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ORIGINAL ARTICLE

Factors influencing the temporal diffusion of broadband adoption: evidence from Oklahoma

Brian E. Whitacre

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Abstract This paper examines the shifting influence of household characteristics and telecommunications infrastructure on the residential broadband adoption decision for Oklahoma residents between 2003 and 2006. In particular, the spread of wired telecommunications infrastructure (namely cable Internet and Digital Subscriber Lines (DSL)) is examined, along with the effect that this diffusion has had on broadband access rates. The data indicates that the gap in broadband access rates between rural and urban areas has remained relatively constant over this period despite increased levels of cable and DSL throughout the state. In addition, an inter-temporal decomposition shows that the increasing levels of infrastructure are *not* the dominant cause of higher broadband rates over time. Instead, shifting returns to specific characteristics (namely income) are found to be the primary contributors.

JEL Classification R11 · O18 · C1

1 Introduction

Internet access has had an undeniable impact on today's society. The ability to connect instantaneously to vast amounts of information has changed the way most individuals and businesses interact with one another. Enhanced opportunities for communication, commerce, entertainment, income, and education are all components of this "information revolution." One sign of the growing importance of these opportunities is the

B. E. Whitacre (✉)
Department of Agricultural Economics, 504 Ag Hall, Oklahoma State University,
Stillwater, OK 74078, USA
e-mail: brian.whitacre@okstate.edu

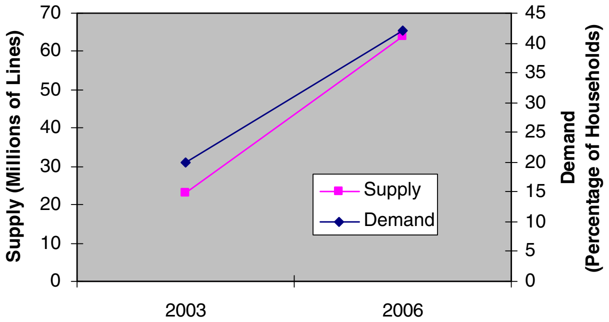

Fig. 1 US broadband demand and supply, 2003 and 2006. *Sources*: Horrigan (2003, 2006); FCC (2003, 2006)

nation's shift towards high-speed, or broadband, connections.[1] The demand for, and supply of, broadband access has been increasing dramatically. In the period between 2003 and 2006, rates of residential broadband access increased from 20% to 42% throughout the USA (Horrigan 2006). Over this same period, the number of broadband lines supplied by various providers increased from 23 million to 64 million (Fig. 1). Despite this jump, broadband infrastructure and access rates diffused unevenly across the nation. Some areas had multiple providers while others had none. Even when broadband infrastructure was available, different segments of the population showed very different adoption rates. In particular, several studies have noted "digital divides" between various groups including rural and urban residents, higher- and lower-income households, and specific racial or ethnic groups such as Hispanics or African-Americans and Caucasians (GAO 2006; Whitacre and Mills 2007; Horrigan 2005b, 2007a). Given the increasing rates of access over time, an interesting yet currently unanswered empirical question is, What is the underlying cause of this diffusion? If the increase stems from higher levels of infrastructure developing across the nation, policies to further expand such infrastructure may find additional public support. Alternatively, shifting returns to household characteristics such as education, income, or rural status through the normal process of innovation diffusion may be the dominant source of the increase. If this premise is correct, policies to increase future rates of access may focus less on promoting infrastructure, and instead, center on educating individuals with low propensities for adoption about the benefits of broadband access. Although the United States has taken a largely "hands-off," market-driven approach for providing broadband infrastructure, some state-level policies have influenced its availability. Evaluating how this infrastructure is diffusing and to what extent its dispersion impacts access rates can have important implications for future policy measures.

The purpose of this paper, in light of the current environment for broadband access, is threefold. First, the paper recalls elements of diffusion and adoption theory, and addresses how they relate to the spread of broadband access over time. Second, the

[1] High-speed connections are defined by the Federal Communications Commission as over 200 kilobytes (Kbps) of data throughput per second in at least one direction. This is roughly four times faster than a typical dial-up modem.

paper describes data and methodology for examining the spread of wired telecommunications infrastructure at a state level (using Oklahoma as an example), looking particularly at discrepancies between rural and urban areas by technology type. Third, logistic regressions over two time periods and resulting inter-temporal decompositions uncover the roles of shifting characteristics over time (such as infrastructure) and shifting parameters over time (such as the impact of education) on the broadband access decision. The paper concludes with a discussion of the model results and policy implications.

2 A brief discussion of diffusion and adoption

As broadband access becomes increasingly commonplace, it is worthwhile to examine the theories of diffusion and adoption in relation to the access decision. In general, diffusion theory focuses on how the flow of information and individual adoption decisions over time impact the broader social network, while adoption theory isolates factors that influence the household decision making process. Several recent studies have incorporated these concepts when analyzing broadband adoption and are included in a brief literature review.

