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Telecommunications and travel demand and supply: Aggregate structural equation models for the US

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Abstract

Disaggregate studies of the impacts of telecommunications applications (e.g. telecommuting) on travel have generally found a net substitution effect. However, such studies have all been short-term and small-scale, and there is reason to believe that when more indirect and longer-term effects are accounted for, complementarity is the likely outcome. At least two aggregate studies have focused on the relationships between telecommunications and travel from economic perspectives (consumer and industry). However, both use the monetary value of consumption or transactions rather than actual activity measures (e.g. miles, number of calls), and neither fully explains the direct and indirect causal relationships between the two. The purpose of this study is to develop a conceptual model in a comprehensive framework, considering causal relationships among travel, telecommunications, land use, economic activity, and socio-demographics, and to explore the aggregate relationships between telecommunications and travel, using structural equation modeling of national time series data spanning 1950–2000 in the US. In this paper we focus on number of telephone calls as the measure of telecommunications, and passenger vehicle–miles traveled as the measure of transportation. Future research will investigate additional measures of these two constructs. Our empirical results strongly support the hypothesis that telecommunications and travel are complementary. That is, as telecommunications demand increases, travel demand increases, and vice versa. These results offer a more realistic picture to policy makers and transportation planners than has been available till now, and suggest useful directions for them to develop transportation or telecommunications strategies designed to reduce traffic congestion, air pollution, and energy consumption.
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Keywords: Telecommunications–travel relationships; Structural equations modeling; Induced demand; VMT (VKT) modeling

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1. Introduction

Transportation can be defined as the movement of people, goods, services, and information. Thus, a lot of travel is undertaken for the purpose of exchanging information (Salomon, 1986). Similarly, advanced telecommunications technologies including information technology and telematics (referring to systems and services linking computers and devices using telecommunications) can allow a large amount of information to be transmitted over a telecommunications network. Such technologies have moved our society from the Industrial Era to the "Information Age" and changed people's daily lifestyles as well as travel behavior. As such, transportation and telecommunications have in common the characteristic that both are means of sharing information among people, and for that reason they are also closely interrelated with each other as substitutes and/or complements.

For the past five decades, the use of telephones in the US has rapidly increased. Looking at the number of local telephone calls, on average 14 calls were made by households every day in 2000, which is nearly five times higher than in 1950 (FCC, 2002). Similarly, passenger car vehicle–miles traveled (VMT) were 2534 billion miles in 2000, which means a household drives 66 miles per day. The VMT per household is almost three times higher than that in 1950 (FHWA, 2002). Those trends simply show that telecommunications and travel both increase over time. But what type of relationship exists between telecommunications and travel over time? Are there any causal relationships between the two indicators? Or, do those trends come from third-party correlation effects (such as with economic and demographic factors)?

A number of studies (Salomon, 1986; Harkness, 1977; Mokhtarian, 1990, 2000, 2002; Mokhtarian and Salomon, 2002; Niles, 1994) have identified the potential relationships between telecommunications and travel: substitution (reduction, elimination), complementarity (stimulation, generation), modification (change time, mode, destination, and so on with respect to a trip or communication that would have occurred otherwise), and neutrality (no impact of one medium on the other, e.g. as many e-mail messages have no impact on travel and conversely). However, those studies of the relationships between telecommunications and travel tend to be conceptual, suggestive, and speculative without empirical analysis. Further, they generally fail to place telecommunications and travel within a more comprehensive framework, considering other factors such as the economy, land use, and socio-demographics.

In addition, numerous empirical studies have been conducted at the disaggregate level, focused on the impacts of specific telecommunications applications, especially telecommuting, on travel. Those studies demonstrate a net impact of substitution by telecommuting (see Mokhtarian et al., 1995; Mokhtarian, 1998; Nilles, 1988). However, Mokhtarian and Meenakshisundaram (1999) argued that since all those studies were short-term and small-scale, they will underestimate complementary effects by failing to consider the more indirect and longer-term relationships (such as induced demand and residential location effects). One way to partially overcome this shortcoming is through aggregate studies, which broaden the scope of inquiry beyond a small self-selected sample focusing on a single application, in the short run. To date, however, only a few aggregate studies on this subject (reviewed in the following section) have been carried out. It is noteworthy that none of these studies fully explain the direct and indirect causal relationships between the actual demand for travel and telecommunications.

Further, to our knowledge, no studies have explored the aggregate relationships between physical (as opposed to economic) measures of passenger travel and telecommunications, assessing the extent of causality by accounting for other variables that can be expected to influence both. The distinction is important because the relationship of the monetary value of consumption or transactions (as an economic measure) to the actual level of travel and telecommunications may change over time, and thus the true relationship between telecommunications and travel may be obscured by focusing purely on economic measures.

The purpose of this study is to develop a conceptual model in a comprehensive framework, considering causal relationships among travel, telecommunications, land use, economic activity, and socio-demographics, and to explore the aggregate relationships between telecommunications and travel (in this paper, specifically between VMT and local telephone calls), using structural equation modeling of national time series data spanning 1950–2000 in the US. Identifying the causal relationships can provide valuable information on system-wide flows and the impacts of both telecommunications and travel. Such results will offer a more realistic picture to policy makers and transportation planners than has been possible with the limited results to date, and may suggest useful directions for them to develop transportation or telecommunications strategies designed to reduce traffic congestion, air pollution, and energy consumption.

The organization of this paper is as follows. The following section discusses key literature providing empirical results at the aggregate level. The next two sections present the conceptual model and methodology, respectively. Then, we describe the data used for this study and present the model results. Finally, conclusions are discussed.

2. Literature review

Our study focuses on aggregate relationships between telecommunications and travel. Here, we briefly discuss findings of aggregate empirical studies between the two. Among the few aggregate empirical studies conducted to date, two are especially worthy of mention. They both take economic perspectives, but focus on different aspects of the subject.

