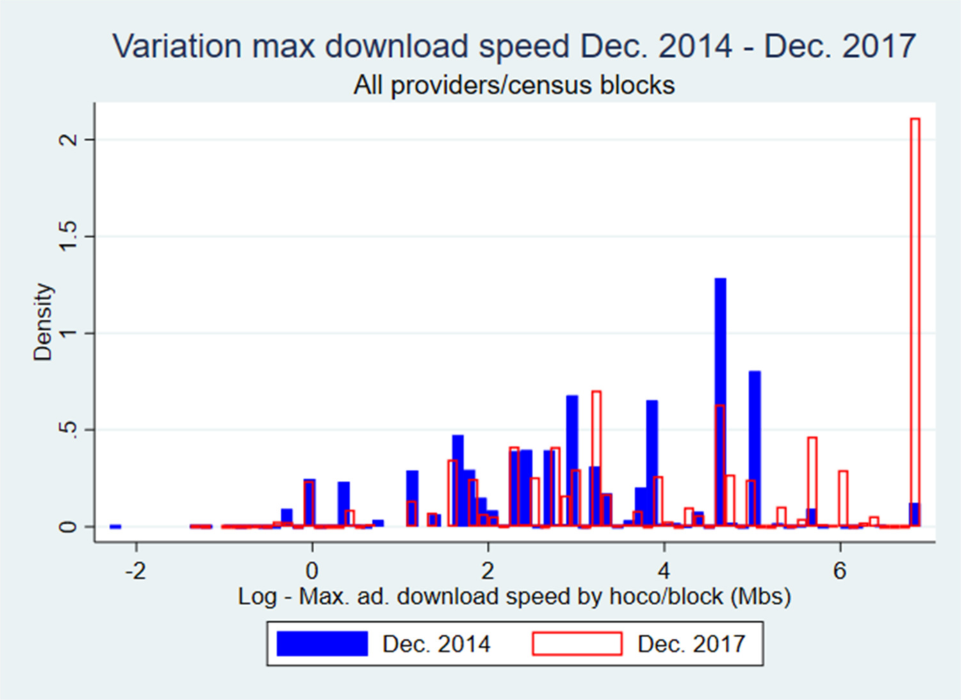
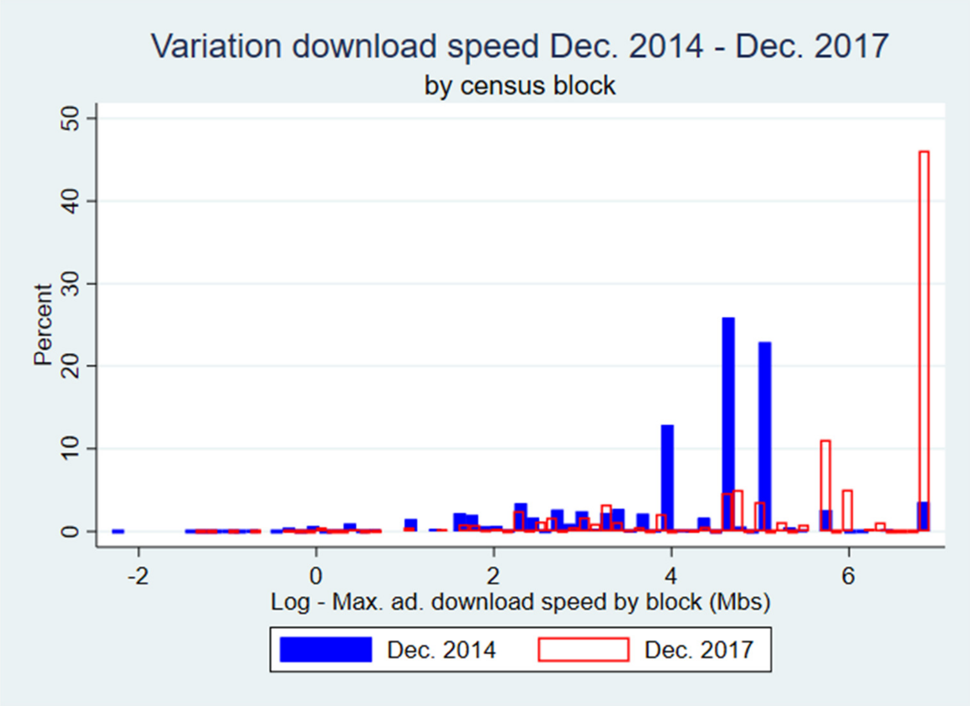


Figure 4. Distribution of Maximum Available Download Speed by Census Block



The FCC international bureau's estimate of weighted average actual mean broadband speed in the U.S., at the national level, rises from 28 Mbps in 2014, to 40 in 2015, and 55 in 2016. This translates into about a 96% increase from 2014 to 2016, and compares with about a 100 percent increase in median maximum offered download speed within all US census blocks.[12] Despite the similarity in observed trends, the 55 Mbps mean for maximum broadband speed delivered to consumers was only a quarter of the magnitude of the median maximum broadband speed available to consumers within census blocks in 2016. This suggests that maximum download speeds are priced at premium levels that limit take-up in the population.

The data we just reviewed suggest that maximum available quality (download speed) per census block increased at vastly higher rates than the 3.4% decline registered by the BLS' quality-adjusted broadband PPI from December 2016 to December 2017. Figure 5 illustrates why we must take care not to assume that increases in maximum available service quality (measured by maximum available download speed) translate into declines in quality-adjusted price levels. The Y-axis on this graph measures nominal service price, and the X-axis service quality. The blue line is the original underlying linear "hedonic" relationship between service price and service quality—the '+' symbols represent actual observed prices, and include idiosyncratic random deviations from the underlying (blue) linear hedonic relationship. Now suppose that a new and higher quality service tier is subsequently introduced (the red dot), and priced using the same linear relationship between price and quality (plus/minus a random deviation), depicted as a red-dashed extension to the blue line. There is zero change in a properly measured quality-adjusted (constant quality) price after the higher quality product is introduced, since the underlying hedonic relationship between price and quality is completely unchanged.[13]

The green dashed line on the other hand, represents an increase in quality that is simultaneously accompanied by a downward shift in the underlying relationship between price and quality, i.e., a decline in quality-adjusted (constant quality) price. The figure is drawn to show quality-adjusted price (the Y-intercept of the red- and green-dashed lines) declining by very much less than the relative increase in service quality (maximum download speed), the scenario that actual empirical data seem to make most plausible.

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[12] The FCC estimates are based on proprietary Ookla Speedtest data aggregated at the city level. City-year observations are collapsed to the country-year level and are weighted by the number of tests.

[13] This does not mean that consumer welfare has not increased. Any consumer observed shifting to the new, higher quality plan reveals that her willingness to pay for the newly available higher quality service equals or exceeds the higher price. But constant-quality price has not changed; the consumer gain comes entirely from the higher quality service that is now available to consumers with a greater willingness to pay for quality, and not from a reduction in price for a given quality of service affecting all consumers.

Figure 5. Effect of Increase in Maximum Broadband Service Quality on Quality-Adjusted Price

Even with only small improvements over time in quality-adjusted broadband price being observed, ISPs may be highly motivated to introduce new, higher quality speed tiers as technology improves. Higher speed tiers may be much more profitable, and broadband providers very motivated to shift consumers to higher speeds.[14] Higher quality content may require higher speeds, and the local incumbent wireline service providers in monopoly and duopoly blocks typically also have a very profitable business selling premium media content utilizing greater bandwidth to their subscribers. Lowering prices for a slower speed service, when network speeds go up as new technology is deployed, in order to attract new customers, may not be a profit-maximizing strategy for incumbent wireline network owners with a large installed customer base.[15] However precisely that strategy (lower quality service at a discount from the price of the closest comparable incumbent's higher quality service plan) may be attractive to entrants lacking a proprietary media content pipeline and a large existing

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[14] For anecdotal evidence of this provided by journalists, see S. Ramachandran, T. Gryta, K. Dapena, and P. Thomas, "The Truth About Faster Internet: It's Not Worth It," *Wall Street Journal*, August 20, 2019.

[15] The new service plan might cannibalize too many existing customers from higher-priced, more profitable service tiers.

customer base. In effect, technology and costs permitting, it may be the case that new entrants find it profitable to operate as a competitive fringe, offering somewhat lower quality, lower speed service plans at a perceptible discount from the duopoly providers' lowest tier price floor.

There has been a significant amount of entry by new competitors into many local broadband service markets since 2014. While many local markets continue to have very limited numbers of competitors, there nonetheless was a significant amount of recent entry in a relatively large group of the roughly six million populated census blocks in which US households reside. Detailed FCC data that become available after 2014 portray an important change in market structure at the census block level. In December 2014, there were only one or two ISPs in 63% of all populated census blocks. That share declined to 52% by 2017. As we discuss below, a previous literature links market structure (i.e., competition) to market quality outcomes.

Table 1 shows that there was a net increase of about .26 ISPs per census block, on average, across the United States, from 2014-2017. This would be the outcome observed if, for example, on average a new ISP entered the local market in 1 out of every 4 census blocks. What is most interesting is that almost all of the net entry is coming from service providers who use fixed wireless technology to deliver broadband service to that block, either in tandem with wireline service delivery, or as "pure" fixed wireless technology ISPs.

Table 1		**Mean ISPs per Census Block**			
		by ISP Tech Type			
		All	Mixed Wireline + Wireless	Fixed Wireline Only	Wireless Only
Rural	**2014**	1.838366	0.044432	1.127036	0.666898
		100.00%	2.42%	61.31%	36.28%
	2017	2.109234	0.186894	1.150524	0.771816
		100.00%	8.86%	54.55%	36.59%
Urban	**2014**	2.54238	0.020779	1.997836	0.523765
		100.00%	0.82%	78.58%	20.60%
	2017	2.802011	0.204625	2.024016	0.57337
		100.00%	7.30%	72.23%	20.46%
		Change in ISPs/census block 2014-2017:			
Rural		0.270868	0.142462	0.023488	0.104918
	Share of Change	100.00%	52.59%	8.67%	38.73%
Urban		0.259631	0.183846	0.02618	0.049605
	Share of Change	100.00%	70.81%	10.08%	19.11%

Source: Author's calculations based on FCC Form 477 data.

