ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

Research Report – UCD-ITS-RR-04-49

Aggregate Relationships Between Telecommunications and Travel: Structural Equation Modeling of Time Series Data

2004

Sangho Choo

Institute of Transportation Studies ◦ University of California, Davis
1605 Tilia Street ◦ Davis, California 95616
PHONE (530) 752-6548 ◦ FAX (530) 752-6572
www.its.ucdavis.edu

Aggregate Relationships between Telecommunications and Travel: Structural Equation Modeling of Time Series Data

By

SANGHO CHOO

B.S. (Hanyang University, Seoul, Korea) 1989
M.S. (Hanyang University, Seoul, Korea) 1995

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

____

____

____

Committee in Charge

2004

To my family

ACKNOWLEDGEMENTS

I would like to gratefully acknowledge my dissertation committee chair and advisor Professor Patricia L. Mokhtarian for her financial and intellectual support, guidance, and encouragement. She was very enthusiastic as a researcher and teacher (you might earn a Novel Prize of teaching!), and helped me gain valuable research and teaching experience. I would also like to thank the other dissertation committee members, Professor Debbie A. Niemeier and Professor James A. Chalfant, for their valuable suggestions. Thanks also goes to Professor Michael H. Zhang and Professor Rahman Azari for being members of my qualifying examination committee.

I would like to acknowledge Professor Ilan Salomon for his invaluable input at the early stage of this research. I would like to express my sincere gratitude to my fellow students at the Institute of Transportation Studies (ITS), especially Gustavo Collantes, Michael Clay, Xinyu Cao, Taihyeong Lee, and Ethan Abeles. In addition, I am most indebted to the staff members of ITS for their expert support. This research was funded by a dissertation grant from the University of California Transportation Center, and benefited from additional support from the California Energy Commission.

Finally, I would like to thank my wife, Youngpill, and my sons, Bumjun and Bumseok, who had the greatest patience (maybe in the world) and strongest support for me during my studies. This dissertation would not have been possible without their love.

TABLE OF CONTENTS

TABLE OF FIGURES AND TABLES

Figures

Tables

ABSTRACT

The purpose of this study is to explore the aggregate relationships (substitution, complementarity, or neutrality) between telecommunications and travel and to compare such relationships across transportation modes. This study first presents a conceptual model, considering causal relationships among travel, telecommunications, land use, economic activity, and socio-demographics. Then, based on the conceptual model, the aggregate relationships between telecommunications (local telephone calls, toll calls, and mobile phone subscribers) and travel (VMT, transit passengers, and airline PMT) are explored in a comprehensive framework, using structural equation modeling of national time series data spanning 1950-2000 in the U.S. At the most detailed level, individual and joint structural equation models for telecommunications and ground travel or airline travel were developed, using selected subsets of the endogenous variables, and then the causal relationships between the two were compared by mode. The model results suggest that most significant causal relationships between telecommunications and travel are complementary. That is, as telecommunications demand increases, travel demand increases, and vice versa. The only exceptions are the two causal relationships between transit passengers and mobile phone subscribers, which are substitutive. Furthermore, there are a number of neutral (zero net) effects of telecommunications on travel or vice versa. Overall, causal effects between telecommunications and travel are different among their modes. However, most of them are complementary regardless of the causal direction. At a less detailed level, composite indices for eight endogenous variable categories were constructed by combining the variables of a given category into a single composite indicator for that category through confirmatory factor analysis. Then,

structural equation models for travel and wired (telephone calls) or mobile (mobile phone subscribers) telecommunications were estimated, using the composite indices and socio-demographic variables. The estimated models also support 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. Consequently, the empirical results from both levels of structural equation modeling strongly suggest that the aggregate relationship (or system-wide net effect) between actual amounts of travel and telecommunications is complementarity, not substitution.

CHAPTER 1. INTRODUCTION

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. They have also contributed to the growth of the U.S. economy in efficiency and productivity (US DOC, 1995). Moreover, the widespread use of the Internet on computer networks provides significant benefits to individuals and industries. In 2000, more than 300 million people worldwide accessed the Internet, three times that in 1998, and the U.S. and Canada comprises nearly 50% of this population (US DOC, 2000). The use of telephones in the U.S. has increased as well. Looking at the penetration rates, 94% of the total households of the U.S. received telephone services, and 109 million people subscribed to mobile phones in 2000, compared to 87% in 1970 and 5 million people in 1990, respectively (FCC, 2000; CTIA, 2000).

In general, transportation can be defined as the movement of people, goods, services, and information. Thus, a lot of travel (even within the first three categories) is undertaken for the purpose of exchanging information (Salomon, 1986). Similar to telecommunications, passenger vehicle-miles traveled (VMT) were 2,534 billion miles, and domestic airline passenger-miles traveled (PMT) were 515 billion miles in 2000, compared to 418 and 8 billion miles, respectively, in 1950 (FHWA, 2002; BTS, 2002). Those trends simply indicate that as the amount of telecommunications increases the amount of travel increases, and vice versa. Here, interesting questions arise. 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 economic and demographic factors)?

A number of studies (Harkness, 1977; Mokhtarian, 1990, 2000; Mokhtarian and Salomon, 2002; Niles, 1994; Owen, 1962; Salomon, 1985, 1986; Salomon and Schofer, 1988) 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., many e-mail messages have no impact on travel and conversely). Similarly, Golob and Regan (2001) also described the relationships between information technology (IT) and travel, including personal and commercial vehicle travel. They emphasized that a variety of IT services such as e-commerce, telemedicine, and teleworking affects not only travel behavior patterns but also the commercial vehicle operations and logistics industry, and suggested various research directions and survey methods. Interestingly, Marvin (1997) underlined the complementary relationships between telecommunications and the environment as well as transportation; for example, telecommunications needs new physical space for its infrastructure and induces travel demand, thus it can bring about damage of environmental resources and air pollution. Overall, these studies on the relationships between telecommunications and travel tend to be conceptual, suggestive, and speculative without empirical analysis.

Furthermore, there have been several studies on the relationship between telecommunications and social trends, including urban land use patterns. Giuliano and Gillespie (1997) discussed such relationships with respect to societal change (such as population and urban patterns). The authors argued that telecommunications (such as home or electronic shopping and telecommuting) may have different effects on consumption patterns and social behavior among different income-based population segments due to the affordability of personal computers. They further argued that "[one important] impact of ICTs [information and communications technologies] upon travel patterns arises from changes in the location of jobs associated with ICTs, and hence with changing urban form" (p. 172). In a similar context, Cairncross (2001) pointed out that steep reductions in telecommunications prices would affect where to work and live, so they will change the location of work, and ultimately city form. She suggested that telecommunications changes the role of home, such that "[t]he home will once again become, as it was until the Industrial Revolution, the center for many aspects of human life rather than a dormitory and a place to spend the weekend" (p. 267). Castells (1989) and Graham and Marvin (1996) argued that telecommunications effects social, economic, environmental and geographical changes, and those changes will contribute to urban restructuring. The studies above suggest that the relationships between telecommunications and travel should be identified within a more comprehensive framework, considering other factors such as the economy, land use, and society.

Among the possible relationships between telecommunications and travel, substitution of telecommunications for travel has been the most desirable form for policy makers and transportation planners hoping to reduce traffic congestion and air pollution. There are various types of telecommunications applications with substitution potential: telecommuting, teleconferencing, teleshopping, and teleservices (e.g. for banking, education, and medicine). In contrast, however, telecommunications may also have a complementary relationship to travel through facilitating or generating travel for face-to-face interactions (enhancement) or through increasing supply capacity such as Intelligent Transportation Systems technology increasing the effective capacity of the transportation system (efficiency) (Salomon, 1985). Transportation can have similar substitution and complementary effects on telecommunications as well; for example, drivers on congested highways can increase the use of mobile phones to obtain better driving information. Therefore, to fully assess the relationships between telecommunications and travel, measures of complete amounts of both telecommunications and transportation, and models allowing both directions of causality (e.g. a structural equation model), are needed.

For the last three decades, 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 such studies to date have been short-term and small-scale, they will underestimate complementary effects by failing to consider the more indirect and longer-term effects (such as induced demand and residential location effects). Additionally, several previous studies on teleconferencing suggest that teleconferencing is likely to have a more complementary impact on business travel than a substitution impact (Mokhtarian and Salomon, 2002). On the other hand, there are so far few empirical studies on the impacts of teleshopping and teleservices on travel. Several studies have emphasized that teleshopping may not substitute store shopping due to the uncertainty of teleshopping (involved in the purchasing decision) and the social-recreational function associated with store shopping (Salomon and Koppelman, 1988, 1992; Mokhtarian, 2004). It is further speculated that to some extent the time saved by teleshopping (or boredom due to the increased time spent on in-home activities) will be compensated for by additional out-of-home trips (Gould and Golob, 1997; Mokhtarian, 2000).

On the other hand, to date, only a few aggregate studies have been carried out, taking different perspectives (consumer and industry). Selvanathan and Selvanathan (1994) found that all three sectors of private transportation, public transportation, and communications have pairwise substitution relationships, using a simultaneous equation system for consumer demand based on 1960-1986 time series data from Australia and the United Kingdom. Conversely, Plaut (1997) found that uses of transportation and communications services by industry have a complementary relationship, using input-output analysis based on nine countries of the European Community in 1980. It is noteworthy that neither study fully explains the direct and indirect causality with respect to the actual demand for travel and telecommunications.

Further, to my 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 activities *per se* may be obscured by a focus on economic measures.

The purpose of this study is to explore the aggregate relationships between telecommunications and travel, using structural equation modeling of time series data in the U.S., and to compare such relationships across the transportation modes of car, transit, and airplane. The central questions of this study are as follows:

- How does telecommunications directly and indirectly affect travel at the aggregate level, and vice versa?
- Is the net system-wide impact of telecommunications on travel one of substitution, complementarity, or neutrality?
- Are those relationships between telecommunications and travel different among transportation modes?

This thesis will constitute the first known attempt to assess the mutual causal relationships between telecommunications and travel, especially with respect to activity rather than economic measures, in a comprehensive and detailed way. As such, it also constitutes one of the first known applications of time series structural equation modeling in this context.

Identifying 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, and may suggest useful directions for them to develop transportation or telecommunications strategies designed to reduce traffic congestion, air pollution, and energy consumption. Of course, a better understanding of the aggregate relationships between telecommunications and travel can also offer new insights to conventional travel demand modeling, which currently does not consider telecommunications as a key factor.

The organization of this thesis is as follows. The following chapter discusses key literature related to the empirical results (at both aggregate and disaggregate levels) and analytical methods for studying the relationships between telecommunications and travel. Chapter 3 describes the conceptual model, considering telecommunications and travel demand, supply and costs, together with land use, economic activity, and socio-demographic variables, and the general methodology of structural equation modeling used in this study. Chapter 4 discusses the acquisition of data on the key variables, and also presents time trends for those key variables. Chapter 5 presents the results of structural equation models of telecommunications (local telephone calls, toll calls, and mobile phone subscribers) and travel (VMT, transit passengers, and airline PMT) by pairs of modes separately. Chapter 6, on the other hand, describes the development of composite indices for endogenous variable categories by confirmatory factor analysis and discusses structural equation models for telecommunications (telephones call and mobile phone subscribers, separately) and travel, using the composite indices and socio-demographic variables. Finally, Chapter 7 discusses the conclusions and suggests some directions for further research.

CHAPTER 2. LITERATURE REVIEW

In this chapter, key literature relevant to the relationships between telecommunications and travel is reviewed, divided into empirical studies and analytical methods. The first section describes empirical studies of the relationships between telecommunications and travel, classified into two categories by research scope (e.g. nations or regions, and individuals or households): aggregate (macro) and disaggregate (micro) levels. In the next section, analytical methods for aggregate studies using time series data, especially in the transportation field, are discussed. In the final section, the key findings and limitations of the empirical studies are summarized.

2.1 Empirical Studies of Telecommunications-Travel Relationships

2.1.1 The Aggregate Level

Although numerous studies have described the overall relationships between telecommunications and travel, to date there have been only a few aggregate empirical studies. Among them, two studies (Plaut, 1997; Selvanathan and Selvanathan, 1994) 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 transportation and communication services are used by industry rather than by end consumers. She found a strong complementary effect between the transportation and communication sectors, through input-output analysis. In her later study (Plaut, 1999), a complementary effect between the two was also found in three non-European countries, using the same analysis on 1988 Israel, and 1991 Canada and (date not specified) U.S. data. Specifically, these studies examined the correlations of the input coefficients for transportation and communication, across all industrial sectors (classified into 44-592 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*. (2001) 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 U.S. 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 → distance traveled), this study does not fully explore the causal relationships between teleworking and travel, but shows an association between the two.