2.1 Diffusion theory

Diffusion theory dates back to the early 1900s, when the notion of an S-shaped adoption curve derived by Tarde (1903) implied that individuals learned about an innovation by copying someone else's behavior (Fig. 2). The seminal work on diffusion theory came in 1960, when sociologist Everett Rogers synthesized the most significant findings and compelling arguments in the field. The most recent edition of Roger's *Diffusion of Innovations* (2003) defines diffusion as the interaction of four primary elements: (1) an innovation, (2) communication channels, (3) time, and (4) a social system. In reference to the innovation of broadband access, the remaining three elements are fairly easy to recognize. Communication channels may consist of anything from small-scale conversations with friends (where many of us first heard about the Internet or high-speed

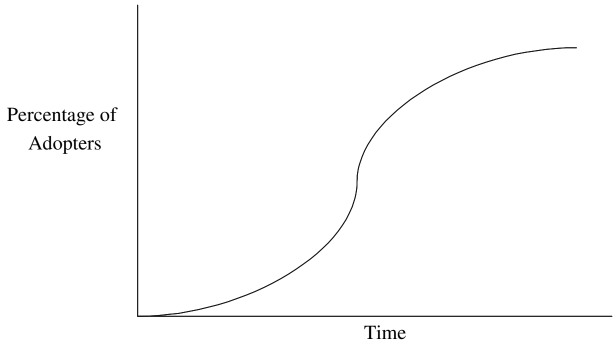

Fig. 2 S-shaped curve representing the rate of adoption over time

access) to large scale media campaigns in newspapers, television, or radio (which constantly reference web addresses or advertisements for broadband providers). Temporal resistance is well documented in terms of broadband access, with broadband infrastructure appearing earlier in urban areas due to higher population densities and income levels (Strover 2003). This temporal resistance is also caused by technology adoption propensities that vary by person (as noted in the following section on adoption theory). The social system, the last element discussed by Rogers, can be defined as all households in an area (whether at a local, state, or national level) since the residential adoption decision is ultimately made at the household level. Therefore, in general broadband access fits neatly into the diffusion framework, with relatively well-defined elements. Horrigan (2005a) acknowledges the four elements related to broadband technology. Coupled with national-level survey data over a 4-year period, he estimates a model where the impact of online experience (in years) initially helps to explain broadband adoption but then this impact disappears over time. This result is an example of how factors affecting the adoption decision can vary over time. Horrigan's effort is similar to the model employed in this paper in that it does not attempt to estimate the logistic form displayed in Fig. 2. Instead, point estimates over time show how various determinants of adoption have changed. The data included in this paper, however, allows the role of shifting levels of infrastructure to be identified, a factor omitted by Horrigan.

2.2 Adoption theory

While diffusion theory focuses primarily on the temporal aspect of the innovation's dispersion and how the social system responds, adoption theory determines whether or not each household decides to implement the innovation. Adoption theory emphasizes the role of individual characteristics in determining whether or not adoption occurs on a case-by-case basis. The primary difference between diffusion theory and adoption theory is that diffusion occurs among units of a social system, while adoption takes place in the mind of an individual (Rogers and Shoemaker 1971). Rogers (2003) hypothesizes that potential adopters are normally distributed according to their innovativeness, and that five separate categories of potential adopters exist. These categories are depicted in Table 1 along with some associated characteristics. They range from innovators, the first to adopt, to laggards, who are set in their ways and suspicious of change. By influencing the time frame within which individuals choose to adopt, these categories play a role in the diffusion process. As this table indicates, the adoption decision is affected by the characteristics of the household. For instance, individuals with higher income and education levels are more likely to be early adopters. This fact is particularly true for broadband access, since its technological nature may be seen as an obstacle for households unfamiliar with its benefits. Numerous studies have looked at what individual characteristics impact the Internet adoption decision, with dominant results including income and education levels (Cooper and Kimmelman 1999; Mills and Whitacre 2003), age (Rose 2003), racial and ethnic characteristics (Horrigan 2005a, 2006), and rural versus urban status (Strover 2001; Whitacre and Mills 2007).

Table 1 Technology adoption categories and typical characteristics

Adopter categories	Typical characteristics
Innovators	Eager to try new ideas. More years of formal education, higher income. Higher social status. Risk takers
Early adopters	Role models for other members of social system. Upward social mobility, able to lead opinions
Early majority	Interact frequently with peers. Deliberate before adopting new ideas
Late majority	Respond to pressure from peers. Approach innovation with caution, unwillingness to risk scarce resources
Laggards	Resistant to innovation. Suspicious of change, hold on to traditional values. Isolated

Source: Rogers (2003)

Estimating the shifting returns to these variables as broadband adoption increases is one contribution of this paper.

Given a theoretical structure for understanding the diffusion of broadband access, the next section focuses on specific infrastructure and household-level data used in the study. This data is then used to develop a methodology to uncover the relative roles of shifts in characteristics and returns to those characteristics as broadband access diffuses over time.

3 Data and descriptive statistics

The state of Oklahoma's experience with broadband growth (both supply and demand) is analogous to that of the nation. Between 2003 and 2006, the number of residential broadband lines more than doubled (from 220,000 to 519,000); while the percentage of households with broadband access increased from 21% to 42%. Household-level surveys regarding broadband use, coupled with detailed information about the status of "wired" telecommunications infrastructure for these 2 years provide a unique opportunity to explore the diffusion of such infrastructure and whether it has led to increased access rates.