In 2014, about 61% of ISPs' serving rural census blocks and 79% of ISPs serving urban blocks only used fixed wireline technologies (cable, DSL, or fiber) to serve their customers in those blocks. By 2017 those "pure" wireline shares had dropped to 55% and 72%, respectively.

In contrast, the share of ISPs making use of a mix of both wireline and fixed wireless technology within the same census block to serve their customers increased substantially over the same period. In rural blocks, use of mixed wireline/wireless technology went from 2% to almost 9% of ISPs serving those blocks, while in urban blocks, ISPs using a mix of wireline and wireless technology went from under 1% to over 7%. The share of ISPs using "pure" fixed wireless connections to households was basically constant and unchanged over time, accounting for roughly 36% of ISPs serving rural blocks, and 20% of ISPs in urban blocks.

The important role of increasing wireless technology use by new entrants is particularly evident if we decompose the net increase in ISPs per census block into a net increase by technology types used for service delivery. Of the .27 average ISP increase per rural census block over 2014-2017, 53% came from net increases in mixed wireline/wireless ISPs, 39% from a net increase in "pure" fixed wireless ISPs, and less than 9% from a net increase in pure wireline ISPs. Similarly, in urban blocks, 71% of the increase in ISP competitors per block came from mixed wireline/wireless providers, 19% from pure wireless ISPs, and just 10% of the increase was accounted for by a net increase in pure wireline operators**. In both urban and rural areas, then, 90 percent or more of the entry—the net increase in numbers of competing ISPs—is attributable to firms that are making use of fixed wireless network technologies.**

The dominant role of mixed wireline/wireless providers in new broadband entry is an interesting and novel development. It suggests that traditional wireline broadband ISPs using wireless technology to push into unserved locations in adjoining census blocks, mainly extending their existing wireline networks with wireless links to new locations, has been an important factor in explaining the new entry that was observed over the 2014-17 period.

Major technological improvements in fixed wireless technology enabled much of the new entry observed over the 2014-17 period. Beginning around 2013, communications equipment manufacturers began shipping equipment embodying a new fixed wireless standard, 802.11ac. This newly developed technology standard made use of a set of advances first pioneered in mobile wireless communications, including channel aggregation/binding, beam-forming (use of multiple antennas to shape multiple focused spatial data streams) with MU-MIMO (multiple user, multiple input-multiple output—multiple input and output streams to multiple separate users), and improved modulation techniques. These technologies were deployed in transceivers using radio technology that could make use of both licensed and unlicensed wireless spectrum. These improvements were also incorporated into proprietary (non-standard) fixed wireless equipment that was marketed to fixed wireless ISPs.

The overall impact was a significant improvement in the efficiency (data-carrying capacity) of spectrum used, faster speeds, longer distance ranges, and lower costs per user served. Effectively, the data-carrying capacity of fixed spectrum was multiplied, and the range for wireless communication was extended,[16] even as the cost of the equipment fell. The standard was later improved in "Wave 2" equipment that shipped around 2016, and an even better, improved standard (802.11ax) came to market in 2019.[17]

IV. The Connect America Broadband Subsidy Program

The time period during which these technological improvements were observed coincides with the deployment of a new and evolving set of government programs designed to increase the quality of available broadband service in areas historically receiving "high cost" telephone service subsidies. For that reason, we must disentangle the effects of increased number of competitors from any direct impact that subsidies to incumbent providers in affected rural areas might be having on broadband service quality.

In 2011, the FCC issued a report and order transforming the process by which Universal Service Fund subsidies of communications services to "high cost" areas would be undertaken.[18] While previously voice telephone service to (mainly) rural households had been supported by subsidies from Universal Service funds (generated by fees paid by all U.S. voice service purchasers), the Commission now expanded subsidies to include both voice and broadband service in so-called "high cost" areas. Accompanied by extensive public comment—and litigation—a subsequent 2014 report and order set out the specifics of how this reformed system was to operate.[19] A brief summary of the transitional mechanisms for this new set of subsidy mechanisms—the Connect America Fund (CAF)—is given in Appendix B.

We do not attempt to translate this complex menu of transitional broadband subsidy mechanisms into specific impacts by subsidy mechanism. Acceptance of CAF subsidies by service providers was tied to future broadband service quality obligations in high cost rural census blocks. Our strategy to control for the average impact of these subsidies on broadband speeds in affected census blocks is to create annual subsidy "vintage" variables. The "vintage" of subsidies affecting a rural census block is defined by the year in which the first claim for a broadband subsidy to a location in that census block was made.

We interpret the year the first broadband subsidy claim was made for a location within a census block as an indicator of the mix of subsidy mechanisms put into place when a rural census block was "converted" to the new CAF funding system. The FCC subsidy offers reflected how the FCC cost model in use at the time evaluated block characteristics (and profitability, at prices like

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[16] For a detailed explanation of these technological advances, see, for example, https://www.duckware.com/tech/wifi-in-the-us.html .

[17] The same technologies are used in 5G equipment, and the new 5G standard effectively unifies mobile and fixed wireless communications standards.

[18] For a brief history, see FCC, "*In the Matter of Connect America Fund*," Report and Order, FCC 14-190, W.C. Dockets No. 10-90, 14-58, 14-192, December 2014.

[19] *Ibid.*

those faced by a "reasonably comparable" urban household[20]); acceptance of the offer by the incumbent local exchange carrier (ILEC) presumably indicates that the ILEC expected service to be profitable using its own internal expectations of cost net of subsidy, and pricing. Subsidy acceptance was accompanied by an obligation to serve new locations in subsidized blocks if the improved service level could be provided "at reasonable cost".[21]

Broadband subsidy funding vintages for years no later than 2014 (the first year of our sample) will effectively be incorporated into a census block fixed effect. Census block vintages first associated with high cost broadband-related subsidy claims filed in 2015 and 2016 most likely reflect the new (Connect America Model) CAM-based subsidies in census blocks served by so-called "price cap" incumbent carriers. High cost census blocks first receiving broadband subsidy funding in 2017 are probably a mix of CAM price cap blocks and the inaugural class of Alternative Connect America Model (ACAM) census blocks served by so-called "rate-of-return" carriers. (The more competitive CAF Phase II reverse auction mechanism mentioned in Appendix B did not come into use until after the end of our sample period.)

As previously noted, CAF broadband subsidies were offered by the FCC to a subset of "grandfathered" rural census blocks that had previously received legacy high cost voice subsidies. The FCC began this process by analyzing the new and more detailed Form 477 data that became available at the census block level after 2014. (See Appendix A.) Information on broadband availability tabulated from prior year Form 477 data was available to determine which census blocks within a "high cost" ILEC local voice service territory (or "study area") lacked adequate broadband service, and therefore potentially justified a subsidy offer. The first claims by price-cap ILECs for CAM-based subsidies at the census block level begin the following year, in 2015.

The cost models used by the FCC to formulate subsidy offers combined engineering cost models with cross-sectional data on census block characteristics. The resulting cost model allowed for variation across blocks in population, housing counts, and spatial density. Based on census block characteristics, incumbent voice service providers were offered model-driven funding levels in exchange for provision of specified broadband speed levels to existing network customers upon request, and to additionally accept an obligation to serve new locations in

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[20] "Each year, the FCC conducts a survey of the fixed voice and broadband service rates offered to consumers in urban areas. The FCC uses the survey data to determine the local voice rate floor and reasonable comparability benchmarks for fixed voice and broadband rates for universal service purposes." https://www.fcc.gov/economics-analytics/industry-analysis-division/urban-rate-survey-data-resources .

[21] "See April 2014 *Connect America Order*, 29 FCC Rcd at 7070-75, paras. 59-72. C.f. 47 CFR § 54.202 (requiring any carrier petitioning to be federally-designated ETCs [Eligible Telecommunications Carriers] to "[c]ommit to provide service throughout its proposed designated service area to all customers making a reasonable request for service" and to certify that it will provide service "on a timely basis" to customers within its existing network coverage and "within a reasonable time" to customers outside of its existing network coverage if service can be provided at reasonable cost)." FCC, *REPORT AND ORDER, ORDER AND ORDER ON RECONSIDERATION, AND FURTHER NOTICE OF PROPOSED RULEMAKING*, FCC 16-33, WC Dockets No. 10-90, 14-58, 01-92, March 2016, p. 68.

subsidized blocks if the improved service level could be provided "at reasonable cost".[22] Simple economic logic predicts that profit-maximizing incumbent providers would first accept these subsidy offers for those particular census blocks where net profit after subsidy would have been highest, and decline these offers when the expected net return was too low, or even negative.

V. Data Sources

The primary data source for this analysis is the Fixed Broadband Deployment Data collected by the Federal Communications Commission (FCC) through its Form 477. All facilities-based fixed broadband service providers are required to report a variety of data for census blocks in which they ***could*** offer internet access service at speeds over 200 kbps in at least one direction (i.e., download or upload).[23]

The Fixed Broadband Deployment Data is published twice per year (June and December). For each census block, broadband service providers are identified by their "Holding Company" (HOCO) name. For each technology deployed by a provider in that census block, the data contains the maximum advertised download and upload speed, and whether that service is sold to households or business.[24] Technologies identified include various flavors of cable DOCSIS standards, various flavors of DSL, other wireline, fiber, satellite, and terrestrial fixed wireless. In its current format (at the census block level), this data is available from December 2014 to December 2017. Within that period all variables are comparable across years. We have reclassified all flavors of wireline DOCSIS networks as "cable," and all flavors of wireline DSL networks as "DSL".

