Scale Economies In Cellular Telephony: Size Matters

R. Dean Foreman, Ph.D.[1]
Edward Beauvais, Ph.D.

ABSTRACT

Strategic positioning and potential cost savings are popular explanations for growing consolidation in the wireless telephone industry. This research estimates economies of scale for a large panel of GTE Wireless cellular market areas. Contrary to previous findings, our results indicate scale economies exist throughout the system and provide a rationale for the industry trend of consolidation.

Key words: Cellular, Wireless, Telecommunications, Scale Economies, Translog
JEL Classification: L96, Industry Studies--Telecommunications

[1] Email: Dean.Foreman@telops.gte.com, Economist, GTE Regulatory Planning & Policy; Email: Edward.Beauvais@telops.gte.com, Chief Economist, GTE Pricing. Mailing address: 600 Hidden Ridge, HQE01J22, Irving, TX 75063. We are grateful to Dennis Weller, Jeff Olson, Robert Brooks, and John Bareham.

I. Introduction

In many segments, competition among providers of Commercial Mobile Radio Service (CMRS) is growing more than it ever has before.[2] The rapid emergence of personal communications services (PCS), two-way paging, and other variants of two-way radio services has placed significant competitive pressure on cellular carriers. Most recently, consolidation among wireless telephone providers has accelerated. For example, pending mergers involve SBC with Ameritech, GTE with Bell Atlantic, and Airtouch with Vodaphone. Consolidation is not uncommon as industries mature, and the ability to offer customers larger, seamless wireless telephone coverage has emerged as a prime consideration. While competition focuses on the ability to market bundles of wireless services nationally and to deliver maximum customer value, the question of whether and to what extent scale economies accompany the growth and expansion of a cellular carrier's network footprint becomes important. At least one recent published study of scale economies has found that cellular telephony generally exhibits *dis*economies of scale and is a constant returns business at best.[3]

In contrast, we present strong new evidence that mild scale economies exist for cellular telephony. Constant returns to scale is rejected, and diseconomies are rejected emphatically so. The size and detail of our data rival those of any recent econometric analyses of scale economies in telecommunications, wireless or wireline. We focus on the cellular operations of one of the larger and geographically diverse providers -- GTE Wireless Incorporated. The data consist of a panel of monthly observations on over 100 cellular market areas for nearly three years. The scope and length of the company's operations allow for more robust empirical tests than have been conducted previously. We utilize a translog multi-output cost function to obtain estimates of input factor cost shares and scale economies. Our findings suggest that, in addition to strategic considerations, growth and consolidation yield some cost savings in cellular telephony.

[2] CMRS includes the entire range of wireless communications. See FCC (1998) for a status report on competition in the industry.
[3] McKenzie and Small (1997).

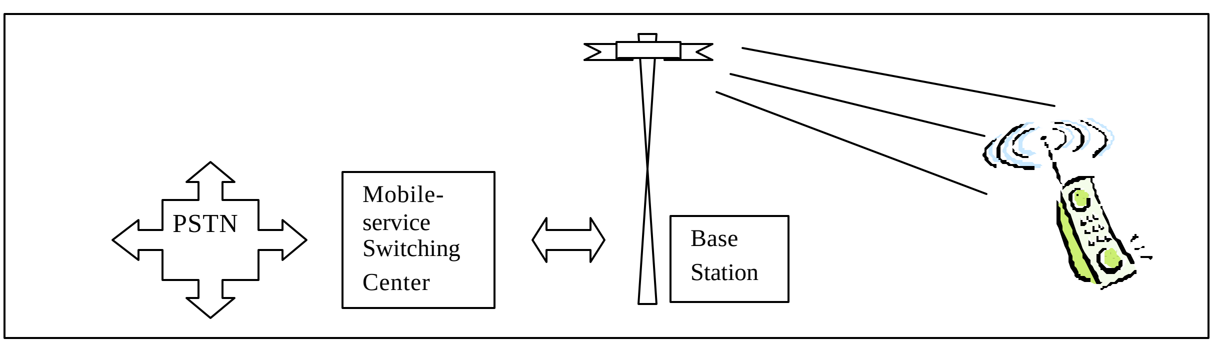
The paper is organized as follows. Section two provides background information that is necessary to understand the determination of costs in the industry. Section three introduces the cost model. Section four describes the data and variables, and section five presents and discusses the results.