Broadband service to the citizens of Oklahoma is much like the rest of the nation in that it is dominated by two sources: cable Internet (provided by the cable TV company) and Digital Subscriber Lines (DSL) (provided by the phone company). In fact, in both 2003 and 2006, these two sources composed over 95 percent of the nation's residential and small business lines (Fig. 3). Data on the availability of these sources are taken from Warren Publishing's *Television and Cable Factbook*, which lists information on every cable system in the USA (including the availability of broadband Internet access), and the National Exchange Carrier Association (NECA) Tariff#4 dataset,

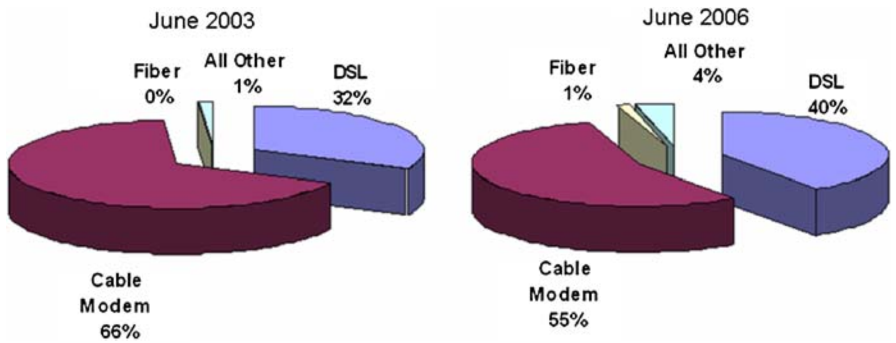

Fig. 3 Residential high speed lines by technology, June 2003 and June 2006. *Source*: FCC Industry Analysis and Technology Division, 2003, 2006

which provides similar information on every telephone office. This data represents the most comprehensive source of information on the presence of wired telecommunications infrastructure in each year although other, more well-known data sources also exist. The Federal Communications Commission collects data on broadband availability every six months through Form 477, but this data has several known drawbacks. This form requires all high-speed providers with more than 250 subscribers to file information regarding the number of lines serviced and the ZIP codes where service is provided.[2] The FCC then reports all ZIP codes being served, along with the number of providers servicing each ZIP code. Thus, a ZIP code is depicted as being served if a single subscriber exists within its boundaries. Furthermore, Form 477 does not differentiate between various types of high-speed service (such as cable Internet, DSL, wireless, and satellite) and may therefore give the impression that wired infrastructure exists when in fact it does not. These drawbacks were noted by the Government Accountability Organization, who indicated that the FCC data "may not provide a highly accurate depiction of local deployment of broadband infrastructures for residential service, especially in rural areas." (GAO 2006, p. 2). In fact, of the 589 ZIP codes included in the FCC's map of Oklahoma, Form 477 indicated that 533 had subscribers in 2003. This is dramatically higher than the 185 ZIP codes with wired infrastructure (cable Internet and DSL) as indicated by listings from the *Television and Cable Factbook* and Tariff#4 data. Given the dominance of these lines for residential access, assessing their availability and level of use throughout the state is important in understanding what factors are driving increased access rates over time.

In 2003, 320 cable systems were serving at least some portion of Oklahoma, and approximately 640 telephone central offices existed throughout the state. However, only a small fraction of these cable companies and phone offices offered broadband service to their customers (8% and 10%, respectively). Cable and phone companies must make significant financial investments to be able to provide broadband service. Cable companies must install routers, switches, and cable modem termination sys-

[2] Therefore, the presence of infrastructure by a company with less than 250 subscribers would not show up on Form 477 data in 2003. This provision was changed for all data collected after June 2005, with all companies (including those with less than 250 subscribers) required to report.

Table 2 Oklahoma cable systems and central offices with broadband capability, 2003 and 2006

	Cable systems	Central offices
	Total number of systems	
2003	320	640
2006	299	693
	Number with broadband capability	
2003	27	62
2006	55	142
	Percentage with broadband capability	
2003	8.4%	9.7%
2006	18.4%	20.5%

Source: NECA Tariff# 4 Data; *Television and Cable Factbook* (2003, 2006)

tems to allow transmission in two directions. In many cases, the fiber cable itself must be re-laid. This process is not cheap, with over $65 billion spent by cable companies between 1996 and 2002 (NCTA 2004). Phone companies must also provide equipment to enable DSL capability on traditional copper lines, but face an additional distance restriction. If a phone line extends beyond 18,000 feet (roughly three miles) from the central office, the line loses DSL capability. While some DSL-extending technology continues to be developed, significant limitations still exist for rural companies seeking to provide broadband service to their customers. In 2006, NECA estimated the cost of upgrading 5.9 million rural telephone lines to provide DSL capability at $11.9 billion (NECA 2006). Despite these costs, many cable and phone companies in Oklahoma chose to invest in broadband capability during the period between 2003 and 2006. This investment was partly driven by the state legislature passing House Bill 2796 in 2002, which was a "broadband parity" bill that eased the regulatory environment for high-speed networks. Such deregulation included ending the requirement for telephone incumbents to share or "unbundle" their lines. This bill was widely credited for the rapid deployment of DSL across the state (Carter 2003; Armstrong 2005). By 2006, the percentage of both telephone and cable companies offering broadband service to their customers had doubled (Table 2). Interestingly, this Oklahoma data runs counter to the predictions of several studies on broadband legislation which suggested deregulation would not result in increased levels of infrastructure (Grubesic 2003; Hall and Lehr 2002).