Selvanathan and Selvanathan (1994) estimated a simultaneous equation system (a Rotterdam demand system) of the consumer demand (in terms of per capita consumption expenditures) for four kinds of goods: private transportation, public transportation, communications, and all others. They used 1960–1986 time series data from Australia and the United Kingdom, and found that private transportation, public transportation, and communications have a pairwise substitution relationship, showing all positive cross-price elasticities among those three (meaning that an increase in the price of one kind of good increases the consumption of the other kinds).

Plaut (1997) identified the relationship between transportation and communication services in industry for nine countries of the European Community in 1980, emphasizing that about two thirds of all expenditures on transportation and communication services are made by industry rather than by end consumers. Using input–output analysis, this study examined the correlations of the input coefficients for transportation and communication, across all industrial sectors (classified into 44 categories). These correlations were predominantly positive, indicating complementarity. That is, as communications inputs to a given industry category are high, transportation inputs also tend to be high, and vice versa. However, this approach cannot explain the relationship between transportation and communication on a sector-by-sector basis due to the use of contemporaneous data only (i.e. the correlation must be taken across sectors; it is not possible to obtain a separate value for each sector). This is a limitation, since it is obvious that such a relationship varies by sector and over time. These two studies show opposite relationships between transportation and communication, but these results are likely to come from different methodologies and data characteristics: time series versus cross-sectional data, and consumer versus industrial sectors. Nonetheless, they neither explain the causal relationship between transportation and communication, nor measure demand effects in units capturing quantities of actual travel and telecommunications, rather than simply expenditures. That is, how many *miles* would be reduced (generated) due to a one-unit decrease (increase) in consumer (industrial) expenditure on transportation prompted by the use of telecommunications?

Most recently, another aggregate study has been conducted for a particular telecommunications application, teleworking. Choo et al. (2002, 2005) explored the impact of teleworking (measured by number of telecommuters) on transportation (in terms of vehicle–miles traveled and airline passenger miles traveled), using a two-stage multivariate time series analysis of 1966–1999 nationwide data (1988–1998 data for teleworking) in the US. They found that teleworking appears to reduce VMT (by an amount as little as 0.34% of the observed VMT in 1998) with 94% confidence, while teleworking has no impact on airline PMT. Those results indicate that to some extent teleworking has a net substitution effect on travel, although the teleworking time series is very short, and probably not very accurate. Since it focused only on a single direction of causality (teleworking $\rightarrow$ distance traveled), this study does not fully explore the causal relationships between teleworking and travel, but shows an association between the two.

Thus, the true causal relationships between actual amounts of telecommunications and travel at the aggregate level over time have not yet been fully explored. Remedying that deficiency is the purpose of the present study.

3. Conceptual model

Several studies (e.g. Giuliano and Gillespie, 1997; Graham and Marvin, 1996) have suggested various complex relationships among telecommunications, urban patterns (land use), economic activity, and travel. Mokhtarian (1990) emphasized the relationships between the demand and supply of both telecommunications and travel. In this section, we synthesize these and other hypothesized relationships into a comprehensive conceptual model, to our knowledge the most complete model of its kind. In this study, we focus on the consumer's rather than industry's point of view, and on passenger travel, not goods movement.

The conceptual model appears in Fig. 1, in which a shaded rectangle represents categories of endogenous variables and the white rectangle the category of exogenous variables. The model comprises eight endogenous variable categories (travel and telecommunications demands, transportation and telecommunications system infrastructures, land use, travel and telecommunications costs, and economic activity) and one exogenous variable category (socio-demographics). Each variable category consists of a set of key individual variables, but here those individual variables are not discussed in detail. An arrow indicates the direction of a hypothesized relationship. The major relationships in the conceptual model are discussed below in terms of logical groupings based on the economics and transportation literatures.

3.1. Demand, supply, and costs

- *Travel Demand* $\Longleftrightarrow$ *Telecommunications Demand*: It is hypothesized that travel demand and telecommunications demand have a bi-directional causality. In general economic theory, two commodities can be related to each other as substitutes, complements, or independents. For example, suppose that as the price of one commodity decreases, the demand for that commodity increases, but the demand for the other one decreases. Then, the commodities have a substitute relationship. However, if the demand for the other one also increases, then the commodities are complementary. On the other hand, if the demand for the other one does not change, then the commodities are independent. Based on those concepts, the relationships between telecommunications and travel have often been classified into two broad categories: substitution

