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Do Telecommunications Affect Passenger Travel or Vice Versa?

Structural Equation Models of Aggregate U.S. Time Series Data Using Composite Indexes

Sangho Choo and Patricia L. Mokhtarian

This study explores the aggregate causal relationships between telecommunications and travel in a comprehensive framework, considering their demand, supply, and costs, together with land use, economic activity, and sociodemographic variables. On the basis of a hypothesized conceptual model, composite indexes were developed for endogenous variable categories (telecommunications and travel demand, supply, costs, land use, and economic activity) by confirmatory factor analysis, with the use of national time series data (1950–2000) in the United States. Then, single-equation and structural equation models for telecommunications (telephone calls and mobile phone subscribers, separately) and travel were estimated, with the composite indexes and sociodemographic measures used as explanatory variables. Overall, the model results suggest that the aggregate relationship between actual amounts of travel and telecommunications is complementarity, not substitution. That is, as telecommunications demand increases, travel demand increases, and vice versa. In addition, it was found that the causal effects of travel demand on telecommunications demand were larger than those in the reverse direction.

The impact of telecommunications on travel can take several forms (1, 2). Substitution of telecommunications for travel is the impact most desired from a public policy perspective, but it is not the only possibility. In particular, telecommunications may also have a complementary relationship to travel (3), through (a) increasing the size of one's contact set (which forms the basis for generating travel for face-to-face interaction), (b) facilitating or generating travel directly (e.g., using information and communications technologies to support organizing in-person meetings or last-minute auctions of airline seats through the Internet), (c) supply-side applications such as intelligent transportation systems (ITS) technology increasing the effective capacity of the transportation system, and (d) freeing time from other activities (including but not limited to traveling), some of which time may then be devoted to more traveling.

Transportation can have similar substitution and complementary effects on telecommunications as well. To assess fully the interactive relationships between these two indicators, measures of complete amounts of both transportation and telecommunications and models

allowing both directions of causality are needed. Thus, a complete study of the aggregate relationships between telecommunications and travel would ideally involve a structural equations model system allowing each measure to affect the other over time. A few aggregate studies have taken related approaches. Plaut (4) performed an input–output analysis of industrial consumption of transportation and communication services by nine countries of the European Community in 1980. She found strong evidence of complementarity in the sense that use of transportation inputs was strongly positively correlated with use of communications inputs. However, the results do not speak to the degree of direct causality between the two sectors; the observed correlations may be due in some part to independent mechanisms that separately generate congruent transportation and communication demands.

Another aggregate study focused on per capita consumption expenditures on private transportation, public transportation, and communications. Using 1960–1986 time-series data from Australia and the United Kingdom, Selvanathan and Selvanathan (5) estimated a simultaneous equation system of the consumer demand (in monetary terms) for these three kinds of goods separately, plus all others combined. Interestingly, this study found a pairwise substitution relationship among all three sectors.

The Selvanathan and Selvanathan and the Plaut studies both analyzed monetary measures of transportation and communications consumption. But this focus can obscure relationships between actual activities of both kinds, especially as prices of many telecommunications activities have generally fallen over time, whereas those of some travel activities have been rising. Given that from an urban/transportation-planning standpoint it is the activities themselves that are relevant (e.g., to congestion), it would be of great interest to explore the aggregate relationships between actual amounts of passenger travel and telecommunications, assessing the extent of causality by accounting for other variables that can be expected to influence both.

The purpose of this study is to explore the aggregate causal relationships between telecommunications and travel in a comprehensive framework, considering their demand, supply, and costs, together with land use, economic activity, and sociodemographic variables. First, based on a hypothesized conceptual model, composite indexes were developed for endogenous variable categories (telecommunications and travel demand, supply, costs, land use, and economic activity) by confirmatory factor analysis, using national time series data (1950–2000) in the United States. Then, single-equation and structural equation models for telecommunications (telephone calls and mobile phone subscribers, separately) and travel were estimated, using the composite indexes and sociodemographic variables.

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This paper is organized as follows. The following section presents the hypothesized conceptual model. Then, the general methodology for structural equation modeling (SEM) is described in the third section and the data used for this study are described in the fourth section. In the fifth section, the model results for the single equations as well as the structural equation systems are discussed. Finally, conclusions are discussed.

CONCEPTUAL MODEL

A number of studies (2, 6) have suggested various relationships among travel, telecommunications, urban patterns (land use), and economic activity. In this study, these and other hypothesized relationships are synthesized into a comprehensive conceptual model—to the authors’ knowledge, the most complete model of its kind. The analysis focuses primarily on passenger travel, not goods movement, but aside from that includes both consumer and producer activities.