2.1.2 The Disaggregate Level

Differing from the aggregate studies, most disaggregate empirical studies have focused on specific telecommunications applications: for example, telecommuting, teleconferencing, and teleshopping. Here, I briefly discuss findings based on these three telecommunications applications. Another study, the only known disaggregate study modeling relationships between travel and telecommunications more broadly (Mokhtarian and Meenakshisundaram, 1999), is discussed in Section 2.2.3.

2.1.2.1 Telecommuting

Telecommuting, a term coined by Jack Nilles in 1973, is commonly defined as working at home or a location closer to home than the regular workplace, during regular work hours, using telecommunications and information technologies (see Mokhtarian, 1991; Nilles, 1988; Nilles *et al*., 1976 for more detailed descriptions). It has been noted that travel for work purposes comprises the single largest category of daily trips, so traffic congestion is mainly caused by work trips, especially commuting. In fact, commuting trips account for 22.5% of the total daily person-miles traveled, based on the 1995 Nationwide Personal Transportation Survey results (Hu and Young, 1999). Thus, emphasizing substitution for commute travel, telecommuting has been widely adopted as a transportation policy strategy to reduce congestion, energy consumption, and air pollution.

A number of empirical studies (e.g. Hamer *et al*., 1991; Henderson and Mokhtarian, 1996; Koenig *et al*., 1996; Mokhtarian and Varma, 1998; Pendyala *et al*., 1991) have established the short-term impacts of telecommuting on transportation at the disaggregate level, using travel diary or questionnaire data. Detailed overviews of telecommuting empirical research have appeared in Nilles (1988), Mokhtarian *et al*. (1995), and Mokhtarian (1998). Their key findings are as follows: vehicle-miles traveled are substantially reduced for telecommuters on telecommuting days; non-commute trips do not significantly change (increase); the impact on change of mode (into transit and ridesharing or driving alone) is small; no significant change in residential location is found (Mokhtarian and Salomon, 2002).

Overall, the empirical studies on telecommuting support the substitution impact on travel. However, Mokhtarian and Salomon (2002) and Mokhtarian and Meenakshisundaram (1999) have argued that those results are partly a consequence of the short-term and small-scale approaches taken in these studies. They suggest that the long-term, system-wide effect of telecommuting will be smaller due to induced demand and residential relocation (farther from the workplace). Nevertheless, the aggregate study cited earlier (Choo, *et al*., 2001) still found a small but statistically discernible reduction in VMT attributable to telecommuting, using a methodology that accounts for longer-term and indirect effects.

2.1.2.2 Teleconferencing

In general, a teleconference is a meeting with people at different places using telecommunications equipment such as audio, video, and computer. While teleconferencing gives some benefits to the participating organization or company (e.g. creating or exchanging a high quality of information due to increases in the number of attendees, and reductions in travel costs), it can have a complementary impact on travel because increased convenience may result in more meetings being held and more people attending, which (as long as some travel is involved even for the teleconference) may lead to more travel on net. Teleconferencing is also likely to replace routine business travel, but the time and money savings are likely to be devoted to more sensitive meetings for which travel remains important (Mokhtarian, 1988). Additionally, Salomon *et al*. (1991) demonstrated that the relative costs between telecommunications and travel can vary by location, number of participants, and length of meeting; when a videoconference involves a longer meeting, shorter-distance travel and fewer attendees, the corresponding telecommunications costs can be lower than travel costs.

There has been little empirical research on the impact of teleconferencing on business travel. Nonetheless, other small-scale studies (Bennison, 1988; Mokhtarian, 1988) indicate that teleconferencing is likely to have a complementary effect on travel, all the more at the aggregate level. On the other hand, Denstadli (forthcoming) found that videoconferencing had a limited substitution effect on business air travel, ranging around 2.5 to 3.5%, using both survey data from 163 employees of Norwegian companies in 2003 and air travel statistics. However, the study made the dubious assumption that reductions in intra-company business air travel are caused only by videoconferencing, without considering other factors. Overall, it appears that teleconferencing is not likely to reduce business travel on net.

2.1.2.3 Teleshopping

Teleshopping is defined as "the activity of obtaining information on products [including purchasing] through electronic means [such as TV, telephone, and computer], [and it] usually provides the shopper with attribute information on a defined set of products" (Manski and Salomon, 1987, p. 110). Most studies on teleshopping that have addressed the travel behavior impacts at all have done so only at a conceptual level, although a number of empirical studies on adoption are in progress, and there may be some investigations of travel impacts underway as well.

Salomon and Koppelman (1988, 1992) argue that teleshopping may not substitute for store shopping because of the uncertainty involved with respect to the purchasing decision. They also emphasize that the social-recreational function associated with store shopping is sometimes more important than the convenience of teleshopping. Mokhtarian (2000) points out "second-order consumer effects" of e-commerce and teleshopping on travel behavior. That is, to some extent time saved by teleshopping (or boredom due to increased time of in-home activities) may be compensated for by additional out-of-home trips. Empirically, using structural equation modeling, it has been found that the shopping time saved (e.g. by electronic home shopping) by working women would be converted to additional shopping and other maintenance activities (Gould and Golob 1997; Gould *et al*., 1998). In addition, Casas *et al*. (2001) found that there was no significant difference in the number of traditional shopping trips between Internet and non-Internet shoppers based on data from a 1999 household travel survey in Sacramento, California. Using year 2000 activity diary data from the San Francisco Bay

Area, Ferrell (2004) also found that teleshoppers tend to generate more out-of-home shopping trips, shopping person-miles traveled, and shopping trip chains. On the other hand, from a sample of 429 customers of James Telesuper (a teleshopping service company) of the Netherlands in 1988, Tacken (1990) found that teleshopping substitutes for shopping travel in terms of saved time and distance, especially for young two-earner families and the elderly, and changes modal split for shopping trips, from car to bicycle and walking.

In sum, the results of these studies suggest that teleshopping is unlikely to reduce shopping travel, thus its system-wide impacts on travel can be expected to be close to zero or perhaps even positive. The efficiency of the delivery trips derived from teleshopping is an important factor in calculating the net travel impacts, and other telecommunications technologies such as ITS can play a role in that respect.

2.2 Analytical Methods

In this section, analytical methods found in the literature on the relationship between telecommunications and travel will be reviewed, especially methods for aggregate studies. However, as previously discussed, only three studies (including one on teleworking) involve aggregate methods, and one of them used cross-sectional data rather than time series data. Thus, the review of analytical methods will be extended to travel demand models using time series data (similar to the data available for this study), even though not involving telecommunications.

2.2.1 Single Equation Approach

Aggregate travel demand models using time series data have been found in the literature on both gasoline demand (such as the demand for car usage) and induced travel demand (as an effect of highway capacity improvements on travel). Due to the limited availability of time-dependent data, such travel demand models mainly consider vehicle-miles traveled (VMT) as a proxy variable for travel demand, and generally employ a single equation approach.

Since the oil embargo in 1973, many researchers and policymakers have been interested in gasoline demand, VMT, and fuel efficiency (Dahl, 1986). Based on nationwide aggregate time series data, many studies (e.g. Springer and Resek, 1981; Gately, 1990; Greene, 1992; Jones, 1993; Schimek, 1996) in this literature have modeled VMT (direct or per capita) as a function of income (GNP or GDP), gasoline price, fuel efficiency, and number of drivers. Those functional forms commonly involve either a linear or loglinear (using logarithmic transformations) model, and are estimated by the ordinary least squares (OLS) method (Blum *et al*., 1988; Dahl, 1986).

Similarly, a number of studies (e.g. Fulton *et al*., 2000; Hansen and Huang, 1997; Noland, 2001) on induced travel demand have used either aggregate time series data or aggregate cross-sectional/time series data. In those studies, VMT has been modeled as a function of (contemporaneous or lagged) highway lane miles, income, and population, using a loglinear model with OLS estimation.

In a first-of-its-kind study of teleworking and transportation, Choo *et al*. (2001) modeled VMT per capita as a function of GDP, gasoline price, fuel efficiency (such as miles per gallon), consumer price index (CPI), and population at the first stage, and then the number of telecommuters variable (for a shorter length of time) was regressed on the residuals of the first stage model. They estimated a multivariate time series model using OLS, after differencing or transforming all variables to obtain stationarity of the data.

The single equation approach has several problems. First, those models have an endogeneity bias. That is, endogenous variables (e.g. fuel efficiency, highway lane miles, and number of telecommuters) on the right hand side in a single equation are correlated with the disturbance term, so it can result in biased OLS estimates. Thus, a structural (or simultaneous) equation modeling approach is needed (Cervero and Hansen, 2002; Wheaton, 1982). Secondly, interestingly, most such models (except the teleworking model) have extremely high adjusted R^2s, greater than 0.9. It is well-known that a regression on non-stationary data can give a spuriously high value of R^2, resulting in misspecifications due to invalid statistical inferences (Kennedy, 1998). Finally, those equations have the potential for multicollinearity problems among independent variables (e.g. income and highway lane miles), causing higher variances (less precision) of the estimated coefficients, which again could lead to specification error (omission of relevant variables because their coefficients do not appear to be statistically significant).

2.2.2 Simultaneous Equation System Approach

Considering the problem of endogeneity bias, a few studies of VMT have used simultaneous equation systems[1]. The simultaneous equation approach has been widely used in macroeconomic models such as market equilibrium and consumption models involving supply and demand functions (Greene, 2000; Kmenta, 1997).

Among the induced demand studies, Cervero and Hansen (2000) estimated simultaneous equation models, considering VMT and highway lane miles as endogenous variables, with a two-stage least squares method. They found that the impacts of VMT and highway lane miles on each other are both significant.

On the other hand, Selvanathan and Selvanathan (1994) estimated a simultaneous equation model (specifically, a Rotterdam demand equation model) of consumer demand (per capita consumption expenditures), using full information maximum likelihood (FIML) estimation. They found that private transportation, public transportation, and communications goods are significantly interrelated, serving as pairwise substitutes for each other.

[1] Kmenta (1986) notes that "[a] model is said to constitute a system of simultaneous equations if all of the relationships involved are needed for determining the value of at least one of the endogenous variables included in the model" (p. 652).

2.2.3 Structural Equation Modeling (SEM) Approach

The structural equation modeling (SEM) approach can be described as an improved, more flexible simultaneous equation system approach, dealing with any type of variable such as linear, non-linear (e.g. discrete), and latent types in a system. However, in contrast to the conventional simultaneous equation model, which uses the joint sample probability, application of the maximum likelihood technique to SEM centers on the sample covariance structure (described in Section 3.2 in more detail). Specifically, it should be noted that simultaneous equation modeling is a subset of structural equation modeling, under the special case of no measurement errors. For example, 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 the joint probability of obtaining the sample observations themselves (Jöreskog, 1973).

SEM has been a popular data analysis method in social science research areas such as sociology, psychology, and education. Although the precise origin of SEM is obscure, it probably comes from path analysis introduced by Wright (1934). In the 1970s, Jöreskog (1973, 1977), Keesling (1972, as cited in Mueller (1996)), Goldberger (1972), and Wiley (1973) contributed to generalizing an SEM method, incorporating path analysis with confirmatory factor analysis based on simultaneous equation methods, and Jöreskog and

Sörbom (1976) also developed a computational tool, LISREL (Linear Structural Relationships). Since then, much research in various fields, including travel behavior, has been conducted, using SEM methods to explore causal phenomena, and several other computer software programs (such as LISCOM, EQS and AMOS) related to SEM have been developed and commercialized.