Tariff#4 and the *Television and Cable Factbook* data (typically listed by city) were mapped to ZIP codes using ZIP code database finder software that resulted in state-level maps that showed the availability of such infrastructure in both 2003 and 2006 (Fig. 4).[3] These maps indicate that while the dominant urban centers such as Oklahoma City and Tulsa have relatively high levels of broadband infrastructure, various types of infrastructure are spread throughout the state. Furthermore, access to broadband infrastructure undoubtedly increased between 2003 and 2006. In fact, the percentage

[3] This mapping implicitly assumes that all residents of a city's ZIP code(s) will have the same level of access as the city itself. While this is not necessarily true (recall in particular the three-mile limitation for DSL service), it is a product of the dataset. The limitations of this assumption are discussed in the conclusion.

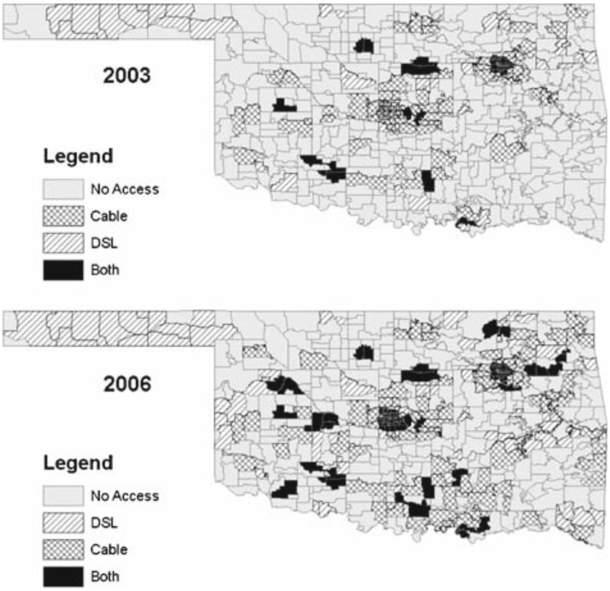

Fig. 4 DSL and cable Internet availability in Oklahoma, 2003 and 2006. *Sources:* Television and Cable Factbook; NECA Tariff#4 Dataset (2003, 2006); Dynamap Mapping Software

of ZIP codes with some type of wired access increased from 31% to 47% over this period.

Data on residential broadband access rates in Oklahoma comes from telephone surveys of approximately 1,200 random households conducted by Oklahoma State University in late 2003 and in 2006. The same households were not interviewed across years, but the lack of a panel dataset does not hinder any inter-temporal analysis as the surveys are representative of the state when sample weights are applied. After removing observations with missing or inconsistent data, 928 and 959 observations are available for 2003 and 2006, respectively. Descriptive characteristics from these surveys on adoption rates and household characteristics previously found to impact those rates (education, income, age, race, and location) are displayed in Table 3.[4] Several patterns are noticeable. First, while rates of general Internet access increased only slowly (from 53% to 63%), the rates of broadband Internet access increased much more rapidly (from 21% to 42%), which indicates a change from dial-up to broadband access for numerous households. This change is consistent with national trends. Horrigan (2005a) documents a dramatic increase of experienced dial-up users who switched to broadband over this period. In terms of education and income levels, this three-year period appears to have been fairly productive for Oklahoma residents. Between 2003 and 2006, the percentage of household heads without high school diplomas fell by four percentage points, while the percentage rose for heads with either

[4] Since ZIP codes are the geographic unit of analysis, rurality is measured via Rural/Urban Commuting Area (RUCA) codes as defined by the USDA/ERS. Codes 1 through 3 are for metropolitan areas and are therefore classified as urban; codes 4–10 are for micropolitan or rural towns and are classified as rural.