II. Basic Background On The U.S. Cellular Industry And Network Technology

Mobile telephony represents the largest segment of CMRS. In 1997, mobile telephony in the United States represented about $27 billion in revenue, 55 million subscribers, and a national penetration rate of 20 percent. Compared to 1996 levels, subscribers increased 25.6% while revenues grew 16.5%.[4] Price competition, both direct and through service packaging, has reduced margins for the segment as evidenced by the disparity between the subscriber and revenue growth rates.

Amidst this remarkable segment growth lies a straightforward underlying concept: typical mobile devices communicate with a fixed radio tower (base station) which, in turn, connects with the public switched telephone network (PSTN) through a mobile-service switching center (MSC). A wireless carrier usually owns or leases connections between its cell sites and the MSC. Traffic is exchanged with the PSTN under terms and conditions of an interconnection agreement with a wireline local exchange carrier in the area. When a customer ventures from one cell into the range of another, a telephone call is transferred automatically to the appropriate serving cell. See figure 1 for a cellular system depiction.

Figure 1. A Basic Cellular System



[4] FCC (1998) at 14. Penetration rate cited relative to U.S. population.

A cellular system can employ many small radio coverage areas (cells) to serve hundreds of square miles.[5] Network planning for a cellular operation involves careful consideration of the number and type of cells as well as the distance between them. Whereas analog cellular technology currently serves only one subscriber at a time on a given radio channel, digital technologies--such as Code Division Multiple Access (CDMA) which is deployed ubiquitously by GTE and many other domestic cellular carriers--greatly expand capacity by enabling multiple users to share a radio channel. Whether analog or digital technology is deployed, capacity to serve additional subscribers eventually must be added as cellular systems mature. Capacity may be augmented by adding more radio channels in a cell or by constructing new cells. Two techniques for adding capacity are cell sectoring (using directional antennas so that only a portion of a cell area uses a single radio channel) and cell splitting (adjusting power levels and/or the antenna height to alter cell coverage areas). The rate at which a system is built-out and the most cost-effective technique for doing so depend on demand, existing capacity, and regional factors, such as terrain and governmental or regulatory hurdles to obtain appropriate zoning or rights-of-way.

Wireless telephony is a high-growth industry that necessitates substantial network investments. Once the physical components are installed, variable network costs are relatively constant and low up to capacity constraints, and the overall network cost structure depends on network planning and deployment. Capacity is a key driver. The heightening level of competition, however, also foreshadows that expenses for sales and marketing, customer retention, and customer care should be gaining in relative importance.

III. Cost Model

To determine the technological structure of traditional cellular telephony, we write the long-run multi-output cost function as

$$C = C(w, y, a, r, t),$$

[5] See Harte et. al. (1997) for a comprehensive source on cellular and PCS technologies.

where C represents long-run total costs, w is a vector of factor prices, y is a vector of outputs, a is a vector of operating characteristics, r is a vector of regional indicator variables, and t is a time trend. We assume that this cost function is twice-differentiable and can be approximated by a second-order Taylor series expansion.