Numerous studies using SEM methods have been conducted on travel demand and travel behavior, but they have mainly used either disaggregate cross-sectional or panel data, not aggregate time series data. Only a few studies among them are related to travel and telecommunications models with panel data. Mokhtarian and Meenakshisundaram (1999) explored the relationships among three types of communication (electronic communications, information objects transferred, and personal meeting) and travel (number of trips). They estimated a structural equation model with lagged endogenous variables and exogenous variables (such as elapsed time, seasonal dummies, and socioeconomic variables), using 1994-95 panel data (with two waves occurring about six months apart) from 91 respondents in the city of Davis, California. The study found that there were cross-mode complementary effects among communications modes and self-generation effects of each mode over time, whereas there were no significant relationships between electronic communications and personal meetings, or between electronic communications and trips. Recently, Senbil and Kitamura (2003) examined the relationships between telecommunication devices (home and mobile phones) and activities (work, discretionary, and maintenance activities) using the survey data of 766 individuals in the Osaka metropolitan area, Japan. They estimated structural equation models for activities, considering numbers of home and mobile phone calls as exogenous variables. The authors found that there are different types of telecommunications effects on activity engagement: substitution for work activities, complementarity for discretionary activities, and neutrality for maintenance activities.

2.2.4 Input-Output Analysis Approach

From the economic point of view, an input-output analysis, such as that conducted by Plaut (1997), is often used to present direct and indirect effects among industrial sectors. It is also called a structural economic analysis. However, in a similar context, Saunders *et al*. (1994) pointed out that using input-output analysis to identify the relationship between telecommunications and economic activity has potential problems: lack of proper weighting by the proportions of total communications consumption by each industrial sector (for example, although the service and agriculture sectors consume 50% and 1% of all communications services, respectively, both sectors are treated as a single group without any weighting in the analysis) and an inherent conceptual deficiency in the input-output approach (because the monetary value of transactions may not indicate the actual level of activities). These problems also apply to analyzing the relationship between telecommunications and travel using input-output analysis.

2.3 Summary of Literature Review

Numerous empirical studies on the relationships between telecommunications (including telecommunications applications) and travel have identified either a substitution or a complementary relationship. In fact, few studies have offered strong evidence for a complementary relationship, although this complementarity has been conceptually argued in the literature. As mentioned earlier, most empirical studies consist of short-term and small-scale approaches, so the long-term, system-wide approach needs to be considered. On the other hand, no aggregate study has been found that explores the true causal relationships between telecommunications and actual amounts of travel, regardless of time frame.

With respect to methodologies, many aggregate travel demand models have used single equation models, but only a few have used simultaneous equation models. However, it can be pointed out that the single equation method has a higher possibility of *endogeneity* bias, considering the causal relationships between travel and other factors (such as telecommunications, transportation infrastructure, and land use). In contrast, the structural equation modeling method can solve the above problem to some extent, and permits the development of complex structural models explaining various causal relationships between variables. This approach seems to be the most appropriate for this study.

CHAPTER 3. CONCEPTUAL MODEL AND METHODOLOGY

This chapter discusses a conceptual model of telecommunications and travel relationships in a comprehensive framework, and a methodology to estimate the model. In the first section, the comprehensive framework is constructed centered on telecommunications and travel demand, and each possible relationship between category variables is described. In the second section, structural equation modeling is introduced as a proper methodology for this study.

3.1 Conceptual Model

As mentioned earlier, several studies (e.g. Giuliano and Gillespie, 1997; Graham and Marvin, 1996) have suggested 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, these and other hypothesized relationships are synthesized into a comprehensive conceptual model, to my knowledge the most complete model of its kind. The model focuses on passenger travel, not goods movement. However, it includes business as well as personal measures of travel and telecommunications activity. As can be seen from the discussion in Chapter 4, however, the data available do not always permit this distinction empirically. For example, an indicator such as number of mobile phone subscribers will inevitably be capturing growth in business as well as personal uses of mobile phones.

The conceptual model appears in Figure 3.1, in which the shaded rectangles represent categories of endogenous variables and the unshaded rectangle the single category of exogenous variables. The model comprises eight endogenous variable categories (namely travel and telecommunications demand, transportation and telecommunications supply, 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 (see Chapter 4). An arrow indicates the direction of a hypothesized relationship.

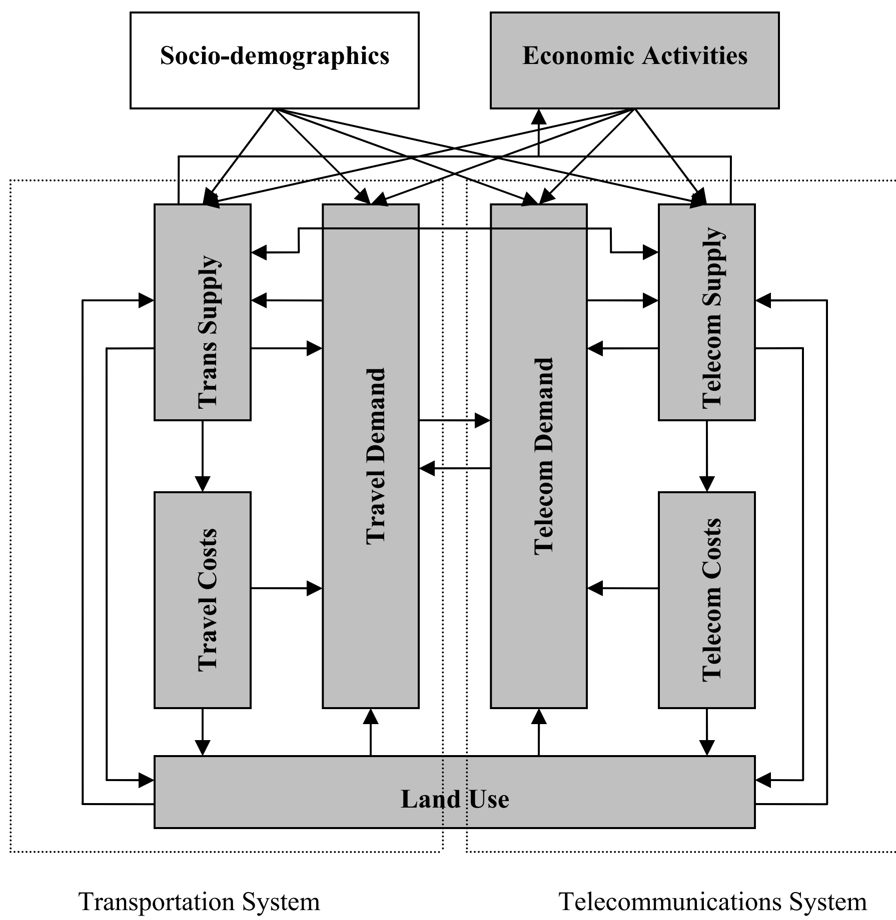


Figure 3.1: Conceptual Model of Telecommunications and Travel

In the remainder of this section, the major relationships in the conceptual model are discussed in terms of logical groupings based on the economics and transportation literatures.

3.1.1 Demand, Supply, and Costs

3.1.1.1 Travel Demand ⇔ Telecommunications Demand

It is hypothesized that travel demand and telecommunications demand have a bi-directional causality. In general economic theory, the relationship between two commodities can be presented as substitution, complementarity, or independence. 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 substitutive 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 facts, the relationships between telecommunications and travel have often been classified into two broad categories: substitution and complementarity (e.g. Salomon, 1986; Mokhtarian, 1990):

- In a substitutive relationship, telecommunications can reduce travel demand, and vice versa. In fact, various types of telecommunications-related activities such as on-line (telephone) shopping and teleservices for banking and transactions can reduce or eliminate travel. For example, you can order a music CD via Internet or telephone without traveling to a music store downtown, even download your favorite songs in a music CD directly through the Internet without a vendor's delivery trip. In addition, telecommunications can make people's travel, even lives, more efficient by eliminating unnecessary trips. If you obtain information about cancellation of a baseball game due to rain via phone or on a website, you can save the unnecessary round trip to watch the game on that day. In the aggregate, perhaps thousands of trips can be saved by the prospective spectators. Conversely, if you are able to visit your friends frequently, you may be less likely to call them as often.

- In a complementary relationship, telecommunications generate physical travel and vice versa. Information gains through telecommunications can generate personal travel such as visiting attractive places and making impetuous shopping trips. For example, telephones enable people to set up a variety of social activities such as eating out and event invitations very easily, sometimes resulting in unexpected trips. On the other hand, recently, when people travel, they are more likely to use mobile phones for various reasons such as convenience and obtaining necessary information.

Overall, telecommunications demand and travel demand are expected to be interrelated, either positively or negatively. Or, since effects in both directions are plausible, it can be hypothesized that both types of effects may cancel each other, resulting in net effects of zero.

3.1.1.2 Travel (Telecommunications) Demand ⇔ Transportation (Telecommunications) Supply

A bi-directional and positive 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 travel demand. The same has been true for telecommunications. In the other direction, as the literature on induced demand (e.g. 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 conceptual model. At the micro-level, Downs (2004) pointed out "triple convergence" demand effects on the improved or added highway supply: spatial (moving from the existing to the added highways), temporal (switching from the off-peak to the peak hours), and modal (changing from transit to driving) convergences. 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.

3.1.1.3 Transportation Supply ⇔ Telecommunications Supply

It is hypothesized that the causality between travel supply and telecommunications supply is bi-directional and generally positive. 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). There can be indirect effects of telecommunications supply on transportation supply, through the impact of telecommunications supply on travel demand (e.g. telecommunications supply → telecommunications demand → travel demand → transportation supply). However, there are also direct effects without need for consumer intervention (e.g. synchronized signal timing, ramp metering, and automated light rail transit), which make travel more efficient.

3.1.1.4 Travel (Telecommunications) Costs ⇒ Travel (Telecommunications) Demand

Obviously, travel costs should 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, demographics, and 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 the gasoline price (e.g. Dahl, 1986). Similarly, telecommunications costs negatively affect the demand for telecommunications. For example, as the prices of telephone calls decrease, the number of telephone calls increases. In the reverse direction, we hypothesize that demand affects costs only through its impact on supply (see Section 3.1.1.5 below).

3.1.1.5 Transportation (Telecommunications) Supply $\Rightarrow$ 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) supply negatively affects travel (telecommunications) costs. In the reverse direction, it is hypothesized that costs affect supply only through their effect on demand. Although the direct effect is possible (supply might be provided simply because it is inexpensive, in hopes that demand would follow), it is considered less strong than the converse and suppressed for simplicity. In practice, not every possible relationship can be allowed due to identifiability problems (discussed in Sections 3.2 and 5.1) in empirical models based on the conceptual model, so parsimonious model specifications are recommended.

3.1.2 Demand, Supply, and Land Use

3.1.2.1 Land Use $\Rightarrow$ Travel (Telecommunications) Demand

It is hypothesized that land use affects travel demand and telecommunications demand. As numerous studies (e.g. 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 travel 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.

3.1.2.2 Transportation (Telecommunications) Supply ⇔ Land Use

Cervero and Landis (1997) 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 supply affects land use, and vice versa.

3.1.2.3 Travel (Telecommunications) Costs ⇒ Land Use

In addition to relatively low gasoline prices, transportation and market policies have failed to make drivers pay for their external costs such as those due to air pollution, traffic accidents, and congestion. Such artificially low driving costs have increased 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 toll or mobile phone rates 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, 1995). Hence, it can be hypothesized that travel and telecommunications costs affect land use, especially over the long term.

3.1.3 Demand, Supply, Economic Activity, and Socio-demographics

3.1.3.1 Transportation (Telecommunications) Supply ⇔ 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 GDP, the more federal funds available for highway investments. Thus, a positive bi-directional causality can exist between transportation supply and economic activity. Similarly, investments in telecommunications system infrastructures have accelerated business and industrial effectiveness 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 supply and economic activity also can have a positive bi-directional causality.

3.1.3.2 Economic Activity $\Rightarrow$ Travel (Telecommunications) Demand

Numerous studies of VMT (e.g., Choo *et al*., 2001; Greene, 1992; Schimek, 1996) have found that economic activity (such as GDP and gross national product (GNP)) significantly positively affects travel demand. Additionally, Schafer (1998) found that the growth of traffic volumes is attributed in part to the increase in personal income as indicated by GDP, based on 1960-1990 time series data of 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. Although it is plausible that demand directly affects economic activity, it is considered less strong than the converse and suppressed for simplicity and identifiablility. Thus, it is hypothesized that demand affects economic activity only through its effect on supply.

3.1.3.3 Socio-demographics ⇒ Travel (Telecommunications) Demand

It is apparent that demographic variables (such as population, number of drivers, 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.

3.1.3.4 Socio-demographics ⇒ Transportation (Telecommunications) Supply

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.