As indicated in Figure 1, the model comprises eight endogenous variable categories (travel and telecommunications demand, transportation and telecommunications supply, travel and telecommunications costs, land use, and economic activity) and one exogenous variable category (sociodemographics). Arrows indicate the direction of hypothesized causal relationships. The major relationships in the conceptual model are as follows:

- Travel demand ↔ telecommunications demand. It is hypothesized that travel demand and telecommunications demand have a bidirectional causality, with relationships that could be either positive or negative (1, 2). That is, as the demand for telecommunications

increases, the demand for travel either decreases (substitution) or increases (complementarity), and vice versa.

- Travel (telecommunications) demand ↔ transportation (telecommunications) supply → travel (telecommunications) costs → travel (telecommunications) demand. Obviously, a bidirectional causality can be hypothesized between demand and supply. Additionally, some lagged effects of supply on demand are considered, and vice versa. Looking at general demand and supply curves with respect to price, as supply goes up, the market price goes down. It is clear that increases in supply can reduce costs and that costs negatively affect demand.

- Transportation supply ↔ telecommunications supply. A bidirectional causality between travel supply and telecommunications supply is plausible. Mokhtarian (2) identified such relationships: for example, some fiber optic networks are heavily dependent on transportation rights-of-way (such as railroads and subways), and telecommunications applications such as ITS technologies increase or improve existing highway capacities (7). For example, real-time traffic information can reduce traffic congestion on highways and increase their levels of service.

- Transportation (telecommunications) supply ↔ land use → travel (telecommunications) demand. First, a bidirectional causality between supply and land use is hypothesized. For example, investments in transportation strongly influence urban structures such as land use patterns, population densities, and housing prices (8). In fact, highway construction has been accelerating suburbanization, providing higher accessibilities to urban areas. The telecommunications infrastructure can also allow people to obtain information by phone or the Internet at a distance, so the need to live in urban areas potentially decreases. Second, it is apparent that land use affects travel and telecommunications demand. As numerous studies (9) have characterized

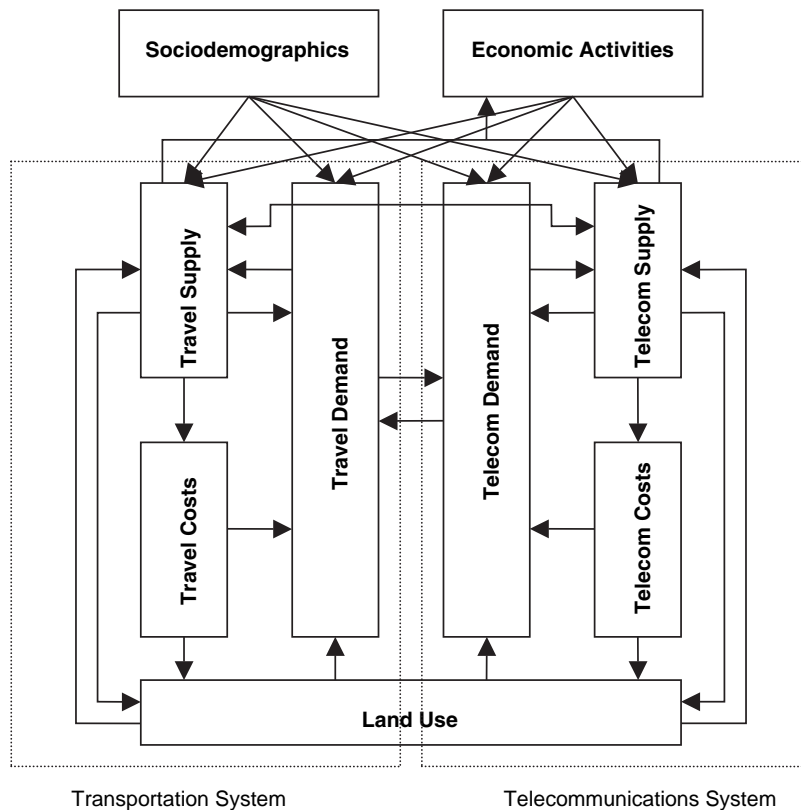


FIGURE 1 Conceptual model of travel and telecommunications relationships.

the relationships between travel and land use, suburbanization (due to lower land prices and increased accessibilities to highways) has affected personal travel and freight transportation patterns, resulting in longer commutes as well as nonwork trips. Also, land use can affect telecommunications demand. For example, the farther apart family members live, the more they may call instead of visit each other.

- Travel (telecommunications) costs \rightarrow land use. Lower driving costs have magnified the personal benefits of living in suburbs. On the other hand, decreases in telecommunication costs allow many people to work from “anywhere.” As a result, the benefits of living or locating in central cities have theoretically declined in the long term. Hence, it can be hypothesized that travel and telecommunications costs affect land use, especially over the long term.