A second source of data is the FCC's Mobile Deployment Data. This data is also collected twice per year by the FCC through the Form 477. For each data collection period, each mobile broadband provider must report all geographical areas where they can provide service. A major difference from the Fixed Deployment Data is that the mobile data is reported using shapefiles, so covered areas can be smaller (or larger) than census blocks. In this data, each provider is identified by its "Doing Business As" (DBA) name. Providers have to report a shapefile for each technology they use to offer service (e.g., WiMAX, LTE, etc,). The Mobile deployment data is

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[22] "See April 2014 *Connect America Order*, 29 FCC Rcd at 7070-75, paras. 59-72. C.f. 47 CFR § 54.202 (requiring any carrier petitioning to be federally-designated ETCs [Eligible Telecommunications Carriers] to "[c]ommit to provide service throughout its proposed designated service area to all customers making a reasonable request for service" and to certify that it will provide service "on a timely basis" to customers within its existing network coverage and "within a reasonable time" to customers outside of its existing network coverage if service can be provided at reasonable cost)." FCC, *REPORT AND ORDER, ORDER AND ORDER ON RECONSIDERATION, AND FURTHER NOTICE OF PROPOSED RULEMAKING*, FCC 16-33, WC Dockets No. 10-90, 14-58, 01-92, March 2016, p. 68.

[23] https://www.fcc.gov/general/broadband-deployment-data-fcc-form-477. Note that prior to 2014, service providers only reported their data for areas in which they actually had subscribing customers. See Flamm and Varas (2018) for a detailed discussion of the 477 data definitions and how they have changed over time, along with an analysis of historical trends in competition in local markets.

[24] There will be two separate records if the service is available for both residential and business consumers.

also available every six months from December 2014 to December 2017, except for the period June 2015.

Broadband locations receiving high cost Connect America Fund (CAF) subsidies, at the census block level, are available from the Universal Service Fund Administrative Company's public data portal.[25] We created census block-level binary (0,1) indicator variables taking on value zero if no CAF high cost broadband funding had previously been received in the census block, 1 in any year thereafter. These binary "vintage of CAF" variables were created for the years 2015, 2016, and 2017.[26]

Demographic information from the American Community Survey (ACS) is also utilized in our analysis. We use data regarding population, housing units, income, age, housing value, education, and ethnicity. This data is available at the census block group level. Each ACS 5-year estimate is assigned to the last year of the estimation period. For instance, the estimates for the five-year period 2013-2017 are assigned to the year 2017.

Finally, we use two sources of geospatial data measuring terrain and land cover characteristics. First, we borrow the geographical terrain ruggedness data developed by Nunn and Puga (2012). In particular, we use their Terrain Ruggedness Index (TRI). This index was originally developed by Riley, et al. (1999) and measures the amount of elevation difference between adjacent cells of a geographical grid. The TRI data developed by Nunn and Puga are calculated at the level of 30 arc-second cells on a regular geographic lat/lon grid covering the entire planet[27]. This terrain ruggedness measure is fixed and time-invariant.

Additionally, we utilize the US Geological Survey's CMG (Climate Modeling Grid) dataset, derived from the NASA MODIS (Moderate Resolution Imaging Spectroradiometer) satellite sensor. The USGS CMG (MCD12C1) Version 6 data products are updated annually, and provide a geographic lat/lon projection at a resolution of 0.05 degrees (5,600 meters) for the entire globe from 2001 to 2017.[28] Maps of the International Geosphere-Biosphere Programme (IGBP) land cover classification based on this data are available. For each CMG map cell, we utilize the percentage of the cell area that is classified in each of IGBP land cover categories to construct measures of ubiquity for five aggregate land cover types that are likely to affect the range and data rate for line-of-sight wireless data communication, and the costs of extending wireline networks.[29]

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[25] Available at https://opendata.usac.org/High-Cost/High-Cost-Connect-America-Fund-Broadband-Map-CAF-M/r59r-rpip .

[26] The 2014 vintage baseline value is embedded in a census block fixed effect.

[27] https://diegopuga.org/data/rugged/ .

[28] https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MCD12C1/ .

[29] For a list of the 15 IGBP land cover categories, see https://smap.jpl.nasa.gov/system/internal_resources/details/original/284_042_landcover.pdf .

Data processing details

From the FCC fixed deployment data, we extract the relevant information relating to residential consumer service provision, since competition in the residential broadband services market is the focus of this paper. We also dropped observations on satellite broadband service providers, for two reasons: first, the Form 477 service data from these ISPs lacks granularity, and is provided to the FCC at the state level.[30] Second, the satellite data does not reflect either active local marketing efforts at the individual census block level, or capacity constraints that may limit satellite service availability in particular local markets.[31]

For each provider-census block combination, we calculate the maximum advertised upload and download speeds offered by the provider using either a wireless technology or a wireline technology (or both, when a mix of technology sets is utilized by the provider).[32] For each time period, we then calculate three measures of market structure at the census block level: (i) number of providers using wireline technologies only, (ii) number of providers using fixed wireless technology only, and (iii) number of providers using a mix of both technology sets. The total number of broadband providers is simply the sum of these three numbers.[33]

Based on service provider technology, we also classify each populated census block into one of three analogous census block technology categories: blocks in which all providers use wireline or a mix of wireline/wireless technologies only; blocks in which broadband providers use only "pure" fixed wireless technologies; blocks in which some broadband providers make use of wireline technology, while other providers deploy only "pure" fixed wireless technology.

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[30] Conversation with FCC data administrator, Washington, DC, September 2018.

[31] Because of the change in Form 477 definition of areas served (from actual customers pre-2014, to "could serve"), in most urban markets and even in many rural census blocks there was a noticeable uptick in numbers of providers after 2013 (typically, by two or more providers). Much of this increase was related to satellite-based ISPs now being included in the ISP counts, even for urban census blocks in which they rarely if ever sold a competitive service offering to paying customers. (The theoretical service footprint of the major satellite-based ISPs covers most of the continental U.S.) The FCC clearly took note of this, since beginning in 2014, publicly released data on ISPs by census block distinguish between counts including and excluding satellite-based service providers.

Also, while satellite ISPs can provide upload and download speeds for digital content comparable to fixed terrestrial broadband service, latency (the round-trip time to send, then receive a single digital packet) is about 20 times greater with satellite service. This significantly affects interactive applications, like gaming, or point and click applications (like moving or zooming dynamically on a map or menu). Based on stated preference survey data, one study estimates that a representative consumer would be willing to pay $8.66 monthly to avoid the increased latency associated with moving from terrestrial to satellite broadband service, at a given download/upload speed. Y. Liu, J. Prince, and S. Wallsten, "Distinguishing Bandwidth and Latency in Households' Willingness-to-Pay for Broadband Internet Speed," *Information Economics and Policy*, Volume 45, December 2018.

[32] If a provider does not offer service with a given technology set (either wireline or wireless), then its maximum advertised speed is defined as missing, not zero.

[33] Although we do not observe the share of households served by various individual providers within a census block, the inverse of our market structure measure (1/N)—with N the sum of the provider counts across technology types—defines a lower bound on the Herfindahl-Hirschman Index of concentration (with 1 defined as the upper bound HHI were all households in a block served by a single provider).

We classify blocks in this manner in order to better accommodate the institutional details of broadband service in U.S. markets. As previously noted, broadband services in the majority of US census blocks had been provided by an effective duopoly of wireline service providers. In many local markets (in Texas, for example), analysis of the detailed FCC data suggests that new entrants often consisted of small and often regionally-based firms deploying fixed wireless technology to offer lower quality/speed service at a discount from the price points used by the incumbent wireline duopolists.

The “pure” fixed wireless providers entering into local census blocks in recent years may potentially have had a disruptive and heterogeneous impact on market outcomes in blocks that previously were relatively stable wireline duopolies. Our classification of census blocks accommodates model specifications that capture potentially heterogenous impacts of new “pure” wireless providers on quality competition at the local census block level.

Using the FCC’s mobile deployment data, we can also calculate analogous mobile broadband market structure measures for each successive mobile technology standard (which is also associated with significant service speed improvements). In particular, we have defined market structure measures for 3G and 4G mobile broadband data service providers. Note that these measures are cumulative: our 3G count includes providers offering 3G or better service, while our 4G count covers 4G or better service. So a 4G provider, for example, would be included in both 3G and 4G provider counts, while a 3G-only provider would be included in the 3G count, but not in the 4G count.

We assign to each census block the value corresponding to the geographic Land Cover and the Terrain Ruggedness Index values for the grid “cell” containing the official Census “interior point”[34] latitude and longitude coordinates of a census block. [35]

Data Panel

Our analytical dataset is a panel dataset where the basic unit is a service availability record at the provider/census block/time period level. Because there is no mobile deployment data available for June 2015, the panel we utilized has four periods: December 2014, December 2015, December 2016, and December 2017. Our data set contains approximately 55 million observations and contains information for approximately 6 million U.S. census blocks, in 3,142 U.S. counties, with 2,184 different broadband providers.

VI. Identification Strategy

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[34] The U.S. Census latitude and longitude coordinates for a census block interior point are effectively the centroid, modified to lie within the census block boundaries for unusual block shapes where it would otherwise not.

[35] Because the raw data is in shapefile format, we use the user-written Stata command *geoinpoly* to count how many providers provide mobile broadband service in each census block. Robert Picard, 2015. "GEOINPOLY: Stata module to match geographic locations to shapefile polygons," Statistical Software Components S458016, Boston College Department of Economics, revised 16 Aug 2015.

Our goal is to estimate a reduced form that will allow us to examine how firm equilibrium quality (measured by maximum download speed) varies with market structure, conditional on demand shifters and cost shifters. We recognize that market structure is likely to be endogenous for two reasons. First, there is likely to be measurement error in our measure of market structure, which can create endogeneity. Second, unobserved factors or shocks that affect service provider quality choices may also affect decisions to enter or exit a local market, leading to endogeneity of our market structure measures. In either case, endogeneity (correlation with the model disturbance term) can bias coefficient estimates.

To the extent that such unobservable factors or measurement errors are time-invariant at the census block level, we can purge their potential biasing effects by using an estimator utilizing block fixed effects. We therefore use a fixed effects estimator, with fixed effects for census blocks.