3.2 Methodology

In the previous section, the conceptual model of telecommunications and travel was discussed, and each causal relationship between variable categories in the model is hypothesized to be either bi-directional or unidirectional. The literature review on analytical methods in Section 2.2 suggests that structural equation modeling (SEM) is a powerful technique for analysis of causal relationships between endogenous variables, and between endogenous and exogenous variables. Hence, in this study, the structural equation modeling method can be employed to estimate the causal relationships of the conceptual model. There are several reasons to choose this approach: (i) structural equation modeling can give better estimates for bi-directional causal relationships without the bias inherent to OLS methods, (ii) structural equation modeling can give coefficients for direct (e.g. $X \rightarrow Y_2$), indirect (e.g. $X \rightarrow Y_1 \rightarrow Y_2$), and total effects (combined both effects) of variables on each other, and (iii) structural equation modeling can deal with any type of variables such as linear, non-linear, and latent variables. In this section, a general structural equation model structure is explored, and then its modeling procedure is discussed, including estimation methods.

3.2.1 Model Structure

Following the matrix notation form of Mueller (1996), a general structural equation model in which all variables are observed can be written[2]

$$\mathbf{Y} = \mathbf{BY} + \mathbf{\Gamma X} + \zeta ,$$

where $\mathbf{Y}$ is a ($N_Y \times 1$) column vector of endogenous variables (N_Y is the number of endogenous variables), $\mathbf{X}$ is a ($N_X \times 1$) column vector of exogenous variables (N_X is the number of exogenous variables), $\mathbf{B}$ is a ($N_Y \times N_Y$) matrix of structural coefficients

[2] In the simultaneous equation context (Greene, 2000), the notation of the structural form is typically described as $\mathbf{Y\Gamma} + \mathbf{XB} = \varepsilon$, where the matrices of $\mathbf{\Gamma}$, $\mathbf{B}$, and ε are similar to $\mathbf{B}$, $\mathbf{\Gamma}$, and ζ, respectively, after combining the two $\mathbf{Y}$ matrices on the left and right sides of the structural equation model.

representing the direct effects of endogenous on other endogenous variables, **Γ** is a ($N_Y \times N_X$) matrix of structural coefficients representing the direct effects of exogenous on endogenous variables, and **ζ** is a ($N_Y \times 1$) column vector of error terms. The case or observation subscript is suppressed for convenience. When **(I − B)** is nonsingular, the reduced form of the above equation is

$$\mathbf{Y} = (\mathbf{I} - \mathbf{B})^{-1}\boldsymbol{\Gamma}\mathbf{X} + (\mathbf{I} - \mathbf{B})^{-1}\boldsymbol{\zeta} .$$

Then, the variance-covariance matrix of the exogenous variables is denoted as **Φ**, and the variance-covariance matrix of the error terms is denoted as **Ψ** (thus, **ζ** ~ (**0**, **Ψ**)). Both variance-covariance matrices need to be specified. In the structural equation model, **Σ**, the population variance-covariance matrix of only the observed variables, **X** and **Y**, can be written as a function of the set of unknown parameters θ. In this study, latent variables are not included in the structural equation model because the conceptual model does not presently include such variables. Then, Σ(θ) may be written as

$$\Sigma(\theta) = \begin{bmatrix} \Sigma_{YY}(\theta) & \Sigma_{YX}(\theta) \\ \Sigma_{XY}(\theta) & \Sigma_{XX}(\theta) \end{bmatrix} = \begin{bmatrix} (I-B)^{-1}(\Gamma\Phi\Gamma' + \Psi)[(I-B)^{-1}]' & (I-B)^{-1}\Gamma\Phi \\ \Phi\Gamma'[(I-B)^{-1}]' & \Phi \end{bmatrix}$$

in terms of **B**, **Γ**, **Φ**, and **Ψ**, where X and Y are measured from their means (E[**X**] = E[**Y**] = 0), and exogenous variables and errors are uncorrelated (E(**X**ζ′)=0).

Thus, the population variance-covariance matrix is unknown, for which the sample variance-covariance matrix **S** constitutes an unbiased estimator. Then, the unknown parameters (such as **B**, **Γ**, **Φ**, and **Ψ)** need to be estimated to minimize the difference between the model-implied population variance-covariance matrix and the sample variance-covariance matrix. In this way, structural equation modeling is based on covariance structure analysis.

3.2.2 Modeling Procedure

The structural equation modeling procedure generally consists of four steps: model specification, model identification, model estimation, and model fit. As shown in Figure 3.2, the overall modeling procedure has several feedback loops, depending on conditions at a particular step, to obtain a final model. Each step of the procedure is discussed in order.

3.2.2.1 Model Specification

In this step, trial model specifications can be made, based directly on the conceptual model. Here, many candidate variables related to each category are explored with respect to their measurements and characteristics. For example, which variable is more representative of travel demand, VMT or number of trips? Can this variable be endogenous? Further, the selection of a set of variables for a structural equation model is strongly related to the conceptual model, but to some extent it is more subjective.

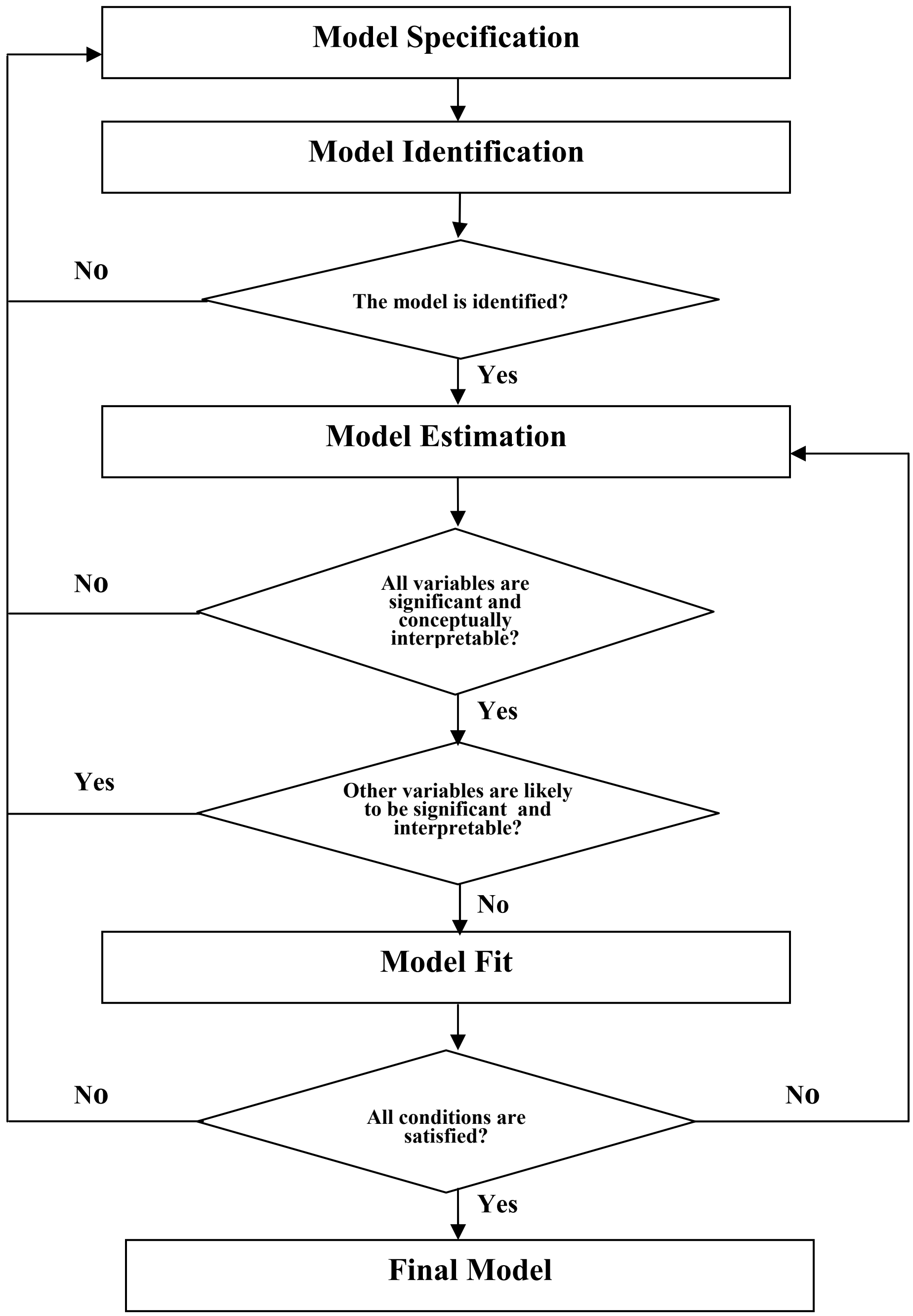


Figure 3.2: Structural Equation Modeling Procedure

As a complementary approach to the confirmatory variable selection for the conceptual model, any important missing variables in the trial model specifications may be found by examining a single equation model for each endogenous variable as a function of other endogenous and exogenous variables, including lagged variables. This approach can be helpful in choosing a powerful variable set for the full model. Using both approaches, better model specifications can be constructed.

3.2.2.2 Model Identification

This step is very important for operationalizing a structural equation model (as well as a simultaneous equation model). Identification is the investigation of whether a structural equation model can be mathematically calculated or not. In general, identification has three types of results based on the degree of correspondence between the restricted and the unrestricted parameters: exact (or just) identification, overidentification, and underidentification (see Kmenta, 1997, p. 661). If any of the equations in a structural equation model are underidentified (or called 'not identified'), the model cannot be estimated.

Two methods are frequently used to determine identification of a structural equation model: order and rank conditions. The order condition, a necessary condition, is that the number of excluded predetermined (exogenous and lagged) variables must be greater than or equal to the number of included endogenous variables in each equation. The rank condition, which is necessary and sufficient, is that the rank of a restricted coefficient submatrix, obtained by deleting from the full coefficient matrix ($\mathbf{I} - \mathbf{B} - \mathbf{\Gamma}$) any columns that don't have zeros in a row (equation) to be tested, is greater than or equal to the number of endogenous variables minus one (e.g. Greene, 2000). Through both methods, a model specification from the previous step is tested. If the model is not identified, its specification needs to be modified by giving some restrictions (e.g. constraining some parameters to equal zero), or use of more exogenous information such as the addition of exogenous variables (Kennedy, 1998).

3.2.2.3 Model Estimation

Structural equation modeling has generally used three types of model estimation techniques: maximum likelihood (ML), normal theory generalized least squares (GLS), and asymptotic distribution free (ADF).

Among them, the ML estimation technique has been most commonly used in structural equation modeling, especially in the transportation field. The first two estimation techniques are applied under the multivariate normality assumption for the data, and the other is not. However, the ADF method can yield incorrect chi-square statistics for small samples, even though it does not depend on any distribution type of the data (Hu *et al.*, 1992; Mueller, 1996). On the other hand, Chou and Bentler (1995) found that ML estimation is more robust under a violation of normality than the other two techniques, using Monte Carlo experiments based on a sample size of 200.

Additionally, to estimate a structural equation model, a scalar fitting function, $F[\mathbf{S}, \Sigma(\theta)]$, is required for optimization. F indicates the difference between two variance-covariance matrices: one is the sample estimate of Σ, i.e. $\mathbf{S}$, and the other is the model-implied variance-covariance matrix, $\Sigma(\theta)$. Following the expressions of Mueller (1996, p. 155), the fitting functions for ML and GLS are written as

$$F_{ML}[\mathbf{S}, \Sigma(\theta)] = \ln|\Sigma(\theta)| - \ln|\mathbf{S}| + \mathrm{tr}\,[\mathbf{S}\Sigma(\theta)^{-1}] - (N_X + N_Y), \text{ and}$$

$$F_{GLS}[\mathbf{S}, \Sigma(\theta)] = \tfrac{1}{2}\,\mathrm{tr}\,\{[\mathbf{S}^{-1}(\mathbf{S} - \Sigma(\theta))]^2\}.$$

Thus, estimates of parameters are obtained by minimizing the fitting function. In this study, the ML fitting function is used for model estimation due to the desirable asymptotic properties of maximum likelihood estimates.