Table 3 Household characteristics—2003 and 2006

Characteristic	Variable name	2003	2006
Home Internet access			
Anytype	netaccess	0.53	0.63
Broadband	highspeed	0.21	0.42
Education			
No high school		0.20	0.16
High school diploma	hs	0.31	0.31
Some college	scoll	0.29	0.31
Bachelor's degree	coll	0.14	0.14
Higher than bachelors	collplus	0.06	0.07
Income			
Under $10K		0.14	0.10
$10K–$20K	hhinc2	0.16	0.16
$20K–$30K	hhinc3	0.20	0.16
$30K–$40K	hhinc4	0.12	0.15
$40K–$50K	hhinc5	0.10	0.10
$50K–$60K	hhinc6	0.08	0.06
$60K–$75K	hhinc7	0.08	0.07
$75K–$100K	hhinc8	0.08	0.09
$100K +	hhinc9	0.06	0.10
Other HH characteristics			
Age of head	age	40.81	42.73
Married	married	0.51	0.51
Number of children	numberkids	0.95	0.89
Hispanic	hisp	0.06	0.08
African-American	black	0.09	0.05
Native American	indian	0.08	0.10
Other race	othrace	0.09	0.12
Rural	rural	0.42	0.43
Telecommunications infrastructure			
Both cable and DSL	both	0.15	0.34
Cable Internet only	cable	0.49	0.33
DSL Only	DSL	0.04	0.05
Either cable or DSL	some	0.68	0.73
Number of observations		928	959

Characteristics without names represent the base category for that group

some college (2 points) or more than a bachelor's degree (1 point). The percentage of households making less than $10,000 per year fell from 14% to 10% over this period, while the percentage making more than $100,000 rose from 6% to 10%. This dramatic increase in income levels is supported by other economic data from the state, which enjoyed a large boom over this period thanks to the oil industry (Page 2006;

Table 4 Percentage of rural / urban residents with infrastructure availability and Internet access (2003 and 2006)

	Rural		Urban	
	2003	2006	2003	2006
Infrastructure				
Both	0.08	0.14	0.20	0.49
Cable only	0.31	0.31	0.61	0.35
DSL only	0.09	0.08	0.01	0.03
Some	0.48	0.53	0.82	0.87
Access rates				
Any	0.47	0.59	0.57	0.65
Broadband	0.14	0.34	0.26	0.48

Associated Press 2007). Other household characteristics, including age and household composition characteristics such as the percentage of married household heads, the percentage of male household heads, and the number of children, have remained relatively consistent over the three years. The state did become slightly more diverse over this period, with more Hispanics, Native Americans, and individuals of other racial categories. Rural residents comprise approximately 42% to 43% of the state, which is comparable to the rates documented in the 2000 Census.[5] Cross-referencing the ZIP code of the respondents to the ZIP code mapping of cable Internet and DSL availability provides a quick look at the infrastructure situation across the state. The proportion of residents with access to both cable and DSL infrastructure increased from 15% in 2003 to 34% in 2006, which supports the information depicted geographically in Fig. 4. The extent to which these changing characteristics impact the broadband adoption decision is examined later in the paper.

One area that typically receives a lot of attention in most broadband debates is the supply side of the rural – urban digital divide. As Table 4 shows, only 8% of rural residents had both cable Internet and DSL access available to them in 2003. This number rose to 14% by 2006. In contrast, the percentage of urban residents with both types of access available rose from 20% in 2003 to 49% in 2006. Rural areas with only one type of wired access available stayed about the same over this period, but increases in areas with both types indicate that cable and DSL grew at similar rates over this period. In urban areas, however, the percentage of urban residents with only cable access dropped dramatically, which indicates that as DSL availability rose, most urban residents had access to both types of infrastructure.

Looking at this issue from another perspective, only 53% of rural residents had some type of wired broadband access available to them in 2006, compared with 87% of urban residents. Thus, a supply gap certainly exists for rural Oklahoma residents regarding

[5] While this study uses RUCA codes to measure rurality at the ZIP code level, the Census bureau uses definitions at the census tract level from the Office of Management and Budget (OMB), which is likely the source of any discrepancy.

wired telecommunications infrastructure. Urban dominance of broadband infrastructure has also been noted in other state-level studies, namely Ohio and Pennsylvania (Grubesic 2003; Glasmeier and Wood 2003). On the demand side, the rural/urban gap in broadband access rates in Oklahoma actually increased over this period, from 12 percentage points in 2003 to 14 in 2006. The impact of infrastructure and rural status on the adoption decision is modeled in the following section.

4 Methodology

The statistical model for estimating the impact of household characteristics and wired telecommunications infrastructure on the broadband adoption decision at time t is specified as

$$\begin{aligned} y_i^* &= X_i\beta + Z_i\delta + O_i\gamma + I_i\tau + R_i\pi + \varepsilon_i \\ y_i &= 1 \quad \text{if } y_i^* \geqslant 0 \\ y_i &= 0 \quad \text{if } y_i^* < 0 \end{aligned} \tag{1}$$

where y_i^* is an unobservable measure of the relative costs and benefits from broadband Internet access for household i, y_i is the actual observation of household broadband Internet access, X_i is a vector of household income levels, Z_i is a vector of household education levels, O_i is a vector of other household characteristics, I_i is a vector of various types of infrastructure availability (including access to cable Internet, DSL, and both), R_i is a vector of rural/urban status; $\beta, \delta, \gamma, \tau$, and π are the respective associated parameter vectors; and ε_i is the statistical model's error term. The binary nature of the adoption decision suggests that a logit model should be used.[6]