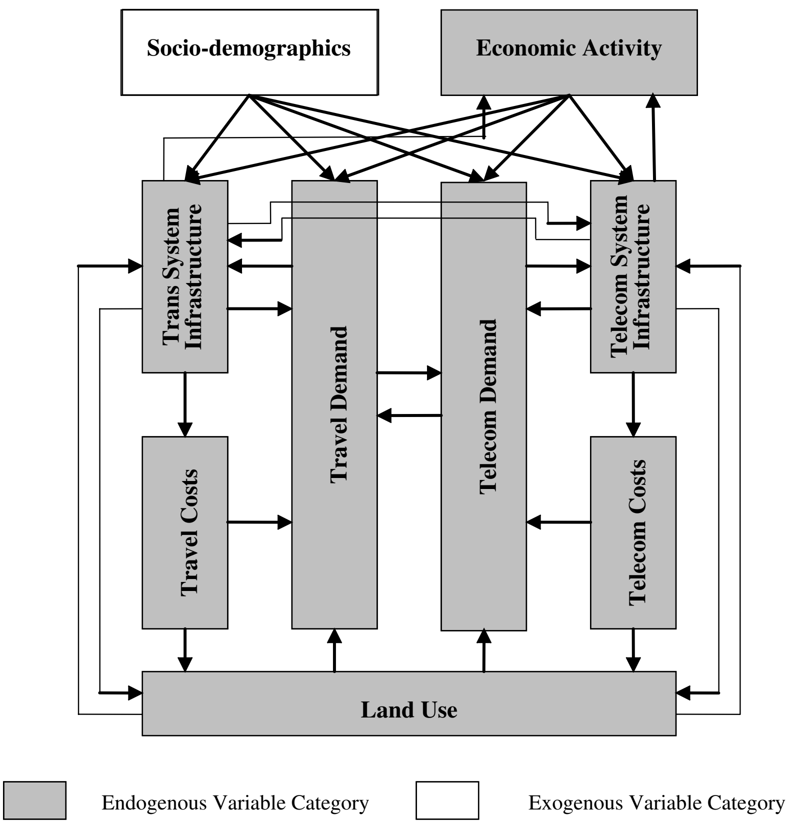

Fig. 1. Conceptual model of telecommunications and travel relationships.

and complementarity (e.g. Salomon, 1986; Mokhtarian, 1990). That is, as the demand for telecommunications increases, the demand for travel decreases (or increases), and vice versa.

- *Travel (Telecommunications) Demand* $\Longleftrightarrow$ *Transportation (Telecommunications) System Infrastructure*: A bi-directional causality can be hypothesized between demand and supply. Historically, as the demand for travel has increased, the supply of travel such as highways has increased to accommodate the additional demand. The same has been true for telecommunications. In the other direction, as the literature on induced demand (e.g. Goodwin, 1996; Noland, 2001; Hansen and Huang, 1997; TRB, 1995) has pointed out, increased highway capacities can stimulate auto travel, resulting in the increase of travel demand. Interestingly, using 1973–1990 time series data on VMT and lane miles for state highways in California, Hansen and Huang (1997) found that VMT is strongly related to the second- or fourth-order lagged variables of lane miles at the county and metropolitan levels, respectively. This suggests that some lagged effects of lane miles on VMT may be considered in the empirical model. Similar to travel, it is obvious that adding to the telecommunications network affects the demand for telecommunications: for example, as the telephone network is extended to a particular area, a number of calls to and from the area will be generated.
- *Transportation System Infrastructure* $\Longleftrightarrow$ *Telecommunications System Infrastructure*: It is hypothesized that the causality between travel supply and telecommunications supply is bi-directional. Mokhtarian (1990) identified such relationships: for example, new fiber optic networks are heavily dependent on rights-of-way of transportation facilities (such as railroads and subways); and telecommunications applications such as Intelligent Transportation System (ITS) technologies increase or improve the existing highway capacities (Costantino, 1992). For example, real-time traffic information can reduce traffic congestion on highways and increase their levels of service.
- *Travel (Telecommunications) Costs* $\Rightarrow$ *Travel (Telecommunications) Demand*: Obviously, travel costs negatively affect the demand for travel. That is, as travel costs increase, the demand for travel decreases. Typically, aggregate travel demand models such as the direct demand model have included travel times and costs, and demographics as well as land use characteristics as key explanatory variables (Small and Winston, 1999). In addition, most travel demand models in gasoline studies found that VMT is significantly negatively related to gasoline price (e.g. Dahl, 1986). Similarly, telecommunications costs affect the demand for telecommunications. For example, as the prices of telephone calls decrease, the number of telephone calls increases.
- *Transportation (Telecommunications) System Infrastructure* $\Rightarrow$ *Travel (Telecommunications) Costs*: 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 transportation supply can reduce travel costs (by decreasing travel times). Telecommunications has the same effect on its cost. Once a telephone network is built, the marginal cost of connecting a telephone at home is lower. Hence, it is hypothesized that transportation (telecommunications) infrastructure negatively affects travel (telecommunications) costs.

3.2. Demand, supply, and land use

- *Land Use* $\Rightarrow$ *Travel (Telecommunications) Demand*: It is hypothesized that land use affects travel demand and telecommunications demand. As numerous studies (e.g. Cervero and Landis, 1996; Gordon and Richardson, 1997; Pickrell, 1999) have characterized 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 commute as well as non-work trips. Also, land use can affect telecommunications demand. For example, the farther apart that family members live, the more they call instead of visit each other.
- *Transportation (Telecommunications) System Infrastructure* $\Longleftrightarrow$ *Land Use*: Cervero and Landis (1996) argued that investments in transportation strongly influence urban structures such as land use patterns, population densities, and housing prices. In fact, highway construction has been accelerating suburbanization, providing higher accessibilities to urban areas. The telecommunications system infrastructure can also allow for people to obtain information by phone or fax at a distance, so the necessity to live in urban areas potentially decreases. Gordon and Richardson (1997) pointed out that telecommunications have created benefits of agglomeration over areas of greater extent, at least partly avoiding congestion costs. The other

direction is also plausible. Suburbanization can necessitate more telecommunications and transportation system infrastructures to enhance accessibilities and connections to central cities. Thus, it is hypothesized that both infrastructures affect land use, and vice versa.

- *Travel (Telecommunications) Costs ⇒ Land Use*: In addition to relatively low gasoline prices, transportation markets and policies have failed to make drivers pay for their external costs such as those due to air pollution, traffic accidents, and congestion. Such lower driving costs have magnified the personal benefits of living in suburbs. On the other hand, advanced telecommunications technologies as well as growth in the number of telecommunications service providers have rapidly decreased telecommunications costs. For example, decreases in telecommunication costs can 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. These phenomena gave rise to the noted (albeit disputed) phrase 'the death of distance' (Cairncross, 2001). Hence, it can be hypothesized that travel and telecommunications costs affect land use, especially over the long-term.