To the extent that measurement errors, unobservable factors, and unobservable shocks vary over time, we address their potential correlation with our market structure measures by using instrumental variables. Our basic idea is to make use of the fact that technological change in wireless technology had an important effect on ISP entry into local block markets, but an effect that was highly dependent on terrain and land cover in a block. Wireless communication technology is line-of-sight, and speed and range will be greatly affected by terrain and land cover characteristics. Therefore, natural variation in the extent to which wireless technology can be deployed, based on terrain roughness and land cover, is likely to be an important determinant of the cost of investing in a fixed wireless network, and ultimately the number of firms choosing to enter the market.

The same terrain and land cover variables are also likely to have some effect on cost, and therefore on entry and exit, for service providers considering deployment or expansion of wireline networks. But once trenches are dug, wirelines buried or strung, and remote equipment enclosures installed, terrain and land cover should have no direct impact on ISP wireline speeds available to consumers.

The same cannot be said for fixed wireless networks, since land cover and terrain roughness can directly affect range and speed for wireless communications. Therefore, because our spatial/geographic instrumental variables are likely to directly enter into the determination of fixed wireless speed for technological reasons, we drop “pure” fixed wireless ISP speeds from our dataset, and confine our analysis to quality outcomes only for pure or mixed wireline ISPs, where it is reasonable to posit that these terrain variables will not directly affect maximum speeds offered in a block.

To be more precise, we are modeling what the impact of within-block variation in market structure is on wireline ISP service quality, conditional on our demand and cost shifters. Our geographic and spatial instruments are assumed to affect wireline communications speed only through their geography-mediated impact on initial wireline network investment costs and entry, for wireline service providers. In effect, after conditioning on other market characteristics, local geography is being viewed as a "natural experiment" shifting the costs of entry up and down spatially, across local markets. Given the central role of wireless technology in the observed historical changes in market structure, and the strong impacts of our spatial instruments on both wireline and wireless network investment costs, we have reason to be optimistic that these will be strong and highly relevant instruments.

Note that terrain roughness is constant over time within a block, and therefore cannot be directly used in a fixed effects model relying on within-census block variation to identify covariate effects. However, wireless technology improved rapidly during the time period of our study (2014-17). So, interactions of the terrain roughness index with time dummy variables should capture identifying terrain-specific variation across census blocks in the impact of changing technology on terrain-dependent investment costs affecting entry, and therefore serve as effective instruments. Unlike terrain roughness, land cover measurements change over time, and can therefore work as standalone instruments in a fixed effects model.

We think of the CAF subsidy vintage variables described earlier in our discussion of the FCC Connect America Fund as controls for the average effects of accepted CAF broadband subsidy offers on advertised download speeds in subsidized rural census blocks. Conditioning on these binary indicator variables is intended to remove a potential threat to identification of the effects of market structure on download speed, in high cost rural census blocks.

We will next describe a fixed effects model which includes controls for census blocks receiving high-cost CAF subsidies. In this model, we capture all census-block-specific, time-invariant cost or demand shifters as components of a fixed effect. We also include time-varying explanatory covariates for census blocks, including U.S. census variables relevant to broadband cost (like population, housing units, and population and housing density[36]), time-technology interaction dummy variables intended to capture the common (across census block) impact of changing technology on both service speed and deployment cost over time, as well as detailed time-varying measures of census block household characteristics relevant to demand. It is therefore reasonable to suppose that the selection mechanisms for offer and acceptance of CAF subsidies are based on observables already included as explanatory covariates in our main statistical model.[37]

Model structure/assumptions

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[36] Since we use logs of these variables, census block areas are fixed over time, and log of (variable divided by area) is log(variable) – log (area). Log(variable) is time-varying and included as a model covariate, while log(area) is another component of the census block fixed effect.

[37] We therefore believe it unlikely that (after conditioning on observed covariates) unobservables relevant to determination of an ISP's maximum service speed (as embedded within a statistical disturbance term) would be correlated with our CAF subsidy vintage dummy variables. According to this logic, we therefore do not need to worry about possible endogeneity of our subsidy vintage dummy variables.

Our primary goal is to estimate the impact of market structure (measured by number of competitor ISPs serving a census block) on the maximum offered download speed (our measure of "quality") by ISPs using wireline technology. In our economic narrative, broadband competition at the extensive margin, in the form of entry and exit of competitors from local markets, takes place in the long run, varying from year to year. Quality (and price, to the extent it is significant) competition is at the intensive margin, generating observed market outcomes in the short and medium run, with more frequent updates possible. We happen to observe quality at the same time we observe our longer run market structure measures, however.

We divide our broadband universe into three groups of census blocks. Group 1 we label "wireless" markets, where at least one "pure" fixed wireless provider has entered a market to compete with firms using wireline technology. Group 2 we label "wireline" census blocks, where all competitors use wireline technologies (including wireline providers who have adopted fixed wireless technologies in serving some of their customer base within a block). Group 3 is wireless only census blocks, where all broadband providers use "pure" wireless connections to their residential customers. Note that particular census blocks can migrate between classification groups over time.

We discard Group 3 from our sample, since we are attempting to measure the effects of market structure on wireline service quality, and there are no wireline competitors in these blocks. We estimate separate models for Group 1 and Group 2, to accommodate potential heterogeneity. We also differentiate between "pure wireless" and wireline technology-using firms in our measures of market structure, since we believe it is possible that they have heterogeneous effects on quality outcomes. This is supported by some statistical evidence of heterogeneity in impact across local market type.[38]

Note that even if market structure is endogenous, a variety of national and state regulatory policies can affect market structure. In Texas, for example, cities and municipalities are barred by state law from providing broadband service to residents. As another example, the FCC's new auction mechanism for universal service subsidies explicitly provides subsidies to entry into "high cost" census blocks with inadequate broadband availability. Understanding the impact of market structure (number of competitors) on service price and quality is relevant to policy choices even if endogenous firm decisions interact with policy in determining market outcomes.

Econometric Model

The basic model we estimate is

(1) $\text{Ln } S_{ijt} = a_i + a_j + b_{Nfm}\, Nfm_{it} + b_{Nw}\, Nw_{it} + b_{3g}\, tmw\_3g_{it} + b_{4g}\, tmw\_4g_{it} + b_{15}\, t15 + b_{16}\, t16$

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[38] In addition to heterogeneity in coefficient estimates, Sargan-Hansen J-statistic tests of overidentified instruments (which are known to be affected by heterogeneity in covariate effect within a sample) support the separation of the sample into these two groups. See P.M.D.C. Parente and J.M.C. Santos Silva, "A cautionary note on tests of overidentifying restrictions," *Economics Letters*, vol. 115, no. 2, 2012.

$$+ b_{17}\ t17 + b_{tech14}\ wtech_{ijt} \times t14 + b_{tech15}\ wtech_{ijt} \times t15 + b_{tech16}\ wtech_{ijt} \times t16$$
$$+ b_{tech17}\ wtech_{ijt} \times t17 + b_{caf15}\ caf15_{it} + b_{caf16}\ caf16_{it} + b_{caf17}\ caf17_{it} + b_{Ntech}\ Ntech_{ijt}$$
$$+ b_{shifters} \times [\text{demand shifters}]$$
$$+ u_{ijt}$$

where subscript i indexes census block, subscript j indexes ISP, and subscript t indexes time period

Ln S_{ijt} is log maximum download speed, the dependent variable

a_i is a census block fixed effect

a_j is an ISP fixed effect

Nfm_{it} is number of ISPs using wireline technology in block i at time t

Nw_{it} is number of “pure” fixed wireless ISPs in block i at time t

tmw_3g_{it} is total mobile 3G providers serving block i at time t

tmw_4g_{it} is total mobile 4G providers serving block i at time t

t14, t15, t16, t17 are time period dummy variables

$wtech_{ijt}$ is a dummy variable taking value 1 if wireline service provider j also uses wireless technology in serving census block i at time t, 0 otherwise

$caf15_{it}$ is a dummy variable taking on value 1 for block i in year t, for $t > 2014$ if that census block claimed high cost Connect America Fund subsidies for the first time in 2015, 0 otherwise

$caf16_{it}$ and **$caf17_{it}$** are defined like $caf15_{it}$ but for 2016 and 2017

$Ntech_{ijt}$ is the number of different technologies (cable, dsl, fiber, other copper, wireless) used by wireline ISP j in block i at time t

u_{ijt} is a disturbance term for census block i, provider j, time period t

[demand shifters] is a vector of demographic/economic variables from the Census ACS at the blockgroup level corresponding to block i in time period t, and FCC estimates of population and housing units at the block level derived using blockgroup level ACS data.

The demographic/economic demand shifter variables included were:
log of block population; log of block housing units; percent of population that is white, Afro-American, American Indian, Asian American, below the poverty line, receiving public assistance income, has less than a high school education, has a college or better education; median family income, median housing value, percent of housing units that are occupied.

Note that this specification allows for two distinct types of general, technology-related shifts over time in maximum download speed affecting all census blocks. One shift is for providers using wireline-only service technology: the coefficients on time dummy variables **t15**, **t16**, and **t17** (the census block fixed effect includes the component reflecting baseline 2014 wireline technology). The other shift terms allow for different shift effects of technology on maximum download speeds for wireline ISPs using both wireline and wireless technologies within the census blocks served: the coefficients on the interaction of $\mathbf{wtech}_{ijt}$ with the time dummy variables. The number of technologies used within census block i variable ($\mathbf{Ntech}_{ijt}$) by wireline provider j at time t counts distinct types of wireline technologies, as well as wireless technology, to control for cost shifting effects of operating with greater technological diversity within a census block.

VII. Results

Recall that the sample being analyzed was divided into two groups: “wireless blocks” with “pure” wireless providers offering service, and “wireline blocks” where all providers use wireline technologies (possibly supplemented by wireless connections). Equation (1) as written above was utilized with the “wireless blocks” subsample. The variable and coefficient for “pure” wireless providers were omitted in the model applied to the “wireline blocks” model; but in all other respects the same specification was used. The covariance matrix used to estimate standard errors was clustered at the county level, i.e., spatial correlation of disturbance terms across blocks and over time, within counties, was assumed and flexibly accounted for.