- Transportation (telecommunications) supply \leftrightarrow economic activity. It has long been argued that investment in highway infrastructures (especially, the national highway system) brings economic benefits of national productivity and employment, providing increased mobility of people and goods (10). On the other hand, it is clear that the higher the gross domestic product (GDP), the more federal funds there are available for highway investments and similarly at state and local levels. Thus, a bidirectional causality can exist between transportation supply and economic activity. Similarly, investments in telecommunications system infrastructures have accelerated business and industrial efficiencies against distance barriers, decreasing the costs of transport and of obtaining a variety of information (11). Therefore, telecommunications supply and economic activity can also have bidirectional causality.

- Economic activity (sociodemographics) \rightarrow travel (telecommunications) demand and supply. Numerous studies of vehicle miles traveled (VMT) (12) have found that economic activity (such as GDP and gross national product) significantly positively affects travel demand. Schafer (13) found that some of the growth in traffic volumes can be attributed to the increase in personal income as indicated by GDP, based on 1960–1990 time-series data for 11 world regions. On the other hand, it is also evident that the higher the income, the greater the affordability of telecommunications equipment (such as computers and mobile phones) and the higher the telecommunications demand. Hence, economic activity can affect telecommunications as well as travel demand. Sociodemographic variables (such as population, number of drivers, and household size) have long been considered key elements of traditional travel demand and supply models. Similarly, population, number of households, and household size can strongly affect telecommunications demand and supply: for example, the more households, the more telephone calls. Consequently, it is hypothesized that sociodemographics affect both travel and telecommunications demand and supply.

METHODOLOGY

The previous section discussed the conceptual model of telecommunications and travel, and each causal relationship between variable categories in the model is hypothesized to be either bidirectional or unidirectional. It is well-known that SEM is a powerful technique for analysis of multiple simultaneous causal relationships among endogenous variables and between endogenous and exogenous variables. In fact, numerous studies using SEM methods have been conducted on travel demand and travel behavior (14), but they have mainly used either disaggregate cross-sectional or panel data and not aggregate time-series data. In this study, the SEM method was used on time-series data to estimate the causal relationships in the conceptual model. Because the data set comprises time series for the variables of interest, stationarity of each series is required for the validity of the estimated parameters. All time-series variables in the data set are nonstationary

(i.e., display a trend over time) in their raw forms [see Choo (15) for plots of the variables of this study], so the natural log-transformed form [i.e., $\log(X_t) - \log(X_{t-1})$] of each series was first-order differenced to achieve stationarity. Lagged endogenous and exogenous variables can be included in the model, considered (together with contemporaneous exogenous measures) to be predetermined variables. Then, all equations in the system can be estimated simultaneously.

A general structural equation model in which all variables are observed can be written as follows:

$$\mathbf{Y} = \mathbf{B}\mathbf{Y} + \mathbf{\Gamma}\mathbf{X} + \boldsymbol{\zeta}$$

where

- \mathbf{Y} = column vector of endogenous variables,
- \mathbf{X} = column vector of exogenous variables,
- \mathbf{B} = matrix of structural coefficients representing the direct effects of endogenous on other endogenous variables,
- $\mathbf{\Gamma}$ = matrix of structural coefficients representing the direct effects of exogenous on endogenous variables, and
- $\boldsymbol{\zeta}$ = column vector of error terms (16).

Then, the unknown parameters need to be estimated so as to minimize the difference between the model-implied population variance-covariance matrix and the sample variance-covariance matrix. In this study, estimates of parameters are obtained by minimizing the maximum likelihood fitting function.

DATA DESCRIPTION

The aggregate data for this study come from secondary sources [provided by Choo (15)], usually collected by trade organizations, government agencies, and other public agencies. Considering the most appropriate representatives of a conceptual category as well as data availability, key variables were selected for each category. All variables were measured at the nationwide level (based on the 50 U.S. states and the District of Columbia), with annual observations on the years 1950–2000. First, individual variables are described by category, and then composite indexes for the conceptual categories are discussed.

- Travel demand. The travel demand category includes three motorized demand measurements: passenger VMT, revenue transit passengers carried, and revenue domestic airline passenger miles traveled (PMT). First, the passenger VMT variable is considered representative of the demand for private transportation. The VMT variable used in this study includes passenger cars, motorcycles, and other two-axle four-tire vehicles such as vans, pickup trucks, and sport utility vehicles [see Choo (15) for details about the VMT variable]. Second, because of data availability, the number of revenue transit passengers carried is used as the measure of public transportation demand instead of transit PMT. This variable includes revenue passengers on motor bus, trolley bus, heavy rail, light rail, commuter rail, demand responsive vehicles, and other transit modes. Last, revenue domestic airline PMT indicates domestic air travel demand (inclusion of international demand was problematic because data were not available for U.S. passengers on international carriers, nor was it possible to distinguish domestic from international passengers on domestic carriers operating overseas). Air carrier employees and infants are not counted as revenue passengers. Included are scheduled or nonscheduled domestic flights by certified domestic air carriers operating in the United States. Thus, these three variables collectively represent travel demand.