3.2.2.4 Model Fit

Finally, this step examines the model estimated based on the previous steps, in terms of how well it explains the observed data. In structural equation modeling, the degree of model fit (or goodness of fit) means how close the model-implied variance-covariance matrix $\Sigma(\theta)$ is to the sample variance-covariance matrix **S**. Generally, the chi-square distribution has been used to do a goodness-of-fit test of the estimated model. Thus, the lower the chi-square statistic, the better the goodness of fit. If the estimated model fails the chi-square test, its model specification needs to be changed by either adding exogenous information or using some restrictions on parameters, or to be estimated again by different methods. Under the violation of normality of the data, Hu *et al*. (1992) and West *et al*. (1995) found that Satorra and Bentler's (1988, 1994) scaled chi-square statistic (adjusted by the degree of multivariate kurtosis of the observed data, the degrees of freedom, and residual weight matrix of the model) performs better than those of the three estimation methods (ML, GLS, and ADF). On the other hand, several models can be compared to select the best model, using the chi-square statistics. In addition, there are a number of other criteria (such as the ratio of the χ^2 statistic to the degrees of freedom, goodness-of-fit index (GFI), normed fit index (NFI), and comparative fit index (CFI)) to measure the goodness of fit (see Mueller, 1996; Ullman, 1996). Most structural equation modeling software packages (such as AMOS, LISREL and EQS) can calculate such criteria. Based on overall goodness-of-fit measures, a final model can be chosen. Among the available software packages, the AMOS 4.0 (Arbuckle and Wothke, 1999) was used to estimate structural equation models in this study because of its user-friendliness and graphical interface.

3.2.3 Model Interpretation

As mentioned earlier, structural equation modeling can provide three types of effects of variables on each other: direct (e.g. $X \rightarrow Y_2$), indirect (e.g. $X \rightarrow Y_1 \rightarrow Y_2$), and total effects (combined both effects). It should be emphasized that interpreting a structural equation model should focus on the total effects, not the direct effects only. It is also of great interest to compare direct and indirect effects of X and Y on Y. Comparing the structural and reduced forms of the structural equation model, the total effects can be written as (Fox, 1980):

- total effect of X on Y:

  $(I - B)^{-1}\Gamma = \Gamma$ (direct effect) + $\{(I - B)^{-1}\Gamma - \Gamma\}$ (indirect effect)

- total effect of Y on Y:

  $(I - B)^{-1} - I = B$ (direct effect) + $\{(I - B)^{-1} - I - B\}$ (indirect effect).

In SEM, standardized structural coefficient estimates are generally used for model interpretation. These estimates are based on standardized (having mean 0 and standard deviation 1) data, so they are useful for comparing the relative importance of the explanatory (endogenous or predetermined) variables in a model. However, caution should be used in interpreting the magnitude of the coefficient. For example, if a standardized structural coefficient estimate of X is 1, then the affected endogenous variable Y will increase by one standard unit (not the original scale) for each standard unit increase in X.

CHAPTER 4. DATA DESCRIPTION

This chapter discusses the data available for the empirical analysis, which explores the conceptual model presented in Chapter 3. Due to the scope (national level) of this study, the data for this analysis, specifically time series data, come 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 (based on the 50 US states and the District of Columbia), ranging from 1950 to 2000. Table 4.1 presents the key variables and their sources. Key variables for each category in the conceptual model are described, and plotted over time.

4.1 Travel Demand

The travel demand category includes four demand variables: passenger vehicle-miles traveled (VMT), revenue transit passengers carried, and revenue airline passenger-miles traveled (PMT) (for domestic and international travel, separately). First, the passenger VMT variable is considered exemplary of the demand for private transportation. Originally, the VMT data are classified by vehicle type (car, truck, and all motor vehicles), and collected by the Federal Highway Administration (FHWA).

Table 4.1: Key Variables for Each Category

Category	Key Variables	Data Sources
Travel Demand	Passenger vehicle-miles traveled Revenue transit passengers carried Revenue airline passenger-miles traveled (domestic and international travel)	Federal Highway Administration (*Highway Statistics*) American Public Transit Association (*Transit Fact Book*) BTS, Office of Airline Information (*Air Carrier Traffic Statistics*)
Transportation Supply	Lane miles (urban and rural areas) Revenue transit vehicle-miles operated Revenue airline available seat miles (domestic and international travel)	Federal Highway Administration (*Highway Statistics*) American Public Transit Association (*Transit Fact Book*) BTS, Office of Airline Information (*Air Carrier Traffic Statistics*)
Travel Cost	Real (inflation-adjusted) gasoline price* Fuel efficiency (miles per gallon) Consumer price indices (CPIs) for private and public transportation, and airline** Real average air fares (domestic and international travel)*	Energy Information Administration (*Annual Energy Review*) Bureau of Labor Statistics (*Monthly Labor Review*) Bureau of Economic Analysis (*National Income &Product Account*) BTS, Office of Airline Information (*Air Carrier Financial Statistics*)
Telecommunications Demand	Number of local telephone calls Number of toll calls Number of international calls Number of mobile phone subscribers	Federal Communications Commission (*Statistics of Communications Common Carriers*, *Trends in Telephone Service*) Cellular Telecommunications & Internet Association (*Semiannual Wireless Survey*)
Telecommunications Supply	Number of telephone access lines (residential and business lines) Total telephone wire length Number of cell sites	Federal Communications Commission (Statistics of Communications Common Carriers) Cellular Telecommunications & Internet Association (Semiannual Wireless Survey)

Notes: For the data sources, names of statistical reports appear in parentheses. Recent data can be found on the websites of the government agencies. * Chained 1996 dollars, ** for all urban consumers, 1996 = 100. BTS: Bureau of Transportation Statistics.

(Table 4.1 continued)

Category	Key Variables	Data Sources
Telecommunications Costs	Consumer price indices (CPIs) for local telephone calls, and inter- and intra-state toll calls** Real average cost per international call* Real average monthly revenue from mobile call services*	Federal Communications Commission (*Trends in Telephone Service*) Federal Communications Commission (*Statistics of Communications Common Carriers*) Cellular Telecommunications & Internet Association (*Semiannual Wireless Survey*)
Land Use	Suburban population ratio to total metropolitan population	U.S. Census Bureau (*Statistical Abstract of the United States*)
Economic Activity	Real Gross Domestic Product (GDP)* Federal Reserve Bank (FRB) interest rate Unemployment rate Female proportion of the labor force	U.S. Government Printing Office (*Economic Report of the President*) Bureau of Labor Statistics (*Monthly Labor Review*)
Socio-demographics	Population Number of households Average household size Number of licensed drivers Female proportion of licensed drivers	U.S. Census Bureau (*Statistical Abstract of the United States*), 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. * Chained 1996 dollars, ** for all urban consumers, 1996 = 100.

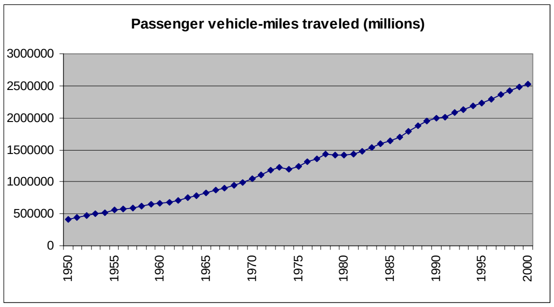
Among the various vehicle types, the VMT variable used in this study includes passenger cars, motorcycles, and other 2-axle 4-tire vehicles such as vans, pickup trucks, and sport utility vehicles. Prior to 1966, the "other 2-axle 4-tire vehicle" category was included under the single unit truck category. Thus, for 1950-1965, we estimated the proportion of single unit truck VMT generated by other 2-axle 4-tire vehicles, by regressing time on the proportions based on the VMT data of 1966-2000 and applying the estimated coefficients to the earlier data. We then multiplied that estimated proportion of VMT by total single unit truck VMT in 1950-1965 to obtain the estimated amount of other 2-axle 4-tire VMT, and combined it with the passenger car/motorcycle VMT to make the definition of the car category consistent across the entire study period.

Secondly, due to data availability, the number of revenue transit passengers carried is used as the measure of public transportation demand, instead of transit passenger-miles traveled. This variable includes revenue passengers on motor bus, trolley bus, heavy rail, light rail, commuter rail, demand responsive vehicles, and other transit modes. Lastly, revenue airline PMT for (domestic and international travel separately) indicates air travel demand. Air carrier employees and infants are not counted as revenue passengers. Included are scheduled or nonscheduled (such as charter flights) domestic flights by certificated domestic air carriers operating in the U.S. and international flights by certificated U.S. air carriers (i.e. passengers carried by American-flagged airplanes only).

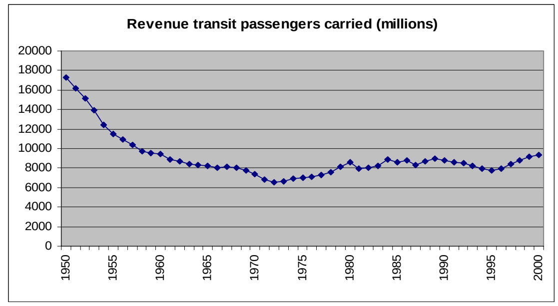
Thus, these four variables collectively represent travel demand. As shown in Figure 4.1, VMT has increased nearly five times over the past five decades, whereas use of transit has decreased almost 50%, but showing a relatively level pattern after about 1965. Interestingly, airline PMT for domestic and international travel increased 63 times and 82 times, respectively, over the time period, an outcome of economic growth (income effect) among other factors (e.g. technological improvements increasing the appeal and reducing the costs of airline travel). Additionally, in 1979, deregulation prompted the entry of many small carriers into commercial aviation, resulting in the rapid increase in passenger miles seen for that year.

4.2 Transportation Supply

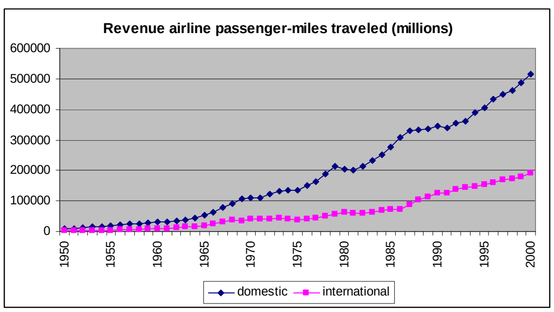
This category includes lane miles, transit vehicle-miles operated, and domestic and international airline seat miles. These variables correspond to those for travel demand.



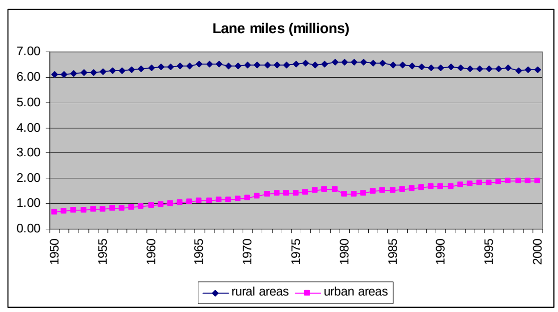
Passenger VMT (millions)
min: 417,601, max: 2,533,815



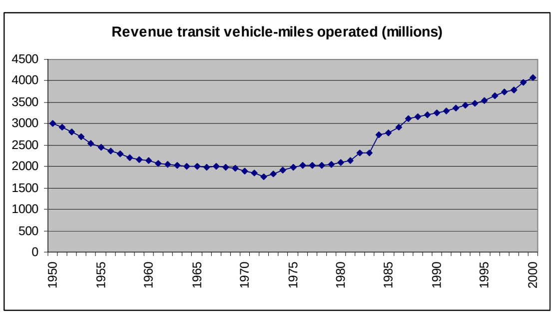
Revenue transit passengers (millions)
min: 6,567, max: 16,125



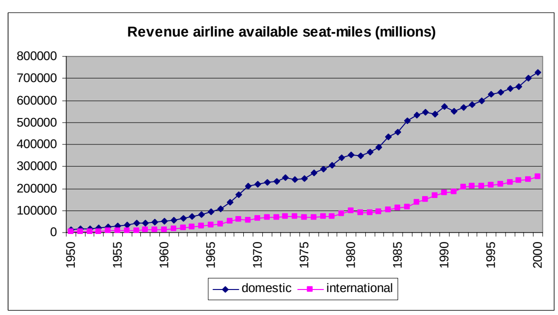
Revenue airline PMT (millions)
min: 8,123, max: 515,277 (domestic travel)
min: 2,336, max: 192,617 (international travel)



Lane miles (millions)
min: 6.12, max: 6.59 (rural area)
min: 0.68, max: 1.92 (urban area)



Revenue transit vehicle-miles operated (millions)
min: 1,756, max: 4,081



Revenue airline available seat miles (millions)
min: 13,261, max: 726,003 (domestic travel)
min: 3,932, max: 253,776 (international travel)

Figure 4.1: Trends in Travel Demand and Transportation Supply

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^2s = 0.996).