The expected signs of most variables are taken from previous studies. These include education and income, where higher levels of both are expected to increase the probability of adoption (NTIA 2002); age, which is expected to have a quadratic effect (Rose 2003; Whitacre and Mills 2007); and Hispanic and African-American status, which are anticipated to decrease the likelihood of access given their lower adoption rates (Horrigan 2007a). Married household heads have been shown to increase the propensity for adoption, possibly due to the presence of two disposable incomes, while popular online tasks such as gaming and music downloading are expected to result in a positive coefficient for the presence of children (Mills and Whitacre 2003; Horrigan 2006). Furthermore, the availability of cable and DSL infrastructure are expected to positively impact adoption propensities, given their necessity for most residential broadband connections. Whether or not the presence of *both* cable and DSL will additionally impact the adoption decision is left as an empirical question. Competition may lead to lower prices and more advertising about infrastructure availability; however, availability of a single source may suffice for adoption needs. Some evidence

[6] Other binomial variable statistical models, such as the linear probability model or the probit, could also be employed. However, the linear probability model has the undesirable property of restricting outcomes to the [0,1] interval; while the probit model does not provide a closed form solution (Prentice 1976).

suggests that intermodal competition does play a role in increasing access rates (Aron and Burnstein 2003; Denni and Gruber 2005). Finally, given the higher access rates found in metropolitan or urban areas, the sign associated with the rural variable is expected to be negative.

One variable notably absent from Eq. (1) is the cost of a residential broadband connection. This is primarily due to a lack of data, as no question regarding cost was asked in the 2003 survey; however, data from the 2006 survey suggests that costs were relatively similar for residents across the state (more than 60% had a monthly cost of between \$35 and 40).[7] This lack of variation among broadband subscribers, coupled with nonexistent data and the recent finding that own-price demand is relatively inelastic for broadband service (Flamm and Chaudhuri 2007) suggest that omitting this variable is not a major concern.

4.1 Decomposition of the logit model

To determine which factors are the most influential to the temporal resistance to adoption, a non-linear version of the Oaxaca–Blinder technique is applied to the above model (Oaxaca 1973; Blinder 1973). Written in a linear manner, this technique focuses on how differences in characteristics and differences in parameters over time contribute to the changing adoption rates:

$$\bar{Y}_t - \bar{Y}_{t-1} = \left(\bar{X}_t - \bar{X}_{t-1}\right)\hat{\beta}_t + \bar{X}_{t-1}\left(\hat{\beta}_t - \hat{\beta}_{t-1}\right) \tag{2}$$

where $\bar{Y}_t$ is the average rate of broadband access, $\bar{X}_t$ is a row vector of average values of independent variables such as education, income, or infrastructure, and $\hat{\beta}_t$ is a vector of coefficient estimates for time t. While most analysis of inter-temporal decomposition has focused on such linear functional forms (Le and Miller 2004), the logistic form of the specification in this paper requires a different technique. Following Fairlie (2003), a temporal decomposition for a non-linear equation such as $Y = F\left(X\hat{\beta}\right)$ can be written as

$$\bar{Y}_t - \bar{Y}_{t-1} = \left[\sum_{i=1}^{N_t} \frac{F\left(X_{it}\hat{\beta}_t\right)}{N_t} - \sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it-1}\hat{\beta}_t\right)}{N_{t-1}}\right] + \left[\sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it-1}\hat{\beta}_t\right)}{N_{t-1}} - \sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it-1}\hat{\beta}_{t-1}\right)}{N_{t-1}}\right] \tag{3}$$

[7] The fact that including cost in the empirical model would require price information from all respondents, including those without a broadband connection, should also be noted. Such data is not readily available, even in the 2006 survey.

or equivalently as

$$\bar{Y}_t - \bar{Y}_{t-1} = \left[\sum_{i=1}^{N_t} \frac{F\left(X_{it}\hat{\beta}_{t-1}\right)}{N_t} - \sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it-1}\hat{\beta}_{t-1}\right)}{N_{t-1}} \right] + \left[\sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it}\hat{\beta}_{t}\right)}{N_t} - \sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it}\hat{\beta}_{t-1}\right)}{N_t} \right] \tag{4}$$

where N_t is the sample size for time period t.

Written this way, changing rates over time are affected by shifts in *characteristics* (the first bracketed term in Eqs. (3) and (4)) and shifts in *parameters* (the second bracketed term). The use of different base parameters in the two equations is the origin of the "index problem" typically encountered in Oaxaca-Blinder decompositions, and can cause dramatically different results. In best case scenarios, similar results are obtained from both equations.

As shown above, the decompositions hinge on the construction of a synthetic access rate: $\sum_{i=1}^{N_{t-1}} \frac{F\left(X_{it-1}\hat{\beta}_t\right)}{N_{t-1}}$ in Eq. (3), and $\sum_{i=1}^{N_t} \frac{F\left(X_{it}\hat{\beta}_{t-1}\right)}{N_t}$ in Eq. (4). Estimation of this synthetic rate allows for the inter-temporal difference to be broken into contributions from characteristic shifts (education, income, and infrastructure) and contributions from changing *returns* to those characteristics.

5 Results

While the data section identified several factors that might impact the broadband access decision over time, the above methodology provides a way to model this relationship at a distinct point in time. It also suggests a method to determine the most important contributors to the observed increase in broadband access rates. This section discusses the results of the general logit model as well as the temporal decomposition in light of expected contributions.