- Transportation supply. Corresponding to their travel demand counterparts, this category includes lane miles, transit vehicle miles operated, and domestic airline seat miles. Data on the number of

through lanes were not available before 1984. Accordingly, lane miles (obtained by multiplying the centerline length by the number of through lanes in that segment) for rural and urban areas were backcasted for the earlier years, using functions of road (centerline) lengths for rural and urban roads separately (both adjusted R^2 values = 0.996).

- **Travel costs.** The travel cost category comprises three consumer price indexes (CPIs)—for private transportation (including vehicle purchases, operations, maintenance, repairs, and insurance), public transportation (here, intracity transit systems), and airline (including airline fares)—as well as real (inflation-adjusted) gasoline prices. The CPI is a measure of the overall level of prices (paid by urban consumers) that indicates the cost of a fixed market basket of consumer goods and services relative to the cost of the same basket in a base year (17). The Bureau of Labor Statistics publishes the CPIs for all items and specific types of goods every month.

- **Telecommunications demand.** There are three variables in the telecommunications demand category: number of local telephone calls, number of toll calls (domestic only, to maximize comparability with the travel demand variables), and number of mobile phone subscribers. The number of mobile phone subscribers represents the demand for wireless telecommunications. Mobile phones were first commercialized in late 1983 and data on their adoption are available only from that point onward. Not surprisingly, mobile phone demand has rapidly increased, by a factor of more than 100 in the last 15 years. The number of toll calls was strongly (albeit temporarily) affected by the court-ordered divestiture of AT&T in 1984.

- **Telecommunications supply.** Telecommunications supply includes residential and business telephone access lines, telephone wire length, and cell sites. Clearly, these variables represent infrastructure measures corresponding to the preceding telecommunications demand variables.

- **Telecommunications costs.** Similar to the transportation cost category, the telecommunications category has three CPIs—for local, interstate, and intrastate telephone services—as well as average monthly revenue of mobile phone services. The latter is a good measure of mobile telephone service prices because it can reflect various types of mobile calling characteristics (see the website www.bls.gov/cpi/cpifactc.htm, accessed April 1, 2004).

- **Land use.** Because of data availability, there is only one variable in the land use category, ratio of suburban population to total metropolitan population, referred to as the suburbanization rate. Of course, metropolitan area boundaries have generally expanded outward, and new metropolitan areas have been added, as population has increased over the 50-year period of this study. However, the definitions of a central city and a metropolitan area have changed little since 1949 [see Appendix II of *Statistical Abstract of the United States* (18)], and the defined ratio appropriately reflects the proportion of total urbanized population that lives in a suburban environment [see Choo (15) for details on the suburbanization rate variable].

- **Economic activity.** The economic activity category has three measures: real GDP, unemployment rate, and female proportion of the labor force. GDP is the market value of the goods and services produced by labor and property located in the United States. The unemployment rate and female proportion are calculated as the ratio of unemployed individuals and the ratio of employed women, respectively, to the total civilian labor force (16 years or older). These measures are often used in macroeconomics to indicate economic status. The unemployment rate, of course, is a negative indicator of economic activity.

- **Sociodemographics.** This category contains population, households, household size, number of licensed drivers, and female proportion of licensed drivers. These variables are used as exogenous variables in the models.

There are 25 different endogenous variables in the categories described. Building a structural equation model with 25 equations, one for each variable, is not possible given that there are only 51 observations (less one, lost to first differencing); there would be more unknown parameters to estimate than there are data points. Further, strong correlations among variables in a given category could make it undesirable to include several of them as explanatory variables in a given equation. Elsewhere [see Choo (15)], structural equation models have been built by using selected subsets of the endogenous variables (i.e., choosing one variable from each of the eight categories and experimenting with different sets of choices). This, however, is unsatisfying because it necessarily ignores a number of variables and relationships that may be important to obtaining a complete picture of the relationships presented in Figure 1. Here, a different approach is taken: the variables of a given category are combined into a single composite indicator for that category. Although this approach necessarily sacrifices specificity in the relationships it identifies, it can capture, in a general sense, a more complete view of the overall relationships among the set of variables of interest.

Accordingly, based on the key variables in the conceptual categories described previously, composite indexes were constructed for the endogenous category variables, using confirmatory factor analysis. That is, a single-factor solution was obtained through factor analysis of each category, based on the set of variables in that category. In reality, the composite indexes are measures of latent variables and, in the ideal application, both confirmatory factor analysis (the “measurement model”) and structural modeling are conducted simultaneously in the structural equation context (19). As Golob (14) pointed out, however, measurement and structural models are seldom estimated together in practice. In view of the sample size limitations (resulting in underidentification of structural equation models), two-step modeling is used in this study. That is, the composite indexes are created by confirmatory factor analysis in the first stage, and then a structural equation model is estimated by treating them as observed variables in the model. A similar approach can be found in other studies [e.g. Bagley and Mokhtarian (20)].