Table 2 displays results[39] for the “wireless block” subsample, and Table 3 presents results for the “wireline only block” subsample. We have more instruments than potentially endogenous variables. This overidentification allows us to test for exogeneity of 4G mobile provider counts. The 8 columns in each table represent different choices of instruments and assumptions about the exogeneity of 4G mobile broadband. Columns 1 through 4 use the full set of instruments—four land cover measures (percent savannas, grasslands, shrublands, and croplands[40]) plus the interaction of the terrain roughness index (TRI) with the three time period dummy variables. Columns 5 through 8 omit the TRI instruments. Columns 1, 2, 5, and 6 permit the 4G mobile provider count variable to be endogenous, while columns 3, 4, 7, and 8 impose the assumption that 4G mobile provider counts are exogenous. Columns 1, 3, 5, and 7 control by vintage of CAF subsidies for high cost broadband Universal Service Fund subsidies being

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[39] The IV panel model in equation (1) was estimated using Sergio Correia’s ***ivreghdfe*** Stata software. This software integrates Correia’s ***reghdfe*** software with Baum, Schaffer, and Stillman’s widely used ***ivreg2*** Stata software. See https://github.com/sergiocorreia/ivreghdfe ; https://ideas.repec.org/c/boc/bocode/s425401.html .

[40] Grasslands are lands with herbaceous cover and less than 10% trees and shrubs—IGBP type 10. Savannas are the sum of open savannas (herbaceous cover with forest cover 10-30%)—IGBP type 9—and woody savannas, with forest cover 30-60%)—IGBP type 8. Shrublands are the sum of open shrublands (woody vegetation less than two meters tall and 10-60% canopy cover)—IGBP type 7—and closed shrublands (under 2 meters but >60% canopy cover)—IGBP type 6. Croplands are lands covered with temporary crops—IGBP type 12—and cropland/natural vegetation mosaics—IGBP type 14.

received in recipient census blocks, while columns 2, 4, 6, and 8 omit the CAF subsidy control variables.

Discussion: Wireless Blocks (Table 2)

Table 2 displays two-stage least squares estimates of Equation (1). There are roughly 14 million observations in this subsample, covering 2.4 million census blocks distributed across 2,593 US counties. A couple of points should immediately be noted.

First, without a full set of instruments (i.e., if we were to exclude the TRI x time dummy interactions), the endogenous market structure variables appear to be underidentified. The Kleibergen-Paap test statistic for underidentification in the least constrained specification has a p-value of .67 (column 5), which does not allow us to reject the null hypothesis of underidentification. In fact, in all specifications tested, dropping the TRI variables results in non-rejection of the underidentification null hypothesis. Therefore, we adopt a specification including the full set of instruments and restrict our further discussion to the first four columns of Table 2.

Second, our overidentification tests (the Hansen J-statistic) do not lead us to reject the null hypothesis that our full set of instruments are orthogonal to the model disturbance terms—the null hypothesis of orthogonality is not rejected at the 10% significance level in all specifications.[41] (For the least constrained specification, column 1, p-value = .18.) Our instruments do appear to be quite strong—the F-statistic for the full set of instruments (first four columns) always exceeds 1700.[42]

Since we have an overidentified equation (more instruments than endogenous variables) we can construct a test for the endogeneity of the 4G provider count. We cannot reject the null hypothesis of exogeneity at the 10% level (Chi-sq(1) p-value = 0.41). That p-value is quite consistent with a null hypothesis of exogeneity. Not having to instrument this variable will deliver more precise parameter estimates with tighter standard errors.

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[41] With the caveat that non-rejection of the null for this statistic is neither necessary nor sufficient for the instruments to be valid. See P.M.D.C. Parente and J.M.C. Santos Silva, "A cautionary note on tests of overidentifying restrictions," *Economics Letters*, vol. 115, no. 2, 2012.

[42] Though using this statistic in a formal test would assume homoscedastic disturbances, and we are actually allowing for a cluster-robust covariance matrix.

Table 2: Wireless Block Estimation Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	TRI instrument	TRI instrument	TRI instrument	TRI instrument	No TRI	No TRI	No TRI	No TRI
	4G Endg.	4G Endg.	4G Exog.	4G Exog.	4G Endg.	4G Endg.	4G Exog.	4G Exog.
	USF	No USF	USF	No USF	USF	No USF	USF	No USF
N mixed ISP: Nfm	0.393	0.382	0.107	0.105	-0.386	-0.363	-0.0978	-0.0954
	(0.91)	(0.88)	(0.26)	(0.25)	(-0.29)	(-0.27)	(-0.22)	(-0.21)
N pure wireless: Nw	1.385*	1.393*	1.511**	1.514**	0.638	0.663	0.718	0.735
	(2.48)	(2.49)	(2.77)	(2.78)	(1.26)	(1.31)	(1.59)	(1.63)
N Mobile 4G: tmw_4G	-0.427	-0.418	-0.162**	-0.163**	0.156	0.136	-0.0945*	-0.0962*
	(-1.42)	(-1.38)	(-3.08)	(-3.09)	(0.15)	(0.13)	(-2.27)	(-2.31)
N Mobile 3G: tmw_3G	0.287	0.282	0.105+	0.106+	-0.147	-0.131	0.0318	0.0344
	(1.39)	(1.35)	(1.88)	(1.91)	(-0.19)	(-0.17)	(0.75)	(0.81)
t15	0.320**	0.319**	0.247***	0.248***	0.236	0.240	0.291***	0.291***
	(2.65)	(2.63)	(3.41)	(3.43)	(0.95)	(0.95)	(5.70)	(5.66)
t16	0.519***	0.517***	0.423***	0.425***	0.425	0.430	0.493***	0.494***
	(3.42)	(3.40)	(5.34)	(5.35)	(1.37)	(1.37)	(8.23)	(8.16)
t17	1.049***	1.047***	0.940***	0.941***	0.946**	0.953**	1.024***	1.025***
	(5.53)	(5.48)	(8.39)	(8.35)	(2.63)	(2.61)	(11.49)	(11.32)
caf15	0.286***		0.291***		0.276***		0.275***	
	(6.53)		(6.43)		(7.49)		(7.52)	
caf16	0.168***		0.179***		0.231**		0.213***	
	(3.56)		(3.78)		(2.76)		(5.41)	
caf17	0.116		0.106		0.244*		0.225**	
	(1.28)		(1.14)		(2.22)		(2.79)	
ISP Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Block Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N obs	14215421	14215421	14215421	14215421	14215421	14215421	14215421	14215421
N blocks	2449579	2449579	2449579	2449579	2449579	2449579	2449579	2449579
N counties	2593	2593	2593	2593	2593	2593	2593	2593
Cragg-Donald F statistic (assumes iid disturbances)	1738.8	1759.1	1782	1802	210	212	1863	1909
p values for statistical tests:								
Hansen J test (H0: all instruments valid)	0.181	0.173	0.261	0.255	0.203	0.206	0.459	0.466
Underidentification test (H0: Endog variables underidentified)	0.0572	0.0563	0.0359	0.0352	0.673	0.671	0.118	0.114
4g endog test (H0: # 4G providers exogenous)	0.4121	0.4329	-	-	0.093	0.077	-	-
t test, H0: Nfm-Nw=0	0.134	0.127	0.007	0.007	0.345	0.352	0.095	0.09
t test, H0: # 3G + # 4G =0	0.162	0.173	0.025	0.026	0.976	0.987	0.01	0.01
all estimated standard errors are cluster-robust, clustering on county								
t statistics reported in parentheses below estimated coefficients								
+ p<.10	* p<.05	** p<.01	*** p<.001"					

We conclude that it is desirable to include the full set of instruments, and that it would be reasonable take 4G provider count as exogenous. Therefore, the column in this table that likely will give us the most useful information is the third column, specification (3), with 4G providers taken as exogenous. Both columns (1) and (3) (without and with exogeneity of 4G provider counts assumed) deliver broadly similar estimates, but column (3) with 4G exogeneity assumed has very much smaller standard errors in all cases, and is therefore our preferred specification. Inclusion of the CAF subsidy vintage dummy variables has very little effect on other estimated coefficients, but results in statistically significant coefficient estimates for these variables.

With either of specifications (1) or (3), the impact of an additional "pure wireless" competitor on maximum wireline download speed is large and highly statistically significant. By contrast, another wireline competitor has a vastly smaller point estimate that is not statistically significant: we can't reject the hypothesis that the wireline competitor coefficient is zero, and do reject the hypothesis that wireline impact is the same as wireless in our preferred specification (3).[43]

The headline result from this analysis is that the positive impact of competition on maximum wireline download speed is driven primarily by increases in the number of pure wireless competitors. On average, an additional wireless competitor has a large effect on maximum wireline download speeds that is both statistically and economically significant. Translating the model coefficient into a point estimate of the average impact would give about 3.9 times greater speeds, though there is substantial uncertainty—it could be even larger or substantially smaller, though still statistically significant (see discussion below).

A related question is what the impact of another 4G mobile provider is on broadband quality. Since our mobile broadband provider count is coded such that an additional 4G provider also adds a 3G provider, the impact of another 4G provider is the sum of the 3G and 4G coefficients. This net impact on broadband speed is negative, and statistically significant. This is consistent with 4G mobile service and fixed broadband being substitutes on the demand side (highly plausible, since 4G availability may reduce demand for fixed broadband) or possibly on the supply side (since 4G and fixed wireless broadband may compete for inputs of scarce spectrum).

Discussion: Wireline Blocks (Table 3)

Next, we turn to what we called our wireline subsample, blocks in which no "pure" wireless competitors offered service. There are 24.8 million observations in this subsample, covering 3.8 million census blocks distributed across 2917 counties.