5.1 General logit model results

Parameter estimates for the household broadband adoption decision for 2003 are displayed in Table 5. A separate column for 2006 shows how these parameters "shift" in this year compared to 2003. This allows for observation of whether or not the shifts in parameter estimates over time have been significant in explaining broadband access. In general, the 2003 parameters display the expected signs, most notably the significant and positive impacts of education and income on the adoption decision. For education, with one minor exception (since parameters for some college and college are very similar), the parameters increase as the level increases, which means that

Table 5 Logit results for broadband access

Dependent variable: highspeed

	2003 shift		2006 shift	
	Coefficient	S.E.	Coefficient	S.E.
hs	0.624	0.498	0.623	0.753
scoll	1.062	0.481**	1.078	0.726
coll	0.972	0.488**	1.223	0.742*
grad	1.314	0.513**	0.949	0.772
hhinc2	0.924	0.675	−0.840	0.831
hhinc3	1.679	0.647***	−0.926	0.802
hhinc4	2.065	0.661***	−1.218	0.811
hhinc5	2.812	0.682***	−2.043	0.844**
hhinc6	2.443	0.684***	−1.653	0.872*
hhinc7	3.415	0.709***	−2.573	0.875***
hhinc8	3.497	0.680***	−2.487	0.852***
hhinc9	3.579	0.748***	−1.241	0.920
age	−0.076	0.036**	0.036	0.050
age2	0.000	0.000	0.000	0.001
married	−0.286	0.225	0.813	0.316**
numberkids	−0.108	0.104	0.108	0.140
retired	0.206	0.357	−0.592	0.524
hispanic	−0.855	0.595	−0.142	0.815
black	0.782	0.425*	−1.350	0.607**
indian	−0.419	0.380	−0.079	0.512
othrace	−0.255	0.536	−0.113	0.743
cable	0.652	0.254**	0.017	0.378
dsl	0.296	0.547	−0.203	0.684
both	−0.107	0.627	−0.134	0.441
rural	−0.078	0.220	−0.288	0.304
constant	−1.323	0.909	−0.364	1.405

*, **, and *** indicate statistically significant differences from zero at the $p = 0.10$, 0.05, and 0.01 levels, respectively. 2006 coefficients represent shifts from 2003 coefficients

the relative odds of broadband adoption increase with higher levels of education.[8] This result holds unequivocally for income levels, with even low levels being highly significant in increasing the probability of access relative to households with income levels under $10,000 per year. The 2006 shifts to these parameters are intriguing. Several highly significant negative income shifts occur, which implies that income has become less of a factor in the adoption decision over time. However, all of the education shifts are positive, and one (college) is even significant, implying that this

[8] Recall that the odds in this case are relative to the “default” household with no high school degree.

level of education is now more important than it was in 2003. This result is somewhat unexpected since adoption and diffusion theory predicts that levels of income and education will become less important over time, but in this study, only income seems to be following this pattern.

The majority of other household characteristics lack significance. Even age, which is negatively associated with access in 2003 (implying that older household heads reduce the probability of broadband), lacks a significant quadratic term. This fact indicates that age and access are simply linearly related. However, the age term does not have a significant shift for 2006, meaning that older household heads are no more likely to adopt in 2006 than they were in 2003. The marriage parameter, insignificant in 2003, has a very significant positive shift in 2006, which suggests that households with married heads have become more likely to have broadband access. Interestingly, the number of children in a household is not significant in either year. This result is somewhat unexpected given the necessity of broadband for many of the popular online trends associated with this group, such as gaming, music and video downloading, and school research. However, the lack of significance for children may be related to the age and marriage variables that have already been accounted for. Since young households (with potentially school-aged children) and married households (probably with children) are more likely to have access in 2006, the presence of children may not additionally impact the broadband adoption decision.

In terms of racial and ethnic characteristics, the parameter associated with African American household heads has an unexpected positive sign in 2003, indicating a higher propensity for adoption among this racial group. While African American households have been exhibiting strong growth in broadband adoption over this period (Horrigan 2006, 2007a), this result suggests the opposite of the documented "digital divide" between African American and white households. This impact disappears in 2006, with the parameter value for African Americans displaying a statistically significant negative shift, which is more consistent with the digital divide literature. In terms of infrastructure, the only variable with a statistically significant impact is cable Internet availability, which is positive in 2003. Thus, the availability of cable Internet, and not DSL, has a positive impact on the probability of broadband adoption. While the dominance of cable access over DSL in terms of residential access (Fig. 3) lends some credence to this result, the lack of significance for DSL is somewhat surprising given that the two are commonly seen as substitutes for each other. Furthermore, the presence of both cable and DSL is not significant, indicating that adoption is not notably higher in areas with both types of infrastructure. This result is contradictory to the work of both Aron and Burnstein (2003) and Denni and Gruber (2005), both of whom found competition to be beneficial in terms of broadband diffusion. However, the data in this paper is limited to a single state and is at a smaller scale (ZIP code versus state), suggesting that variation at this lower level may alter this finding.