Ultimately, factor score variables were developed for all endogenous variable categories except land use, because there is only one individual variable (suburban proportion of total metropolitan population) in that category. The suburbanization rate was entered directly into the models as the variable representing the land use factor. Additionally, mobile phone-related variables did not work in the corresponding factor categories, showing counterintuitive signs in their factor loadings, so these measures were allowed to constitute single-variable factors like the land use factor. As a result, two structural equation models were developed: for travel and telephone calls and for travel and mobile phone subscribers. Table 1 presents the component variables and their score coefficients for each composite index. Each component variable is standardized at the outset of the factor analysis to control for differences in scale among variables comprising the same factor. Thus, the resulting composite indexes are scale-free linear combinations of the standardized component variables. The composite indexes account for 40% to 70% of the total variances in the variables composing their categories.

MODEL ESTIMATION

Model Specifications

Based on the conceptual model, two structural equation models were developed (for travel and telephone calls and for travel and mobile phone subscribers), using composite indexes and (first-order differ-

TABLE 1 Composite Indexes

Composite Index	Component Variables (1st differenced, natural-log form, $\log(X_t) - \log(X_{t-1})$)	Component Score Coefficient
Travel demand (60%)	Vehicle miles traveled (VMT)	0.485
	Revenue transit passengers carried	-0.376
	Revenue domestic airline passenger miles traveled	0.429
Transportation supply (40%)	Lane miles (rural areas)	0.228
	Lane miles (urban areas)	0.353
	Revenue transit vehicle miles operated	-0.483
	Revenue domestic airline available seat miles	0.469
Travel costs (68%)	Real gasoline price	0.291
	CPI for private transportation	0.361
	CPI for public transportation	0.244
	CPI for airline	0.339
Telecommunications demand (57%)	Number of local telephone calls	0.660
	Number of domestic toll calls	0.660
	Number of mobile phone subscribers*	Single-variable factor
Telecommunications supply (64%)	Number of telephone residential access lines	0.506
	Number of telephone business access lines	0.461
	Telephone wire length	0.243
	Number of cell sites*	Single-variable factor
Telecommunications costs (56%)	CPI for local telephone calls	0.384
	CPI for intrastate toll calls	0.533
	CPI for interstate toll calls	0.406
	Real average monthly revenue of mobile call services*	Single-variable factor
Land use	Suburban population ratio to total metropolitan populations	Single-variable factor
Economic activity (67%)	Real gross domestic product (GDP)	0.466
	Unemployment rate	-0.473
	Female proportion of the labor force	0.245

NOTE: The numbers in parentheses represent percentages of the total variance in the variables of that category (not including single-variable factors), that are explained by that index.

*This variable is not included in the corresponding composite index.

enced, natural log-transformed) sociodemographic variables. First, single equations were estimated for each endogenous variable as a function of other endogenous and exogenous variables, including lagged variables, to refine the initial model specifications. Proceeding to the structural equation model, however, was not straightforward in view of the limitations of this context. For example, the sample size (50 after differencing and 49 when using lagged variables) is so small that the conceptual model may not be estimable with more than 20 parameters. Further, because the conceptual model has eight endogenous categories and only one exogenous category (an eight-equation system) and is nonrecursive (having feedback loops), the parameters of the structural equation model may not always be statistically identifiable. In view of these limitations, a nested series of constrained alternatives of the conceptual model were also tested, by successively switching more and more exogenous variables to endogenous (by adding more equations to the system). Last, to improve the goodness of fit of the resulting models, all insignificant paths and correlations were restricted to zeros, and some paths and correlations that had been fixed to zeros were unrestricted, after examining modification indexes (21). The AMOS module of the SPSS software package (22) was used to estimate the structural equation models in this study because of its user-friendliness and graphical interface.

Through this estimation procedure, the final models were achieved. Among them, some relationships that are hypothesized in the conceptual model could not be included in the final model of travel and mobile phones because of nonidentifiability. In particular, this model does not include a mobile phone cost equation. Also, where conceptually supported, the final models retain a few variables with lower signif-

icance (but always with a P value of .3 or better, meaning at least 70% confidence of being right in rejecting the null hypothesis of no impact) because of the small sample size and the exploratory nature of the study. This is consistent with the advice given by Horowitz et al. (23) for retaining policy-relevant variables in discrete choice models if their t -statistics are greater than 1 in magnitude.