3.3. Demand, supply, economic activity, and socio-demographics

- *Transportation (Telecommunications) System Infrastructure ⟺ 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. For example, Keane (1996) found that a 10% increase in investment in highway infrastructure gives rise to a 4% increase in national output, using a production function; and that the total employment effect is estimated at up to 42,100 jobs per one billion dollars of investment in highway infrastructures, using input–output analysis. Similarly, Novak and McDonald (1998) contended that ITS-related investment has potential impacts on the economy: direct employment, economic multiplier, national productivity gains, technological spin-offs, and competitiveness. On the other hand, it is clear that the higher the gross domestic product (GDP), the more federal funds that are available for highway investments. Thus, a bi-directional causality can exist between transportation system infrastructure 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. Saunders et al. (1994) argued that investment in telecommunication systems can provide more timely information on the availability and price of goods and services in commerce, and coordinate various industrial activities with regard to supplies, stocks, labor, and delivery, resulting in increased efficiencies of service and higher productivity. Also, actors in a growing economy are more likely to invest in expanding telecommunications system infrastructures to get information faster. Therefore, telecommunications system infrastructure and economic activity can have a bi-directional causality.
- *Economic Activity ⇒ Travel (Telecommunications) Demand*: Numerous studies of VMT (e.g. Choo et al., 2005; Greene, 1992) have found that economic activity (as measured by indicators such as GDP and gross national product) significantly positively affects travel demand. Schafer (1998) 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. At the disaggregate level, numerous studies using travel diary data have established that higher-income individuals or households generate more and longer trips. On the other hand, it is also evident that the higher the income, the greater the affordability of telecommunications equipment (such as computers or mobile phones) and the higher the telecommunications demand. Hence, economic activity can affect both travel and telecommunications demand.
- *Socio-demographics ⇒ Travel (Telecommunications) Demand*: Socio-demographic variables (such as population, number of drivers, household size, and number of households) have long been considered key elements of traditional travel demand models. Similarly, population, number of households, and household size can strongly affect telecommunications demand: for example, the more households, the more telephone calls. Consequently, it is hypothesized that socio-demographics affect both travel and telecommunications demand.
- *Socio-demographics ⇒ Transportation (Telecommunications) System Infrastructure*: In principle, socio-demographic factors indirectly affect supply through demand. Many single-equation models of supply, however, allow for direct impacts of socio-demographic characteristics because there is no other way to

account for them in a single equation. If socio-demographic impacts are indeed entering only through their effect on demand, and if variables and equations are perfectly specified, then there should be no need for this link. But, in fact there may be direct linkages aside from the indirect one through demand, and so we test for this link.

4. Methodology

In the previous section, the conceptual model of telecommunications and travel was discussed, and each causal relationship between variable categories in the model was hypothesized to be either bi-directional or unidirectional. In general, structural equation modeling (SEM) is a powerful technique for analysis of causal relationships among endogenous variables, and between endogenous and exogenous variables. For example, SEM can give better estimates for bi-directional causal relationships without the bias inherent to ordinary least squares methods; SEM can give coefficients for direct (e.g. $X \rightarrow Y_2$), indirect (e.g. $X \rightarrow Y_1 \rightarrow Y_2$), and total (direct plus indirect) effects of variables on each other; and SEM can deal with many types of variables including linear, non-linear, and latent variables. Simultaneous equation modeling is a subset of structural equation modeling under the special case of no measurement errors, i.e. no latent variables and no measurement model. Specifically, if a structural equation system is linear (i.e. all variables in the model are continuous and all relationships are linear) without measurement errors, the results of structural equation modeling are identical to those of simultaneous equation modeling, although the former results are estimated using covariance structure analysis (e.g. maximizing the likelihood of obtaining the observed sample covariance structure) and the latter by maximizing the likelihood of obtaining the sample observations themselves (Jöreskog, 1973).

Numerous studies using SEM methods have been conducted on travel demand and travel behavior (see Golob, 2003). In this study as well, the structural equation modeling method is employed, on time-series data, to estimate the causal relationships in the conceptual model. Because our 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 non-stationary (i.e. display a trend over time) in their raw forms, so we first-order differenced the natural log-transformed form (e.g. $\log[X_t] - \log[X_{t-1}]$) of each series to achieve stationarity. Lagged endogenous and exogenous variables can be included in the model, considered (together with contemporaneous exogenous measures) to be pre-determined variables. Then, all equations in the system can be estimated simultaneously. The conceptual model shown in Fig. 1 and discussed in the previous section can be expressed in structural equation form, for year t, as:

$$\Delta\log[\mathrm{TD}_t] = f(\Delta\log[\mathrm{TED}_{t-k}], \Delta\log[\mathrm{TS}_{t-k}], \Delta\log[\mathrm{TC}_{t-k}], \Delta\log[\mathrm{LU}_{t-k}], \Delta\log[\mathrm{EC}_{t-k}], \Delta\log[SD_{t-k}], \varepsilon_{\mathrm{TD},t,})$$
$$\Delta\log[\mathrm{TED}_t] = f(\Delta\log[\mathrm{TD}_{t-k}], \Delta\log[\mathrm{TES}_{t-k},], \Delta\log[\mathrm{TEC}_{t-k}], \Delta\log[\mathrm{LU}_{t-k}], \Delta\log[\mathrm{EC}_{t-k}], \Delta\log[\mathrm{SD}_{t-k}], \varepsilon_{\mathrm{TED},t})$$
$$\Delta\log[\mathrm{TS}_t] = f(\Delta\log[\mathrm{TD}_{t-k}], \Delta\log[\mathrm{TES}_{t-k}], \Delta\log[\mathrm{LU}_{t-k}], \Delta\log[\mathrm{EC}_{t-k}], \Delta\log[\mathrm{SD}_{t-k}], \varepsilon_{\mathrm{TS},t})$$
$$\Delta\log[\mathrm{TES}_t] = f(\Delta\log[\mathrm{TED}_{t-k}], \Delta\log[\mathrm{TS}_{t-k}], \Delta\log[\mathrm{LU}_{t-k}], \Delta\log[\mathrm{EC}_{t-k}], \Delta\log[\mathrm{SD}_{t-k}], \varepsilon_{\mathrm{TES},t})$$
$$\Delta\log[\mathrm{TC}_t] = f(\Delta\log[\mathrm{TS}_{t-k}], \varepsilon_{\mathrm{TC},t})$$
$$\Delta\log[\mathrm{TEC}_t] = f(\Delta\log[\mathrm{TES}_{t-k}], \varepsilon_{\mathrm{TEC},t})$$
$$\Delta\log[\mathrm{LU}_t] = f(\Delta\log[\mathrm{TS}_{t-k}], \Delta\log[\mathrm{TC}_{t-k}], \Delta\log[\mathrm{TES}_{t-k}], \Delta\log[\mathrm{TEC}_{t-k}], \varepsilon_{\mathrm{LU},t})$$
$$\Delta\log[\mathrm{EC}_t] = f(\Delta\log[\mathrm{TS}_{t-k}], \Delta\log[\mathrm{TES}_{t-k}], \varepsilon_{\mathrm{EC},t})$$