As Shin and Ying (1992) note, many past telecommunications cost studies suffer from limited degrees of freedom and possible specification errors. In fact, the sole recent study of costs for wireless telephony, McKenzie and Small (1997), contains only 28 observations.[6] We attempt to circumvent such problems by estimating a cost function for a much larger quantity of wireless market areas and time periods. Our econometric cost model specification is similar to that in Shin and Ying (1992), which examines subadditivity among firms in wireline telecommunications. Although there are many alternatives for the functional form, we adopt the well-known translog flexible functional form.[7] It is written as

$$\ln C = a_0 + \Sigma_i a_i \ln w_i + \Sigma_k b_k \ln y_k + \Sigma_m s_m \ln a_m + \Sigma_z m_z r_z + f_t t + \tfrac{1}{2} \Sigma_{ij} a_{ij} \ln w_i \cdot \ln w_j$$

$$+ \tfrac{1}{2} \Sigma_{kl} b_{kl} \ln y_k \cdot \ln y_l + \tfrac{1}{2} \Sigma_{mn} s_{mn} \ln a_m \cdot \ln a_n + \tfrac{1}{2} f_t t^2 + \Sigma_{ik} t_{ij} \ln w_i \cdot \ln y_k$$

$$+ \Sigma_{im} t_{im} \ln w_i \cdot \ln a_m + \tfrac{1}{2} \Sigma_{km} t_{km} \ln y_k \cdot \ln a_m + \Sigma_{iz} \chi_{iz} \ln w_i \cdot r_z + \Sigma_{kz} g_{kz} \ln y_k \cdot r_z \qquad \textbf{(1)}$$

$$+ \Sigma_{mz} l_{mz} \ln a_m \cdot r_z + \Sigma_i f_{ti} t \cdot \ln w_i + \Sigma_k f_{tk} t \cdot \ln y_k + \Sigma_m f_{tm} t \cdot \ln a_m + e$$

where ε is a disturbance term that contains two components, a remainder term e and a random measurement error term d. All variables except t and the r_z are divided by their respective sample mean.

Assuming cost minimization, Shephard's lemma can be applied to obtain the cost share equations

$$s_i = a_0 + \Sigma_j a_{ij} \ln w_j + \Sigma_k t_{ik} \ln y_k + \Sigma_m t_{im} \ln a_m + \Sigma_z m_{iz} r_z + f_t t + e_i \,,$$

[6] McKenzie and Small (1997) employ a sample based on five firms over 11 quarters but with no one firm having more than seven quarterly observations.

[7] Pulley and Braunstein (1992) discuss myriad alternatives; they compare a composite cost function with standard and generalized translog specifications and with a separable, quadratic specification.

where ε_i is the disturbance term for the *i*th factor share equation. It has two components, a remainder term $e_i = \partial e / \partial w_i$ and white noise d_i. Symmetry and homogeneity of degree one in factor prices are imposed via parameter constraints. We jointly estimate the cost function and factor share equations by iterating Zellner's two-step procedure for estimating seemingly unrelated regressions. Since the factor shares sum to 1.0, one of the cost share equations is deleted to obtain a nonsingular covariance matrix. The parameter estimates that result are asymptotically equivalent to maximum likelihood estimates and thus are invariant to the equation deleted.

IV. Data And Variables

The data consist of a panel of monthly observations on GTE cellular market areas over nearly three years.[8] We observe 101 individual cellular market areas over 33 months, from January 1996 to September 1998, so there are 3333 total observations.[9] All non-indicator variables are scaled by their respective sample mean and expressed in logarithmic form.[10]

The dependent variable, total cost (*TC*), includes total capital/network costs, total sales and marketing costs, total operations support costs, total general and administrative costs, and the net interest expense on working capital. Since the costs are quite recent and span fewer than three years, each is expressed in nominal terms.[11] Also, to mitigate seasonal fluctuations, all costs are divided by the number of equivalent business days in the month of the observation.[12]

Two measures related to output are included. The primary output measure is the quantity of subscribers (*Subs*). Assessing the cost impact of additional subscribers, all else being equal, was the impetus for this research. When a new subscriber is added, typical costs include those to (1) run a credit

[8] The relatively few areas in which GTE provides PCS services are excluded from the data.

[9] Two of the 3333 observations are eliminated with the sale and transfer of GTE's Ashville, NC, wireless operations in August 1998.