In this study, the corresponding single-equation models for travel and telecommunications demand were also examined to explore their unidirectional relationships and compare their coefficients with those in the structural equation models (that is, the final structural equation model specifications were reestimated as single equations to enable an appropriate comparison with the structural equation models). Because in the literature relationships are still most often explored through single-equation models, it is important to analyze the consequences of doing so when a structural equation model is more appropriate. First, the results for the single-equation models are discussed, and then the structural equation models for both travel and telephone calls and travel and mobile phone subscribers are discussed.

Model Results

Single-Equation Demand Models

Table 2 presents the three single-equation (i.e., regression) models for travel and telecommunications demand. The dependent variables are the travel demand index and the two telecommunications demand variables (telephone calls and mobile phone subscribers), and they are

also considered as potential explanatory variables in the other models. The travel demand and mobile phone subscriber models have higher R^2 values (0.73 and 0.99, respectively), whereas the telephone call model has a relatively low R^2 value (0.36). The Durbin-Watson statistics show that there are no autocorrelations among the residuals of the models. Interestingly, the telecommunications cost variables are not significant in the telecommunications demand models. For the mobile phone subscribers model, the reason is that the mobile phone cost variable is highly correlated with the mobile phone supply (number of cell sites) variable ($r = -0.95$), resulting in a multicollinearity problem. This reason did not apply to the telephone call model, however, suggesting that demand in that case is relatively inelastic, at least within the range of experienced costs.

Looking at the coefficients of the explanatory variables, it can be seen that telephone call demand positively affects travel demand, and travel demand positively affects both telecommunications demand variables. That is, as travel increases, telecommunications demand increases, and vice versa. This suggests that telecommunications and travel are complements (although a firm judgment on that point should be reserved for the structural equation models, because endogeneity bias and correlations among included and excluded variables in each equation could greatly affect the results). Interestingly, however, there is no significant effect of mobile phone demand on travel demand. As expected, the supply variables strongly positively affect the corresponding demand variables. The land use and economic activity measures positively affect travel demand but not telecommunications demand. It is logical that the average household size variable negatively affects both telecommunications demand variables, because smaller household sizes indicate larger numbers of households, which would have a larger demand. From the single-equation model results, it can be concluded that travel and telecommunications affect each other. However, precisely because of that, the results also indicate that single-equation modeling for travel and telecommunications demand generates an endogeneity bias, suggesting that simultaneous equation modeling is superior in this context.

Structural Equation Model of Travel and Telephone Calls

Table 3 presents the estimated, standardized (direct and total) effects among endogenous variables and between predetermined (exogenous and lagged endogenous) and endogenous variables for the final model of travel and telephone calls. Goodness-of-fit measures such as the goodness-of-fit index, normed fit index, and comparative fit index indicate that the model has a relatively good fit (all indexes are nearly equal to or greater than 0.8, with a value of 1.0 indicating a perfect fit), considering the small sample size. Also, one rule of thumb for a good-fitting model is that the ratio of the χ^2 statistic to the degrees of freedom be less than 2 or 3 (19). Using this rule, the ratio of the model is less than 3, indicating a good fit. In addition, the stability index (a measure of stability for a nonrecursive linear structural equation model) for the model lies between -1 and 1 ; that is, the model is stable and converges properly.

Turning to the causal effects in the model, both travel and telecommunications (telephone call) demands positively significantly affect each other. That is, as travel demand increases, telecommunications increase and vice versa. This strongly suggests that there is a complementary relationship between travel and telecommunications. Interestingly, comparing the magnitudes of both directions, travel demand affects telecommunications demand more strongly than the reverse. This implies that, although both effects occur, telephone calls are more often generated as a kind of derived demand from travel than as a means of stimulating travel. This appears to be consistent with anecdotal observation in that a much higher proportion of trips appear to involve telecommunications (before the trip to prepare for it and after the trip to continue activities initiated by the trip) than the proportion of telecommunications generating trips. As hypothesized, transportation supply has a positive impact on travel demand, indicating an induced demand effect. Further, it is plausible that the lagged demands for travel and telecommunications positively affect their supply. That is, the travel (telecommunications) demand of the previous year affects the capacity of the transportation (telecommunications)

TABLE 2 Single-Equation Demand Models

Variable	Travel Demand	Telecommunications Demand	
		Telephone Calls	No. of Mobile Phone Subscribers
Travel demand		0.277 (2.13)	0.030 (2.13)
Transportation supply	0.470 (3.12)		
Travel costs	-0.221 (-2.55)		
Telecommunications demand (telephone calls)	0.136 (1.49)		
Telecommunications supply		0.307 (2.35)	
Mobile phone supply (no. of cell sites)			1.000 (70.91)
Land use (suburbanization rate)	0.230 (1.69)		
Economic activity	0.207 (2.42)		
Average household size		-0.381 (-2.81)	-0.027 (-1.88)
R^2	0.73	0.36	0.99
Durbin-Watson statistic	1.58	1.53	1.38

NOTE: All variables are the first-order differenced (natural) log-transformed [i.e. $\log(X_t) - \log(X_{t-1})$] variables. All coefficients are standardized, which is why there is no constant term. Numbers in parentheses indicate t -statistics. $N = 49$.