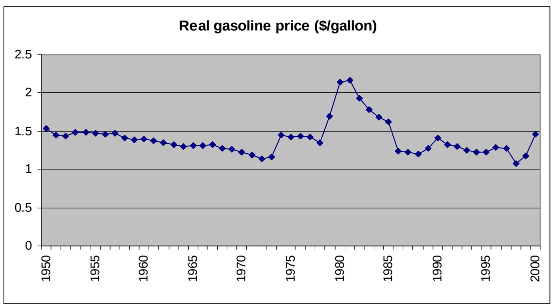
Figure 4.1 illustrates the time trends in transportation supply. The lane miles for rural and urban areas have changed rather gradually over the past five decades, at rates much lower than that of passenger VMT. Here, an urban area is defined by the Bureau of the Census as an area having a population of 50,000 or more people. Thus, the decease in rural lane miles since 1980 is mostly due to the reclassification of rural areas as urban. Overall, such road supply trends partially explain why traffic congestion has increased over the same time frame. The supply of transit, on the other hand, specifically the revenue transit vehicle-miles operated, had decreased until 1972 similar to transit demand, but then more than doubled over the last 30 years even though demand has not kept pace. This may be attributed to government transportation policies (such as the Urban Mass Transportation Assistance Act of 1970 and Intermodal Surface Transportation Efficiency Act of 1991, providing federal funds for improving mass transit systems) to enhance urban transit systems during that time period. With respect to airline supply, similar to airline demand, the available seat miles for domestic and international travel increased 55 times and 65 times, respectively, over the study period. Since it is an operational measure, the available seat miles would be more elastic to its demand than is the case for the lane miles (a physical measure of infrastructure).

4.3 Travel Costs

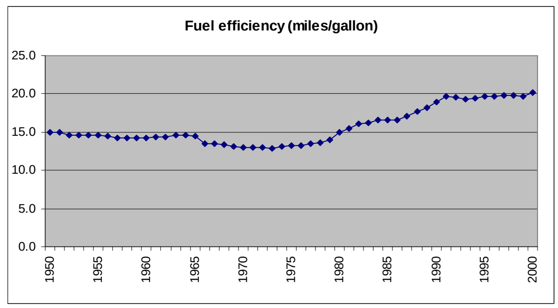
The travel cost category comprises three Consumer Price Indices − for private transportation (including vehicle purchases, operations, maintenance, repairs, and insurance), public transportation (here, intra-city transit systems), and airline (including domestic airline fares) − real (inflation-adjusted) gasoline prices, fuel efficiency (miles per gallon), and real average air fares for domestic and international travel. The Consumer Price Index (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 (Mankiw, 2003). The Bureau of Labor Statistics publishes the CPIs for all items and specific types of goods every month.

The real gasoline price measures the average motor gasoline price in dollars per gallon. It is based on chained (1996) dollars (generally calculated by using a chain-type index for the corresponding service, and called “real” or “inflation-adjusted”) to provide a valid comparison over time. The fuel efficiency variable indicates average vehicle-miles traveled per gallon, dividing total passenger VMT by total passenger vehicle fuel consumption. Similarly, the real average air fares are calculated by dividing total passenger revenue by revenue passengers enplaned for each of domestic and international travel.

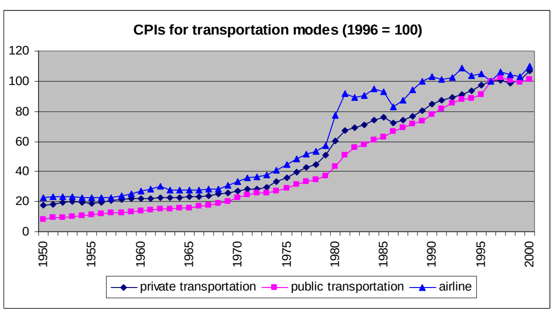
As shown in Figure 4.2, the CPI, fuel efficiency, and domestic air fare cost variables change relatively smoothly, while real gasoline prices and international air fares fluctuate more erratically. Real gasoline prices spiked around the 1979 oil crisis, and fuel efficiency (for the entire passenger cars, including vans, pickup trucks, and sport utility vehicles) gradually increased after 1975 because of the regulation of corporate average fuel economy (CAFE) standards. Real average air fares decreased more for international travel than domestic travel over time. However, the trends of the CPIs indicate that general transportation costs increased regardless of mode.



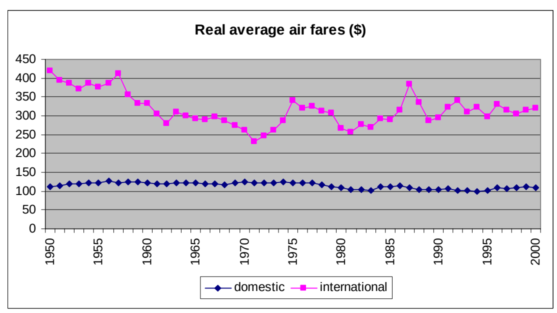
Real gasoline price ($/gallon)
min: 1.1, max: 2.2



Fuel efficiency (miles/gallon)
min: 12.9, max: 20.1



CPIs for transportation modes (1996 = 100)
min: 18, max: 107 (private transportation)
min: 8, max: 102 (public transportation)
min: 23, max: 110 (airline)



Real average air fares ($)
min: 100, max: 126 (domestic travel)
min: 232, max: 412 (international travel)

Figure 4.2: Trends in Travel Costs

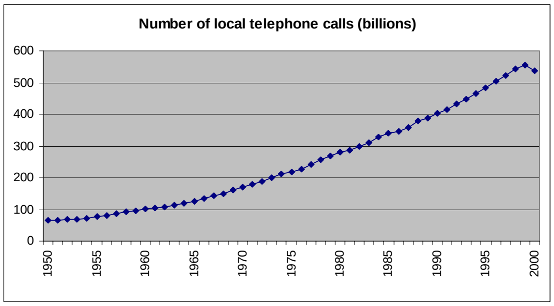
4.4 Telecommunications Demand

There are four variables in the telecommunications demand category: number of local telephone calls, number of toll calls, number of international calls, 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 only available from that point onward.

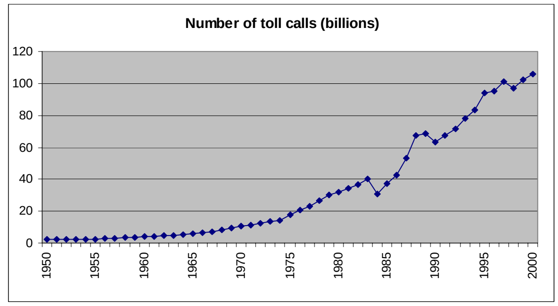
Figure 4.3 shows time trends for these four variables. It can be seen that measurement of the number of toll calls was strongly (albeit temporarily) affected by the court-ordered divestiture of AT&T (that is, divestiture of the local Bell operating companies from the rest of AT&T) in 1984. Not surprisingly, international calls and mobile phone subscribers have rapidly increased in the last 15 years, more than 15 and 100 times, respectively.

4.5 Telecommunications Supply

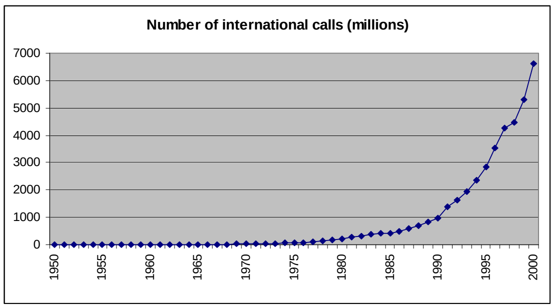
Telecommunications supply includes residential and business telephone access lines, total telephone wire length, and cell sites. Business telephone access lines includes single and multiple lines. The total wire length measures total miles of wire in aerial, underground, buried, submarine, deep-sea, and intra-building network cables. Clearly, these variables represent infrastructure measures corresponding to the telecommunications demand variables above. Figure 4.3 presents trends in telecommunications supply. The total telephone wire length gradually increased over time, whereas the cell sites rapidly increased. These trends are similar to the patterns seen for the telecommunications demand variables local telephone calls and mobile phone subscribers. Interestingly, similar to toll calls, the measurement of the number of telephone access lines was also strongly affected by the court-ordered divestiture of AT&T in 1984.



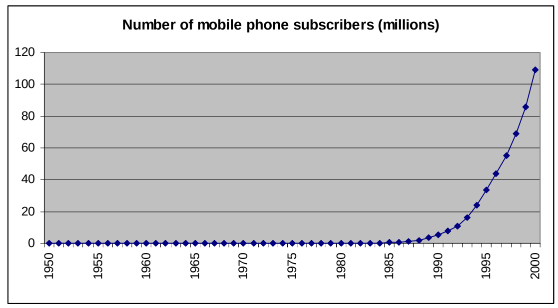
Number of local telephone calls (billions)
min: 65, max: 554



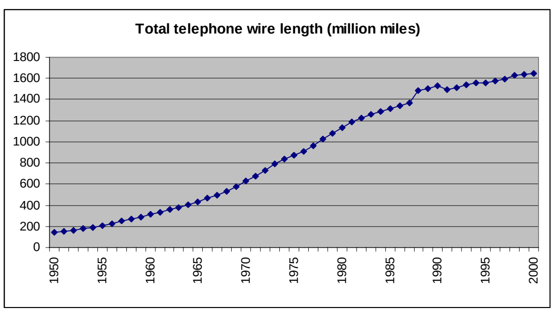
Number of toll calls (billions)
min: 2, max: 106



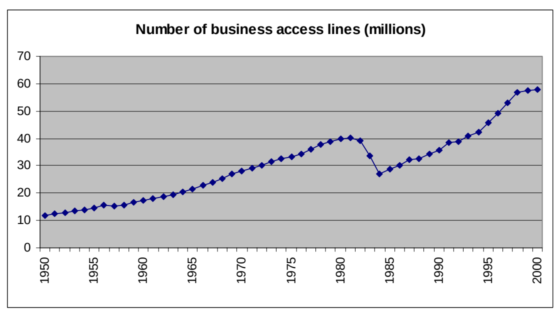
Number of international calls (millions)
min: 1, max: 6,627



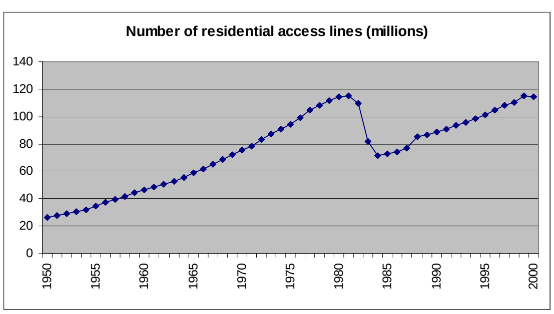
Number of mobile phone subscribers (millions)
min: 0, max: 109



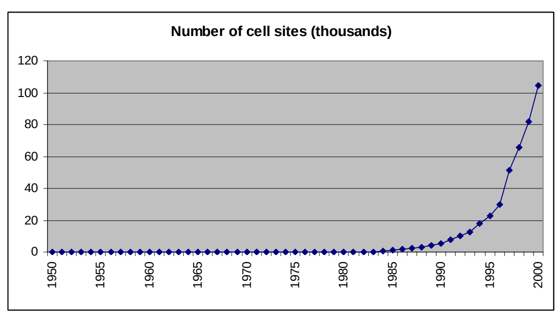
Total telephone wire length (million miles)
min: 147 max: 1,651