where

TD = travel demand variables,
TED = telecommunications demand variables,
TS = transportation system infrastructure variables,
TES = telecommunications system infrastructure variables,
TC = travel cost variables,
TEC = telecommunications cost variables,
LU = land use variables,
EC = economic activity variables,

SD = socio-demographic variables,
ε = error term,
k = Lag $(0, 1, 2, \ldots)$, and $\Delta\log[X_t] = \log[X_t] - \log[X_{t-1}]$.

5. Empirical analyses

5.1. Data

Due to the scope (national level) of this study, the data for this analysis, specifically time series data, comes from secondary sources, usually collected by trade organizations, government agencies, or other public agencies. Considering the most appropriate representatives of a conceptual category as well as data availability, key variables are selected for each category. The variables are also included that appear most often in the models of travel and telecommunications identified in the literature review. All variables are time series data at the nationwide level, ranging from 1950 to 2000. Table 1 presents the key variables and their sources.

All data are based on the 50 US states and the District of Columbia. Vehicle-related data (e.g. VMT, MPG) are classified by vehicle type (car, truck, and all motor vehicles), and calculated by the Federal Highway Administration (FHWA). The car category is the only one used in this study; it includes passenger cars,

Table 1
Key variables for each category

Category	Key variables	Data sources
Travel demand	Vehicle–miles traveled (VMT)	Federal Highway Administration (*Highway Statistics*)
Transportation system infrastructure	Lane miles (urban areas) Lane miles (rural areas)	Federal Highway Administration (*Highway Statistics*)
Travel costs	Real (inflation-adjusted) gasoline price[a] Consumer price indices (CPI) for all, transportation, and private transportation[b] Fuel efficiency (miles per gallon, MPG)	Energy Information Administration (*Annual Energy Review*), US Government Printing Office (*Economic Report of the President*)
Telecommunications demand	Number of local telephone calls	Federal Communications Commission (*Statistics of Communications Common Carriers*, *Trends in Telephone Service*)
Telecommunications system infrastructure	Number of telephone access lines (residential and business lines) Telephone wire length	Federal Communications Commission (*Statistics of Communications Common Carriers*)
Telecommunications costs	Consumer price index (CPI) for local telephone calls[b]	Federal Communications Commission (*Trends in Telephone Service*)
Land use	Metropolitan and suburban populations Ratio of suburban population to total metropolitan population	US Census Bureau (*Statistical Abstract of the United States*)
Economic activity	Real gross domestic product (GDP)[a] Real disposable personal income[a] Employment/Unemployment Federal Reserve Bank (FRB) interest rate (discount rate) Female proportion of the labor force	US Government Printing Office (*Economic Report of the President*), Bureau of Labor Statistics (*Monthly Labor Review*), Bureau of Economic Analysis
Socio-demographics	Population Number of licensed drivers Number of households Average household size	US Census Bureau (*Statistical Abstract of the United States*), Bureau of Labor Statistics (*Monthly Labor Review*), Federal Highway Administration (*Highway Statistics*)

Notes: For the data sources, names of statistical reports appear in parentheses. Recent data can be found on the websites of the government agencies.
[a] Chained 1996 dollars.
[b] For all urban consumers, 1996 = 100.

motorcycles, and other 2-axle 4-tire vehicles such as vans, pickup trucks, and sport utility vehicles. Prior to 1966, the "other 2-axle 4-tire vehicle" category was included under the "single unit truck" category. Thus, for 1950–1965, we estimated the VMT proportion that the other 2-axle 4-tire vehicle category comprised out of the total single unit truck category, by regressing time on the proportions based on the VMT data of 1966–2000 and applying the estimated coefficient to the earlier data. We then combined that estimated proportion of other 2-axle 4-tire VMT with the passenger car/motorcycle VMT to make the definition of the car category consistent across the entire study period.

In the present study, we take number of local telephone calls as our measure of telecommunications demand. Local calls have been less affected by the court-ordered divestiture of AT&T in 1984 than toll calls have been, and their data are more reliable over time. Besides, toll calls comprise only 3–16.5% of total domestic calls during the study period (1950–2000). Future analyses, however, will explore the use of other measures of telecommunications demand.

5.2. Model estimation

In general, structural equation modeling is a confirmatory approach rather than an exploratory one, so the set of variables included in a structural equation model strongly depends on the conceptual model. In this study, however, we also examined single equation models for each endogenous variable as a function of other endogenous and exogenous variables, including lagged variables. This approach, while not definitive, is likely to identify any important missing variables in the structural equation model specification. Using this approach with the conceptual model, we refined our initial model specifications. Based on the first-order differenced log-transformed data, the AMOS module of the SPSS software package (Arbuckle and Wothke, 1999) was employed to estimate the structural equation models in this study, using maximum likelihood estimation.