[10] With the log-transform, the distribution of the dependent variable is approximately log-normal. Absent the transform, an assumption of normality would be inappropriate.

[11] A price index for telephone equipment, such as the proprietary C.A. Turner price index, could be employed. Beyond switching and electronics, however, its components are not applicable to wireless telephony.

check, (2) provide a cellular telephone to the customer at a "subsidized" price, and (3) compensate the agent in the marketing channel as applicable. Of course, subscribers also generate costs for airtime, customer care, and additional network investments (as capacity is approached).

The second measure of output is employed as a control variable: the quantity of airtime minutes per cell-channel (*MPC*), calculated as total airtime minutes divided by the product of the number of cell sites and channels in an area. *MPC* accounts for variation in airtime usage and available network capacity across areas and time. The construction of *MPC* as a ratio also usefully reduces collinearity that otherwise would exist among the levels of subscribers, airtime minutes, cell sites, and channels.[13]

The time trend (t) accounts primarily for changes in technology that are not captured by the other variables. In addition, an accurate comparison of different cellular markets requires we account for the length of time each market has been in service. The start-up dates of GTE's cellular markets span from May 1984 to May 1993.[14] We account for differences in market maturity by expressing the time trend for each market as the number of years that it has been in service and by including both linear and quadratic terms for time (t, t^2).[15]

For the inputs, we classify costs as belonging to one of three categories: capital/network costs, sales and marketing costs, and other costs. As in McKenzie and Small (1997), the traditional separation of labor as an input is not feasible in our data. Capital/network costs include all engineering, facilities expenses (i.e., maintenance, leasing, and repair), property taxes, and network depreciation. The price of capital (*PK*) is expressed as total capital/network costs divided by the number of cell sites in the market area. Sales and marketing costs reflect all advertising, marketing, customer acquisition, and customer

---

[12] With costs expressed per equivalent business day, estimation reveals that monthly indicator variables are superfluous.

[13] There is a 0.978 correlation between the levels of subscribers and minutes of airtime. While we have chosen a specification that represents subscribers, airtime, and the numbers of channels and cell sites. A Tornqvist index or other weighted output vector of subscribers and airtime is an alternative; see Chritensen et. al. (1982) and by Baumol et al. (1988). Our work with weighted output vectors reveals slightly greater scale economies as more weight is placed on the level of airtime. Our specification produces conservative estimates, and in no case do we find constant returns to scale.

[14] The start-up dates for cellular markets are published in the industry survey of Donaldson, Lufkin & Jenrette (1998).

retention activities, including any expense of "subsidizing" a cellular telephone purchased at the time a customer enrolls in a rate plan. Whereas capital costs tend to relate directly to the number of cell sites in an area, sales and marketing costs relate most directly to the number of subscribers. Accordingly, the price of sales and marketing (*PM*) is calculated as total sales and marketing costs divided by the number of subscribers. Other costs include operation support costs (i.e., expenses for customer care, fraud administration, and bad debt), general and administrative costs, and the net interest expense on working capital. Many of these expenses are tied directly to the number of subscribers to be served, so the price of other factors (*PO*) equals the sum of these costs divided by the number of subscribers.

Six variables are included to account for regional variation. First, we attempt to control for regional operation cost differences by including the monthly amount of property tax assessed on each cellular market area (*PropTax*). Since labor costs cannot be extricated from our data, *PropTax* serves as a proxy for the business climate in each specific cellular market area. Second, to capture any remaining regional variation or differences due to local area management and engineering, we include indicator variables for the regional entity of GTE Wireless to which a given market area belongs: California, Florida, Hawaii, MidSouth, MidWest, and Texas/New Mexico.[16] A complete list of the cellular market areas included by state is provided in Table A2 of the appendix.