TABLE 3 Estimated Causal Effects Between Travel and Telephone Call Variables

RHS Variable	Endogenous Variables (LHS Variables)							
	Demand		Supply		Costs		Land Use	Economic Activity
	Travel	Telecom	Travel	Telecom	Travel	Telecom		
Endogenous variable								
Travel demand	0.081	0.364 (0.336)						
Telecommunications demand	0.242 (0.224)	0.081						
Transportation supply	0.795 (0.513)	0.267			-0.176 (-0.176)		1.262 (1.262)	0.173 (0.173)
Telecommunications supply	0.063	0.281 (0.260)				-0.704 (-0.704)		
Travel costs	-0.248 (-0.229)	-0.083						
Land use	0.130 (0.120)	0.044						
Economic activity	0.189 (0.175)	0.064						
Predetermined variable								
1st lagged travel demand	0.090	0.030	0.114 (0.114)		-0.020		0.143	0.020
1st lagged telecom demand	0.016	0.071		0.252 (0.252)		-0.177		
Population	0.028	0.123		0.438 (0.438)		-0.309		
Average HH size	-0.086	-0.385 (-0.356)						
Female driver proportion	0.484	0.163	0.609 (0.609)		-0.107		0.768	0.106
Dummy (1950–1983)						0.460 (0.460)		
R^2	0.72	0.36	0.48	0.26	0.05	0.31	0.36	0.03
Goodness-of-fit measures	$\chi^2 = 130.1$ (df = 52), goodness of fit index (GFI) = 0.76, normed fit index (NFI) = 0.76, comparative fit index (CFI) = 0.83, stability index (SI) = 0.08							

NOTE: Sociodemographic variables are first-order differenced (natural) log-transformed [i.e. $\log(X_t) - \log(X_{t-1})$]. All coefficients are standardized. Open coefficients indicate total effects; those enclosed in parentheses indicate direct effects (total effect = direct effect + indirect effect). Blank cells represent effects that are constrained to be zero in the model, for either conceptual or empirical (statistical insignificance or nonidentifiability) reasons. $N = 49$.

infrastructure in the current year. Logically, travel cost negatively affects travel demand and (indirectly) negatively affects telephone calls. As a cross price effect, it also indicates that travel and telecommunications are complements. Similar to the single-equation model results, however, telecommunications cost is not significant in the model. Additionally, land use and economic activity have positive impacts on both travel and telecommunications demand, with stronger effects on travel.

Both supply variables negatively affect the corresponding costs. It is logical that the lagged demand has a negative, although indirect, impact on the costs by increasing supply in the current year. The impact of telecommunications supply on telecommunications cost is captured by the joint effect of supply and a dummy variable equal to one for the years 1950–1983, with the latter serving to smooth out the abrupt effect of the 1983 divestiture of AT&T on telecommunications supply [see *Statistical Abstract of the United States* (18) for the supply time-series plots]. As hypothesized, the transportation infrastructure positively affects economic activity. That is, an increase in the transportation infrastructure can significantly contribute to economic

growth, by increasing the capacity for transporting goods and services. There are three significant sociodemographic variables. As expected, population positively affects demand and supply, and average household size negatively affects demand. Not surprisingly, the female driver proportion has a strongly positive impact on travel demand and supply as well as land use. This supports the expectation that the growth in the number of female drivers has significantly contributed to an increase in travel demand, resulting in an increase in supply and perhaps an acceleration of suburbanization due to the enhanced mobility of women. The first trend has also been identified in Nationwide Personal Transportation Survey results (24).

Structural Equation Model of Travel and Mobile Phone Subscribers

Table 4 presents the estimated, standardized causal effects among endogenous variables and between predetermined and endogenous variables for the final model of travel and mobile phones. The final

TABLE 4 Estimated Causal Effects Between Travel and Mobile Phone Subscriber Variables

RHS Variable	Endogenous Variables (LHS Variables)							
	Demand		Supply		Costs		Land Use	Economic Activity
	Travel	Telecom	Travel	Telecom	Travel	Telecom		
Endogenous variable								
Travel demand		0.043 (0.043)						
Transportation supply	0.943 (0.536)	0.055		0.018	-0.338 (-0.338)		1.255 (1.255)	0.167 (0.167)
Telecommunications supply (no. of cell sites)		0.779 (0.779)						
Travel costs	-0.160 (-0.160)	-0.007						
Land use	0.249 (0.249)	0.011						
Economic activity	0.246 (0.246)	0.096		0.110 (0.110)				
Predetermined variable								
1st lagged travel demand	0.083	0.005	0.088 (0.088)	0.002	-0.030		0.110	0.015
1st lagged telecom demand (no. of mobile phone subscribers)		0.161		0.207 (0.207)				
Average household size		-0.033 (-0.033)						
Female proportion of licensed drivers	0.601	0.035	0.637 (0.637)	0.012	-0.215		0.800	0.106
R^2	0.71	0.95	0.49	0.05	0.16		0.32	0.03
Goodness-of-fit measures	$\chi^2 = 75.5$ (df = 38), goodness-of-fit index (GFI) = 0.82, normed fit index (NFI) = 0.91, comparative fit index (CFI) = 0.95							