Our sample size of 49 (after differencing and allowing one-year lags) is so small that the conceptual model may not be estimable with more than 20 parameters. Further, with eight endogenous categories and only one exogenous category (an eight-equation system), the parameters of the SEM might not be statistically identifiable (i.e. having unique best estimates) – the more exogenous variables in a model, the easier it is to achieve identifiability. In view of these limitations, we tested a nested series of constrained alternatives of the conceptual model, by successively restricting more and more (ideally endogenous) variables to be exogenous. As shown in Table 2, the models tested are named demand, demand/supply, demand/supply/cost, demand/supply/cost/land-use, and full models according to the variable categories that are treated as endogenous. For example, only travel and telecommunications demand variables are endogenous in the demand model, whereas demand and system infrastructure variables for travel and telecommunications are also endogenous in the demand/supply model.

A number of different model specifications for each alternative were tested. Any models including travel cost equations use CPI for personal transportation as the endogenous variable in their equations, instead of gasoline price, because gasoline prices are heavily affected by external factors (e.g. Organization of Petroleum Exporting Countries' market and domestic gasoline tax polices) as well as by transportation demand and supply. Instead, gasoline price is included in the travel cost equations as an exogenous variable influencing the

Table 2
Alternative structural equation systems for estimation

Alternatives	Variable category								
	Travel demand	Trans system	Travel costs	Telecom demand	Telecom system	Telecom cost	Land use	Economic activity	Socio-demographics
Demand model	•			•					
Demand/Supply model	•	•		•	•				
Demand/Supply/Cost model	•	•	•	•	•	•			
Demand/Supply/Cost/ Land Use model	•	•	•	•	•	•	•		
Full model	•	•	•	•	•	•	•	•	

Note: • = endogenous category, blank = exogenous category.

CPI for personal transportation, to explore its indirect impacts on other endogenous variables. Some relationships that are hypothesized in the conceptual model could not be included in the most complex models shown in Table 2 due to non-identifiability and/or multicollinearity. The population variable did not come into the models because it is highly correlated with the suburbanization variable ($r = 0.87$). In lieu of the population, the household size variable (calculated by population/number of households) was allowed to enter the models. Among the five models shown in Table 2, only the most complicated (full) model is presented here. The model retains a few variables with lower significance (but always p-value = 0.3 or better) because of the small sample size and the exploratory nature of the study. This is consistent with the advice given in Horowitz et al. (1986) for retaining policy-relevant variables in discrete choice models if their t-statistics are greater than 1 in magnitude.

5.3. Model results

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 personal vehicle travel (VMT) and local telecommunications (number of local telephone calls). Goodness-of-fit measures such as the goodness of fit index (Jöreskog and Sörbom, 1984, the closer to one the better), normed fit index (Bentler and Bonett, 1980, the closer to one the better) and comparative fit index (Bentler, 1990, the closer to one the better) indicate that the model has a moderate fit (all indices are greater than 0.7), considering the small sample size, although the χ^2 statistic (the smaller the better) is relatively high. However, 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 two (Ullman, 1996). The ratio of the model is 138/77 = 1.8, indicating a good fit using this rule. In addition, the stability index (Bentler and Freeman, 1983, a measure of stability for a *non-recursive* linear structural equation model in which feedback loops exist) for the model lies between −1 and 1: that is, the model is stable and converges properly. We discuss the casual effects among variables for the model below.

The final model is non-recursive, having a feedback loop between VMT and local calls, and the R^2s (squared multiple correlations) for the travel and telecommunications demand equations are a respectable 0.42 and 0.37, respectively. The average R^2 of the model, representing the proportion of total variance in all the endogenous variables that is explained by the system of equations, is 0.33.

For the causal effects among endogenous variables, both VMT and number of local telephone calls positively significantly affect each other. That is, as VMT increases, number of local telephone calls increases, and vice versa. This strongly indicates that the relationship between telecommunications and travel is complementarity, not substitution. Interestingly, the magnitude of the total effect of the local telephone calls on VMT is higher than that in the other direction. Thus, far from replacing travel, telecommunication appears to be vigorously stimulating it. This is not surprising in view of the central role of the telephone in facilitating economic and social activity in general, and face-to-face meetings (requiring travel) in particular.

Lane miles and its one-year lag have a positive impact on VMT, indicating an induced demand effect, albeit a relatively inelastic one. Their elasticities ($d\log[Y_t/Y_{t-1}]/d\log[X_t/X_{t-1}]$) of VMT are 0.28 and 0.05 (unstandardized coefficients of the model, see Appendix C in Choo, 2004), respectively. Thus, in this model increased highway capacities in both current and previous years lead to more auto travel. Specifically, a 10% increase in lane miles in the current (previous) year appears to generate a 2.8% (0.5%) increase in VMT. As discussed before, a number of studies on induced demand have found similar relationships, although using single equation approaches.[1]

As expected, two travel cost variables, CPI for private transportation and gasoline price, have negative total impacts on VMT, and GDP as an income factor has a positive impact on VMT. It is also found that other measures of economic activity (the Federal Reserve Bank (FRB) interest rate, unemployment rate and female proportion of the labor force) significantly affect travel demand in the logical ways. These results support our hypotheses that the higher the economic activity the higher the travel demand, and the higher the travel costs the lower the travel demand. Likewise, telecommunications supply and cost variables, as well as economic

[1] These studies show regional VMT elasticities relative to lane miles of 0.1–0.9 in the short-term and 0.5–1.0 in the long-term.