In this subsample, using either the same full set of instruments or dropping the TRI x time dummy interactions, the two endogenous covariates (since there are no pure wireless providers in this subsample) appear to be fully identified in all specifications. The Kleibergen-Paap test statistic for underidentification has a p-value of close to zero in all specifications. Our overidentification tests (the Hansen J-statistic), however, lead us to reject the null hypothesis that all our instruments are orthogonal to model disturbances whenever the TRI x time dummy

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[43] Allowing 4G count to be endogenous (column 1) almost quadruples our estimated standard errors on the wireline competitors coefficient; we still can't reject that the wireline coefficient is zero, but we would no longer be able to reject the hypothesis that that it is the same as the wireless coefficient.

interactions are included as instruments. This suggests that the terrain-time interactions are not useful instruments when a count of pure fixed wireless providers is not being included as an endogenous variable in the model specification.

Dropping the TRI x time dummy interactions solves the problem. In this subsample, columns (5) and (7) in the table are the ones on which to focus. The Hansen J statistics with the reduced instrument set now lead us to not reject the hypothesis that we have an overidentified set of valid instruments at any reasonable significance level. As before, our instruments appear to be quite strong—the F-statistic with the reduced set of instruments uniformly exceeds 2500.

Once again, we have an overidentified equation, so we can construct a test for the endogeneity of the 4G provider count. We cannot reject the null hypothesis of exogeneity at the 10% level (Chi-sq(1) p-val = 0.35), and the coefficient estimates with and without exogeneity of the 4G count imposed are again broadly similar. We conclude that it is again reasonable to assume exogeneity for 4G provider counts, and reap the reward of more precise coefficient estimates and much smaller standard errors. Therefore, the column in this table on which we focus is the seventh one, (7).

With either of specifications (5) or (7), the impact of an additional wireline competitor on maximum wireline download speed is a small negative number that is not statistically or economically significant. We can again ask what the impact of another 4G mobile provider is on best available broadband quality. Adding together the 4G and 3G coefficients, we find a negative effect that is statistically significant at the 1 percent level with 4G exogeneity assumed, and very similar in magnitude to the coefficient estimated for the wireless subsample. As before, we interpret this as plausible evidence of substitution between mobile 4G broadband and fixed broadband.

As was the case with the wireless subsample, including the Connect America subsidy controls in the wireline block subsample has essentially no effect on other coefficient estimates. Where coefficients are comparable between the two subsamples, estimated coefficients seem very similar across the two subsamples.

Overall Comparisons

Overall, our results paint a picture of large and statistically significant effects on wireline broadband quality, as measured by maximum download speed, induced by adding an additional wireless competitor into the competitive mix in local census block market which already has a “pure” wireless competitor. This is in sharp contrast to the negligible impact from another wireline competitor, cet. par., in census blocks with or without existing wireless competitors. Even though mixed wireline/wireless ISPs dominated the new entry into census block markets that was observed over the sample period, these results suggest that new, “pure wireless” network competitors played a crucial and uniquely disruptive role in stimulating large improvements in wireline quality. The same effect was apparently not felt when legacy wireline broadband networks added new customers in new census blocks at the margins of other ISPs' established legacy networks, making use of the same improved wireless technology.

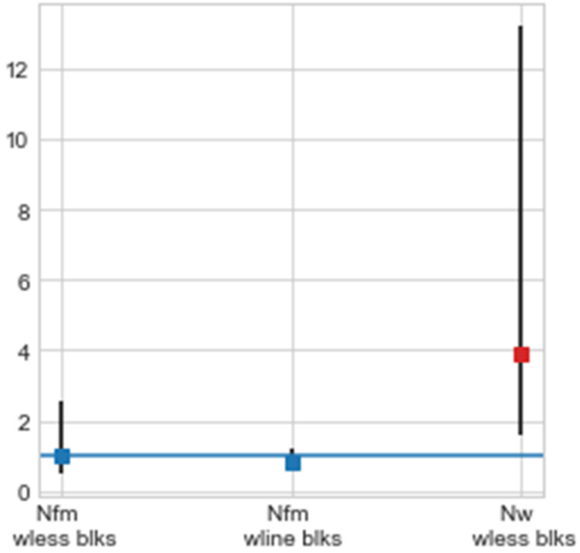
Table 3 Wireline Block Estimation Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	TRI instrument	TRI instrument	TRI instrument	TRI instrument	No TRI	No TRI	No TRI	No TRI
	4G Endg.	4G Endg.	4G Exog.	4G Exog.	4G Endg.	4G Endg.	4G Exog.	4G Exog.
	USF	No USF	USF	No USF	USF	No USF	USF	No USF
N mixed ISP: Nfm	-0.123	-0.132	-0.643***	-0.644***	-0.171	-0.182	-0.213	-0.226
	(-0.63)	(-0.68)	(-3.41)	(-3.42)	(-0.78)	(-0.83)	(-1.05)	(-1.12)
N Mobile 4G: tmw_4G	-0.608*	-0.596*	0.0227	0.0231	-0.339	-0.364	0.0207	0.0212
	(-2.36)	(-2.32)	(1.12)	(1.14)	(-0.78)	(-0.82)	(1.04)	(1.06)
N Mobile 3G: tmw_3G	0.340*	0.333*	-0.0934***	-0.0926***	0.160	0.178	-0.0797**	-0.0792**
	(2.08)	(2.04)	(-3.68)	(-3.65)	(0.55)	(0.60)	(-3.24)	(-3.23)
t15	0.332***	0.330***	0.191***	0.193***	0.272**	0.279**	0.191***	0.192***
	(5.15)	(5.17)	(17.27)	(17.38)	(2.83)	(2.86)	(18.01)	(18.11)
t16	0.728***	0.727***	0.604***	0.606***	0.673***	0.680***	0.599***	0.601***
	(9.11)	(9.17)	(20.56)	(20.74)	(7.42)	(7.38)	(21.01)	(21.23)
t17	1.296***	1.298***	1.262***	1.265***	1.230***	1.244***	1.135***	1.141***
	(15.22)	(15.32)	(17.89)	(17.97)	(10.12)	(10.03)	(20.42)	(20.57)
caf15	0.290***		0.316***		0.301***		0.315***	
	(15.83)		(17.49)		(12.20)		(17.30)	
caf16	0.186***		0.218***		0.192***		0.200***	
	(5.00)		(7.61)		(5.80)		(6.37)	
caf17	0.365***		0.261***		0.332***		0.290***	
	(7.00)		(6.15)		(5.18)		(7.59)	
ISP Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Block Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N obs	24765733	24765733	24765733	24765733	24765733	24765733	24765733	24765733
N blocks	3771554	3771554	3771554	3771554	3771554	3771554	3771554	3771554
N counties	2917	2917	2917	2917	2917	2917	2917	2917
Cragg-Donald F statistic (assumes iid disturbances)	9622	9585	3.10E+04	3.10E+04	2614	2555	1.40E+04	1.40E+04
p values for statistical tests:								
Hansen J test (H0: all instruments valid)	0.0000217	0.0000169	0.000136	0.000102	0.266	0.2539	0.411	0.381
Underidentification test (H0: Endog variables underidentified)	0.00000295	0.00000314	1.75e-09	1.69e-09	0.00540	0.0062	0.00000558	0.00000553
4g endog test (H0: # 4G providers exogenous)	0.3764	0.3207	-	-	0.3456	0.3234	-	-
t test, H0: # 3G + # 4G =0	0.006	0.006	0	0	0.216	0.205	0	0
all estimated standard errors are cluster-robust, clustering on county								
t statistics in parentheses								
+ p<.10	* p<.05	** p<.01	*** p<.001"					

We next calculate marginal effects based on exponentiating coefficients in our preferred specifications—Table 2, column 3, and Table 3, column 7. As is well known, exponentiating coefficients in the model of log speed in equation (1) delivers consistent but biased estimates of multiplicative impacts in the implied multiplicative model of speed (exponentiating log speed), so we calculate bias-corrected estimates of average effects using a standard method of reducing finite sample bias.[44] Exponentiating limits of the 95% confidence intervals for parameters in the log model, however, does not require a correction in order to yield valid estimates of confidence intervals for the exponentiated parameter.[45]

Impacts of Additional Wireline Competitors. We earlier noted that an additional wireline competitor (using either 'pure' wireline or using 'mixed' technology including wireless connections within a census block) had an impact on download speed that was close to zero, in both subsamples of census blocks. In contrast, the impact of an additional wireless competitor on maximum wireline download speed was substantial, positive, and statistically significant at the 1 percent level (Table 2, column 3). We can exponentiate these coefficients to get an estimated multiplier, and calculate estimated confidence intervals.

Figure 6. Estimated Multiplicative Effect of 1 More Competitor on Max ISP Download Speed No Impact =1



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[44] The issue is that because an estimated coefficient from equation (1) has an asymptotically normal distribution, the exponentiated coefficient has an asymptotically lognormal distribution. The lognormal distribution is skewed, with a mean that is less than the median, unlike a normal distribution, where they coincide. We calculate bias-reduced means as exp(estimated coefficient – (estimated standard error^2/2)). See P. Kennedy, "Estimation with Correctly Interpreted Dummy Variables in Semilogarithmic Equations," *American Economic Review*, Vol. 71, No. 4 (Sep., 1981), p. 801; also, A.S. Goldberger, "The Interpretation and Estimation of Cobb-Douglas Functions," *Econometrica*, Vol. 36, No. 3/4 (Jul. - Oct., 1968). This bias reduction correction has become standard in the hedonic price index literature.

[45] As Goldberger observes, "any order statistic of a monotonic function is the function of the order statistic". Because exponentiation is a monotone function, exponentiating an order statistic for a random variable (like the median, or other percentiles of the distribution of an estimated coefficient) yields order statistics for the exponentiated random variable. For example, exp(median(x))=median(exp(x)), but E(exp(x)) will not generally equal exp(E(x)), for x a random variable. See A.S. Goldberger, "The Interpretation and Estimation of Cobb-Douglas Functions," *Econometrica*, Vol. 36, No. 3/4 (Jul. - Oct., 1968), 1968, p. 465.

Figure 6 displays these effects. The pattern of effects is unchanged from the original impacts reported in Tables 2 and 3. The bias-reduced estimated mean for impact of an additional "pure" wireless competitor on maximum offered wireline provider speeds in census blocks containing both types of providers is very large, multiplying these speeds by a factor of about 3.9, but also comes with a large margin of error. Nonetheless, it is statistically significant—no effect (a 1x multiplier) is outside a 95% confidence interval. An additional wireline competitor has no statistically significant effect on maximum wireline speed offered in either wireline or wireless census block subsamples.