V. Estimation Results

The estimation results for the translog cost function are presented in the appendix. The overall fit is excellent, and the point estimates are remarkably stable with respect to specification. Of the 70 parameters estimated, 51 are significant at the 1% level, six more are significant at the 5% level, and one is significant at the 10% level. The first-order terms for the independent variables all are significant at the

[15] Construction of t as years-in-service by market shifts the regression intercept when the linear term is included. Additional inclusion of the quadratic term allows for non-linear change of cost with respect to time by market.

[16] Technically, GTEW's San Diego property is managed separately from its other properties in California. Statistically, there was no substantive difference to treating San Diego differently, so San Diego is coded as if it were managed with the rest of California. For a nonsingular covariance matrix, the indicator variable for the MidSouth is dropped in the regressions in the appendix.

one percent level. The results strongly suggest that none of the variables employed in the cost function should be deleted. We discuss the estimated parameters and evaluate their plausibility below.

Although estimates of scale economies are presented in the next section, the estimated parameters for the first and second-order output terms for subscribers (*Subs*) are significant, positive, and less than one in value. Thus, a percent increase in subscribers corresponds to a less than proportionate increase in total cost, approximately 0.82% on average. The first-order estimate for airtime minutes per cell-channel (*MPC*) is negative, significant, and small in magnitude, indicating that areas with higher utilization of available capacity tend to have lower costs other things being equal. This result is expected given that adding cell sites or sectoring existing cells requires costly investments. The cost to add capacity has fallen each year, however, and the interaction term between *MPC* and *t* suggests that the carrying cost for additional capacity is declining slightly over time. Furthermore, the time trend (*t*)—the number of years that a market has been in service—is negative, significant, and of reasonable magnitude. The results suggest that long-run total costs are declining at an annual rate of 3.5%, ceteris paribus.

For the input prices, the cost elasticities or factor shares at the sample mean all are positive with plausible magnitudes. The capital/network, sales and marketing, and other input shares at the mean are 0.273, 0.408, and 0.319, respectively. For each observation, the calculated shares are positive, so the estimated cost function has positive marginal costs over the entire range of data. Also, the estimated cost function is concave at all sample points. The interaction terms with time reveal a tendency for the capacity/network share to diminish over time relative to other the shares; this is consistent with the increasing competitiveness of wireless markets where marketing and operation support/customer care are more important than ever.

The proxies for regional management and operating cost variation are statistically significant and behave as expected. A percent increase in property taxes (*PropTax*) corresponds to total costs that are slightly higher, 0.06%. The interaction term with time suggests that property taxes on GTE Wireless cellular market areas have held steady or declined very slightly over the past three years. The point estimates for the regional indicator variables are relative to the MidSouth region of GTE Wireless. Every region except the MidWest displays costs that are significantly different than the MidSouth at the one percent level. Intuitively, the results reflect costs in Florida and Texas—states with flat terrain and relatively low business costs—that are significantly lower than in the MidSouth. Conversely, the costs in California and Hawaii—states with more varied terrain and higher business costs—are significantly above those in the MidSouth.

Estimates Of Scale Economies

With the excellent fit and significant estimates from the translog cost function, we are able calculate the degree of scale economies with some confidence. At the sample mean, we find that the degree of scale economies equals 1.16, with a 95% confidence interval that ranges from 1.11 to 1.22. Constant returns to scale is rejected.