Table 3
Estimated causal effects among variables in full model ($N = 49$)

RHS variables	Endogenous variables (LHS variables)							
	Demand		System infrastructure		Costs		Land use	Economic activity
	Travel	Telecom	Trans	Telecom	Travel	Telecom		
Endogenous variables								
Travel demand: VMT	0.075	0.246 (0.229)						
Telecom demand: local telephone calls	0.329 (0.306)	0.075						
Transportation system: lane miles (urban areas)	0.377 (0.293)	0.086			−0.218 (−0.218)			
Telecom system: total wire length	0.108	0.354 (0.297)				−0.273 (−0.273)		
Travel costs: CPI for private transportation	−0.286 (−0.266)	−0.066						
Telecom costs: CPI for local telephone calls	−0.038	−0.124 (−0.115)						
Land use: suburbanization rate	0.177 (0.165)	0.041						
Economic activity: GDP	0.398 (0.370)	0.091						
Predetermined variables								
1st lagged travel demand	0.199	0.046	0.527 (0.527)		−0.115			
1st lagged telecom demand	0.031	0.100		0.282 (0.282)		−0.077		
1st lagged trans system	0.065	0.015					0.147 (0.147)	0.097 (0.097)
Gasoline price	−0.176	−0.040			0.617 (0.617)			
FRB interest rate	−0.150	−0.034	−0.398 (−0.398)		0.087			
Unemployment rate	−0.328	−0.075						−0.824 (−0.824)
Female proportion of the labor force	0.029	0.094		0.265 (0.265)		−0.072		
Average HH size	−0.102	−0.334 (−0.310)						
R^2 (average $R^2 = 0.33$)	0.42	0.37	0.31	0.22	0.47	0.07	0.02	0.72
Goodness of fit measures	$\chi^2 = 137.9$ (df = 77), goodness of fit index (GFI) = 0.78, normed fit index (NFI) = 0.72, comparative fit index (CFI) = 0.84, stability index (SI) = 0.07							

Notes: All variables are (natural) log-transformed first-order differenced (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 non-identifiability) reasons.

activity variables, have the same impacts on its demand. Thus, total telephone wire length positively affects number of local telephone calls, and CPI for local telephone calls negatively affects the number of local telephone calls.

A socio-demographic variable, average household size, is significant in the model for telecommunications and travel demand. It makes sense that this variable negatively affects number of local telephone calls because a smaller household size indicates a larger number of households. Logically, the land use variable, suburbanization rate, positively affects VMT, because suburban residents have longer commute distances than those in central cities.

In addition, many indirect causal effects are found in the model, which are logical, although their magnitudes are smaller than the direct impacts of other variables on VMT and local telephone calls. For example, telephone wire length indirectly positively affects VMT. That is, as telephone supply increases, local calls increase, and then VMT increases. Thus, this effect illuminates chained causal effects between telecommunications supply and travel demand. Also, the negative cross effects of prices (i.e. the impacts of CPI for private transportation and gasoline price on number of local telephone calls, and those of CPI for local calls on VMT), although indirect, offer further evidence that telecommunications and travel are complements.

Looking at the supply equations in the model, it is plausible that total wire length and lane miles are positively affected by the lagged number of local telephone calls and VMT, respectively, instead of their contemporaneous counterparts. In other words, transportation and telecommunications systems are infrastructures, so they cannot be immediately supplied in response to increased demand, unlike other manufactured goods in the market. In addition to demand variables, transportation and telecommunications supply are affected by economic activity factors. It is natural that the FRB interest rate has a negative impact on lane miles because a higher interest rate discourages expensive investments in transportation infrastructure. Additionally, the more females in the labor force (an indicator of economic growth) the more extensive the telephone infrastructure. However, no causal relationship between telecommunications and transportation supply could be found. This indicates that expanding lane miles has no significant impact on adding telephone wires.

As discussed before, this model employed CPI for private transportation as the endogenous variable in the travel cost equation, and gasoline price was included in the equation as an exogenous variable influencing CPI for private transportation. As hypothesized, the supply variables negatively affect the cost variables in telecommunications and transportation. Logically, the lagged travel and telecommunications demand variables indirectly negatively affect their corresponding cost variables. That is, as VMT and local calls in the previous year increase, their current infrastructures increase, and then travel and telecommunications costs decrease. The FRB interest rate has a similar indirect effect on travel cost through its effect on transportation supply.

In the GDP equation, the unemployment rate variable, indicating the status of the economy, was included as an exogenous variable to explore its impact on other endogenous variables. Of course, it negatively affects travel and telecommunications demand. As hypothesized, the lagged lane mile variable, an indicator of transportation supply, positively affects suburbanization rate and GDP.

6. Conclusions

This study first presents a conceptual model considering causal relationships among travel, telecommunications, land use, economic activity, and socio-demographics. To our knowledge, this is the first time a model incorporating all these categories has been developed. Then, based on the conceptual model, we explore the aggregate relationships between telecommunications (specifically, number of local phone calls) and travel (passenger VMT) in a comprehensive framework, using structural equation modeling of national time series data (1950–2000) in the US. The data for this study comes from secondary sources such as statistical reports published by trade organizations, government agencies, or other public agencies.

Due to the small sample size and large ratio of endogenous to exogenous variables, we tested several alternatives of the conceptual model as well, restricting some of the endogenous variable categories to be exogenous. Ultimately, the full model was successfully estimated, although some causal links could not be identified. Based on the model, the path diagram in Fig. 2 shows the identified causal directions of the model, compared to the conceptual model. All estimated causal directions including indirect effects are consistent with our hypotheses.

The model shows that system-wide net effects between telecommunications and travel are positive in both directions, indicating that the aggregate relationship between telecommunications and travel is complementarity. That is, as telecommunications demand increases, travel demand increases, and vice versa.