Number of business access lines (millions)
min: 12, max: 58



Number of residential access lines (millions)
min: 26, max: 115

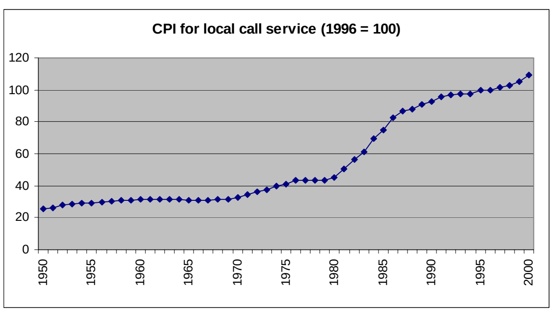


Number of cell sites (thousands)
min: 0, max: 104

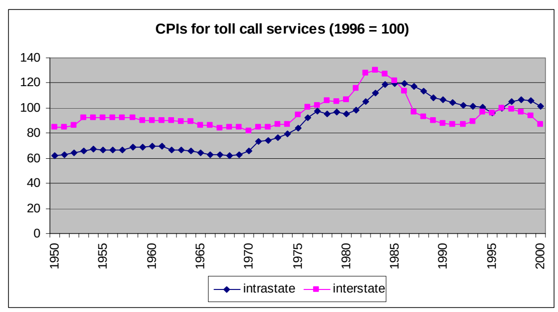
Figure 4.3: Trends in Telecommunications Demand and Supply

4.6 Telecommunications Costs

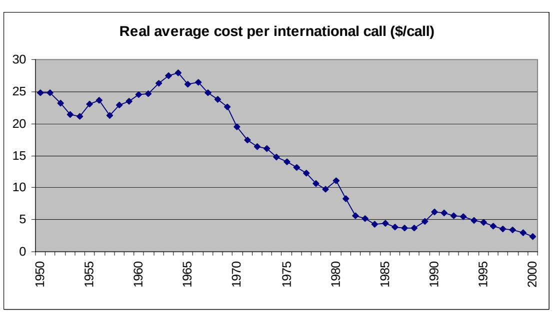
Similar to the transportation cost category, the telecommunication category has three CPIs – for local, inter- and intra-state telephone services – the real average cost per international call, and the average monthly revenue from mobile phone services. The latter is a good measure of mobile telephone 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). The real average cost per international call is calculated by dividing total revenue by number of international calls.



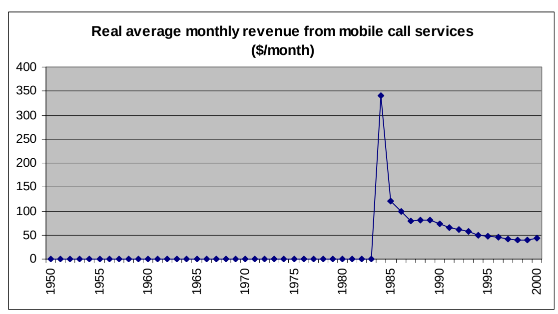
CPI for local call service (1996 = 100)
min: 25, max: 109



CPI for toll call service (1996 = 100)
min: 62, max: 120 (intra-state toll calls)
min: 82, max: 130 (inter-state toll calls)



Real average cost per international call ($/call)
min: 2, max: 28



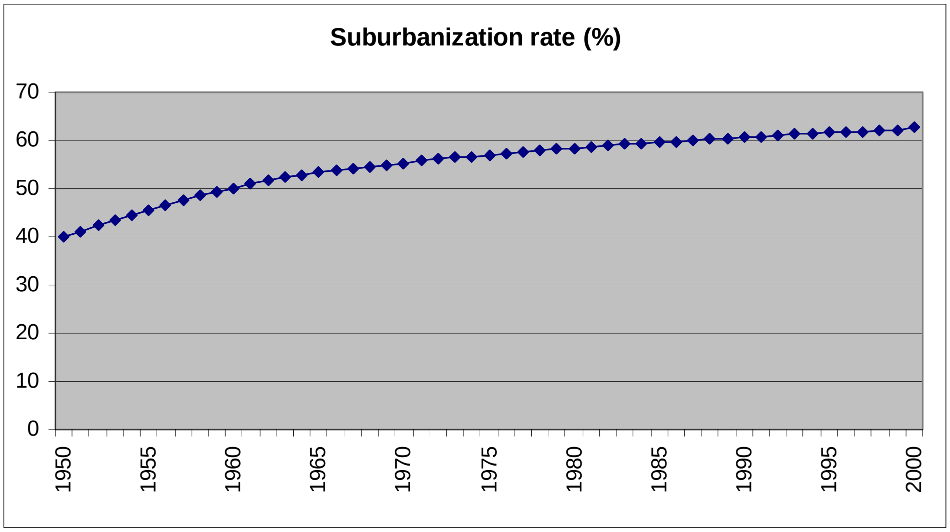
Real avg. monthly revenue from mobile call services ($/month) min: 40, max: 341 (after 1984)

Figure 4.4: Trends in Telecommunications Costs

As shown in Figure 4.4, CPIs for telephone service rapidly increased leading up to 1984, and this in fact was one cause of the divestiture. After 1984, local CPI continued to increase and toll CPI decrease, as previous cross-subsidizing from long-distance to short-distance calls was eliminated. As expected, costs for international call and mobile phone services have dramatically decreased over time, due to advanced technologies and an expanded telecommunications network infrastructure.

4.7 Land Use

Due to 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. During the span of time covered by this study, data on the sizes of the central city and suburban populations were directly available only for the six decennial census years 1950, ’60, ’70, ’80, ’90, and 2000. We used those six observations to fit two models (of central city and suburban population, respectively), using metropolitan area population and a constant term as the only explanatory variables (adjusted R^2s = 0.993 and 0.991, respectively). Those equations were then used to predict central city and suburban populations in all years including the six decennial years (to smooth out the bumps that otherwise occurred between the observed data for the decennial years and the predicted data for the off-years), and the resulting series of suburban populations was divided by the sum of the two populations in each year to obtain the proportion of the total metropolitan population living in suburban areas. Looking at the trend in Figure 4.5, the suburbanization rate has been slowing for several decades, although it has exceeded 50% since 1960.

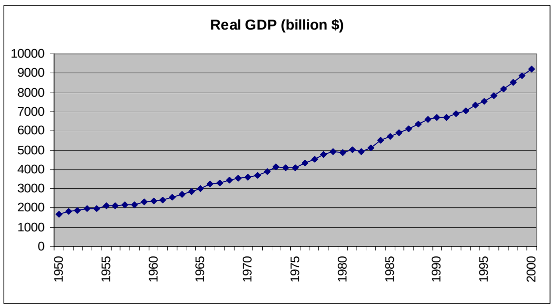


min: 41, max: 63

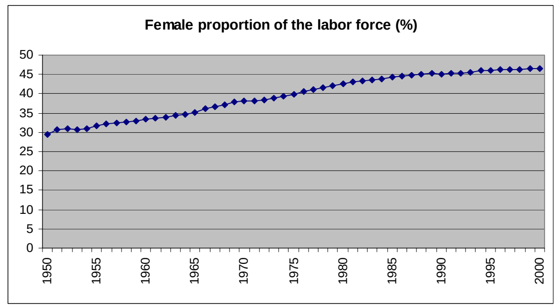
Figure 4.5: Trend in Land Use

4.8 Economic Activity

The economic activity category has four measures: real gross domestic product (GDP), unemployment rate, female proportion of the labor force, and interest rate of the Federal Reserve Bank (FRB). GDP is the market value of the goods and services produced by labor and property located in the U.S. 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. The interest rate of the FRB (called the discount rate) is charged by the FRB when banks borrow federal funds. As an indicator of the demand for money (e.g. for investment), a high interest rate generally corresponds to a strong economy. It can be seen in Figure 4.6, comparing the interest rate with the unemployment rate, that the two series generally move in opposite directions. It is logical that as the female proportion of the labor force increases, the GDP increases, with women's labor force participation potentially being a cause as well as an effect of GDP growth.

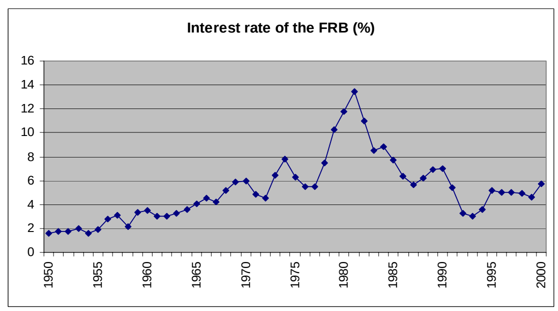


Real GDP (billion $)
min: 1,687, max: 9,191



Female proportion of the labor force (%)
min: 30, max: 47

Unemployment rate (%)
min: 2.9, max: 9.7

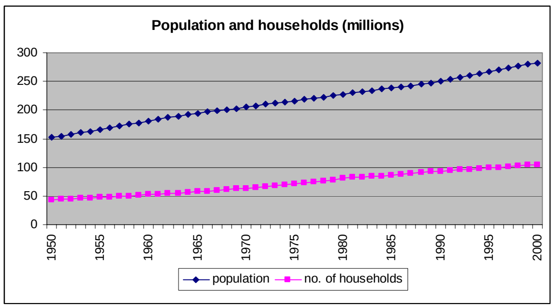


Interest rate of the FRB (%)
min: 1.6, max: 13.4

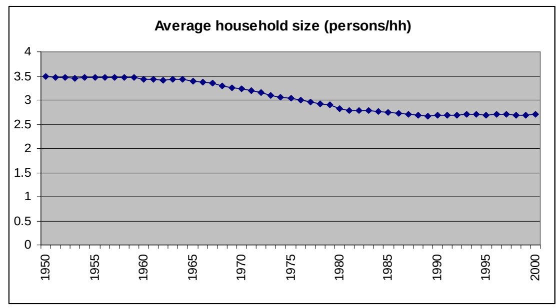
Figure 4.6: Trends in Economic Activity Variables

4.9 Socio-demographics

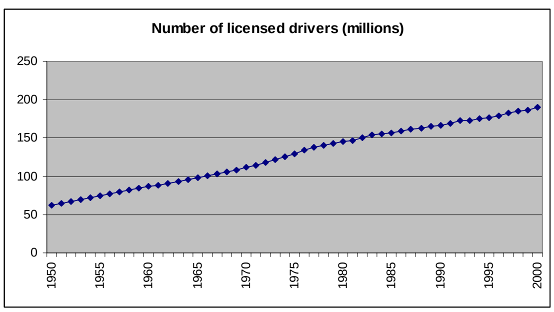
This category contains population, households, household size, number of licensed drivers, and female proportion of licensed drivers. These variables are used as exogenous variables in the models. As shown in Figure 4.7, it is a familiar trend that the average household size has decreased in the past five decades. Additionally, the female proportion of licensed drivers was nearly one-half in 2000. This indicates women's enhanced mobility potential, which has strongly contributed to the increase in travel demand (Pisarski, 1992).



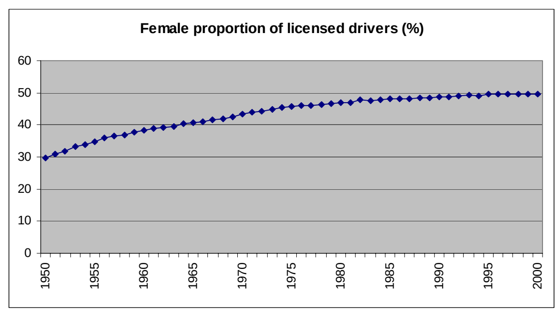
Population and households (millions)
min: 152, max: 282 (population)
min: 44, max: 105 (households)



Average household size (persons/hh)
min: 2.7, max: 3.5



No. of licensed drivers (millions)
min: 62, max: 191



Female proportion of the licensed drivers (%)
min: 30, max: 50

Figure 4.7: Trends in Socio-demographic Variables

CHAPTER 5. CAUSAL RELATIONSHIPS BETWEEN TELECOMMUNICATIONS AND GROUND OR AIRLINE TRAVEL MODES

This chapter develops individual and joint structural equation models for telecommunications (local telephone calls, toll calls, and mobile phone subscribers) and ground travel (VMT and public transit passengers) or airline travel (domestic and international airline PMT) to explore the causal relationships in the conceptual model discussed in Chapter 3, using the key variables for each category described in Chapter 4. The first section describes the model specification process including initial model specifications and model estimation procedure. The second and third sections present the estimation results of individual (e.g. the single pair of VMT and local telephone calls) and joint (e.g. all ground travel and local telephone calls) structural equation models for telecommunications and ground travel or airline travel, respectively. In the last section, causal relationships between telecommunications and travel are compared by mode.