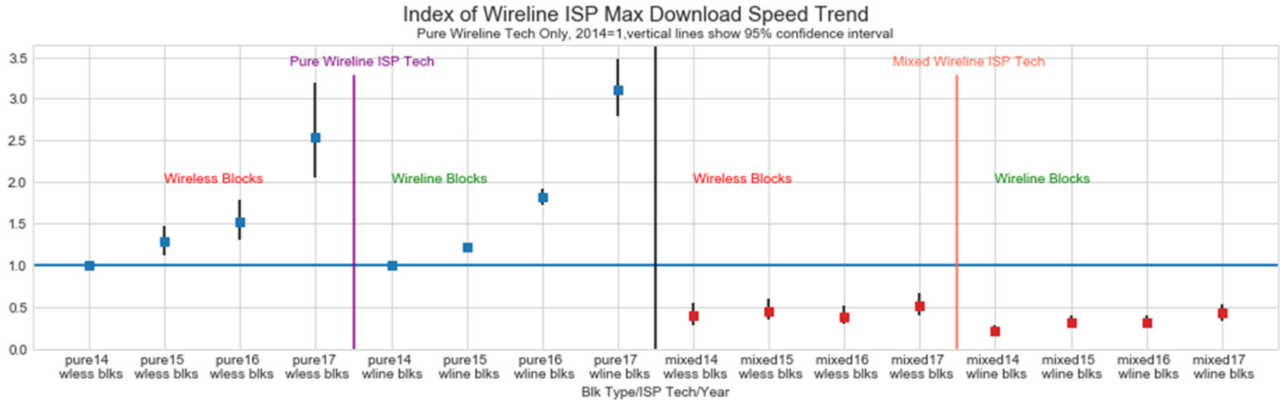
Technology/speed trends over time. The estimated coefficients of the time period dummy variables, and technology ("pure" wireline vs. mixed wireline/wireless) dummy indicator variables interacted with the time period dummy variables, allow us to construct indexes of speed improvement (holding all other explanatory cost and demand shifters, and census block fixed effects, constant) over time in the two subsamples, with "pure" wireline ISP speed in 2014 (incorporated into the census block fixed effect) as a baseline set equal to 1 in both "wireless block" and "wireline block" subsamples.

Figure 7 supplies a useful visualization of these speed trend indexes, with relative "pure wireline" speed in 2014 set equal to 1, using exponentiated linear combinations of estimated coefficients to calculate relative speed indexes, and estimated 95% confidence intervals shown as vertical lines. The left half of the panels show trends in maximum download speeds for wireline ISPs using "pure" wireline connections within a census block over time; the right half shows relative speeds for "mixed" wireline service providers (using a mix of wireline and wireless technologies) in the two distinct subset of census blocks.

There are two principal take-aways from this graph. First, *cet. par.* average maximum wireline speeds, by technology used, basically have the same trends over time across both subsets of census blocks. Second, "pure wireline" ISPs offered maximum *cet. par.* speeds that increased, on average, 2-3 times over 2014-2017, contrasting with "mixed wireline/wireless" ISPs that saw only small improvements in maximum advertised speed over time (from perhaps .2 to .4 of the baseline 2014 maximum "pure wireline" speed in 2014, to roughly half of that same 2014 maximum baseline pure wireline speed level by 2017).

We may reasonably infer that the effects of technological progress over this period in fixed wireless broadband seem to have played out mainly in terms of lowering cost and increasing effective communications range, rather than rapidly elevating maximum speeds offered to existing customers. Maximum advertised speeds for wireline ISPs in census blocks where mixed wireline/wireless connection technology was used increased very slowly over time. Clearly, wireline providers also using wireless technology to connect with their customers seem to have focused primarily on adding new customers at the edges of their existing legacy wireline networks in these census blocks. In contrast, "pure" wireline ISPs, on average, more than doubled the maximum speed offered to their customers from 2014 to 2017.

Figure 7



Effects of CAF Subsidy Vintages on Download Speeds. Another useful set of time-varying effects estimated is the average impact of deployment of Connect America Fund-subsidized broadband connections on ISP speeds in census blocks receiving subsidized connections. While these were included in our model primarily as controls, if our assumption that selection for eligibility, and acceptance of these subsidies by ISPs, was based on other explanatory covariates that we are already conditioning on in our speed model, then we can potentially interpret these estimated effects as a measure of the causal impact of the subsidies on the census blocks that received them. Figure 8 graphs the estimated mean effects (after estimated coefficients are exponentiated), and associated confidence intervals.

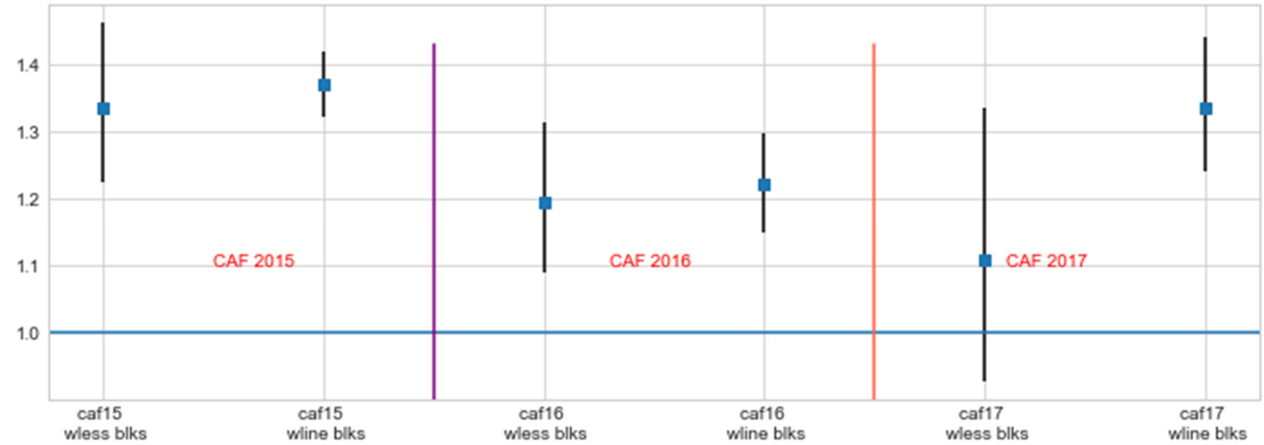
The results visualized in Figure 8 seem sensible. First, note that estimated coefficients are broadly similar across our two subsamples ("wireline" vs. "wireless") census blocks. This is another example of the same reassuring robustness of estimated coefficients, with respect to census block subset used for estimation, that we just saw displayed in speed trends by wireline technology.

Second, the pattern of exponentiated coefficients over time seems reasonable. The first set of subsidies offered (the CAM model-based "price cap" carriers deploying subsidized connections in 2015) increased average maximum download speed rates in recipient blocks by about 35% (after controlling for demand and cost shifters, and numbers of competitors). As might be expected if the most technologically and economically attractive locations were the first ones to receive subsidized deployments, the second "price cap subsidy class of 2016" shows a smaller impact on maximum download speed of closer to 20%.

The results for 2017 vintage subsidies reflect a new group, "rate-of-return" ISPs receiving ACAM model-based subsidies, being added to the Connect America high cost subsidy mix. We see 2017 vintage CAF subsidy-receiving wireline blocks showing a 35 percent higher maximum speed, contrasted with a 2017 vintage CAF subsidy impact on wireless subsample block speeds that further declined, to about 10 percent.

Figure 8. Index of Impact of CAF High Cost Subsidy on Maximum Wireline Download Speed

Cet. par. Unsubsidized Maximum Speed=1, Vertical Line is 95% Confidence Interval

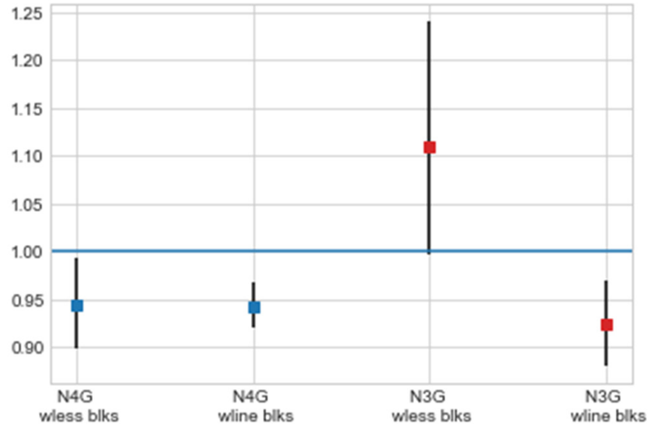


4G and 3G Impacts. Figure 9 shows effects on maximum wireline download speed of an additional 4G and 3G provider (exponentiated coefficients), and estimated 95% confidence intervals. 4G impacts, already discussed above, are evidence of substitution between 4G and fixed broadband services. Once again, estimated effects are reassuringly similar in our wireline and wireless subsamples.

3G impacts, however, vary across subsample. In census blocks without “pure” wireless providers (the wireline subsample), an additional 3G provider is associated with a slight reduction in wireline maximum speed, supporting the idea of “substitution” between 3G and fixed wireline broadband services. In contrast, in blocks containing pure wireless providers, the coefficient is positive, though only marginally significant (at 10%; 95% percent confidence intervals are what is depicted in the figure). This provides slight support to the idea that low speed 3G mobile may be complementary to wireline broadband service in the set of census blocks where lower speed fixed wireless ISPs are also operating.

Figure 9. Marginal Multiplicative Impact, +1 Mobile ISP on Wireline ISP Max Download Speed

No Impact =1



VIII. Conclusion

Using data from multiple sources, we have constructed a rich panel data set covering all broadband services available by ISP, technology and maximum download speed for each of approximately six million populated U.S. census blocks between December 2014 and December 2017. We described trends in market structure, quality and technology utilization over this period.