Figure 1. Degree of Scale Economies Versus Subscribers By Market

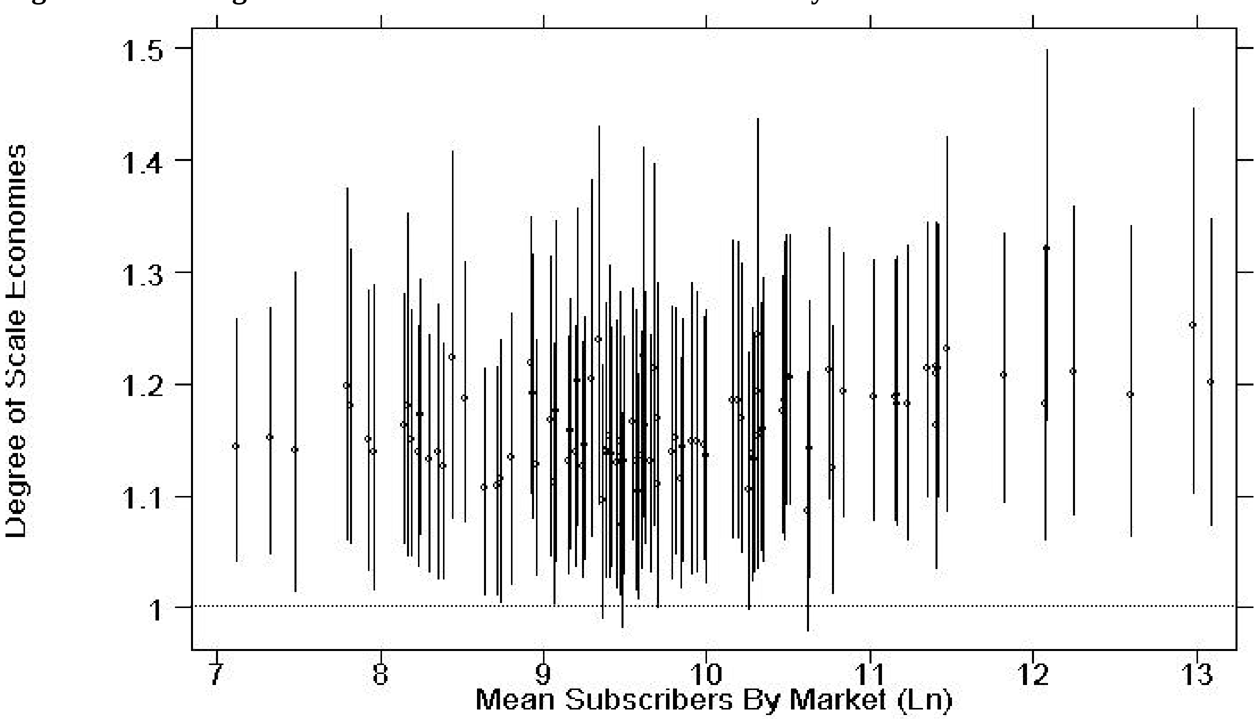


Figure 1 presents the estimated degree of scale economies for each cellular market area plotted against subscribers. The standard errors of the estimates presented in Figure 1 were obtained using a standard bootstrapping procedure with 1000 iterations and 95% confidence intervals. Larger markets demonstrate slightly greater scale economies, everything else being equal. Again, constant returns to scale is rejected. In contrast to the conclusion in McKenzie and Small (1997) that cellular telephony is at best a constant-returns proposition, our analysis suggests that cellular telephony is somewhat better than a constant returns business. The degree of scale economies we find for cellular telephony, however, generally falls below those that have been estimated for wireline technology. For example, Christensen et. al. (1983) found that Bell System economies are in the range of 1.3 to 1.7, whereas our estimates by market area top out at 1.32.

VI. Conclusions

Beyond marketing-driven incentives to compete by offering calling areas nationwide, this research has demonstrated that mild but nonetheless significant scale economies exist in cellular telephony. As one might expect based on knowledge of the technologies involved, the magnitude of the estimated scale economies is less than typical estimates for wireline telephony. From a policy standpoint, however, earlier findings of cellular *dis*economies of scale by McKenzie and Small (1997) supported the hypothesis that regulated duopoly structure of cellular telephony is inappropriate. The mild scale economies we have identified would not belie their conclusion that a duopoly structure may be inappropriate, but the growing concentration of the U.S. cellular industry suggests that scale economies matter.