Furthermore, travel cost variables, gasoline price and CPI for private transportation, significantly negatively affect VMT. This supports the conventional wisdom that any policy strategy related to increasing gasoline prices can help reduce VMT. We also find a large induced demand effect in this equation system: the total effect of urban lane-miles on VMT is among the strongest influences on travel or telecommunications demand, second only to the effect of GDP on VMT (with the impact of telecommunications demand on VMT coming

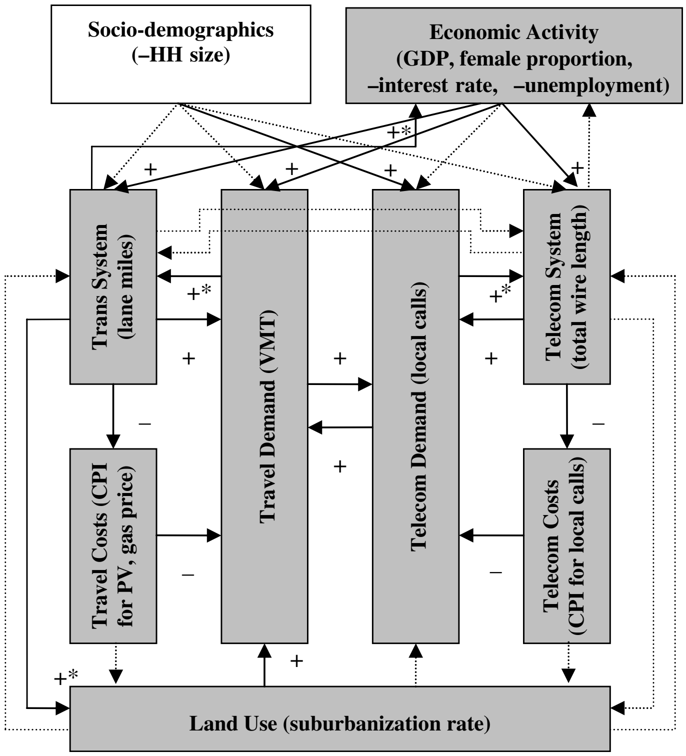

Fig. 2. Identified causal directions in the conceptual model. *Notes*: "+", a positive direct causal effect; "−", a negative direct causal effect; '*', causal effect is only lagged, not contemporaneous. A dotted arrow means a hypothesized but non-identifiable direct causal relationship. "−HH size", "−interest rate", and "−unemployment" mean that the variable is oriented in the direction opposite to the naturally expected/observed relationship. The travel cost variable gas price, and the economic activity variables female proportion, interest rate, and unemployment, are treated as exogenous.

in third). In addition, suburbanization rate, as a land use indicator, significantly affects telecommunications and transportation demand. Our results indicate that the higher the suburbanization rate, the greater the VMT. The implication is that land use policies (e.g. smart growth) that can contain or reduce further decentralization may result in decreased VMT.

An important methodological limitation is that this study is not able to identify the individual proportions of substitution and complementary impacts of telecommunications on travel, and vice versa. An aggregate study is generally focused on the net impact of one variable on another, instead of the detailed components of its total impacts. For example, if it is found that, all else equal, increasing local telephone calls by one standard deviation (s.d.) increases VMT by 0.3 s.d.s, we will not know whether the 0.3 is the net of 0.3 s.d. generation and no substitution, or of 2 s.d.s generation and 1.7 s.d.s substitution, etc. This is a common issue in an aggregate study, whereas a disaggregate study can sometimes obtain more detailed (or finely categorized) information on individual travel and telecommunications by analyzing the impacts of telecommunications on travel by purpose or mode, and vice versa. However, the previous disaggregate studies have the disadvantage that they could not measure the system-wide impacts of telecommunications on travel accurately (nor the simultaneous impacts in multiple directions of causality), although the impacts on individuals' travel were identified in detail.

Therefore, the causal relationships between telecommunications and travel identified in this study provide valuable information on system-wide flows and the impacts of both telecommunications and travel. Such results offer a more realistic picture to policy makers and transportation planners than has been available through the disaggregate, short-term, small-scale, and narrowly focused studies available to date. Since the impact of telecommunications demand on travel is non-negligible, telecommunications demand should be considered in forecasting future travel demand.

In particular, our results point to the difficulty of attempting to decrease travel through various policy instruments, while simultaneously trying to stimulate telecommunications activity – whether as one of those very policy measures expected to reduce travel (through replacing it with telecommunications), or simply as a desirable social goal in its own right. The model presented here indicates that stimulation of the demand for telecommunications will lead both directly and indirectly to the generation of more travel. Perhaps there are individual telecommunications applications or services that will not have such an effect – telecommuting appears to be one, according to both disaggregate and aggregate evidence. But the challenges are (1) to identify the substitutionary applications/services, and (2) to promote them without promoting the complementary ones. The latter goal seems especially elusive, since the same technologies supporting the one type of application will generally support the other.

The empirical study reported here focuses only on VMT and local telephone calls, so there may be different causal relationships between different telecommunication and transportation modes, or multiple interrelationships among transportation modes (such as car, transit, and airplane) and telecommunication modes (such as telephone calls, cellular phones and the Internet). A companion paper (Choo and Mokhtarian, 2005) examines these relationships using composite indicators to represent most variable categories (e.g. using a composite index based on VMT, revenue transit passengers carried, and revenue domestic airline passenger–miles to represent the travel demand dimension). Further analysis of these data will consider the multi-dimensional interrelationships among various transportation and telecommunications modes.

Of course, some telecommunications technologies (notably the Internet and cellular phones) have been available for only a small portion of the 1950–2000 study period, and have further developed dramatically even since the year 2000. Thus, a future analysis of these relationships after longer series of data are available for these indicators will be instructive. Finally, as a way of increasing the sample size, it would be valuable to explore the feasibility of developing this model at the state level rather than the national level. However, not all variables will be available for all states, so adjustments in the specification and/or the sample would probably be necessary.

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