NOTE: Sociodemographic variables are first-order differenced (natural) log-transformed [i.e. $\log(X_t) - \log(X_{t-1})$]. All coefficients are standardized. Open coefficients indicate total effects; those enclosed in parentheses indicate direct effects (total effect = direct effect + indirect effect). Blank cells represent effects that are constrained to be zero in the model, for either conceptual or empirical (statistical insignificance or nonidentifiability) reasons. $N = 49$.

model is recursive (no feedback loop), in contrast to the previous model. Goodness-of-fit measures indicate that the model has a good fit. As mentioned earlier, there is no telecommunication cost equation in the model due to nonidentifiability.

For the causal effects in the model, it can be observed that travel demand has a positive impact on mobile phone demand, indicating a complementary relationship. That is, as travel increases, the number of mobile phone subscribers increases. This is certainly natural, because a main point of mobile phones is to use them while mobile. On the other hand, there is no significant effect of mobile phone demand on travel. Effects in either direction are plausible; mobile phones may increase travel by decreasing its disutility and by generating impromptu meetings requiring trips, but they may save travel by facilitating more efficient scheduling and routing of trips. At least during the time frame of this study (through the year 2000), the net effect of these two influences is apparently zero. But it will be interesting to continue to monitor this relationship over time. Further, it would be preferable to test the relationship with mobile phone calls or minutes instead of subscribers as the measure of demand, if those data should become available.

Most causal effects among demand, supply, costs, land use, and economic activity are similar to those in the previous model. There is also a positive lagged effect of travel demand on mobile phone supply, consistent with the hypothesis. As expected, economic activity positively affects mobile phone supply. This supports the well-established

principle that income (economic growth) positively affects demand and supply, as found in disaggregate studies (high-income people tend to travel and communicate more). Similarly, the female driver proportion strongly affects all categories.

CONCLUSIONS

This study explores the aggregate causal relationships between telecommunications and travel in a comprehensive framework, considering their demand, supply, and costs together with land use, economic activity, and sociodemographic variables. The data for this study (national time-series data in the United States, 1950–2000) come from secondary sources such as statistical reports published by trade organizations, government agencies, and other public agencies. First, based on a hypothesized conceptual model, composite indexes were developed for the endogenous variable categories (telecommunications and travel demand, supply, and costs; land use; and economic activity) by confirmatory factor analysis (retaining several single-variable “indexes” as well). Then, single-equation and structural equation models for telecommunications (telephone calls and mobile phone subscribers separately) and travel were estimated by using the composite indexes and sociodemographic variables. The estimated structural equation models support the hypothesized causal directions in the conceptual model. Among them, telephone calls and travel demand rela-

tionships are positive in both directions, but the relationship between mobile phone subscribers and travel demand is positive in only one direction (from travel to telecommunications). The authors suspect that there is also a positive impact in the converse direction, as for telephone calls, but that it is counteracted by a negative impact unique to mobile phones in particular: the ability of mobile phones to reduce travel through facilitating real-time, trip-in-progress efficiencies in routing and scheduling.

Causal effects of travel demand on telephone call demand are larger than those of the converse in the single-equation and structural equation models. Overall, these results suggest that the aggregate relationship between actual amounts of telecommunications and travel is complementarity, albeit asymmetric in directional weight. That is, as travel demand increases, telecommunications demand increases and (to a lesser extent) vice versa. This finding contrasts with that in the previous aggregate study of Selvanathan and Selvanathan (5), using consumer expenditures on communications and travel over time (see the Introduction), but it appears to be a faithful representation of observed trends in activity measures (instead of monetary measures) of the two concepts.

Furthermore, the final models show that transportation supply, a composite of variables such as lane miles and domestic airline seat miles (total effects = 0.80 and 0.94, respectively, in the two structural equation models), has a stronger impact than economic activity (total effects = 0.19 and 0.25) on travel demand. The effect of travel costs (a composite including gasoline price) on travel demand is relatively low (total effects = -0.25 and -0.16) but significant. Because the impact of telecommunications (telephone calls) demand on travel is non-negligible (total effect = 0.24), transportation planners should consider this effect in forecasting future travel demand. It is also recommended that telecommunications-related questions be added to national and regional travel-related (travel or activity diary) surveys.

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