Appendix

Table A1. Translog Cost Function Estimation Results

Equation	Obs	RMSE	R-Square	Chi2	P
Total Cost	3331	0.04436	0.9986	2975579	0.000
Capital/Network Share	3331	2.692153	0.9321	46186.17	0.000
Sales & Marketing Share	3331	1.761513	0.9786	153636.1	0.000

Parameter	Estimate	Std. Err.	Parameter	Estimate	Std. Err.
PK	0.21164	0.01275	*FL*	-0.03303	0.01220
PM	0.44377	0.01035	*MW*	-0.00119	0.00607
PO	0.34459	0.01132	*TX*	-0.03159	0.00755
Subs	0.89004	0.01462	*HI*	0.66269	0.08262
MPC	-0.04976	0.01165	*CA*	0.05178	0.01213
PropTax	0.06441	0.00843	*TX*x*PK*	-0.00289	0.00765
t	-0.03515	0.00549	*TX*x*PM*	0.00080	0.00492
½ PK^2	0.05359	0.00199	*TX*x*PO*	0.01520	0.00740
½ PM^2	0.07215	0.00106	*TX*x*Subs*	-0.00226	0.00691
½ PO^2	0.08065	0.00185	*TX*x*MPC*	-0.01250	0.00440
½ $Subs^2$	0.01093	0.00209	*TX*x*PropTax*	-0.00670	0.00592
½ MPC^2	0.01264	0.00169	*CA*x*PK*	0.01550	0.00910
½ $PropTax^2$	0.00568	0.00121	*CA*x*PM*	-0.01879	0.00777
t^2	0.00126	0.00027	*CA*x*PO*	0.02074	0.00650
*PK*x*PM*	-0.06352	0.00295	*CA*x*Subs*	0.01209	0.00510
*PK*x*PO*	-0.06657	0.00390	*CA*x*MPC*	0.01883	0.00696
*PK*x*Subs*	-0.06214	0.00329	*CA*x*PropTax*	0.02013	0.00509
*PK*x*MPC*	-0.07181	0.00294	*HI*x*PK*	-0.05197	0.01528
*PK*x*PropTax*	0.00040	0.00278	*HI*x*PM*	-0.06858	0.01584
*PM*x*PO*	-0.07304	0.00251	*HI*x*PO*	-0.01965	0.01532
*PM*x*Subs*	0.06070	0.00269	*HI*x*Subs*	0.03927	0.00878
*PM*x*MPC*	0.03730	0.00273	*HI*x*MPC*	0.05534	0.01504
*PM*x*PropTax*	-0.01545	0.00243	*HI*x*PropTax*	0.20087	0.02602
*PO*x*Subs*	0.00004	0.00001	*MW*x*PK*	-0.01476	0.00570
*PO*x*MPC*	0.02744	0.00316	*MW*x*PM*	0.02201	0.00502
*PO*x*PropTax*	0.01869	0.00248	*MW*x*PO*	0.01455	0.00673
*MPC*x*Subs*	0.02925	0.00285	*MW*x*Subs*	0.01720	0.00477
*MPC*x*PropTax*	0.01410	0.00209	*MW*x*MPC*	0.03032	0.00388
*PropTax*x*Subs*	0.00784	0.00234	*MW*x*PropTax*	0.00352	0.00365
*t*x*PK*	-0.00650	0.00124	*FL*x*PK*	-0.05012	0.01185
*t*x*PM*	0.00003	0.00096	*FL*x*PM*	0.03827	0.00617
*t*x*PO*	0.00293	0.00108	*FL*x*PO*	0.03892	0.01204
*t*x*Subs*	-0.00014	0.00132	*FL*x*Subs*	0.01844	0.00794
*t*x*MPC*	-0.00207	0.00104	*FL*x*MPC*	0.00388	0.00875
*t*x*PropTax*	-0.00255	0.00073	*FL*x*PropTax*	0.00956	0.00584
Intercept	0.19150	0.03031			