The rural dummy variable, although negative, is not significant for either 2003 or its 2006 shift. Therefore, after accounting for levels of education, income, other household characteristics, and infrastructure, households in rural areas are no less likely to adopt broadband than their urban counterparts. This finding suggests that the sizeable rural/urban gap in broadband access rates within the state (approximately 14 percentage points in both years) can be explained primarily by the differences in these

Table 6 Inter-temporal logit decomposition results

	Equation	
	(3)	(4)
2003 residential broadband rate	0.2094	0.2094
2006 residential broadband rate	0.4226	0.4226
2003–2006 gap	0.2132	0.2132
Synthetic residential broadband rate	0.3608	0.3864
Contributions from characteristic shifts	0.0618	0.0362
	29%	17%
Contributions from parameter shifts	0.1514	0.1770
	71%	83%

variables. The extent to which variable shifts explain the inter-temporal differences is examined in the following section.

5.2 Decomposition results

Table 6 presents the results of the inter-temporal decomposition for broadband access rates. The first two rows indicate that the percentage of Oklahoma households with broadband access doubled from approximately 21% in 2003 to 42% in 2006. In Eq. (3), which uses parameters from 2006 as the base, changing characteristics (including higher levels of infrastructure) account for 29% of the higher rates observed over the 3-year period. Shifting parameters account for the remainder of the gap (71%). Under Eq. (4), which uses 2003 parameters; changing characteristics account for even less of the inter-temporal gap—making up only 17% of the observed difference. Thus, the results are similar regardless of the choice of base year, with shifting parameters accounting for between 71% and 83% of the gap. This fact suggests that while levels of DSL and cable infrastructure have seen rapid growth over this period, these increased levels are not the primary contributors to higher residential broadband access rates. Instead, changing returns to those characteristics (particularly shifts to income levels) seem to be primarily responsible for the higher rates.

6 Conclusion

As rates of broadband access continue to rise across the nation, understanding the principal causes of such diffusion is an important yet under-analyzed topic. Most research points out increasing levels of access for specific demographic groups, or looks at determinants of broadband infrastructure, without combining the two and examining the adoption decision over time. This paper has attempted to put telecommunications infrastructure into the overall context of broadband diffusion by examining a case study at the state level. The data suggests that increases in infrastructure are relegated to minor contributors in determining why access rates are higher as time moves forward. This result, while consistent with diffusion theory and perhaps not surprising, is empirical evidence that shifting returns to household characteristics are the primary reason for increasing broadband access rates. In particular, decreasing returns to income levels implies that broadband access is rapidly diffusing to households with lower earning power. This result is supported by descriptive statistics from the state-level surveys, as broadband access rates for households earning less than $30,000 per year increased from 18% in 2003 to 26% in 2006. The statistics do not suggest that the same is happening with education levels. For instance, household heads with a high school education or less had broadband access rates of 23% in 2003 and 24% in 2006.

Such findings suggest that for the state of Oklahoma, efforts to increase future broadband adoption rates should focus on households that have displayed significant temporal resistance. The results from Sect. 5.1 indicate that households with lower education levels and older household heads, in particular, would benefit from programs that discuss the benefits of broadband access. Such programs have already been incorporated by the extension services of several universities, including Minnesota and Nebraska (Coleman 2004; Byers 2006). These recommendations are also very similar to those of Horrigan (2007b), who promotes state and local projects targeted at hard-to-reach populations.

Several limitations arise in the analysis that should be addressed. One is the assumption that all residents of a ZIP code with DSL or cable Internet have access to that infrastructure. As evidenced by DSL's geographic limitations and the fact that cable systems do not pass all households (particularly rural ones) in the ZIP codes they service, this assumption implies that more households are depicted as having infrastructure available to them than actually do. Another limitation is that this analysis looks solely at "wired" telecommunications infrastructure. Wireless broadband and satellite connections are becoming more popular around the nation as evidenced by the increase in responses for the "all other" category between 2003 and 2006 displayed in Fig. 3. Anecdotal evidence from several wireless Internet Service Providers (ISPs) suggest that they are serving rural areas out of reach of DSL and cable Internet service, and typically have between 200 and 1,000 subscribers from a given location. These combined factors somewhat offset each other by understating and overstating, respectively, the importance of wired infrastructure in this study.

Finally, although the results imply that infrastructure diffusion has only a small impact on the adoption process, these results are somewhat tempered by the time frame of the analysis and the overall diffusion framework. The period of analysis consists of only 3 years, not an exceedingly long time for privately-owned companies to invest in and complete infrastructure upgrades. Furthermore; the shifting returns to characteristics are *expected* as broadband adoption diffuses over time. Altering actual levels of those characteristics (infrastructure in particular), however, can have a significant impact on access rates. Worthy of note is the fact that the legislation enacted by the state legislature in 2002 was at least partially responsible for the doubling of broadband capability by DSL and cable providers, which in turn helped account for between 17% and 29% of the increase in broadband adoption rates between 2003 and 2006. Thus, policy measures that deal with infrastructure do not lack consequence; however, they should be combined with other educational policies for maximum impact.

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