Using a novel empirical identification strategy and a set of plausibly exogenous instruments that exploit spatial technological variation among incumbent and entrant broadband ISPs, we were able to identify the effects of entry of new wireless and wireless ISPs on service quality for residential customers in spatially disaggregated local markets. Our results produced evidence that the entry of new wireless ISPs into markets containing both wireline and wireless ISPs had large and statistically significant effects on ISPs' maximum download rates. In markets where pure wireless ISPs did not enter, however, as well as in markets where they had, an increase in the number of wireline ISPs had no significant impact on maximum download speed. The results suggest that intramodal competition (both between fixed wireline and fixed wireless broadband service technologies, and between mobile wireline and fixed broadband ISPs) is a critically important competitive margin driving improvements in U.S. residential broadband service quality. Ultimately, both declines in quality-adjusted U.S. broadband prices, and consumer benefits from utilization of new services requiring higher quality service are likely to benefit from improvements in service quality stimulated by greater competition.

Our empirical results inform four important policy issues. First, our review of both previous data and research findings highlighted how critically important availability of good, highly disaggregated data is in enabling reliable policy analysis. This is an issue that is continually being reconsidered by the FCC. Second, policymakers should think long and hard before implementing policies that potentially reduce the number of broadband competitors, for example, through merger and acquisition policy, in either the fixed or mobile broadband space. Third, the evidence of substitution between 4G mobile and fixed broadband services highlights how policies that foster increased competition in the developing 5G services market could potentially play a strategic role in improving the quality and reducing the price of household access to advanced broadband services. Finally, these results suggest that entry by new, wireless network competitors has played an asymmetric and disruptive role in stimulating large improvements in available service quality. The FCC's recent adoption of an entry-friendly auction mechanism to distribute universal service subsidies for broadband service deployed to underserved high-cost areas seems like a wise choice in light of these results.

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Appendix A The FCC Form 477 Data

Since 2000, the Federal Communications Commission (FCC) has been collecting data on the availability of broadband service across the United States. The original May 2000 Form 477 required "facilities based" broadband service providers to provide a list of all 5-digit ZIP codes in which they provided service to at least one end user, and defined high speed service connections as those with data transfer rates exceeding 200 kilobits per second (kbps).[46] The data was collected twice a year, in June and December.

In 2008, the program was revised significantly: the geographic unit for data collection became the census tract. Fixed wireline and wireless ISPs, as well as satellite providers, now had to report total subscribers by census tract, broken down by technology and speed tier, and the share of those subscribers that were residential customers. Mobile wireless broadband providers were asked to list the census tracts that "best represent" their broadband service footprint, by service tier quality.[47] Beginning around this time, public data released by the FCC, derived from this form, was expanded to include the numbers of mobile wireless providers serving a census tract (as with fixed broadband data, results for the range of 1-3 providers were censored, as were numbers of mobile providers exceeding a cap of 7), and a qualitative coding of the share of households in a census tract with broadband service was added to the public version of the Form 477 dataset.

Shortly afterward, in 2009, in association with passage by Congress of the American Recovery and Reinvestment Act of 2009 (which contained approximately $7.2 billion for broadband-related investment projects), the FCC was directed to create a National Broadband Plan (NBP), released in March 2010. In parallel, when the FCC released 477 data for June 2009, the public release of the 477 data also began reporting numbers of broadband providers exceeding a faster "NBP" threshold of 3Mbps download, 768Kbps upload speeds, by census tract.[48] In August 2013, the FCC revised its 477 program once again. Most importantly, it required

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[46] The history of FCC's Form 477 program is summarized in FCC*, Modernizing the FCC Form 477 Data Program, Final Rule*, published in the Federal Register on August 13, 2013. The FCC originally published this data in the form of a list of zip codes in which broadband service provider reported any customers, and the number of providers reporting customers in the zip code (with numbers of providers in the 1 to 3 range per zip code censored, and reported as an '*'. Unfortunately, zip codes with no end users reported were not shown in the public list, which made these data of limited utility to researchers and policymakers, since zip codes were created and withdrawn by the postal service frequently, and zip codes were never actually used to define stable spatially defined areas. Researchers attempting to use these data were forced to devise ad hoc schemes to associate postal zip codes with Zip Code Tabulation Areas (ZCTAs) defined by the Census during decennial census years, in order to try to figure out what areas had no service at all. After 2004, the FCC began reporting "zero provider" zip codes, which enabled researchers to at least enumerate the universe of zip codes being considered by the FCC for its public reports.

[47] FCC (2013). The speed tiers reported by mobile wireless providers appear to have corresponded to what generation (2G, 3G, 4G non-LTE, 4G LTE) of mobile wireless technology was available to serve customers in a census tract.

[48] The National Broadband Plan actually set a 4/1 Mbps benchmark, but the 3/.768 Mbps tier in the National Broadband Map that was being constructed at the time was the closest speed tier to this benchmark, and ended up becoming the original "NBP broadband speed".

fixed service ISPs (including satellite as well as fixed wireline and wireless providers) to submit lists of all census blocks (vs. tracts) “where they offer service” (vs. where they have actual subscribers!). Finally, in late 2014, the FCC revised rules for its Connect America Fund (subsidies supporting fixed rural broadband) to require minimum 10/1 Mbps connection speeds. Form 477 data submitted from 2014 on report maximum speeds (by technology) of fixed broadband service ISPs, by census block.

Appendix B Connect America Fund Transitional Subsidy Mechanisms, 2014-17

Though simplified somewhat through this process, the distribution of Universal Service subsidy funds remained quite complex. In 2011, there had been no less than 7 different support mechanisms distributing “high cost” subsidies to three different categories of recipient telephone voice service providers. There were the incumbent local exchange carriers (ILECs) in rural areas that were subject to “price cap” regulation of their interstate service charges (generally larger national or regional providers, the “price cap” ILECs); so-called “rate-of-return” ILECs (primarily small local telephone companies serving rural areas); and finally, so-called “competitive eligible telecommunications carriers” (CETCs), in rural areas served by all other firms (presumably those not the historical incumbent local exchange carrier at the time of the breakup of the U.S. Bell System telecommunications monopoly in the 1980s).

From 2012 through 2014, a set of “Phase I” transitional funding mechanisms began shifting both old and new Universal Service subsidy funds to new mechanisms supporting broadband deployment to high cost areas serviced by price cap ILECs. Initially, approximately $486 million in funding was allocated to Phase I subsidies to broadband deployment (initially defined by a 4 Mbps download/ 1 Mbps upload standard, relaxed to a 3 /.768 standard after the initial phase of funding) to about half a million high-cost locations lacking “broadband” (defined by speeds at or exceeding .768/.200). Acceptance of the funding (and service obligations) by the ILEC was voluntary, with frozen “legacy” high cost support available as an alternative.

From 2015 on, the “price cap” ILECs were offered “Phase II” support based on an FCC cost model for broadband provision (the “Connect America Model,” or CAM) on a voluntary basis. The Phase II support obligated price cap ILECs to deploy a minimum 10/1 broadband standard to census blocks lacking an unsubsidized competitor offering broadband service. Frozen legacy voice subsidies to price cap providers in high cost areas were cut sharply during Phase II.[49]

Most recently, after 2018, the FCC added significant funding ($1.5 billion over ten years) to support eligible providers with winning bids in a new reverse auction mechanism. Providers bid the subsidy value at which they would accept broadband service obligations in specified high-

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[49] See FCC, Federal-State Joint Board on Universal Service, *Universal Service Monitoring Report 2018*, (Washington: FCC), 2018, Table 3.3. The CAM support to price cap carriers was reasonably large— set at $1.7 billion annually over 6 years and expected to result in deployment of 10/1 broadband to 3.5 million locations by 2020, See V. Gaither, “Connect America: Modernizing High Cost,” 2018, p. 7, available at https://pubs.naruc.org/pub/FBF37AD4-E376-759C-5844-356368F45E7C .

cost "price cap" census blocks in 45 states. These were an FCC-defined list of census blocks where either the Connect America Model support had been declined by the incumbent price cap provider, or where costs were deemed "extremely high", or blocks had been removed for other reasons from the FCC's previous CAM offers to price cap carriers. This auction, completed in late 2018, was known as the Connect America Fund (CAF) Phase II auction.[50]

The new reverse auction mechanism is a significant qualitative break from previous subsidy mechanisms. It subsidizes new entrants into high-cost census blocks where an incumbent ILEC had declined a previous FCC subsidy offer. Previously, only incumbent voice services providers had been offered subsidies in exchange for broadband service provision commitments in high cost areas.

The second large group of incumbent voice service providers serving rural high cost areas, the rate-of-return carriers, continued to have access to subsidies at frozen legacy levels through 2016. Beginning in 2017, rate of return carriers in high cost areas were offered substantial new subsidies for broadband deployment, as a voluntary option, based on another FCC cost model (the "Alternative Connect America Model," or ACAM). Service speed obligations ranged from under 4/1, to 4/1, to 10/1, and up to 25/3, and were expected to bring broadband to 714,000 new locations by 2026.[51] Legacy universal service support claims from rate-of-return carriers began to decline after the ACAM broadband offers started in 2017.[52]

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[50] See FCC, "Connect America Fund Phase II Auction (Auction 903)," available at https://www.fcc.gov/auction/903 .

[51] The broadband service obligations were complex. "Carriers who elected this option will have the certainty of receiving specific and predictable monthly support amounts over the 10 year support term (2017-2026). Those that elected model support must maintain voice and existing broadband service and offer at least 10/1 Mbps to all locations fully funded by the model. They must also offer at least 25/3 Mbps to a certain percentage of those locations by the end of the support term. In addition, carriers must also offer at least 4/1 Mbps to a certain percentage of capped locations [where caps on ACAM subsidy levels were in effect] by the end of the support term, and provide broadband upon reasonable request to the remainder." https://www.usac.org/hc/funds/acam.aspx . See also Gaither, 2018, p. 8.

[52] See FCC, Federal-State Joint Board on Universal Service, *Universal Service Monitoring Report 2018*, (Washington: FCC), 2018, Table 3.2.