Table A2. List of GTE Wireless Cellular Markets Included by State

State	Market	State	Market	State	Market
AL	AL RSA 1	IL	IL RSA 1	TN	Knoxville
AL	AL RSA 2	IL	Rockford	TN	Memphis
AL	Anniston	IN	Evansville	TN	Nashville
AL	Birmingham	IN	Ft. Wayne	TN	TN RSA 1
AL	Florence	IN	IN RSA 1B1	TN	TN RSA 2
AL	Gadsden	IN	IN RSA 3	TN	TN RSA 3
AL	Huntsville	IN	IN RSA 6	TN	TN RSA 5
AL	Mobile	IN	IN RSA 7-9	TN	TN RSA 6
AL	Tuscaloosa	IN	Indianapolis	TN	TN RSA 7
CA	Bakersfield	IN	Terre Haute	TN	TN RSA 9
CA	CA RSA 4	KY	KY RSA 1	TN	Tri-Cities
CA	CA RSA 5	KY	KY RSA 2	TX	Austin
CA	CA RSA 6	KY	KY RSA 7	TX	Bryan-College Station
CA	CA RSA 9	KY	Lexington	TX	El Paso
CA	Fresno	KY	Louisville	TX	Houston
CA	San Diego	NC	Ashville	TX	TX RSA 10
CA	San Francisco	NC	Burlington	TX	TX RSA 11
CA	Santa Barbara	NC	Fayetteville	TX	TX RSA 16
CA	Visalia	NC	Greensboro	TX	TX RSA 17
FL	FL RSA 1	NC	Raleigh	TX	Victoria
FL	FL RSA 2	NC	Wilmington	VA	Danville
FL	FL RSA 3	NM	LasCruces	VA	Newport News
FL	FL RSA 4	NM	NM RSA 3	VA	Norfolk
FL	Ft. Myers	NM	NM RSA 5	VA	Petersburg
FL	Pensacola	NM	NM RSA 6	VA	Richmond
FL	Tampa/St. Pete./Clearwater	OH	Akron	VA	Roanoke
HI	HI RSA 1	OH	Cleveland-Sandusky	VA	VA RSA 3
HI	HI RSA 2	OH	OH RSA 3	VA	VA RSA 4
HI	HI RSA 3	PA	Erie	VA	VA RSA 5
HI	Honolulu	SC	Charleston	VA	VA RSA 7
IA	Davenport	SC	Florence	VA	VA RSA 8
IA	IA RSA 4	SC	SC RSA 6	VA	VA RSA 9
IA	IA RSA 5	TN	Chatanooga	VA	VA RSA 11
		TN	Clarksville	VA	VA RSA 12

References

Baumol, W. J., J.C. Panzar, and R.D. Willig. 1988. *Contestable Markets and the Theory of Industry Structure.* San Diego: Harcourt Brace Jovanovich.

Christensen, L.R., D.C. Cummings, and P.E. Schoech. 1983. "Econometric Estimation of Scale Economies in Telecommunications." *Economic Analysis of Telecommunications: Theory and Applications*. Eds. L. Courville, A. de Fontenay, and R. Dobell. Amsterdam: North-Holland.

Donaldson, Lufkin & Jenrette Securities Corporation. *The Wireless Communications Industry* 10. Spring 1998 ed..

Federal Communications Commission, "Third Annual CMRS Competition Report." FCC 98-91. Adopted May 14, 1998. Released June 11, 1998.

Harte, L., S. Prokup, and R. Levine. 1997. *Cellular and PCS: The Big Picture.* New York: McGraw-Hill.

McKenzie, D.J., and J.P. Small. 1997. "Econometric Cost Structure Estimates for Cellular Telephony in the United States." *Journal of Regulatory Economics* 12(2): 147-157. September 1997.

Pulley, L.B., and Y.M. Braunstein. 1992. "A Composite Cost Function For Multiproduct Firms with an Application to Economies of Scope in Banking." *Review of Economics and Statistics* 74(2): 221-230.

Shin, R. T., and J.S. Ying. 1992. "Unnatural Monopolies in Local Telephone." *Rand Journal of Economics* 23(2): 171-183. Summer 1992.