Given the small number (50 after differencing and 49 when using lagged variables) of observations, models with more equations, such as the model containing all eight telecommunications and travel demand variables (plus the accompanying supply and the other endogenous variables), were either not estimable at all or could not be considered reliable (having almost as many parameters as observations). In Chapter 6 I incorporate more endogenous variables through the development of composite variables, in which a single index variable (e.g. travel demand) is created as a function of the several related individual variables.

5.1 Model Specification

As discussed in Chapter 3, the structural equation modeling method is employed to estimate the causal relationships in the conceptual model. Because the data set for this study 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 (see time trends of the figures in Chapter 4) in their raw forms, so each series is natural log-transformed and then first-order differenced (e.g., $\log[X_t] - \log[X_{t-1}]$) to achieve stationarity as well as to diminish autocorrelated errors. Lagged endogenous and exogenous variables can be included in the model, considered (together with contemporaneous exogenous measures) to be pre-determined variables.

As a normality check for all variables, normal Q-Q plots of (natural log-transformed, first-order differenced) individual variables were visually inspected. They appear in Appendix A. The plots show that most observations of each variable are not far from the expected normal values, but a few outliers in some variables are found. Although the outliers should be excluded to achieve strong normality, they are kept in the data set, considering the small sample size of 49 (when lagged variables are included) in this study. It is common in the literature for normality checks, or departures from normality, to be neglected. Generally, parameter estimates in SEM are fairly accurate, at least in large samples, when the data are severely non-normal (Kline, 1998). In the present case, overall, all variables are approximately normally distributed, so any set of the variables has approximate multivariate normality.

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, single equation models were examined 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, initial model specifications were refined.

Our 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, since 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 (i.e., having unique best estimates) – the more exogenous variables in a model, the easier it is to achieve identifiability. Accordingly, a nested series of constrained alternatives of the conceptual model was tested, by successively switching more and more exogenous variables to endogenous (by adding more equations to the system). As shown in Table 5.1, the models tested are named demand, demand/supply, demand/supply/cost, demand/supply/land-use, demand/supply/cost/land-use, demand/supply/land-use/econ, 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 supply variables for travel and telecommunications are also endogenous in the demand/supply model. For the sake of brevity, the later sections generally present only final models, which are the full models shown in Table 5.1, or (when full models were not identifiable) alternative models that have the most-possible endogenous variable categories.

Furthermore, 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 indices (Molin and Timmermans, 2003). As mentioned in Chapter 3, the AMOS module of the SPSS software package (Arbuckle and Wothke, 1999) was employed to estimate the structural equation models.

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 (the most complex models shown in Table 5.1) due to non-identifiability and/or multicollinearity. For example, the structural equation models for any travel and mobile phones do not include cost equations. Also, the population variable did not come into the structural equation model for personal vehicle travel and mobile telecommunications because it is highly correlated with the suburbanization variable ($r = 0.86$, see the correlation coefficient table in Appendix B). In lieu of population, the household size variable (calculated by population/number of households) was allowed to enter the model.

Table 5.1: Alternative Structural Equation Systems for Estimation

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

Note: • = endogenous category, blank = exogenous category

In addition, any models including travel cost equations use CPI for private transportation as the endogenous variable in their equations, instead of gasoline price, because gasoline prices are more affected by external factors (e.g. Organization of Petroleum Exporting Countries' market and domestic gasoline tax polices) than by transportation demand and supply. Instead, gasoline price is included in the travel cost equations as an exogenous variable influencing the CPI for private transportation, to explore its indirect impacts on other endogenous variables. Also, where conceptually supported, the final models retain a few variables with lower significance (but always with a p-value of 0.3 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 in Horowitz, *et al*. (1986) for retaining policy-relevant variables in discrete choice models if their t-statistics are greater than 1 in magnitude.

For the final models, t-statistics for direct effects and unstandardized coefficients for total and direct effects appear in Appendix C.

For the goodness-of-fit tests of the final models, all χ^2 statistics except those for the three mobile phone-related models indicate that the null hypothesis, that model-implied covariance is not different from the sample covariance, can be rejected at $p = 0.01$. However, in the structural equation modeling context, even lower p-values are considered preferable for confidently rejecting the null hypothesis, meaning that the rejection implied by $p = 0.01$ is not a strong one in this context. Instead, the ratio of the χ^2 statistic to the degrees of freedom is used for the goodness-of-fit tests, considering the small sample size of the data. In practical terms, if the ratio for a structural equation model is less than two or three, the model has a good fit (Ullman, 1996; Kline, 1998). Using this rule, the ratios of all final models are less than 3, indicating good fits. Three other measures are also calculated for each model: 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). They also indicate that all final models have relatively good fits (all indices are greater than 0.5). Especially for *nonrecursive* models, all stability indces (Bentler and Freeman, 1983; a measure of stability for a nonrecursive linear structural equation model) are examined, and they always lie between -1 and 1: that is, the models are stable and converge properly.

5.2 Causal Relationships between Ground Travel and Telecommunications

5.2.1 Personal Vehicle Travel and Telecommunications

5.2.1.1 Personal Vehicle Travel and Local Telecommunications

Table 5.2 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). The final model is nonrecursive, 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, telecommunications 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 (dlog[Y_t/Y_{t-1}] /dlog[X_t/X_{t-1}]) of VMT are 0.280 and 0.045 (unstandardized coefficients of the models, see Appendix C), 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% (0.45%) increase in VMT. As discussed before, a number of studies (e.g. Noland, 2001, Hansen and Huang, 1997) on induced demand have found similar relationships, although using single equation approaches[3]. 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 FRB interest rate, unemployment rate and female proportion of the labor force) logically significantly affect travel demand. 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 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.

[3] 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 5.2: Estimated Causal Effects among Personal Vehicle Travel and Local Telecommunications Variables (N = 49)

RHS variables	**Endogenous variables (LHS variables)**							
	Demand		Supply		Costs		Land use	Economic activity
	Travel	Telecom	Trans	Telecom	Travel	Telecom		
Endogenous variables								
Travel demand:	0.075	0.246						
VMT		(0.229)						
Telecom demand:	0.329	0.075						
local telephone calls	(0.306)							
Transportation supply:	0.377	0.086			-0.218			
lane miles (urban areas)	(0.293)				(-0.218)			
Telecom supply:	0.108	0.354				-0.273		
total wire length		(0.297)				(-0.273)		
Travel costs: CPI for	-0.286	-0.066						
private transportation	(-0.266)							
Telecom costs: CPI for	-0.038	-0.124						
local telephone calls		(-0.115)						
Land use:	0.177	0.041						
suburbanization rate	(0.165)							
Economic activity:	0.398	0.091						
GDP	(0.370)							

(Table 5.2 continued)

RHS variables	Endogenous variables (LHS variables): Demand – Travel	Demand – Telecom	Supply – Trans	Supply – Telecom	Costs – Travel	Costs – Telecom	Land use	Economic activity
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 supply	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	χ^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.

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 suburbanization rate variable as a land use factor 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 less 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 variables. 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 Federal Reserve Bank (FRB) interest rate (the discount 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, together with economic activity variables, indirectly negatively affect their corresponding cost variables. That is, as VMT and local calls in the previous year increase or income increases, their current infrastructures increase, and then travel and telecommunications costs decrease. 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, as transportation supply, positively affects suburbanization rate and GDP.

5.2.1.2 Personal Vehicle Travel and Long-distance Telecommunications

Table 5.3 shows 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 long-distance telecommunications (number of toll calls). The final model is *recursive* (having no feedback loop), differing from the previous model. The average R^2 of the model is 0.33.

For the causal effects in the model, number of toll calls has a positive impact on personal vehicle travel, indicating a complementary relationship. That is, as toll calls increase, VMT increases. It is plausible that toll calls may generate and supplement long-distance travel for various purposes such as visiting friends and relatives and leisure, more than reducing travel. According to the 1977 National Travel Survey and 1995 American Travel Survey, 84% and 79% of long-distance travel (over 100 miles one way) were made by personal vehicle in those years, respectively (BTS, 1998). Thus, it is logical that the number of toll calls affects VMT. On the other hand, it is found that there is no significant impact of VMT on toll calls, differing from the effect of VMT on local telephone calls. Most variables in the VMT-related equations, except for the fuel economy variable, are similar to those in the previous model. They have logical signs as well. The fuel economy variable, MPG, positively affects VMT because the higher the gas mileage the lower the driving costs.

To achieve identifiability, the lagged variable of CPI for inter-state toll calls, instead of its contemporaneous variable, was included in the demand equation. It makes sense that the telecommunications costs in the previous year negatively affect its demand in the current year. It is clear that total wire length strongly positively affects number of toll calls.

Not surprisingly, the total wire length has a negative impact on its cost, only when it is included together with the dummy variable 1950-1983. As discussed in Chapter 4, telecommunications supply variables are strongly affected by measurement errors due to the 1984 divestiture of AT&T, and toll call costs have decreased since 1984, unlike local telephone call costs. Thus, this suggests that the telecommunications supply variables should be considered with a dummy variable (equal to 1 for the years either before or after 1984) in their cost equations. Differing from the previous model, it is found that total wire length indirectly positively affects lane miles. That is, as total wire length increases, the number of toll calls increases, VMT increases, and then lane miles increase. It indicates a chained causal effect between telecommunications and travel demand and supply. As expected, the lagged lane miles variable positively affects suburbanization rate and GDP. Logically, the unemployment rate has a negative impact on GDP.

Table 5.3: Estimated Causal Effects among Personal Vehicle Travel and Long-distance Telecommunications Variables (N = 49)

RHS variables	Endogenous variables (LHS variables): Demand – Travel	Demand – Telecom	Supply – Trans	Supply – Telecom	Costs – Travel	Costs – Telecom	Land use	Economic activity
Endogenous variables								
Travel demand:								
VMT								
Telecom demand:	0.804							
toll calls	(0.804)							
Transportation supply:	0.528				-0.213			
lane miles (urban areas)	(0.467)				(-0.213)			
Telecom supply:	0.189	0.235				-0.478		
total wire length		(0.235)				(-0.478)		
Travel costs: CPI for	-0.287							
private transportation	(-0.287)							
Telecom costs: CPI for								
inter-state toll calls								
Land use:	0.163							
suburbanization rate	(0.163)							
Economic activity:	0.430							
GDP	(0.430)							

(Table 5.3 continued)

RHS variables	Demand: Travel	Demand: Telecom	Supply: Trans	Supply: Telecom	Costs: Travel	Costs: Telecom	Land use	Economic activity
	Endogenous variables (LHS variables)							
Predetermined variables								
1st lagged travel demand	0.257		0.486 (0.486)		-0.104			
1st lagged telecom demand	0.049	0.061		0.260 (0.260)		-0.125		
1st lagged trans supply	0.068						0.129 (0.129)	0.109 (0.109)
1st lagged telecom costs	-0.092	-0.115 (-0.115)						
Gasoline price	-0.177				0.617 (0.617)			
Fuel efficiency (MPG)	0.163 (0.163)							
FRB interest rate	-0.217		-0.410 (-0.410)		0.087			
Unemployment rate	-0.352							-0.820 (-0.820)
Female proportion of the labor force	0.074	0.092		0.394 (0.394)		-0.189		
Average HH size	-0.188	-0.234 (-0.234)						
Dummy (1950-1983)						0.723 (0.723)		
R^2 (average R^2 = 0.33)	0.22	0.10	0.28	0.26	0.47	0.57	0.02	0.73
Goodness of fit measures	χ^2 = 229.5 (df = 119), Goodness of Fit index (GFI) = 0.75, Normed Fit Index (NFI) = 0.62, Comparative Fit Index (CFI) = 0.74							

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. This is a recursive model (having no feedback loop), so there is no Stability Index.

5.2.1.3 Personal Vehicle Travel and Mobile Telecommunications

Table 5.4 presents the estimated, standardized (direct and total) effects among the variables in the final model of personal vehicle travel (VMT) and mobile telecommunications (number of mobile phone subscribers). The final model is *recursive* (having no feedback loop), and the average R^2 of the model is 0.51, which is the highest among the pairwise models of ground travel and telecommunications. The R^2s of the travel and telecommunications demand equations are very high (0.52 and 0.94, respectively), probably indicating the naturally close relationship between travel (mobile by definition) and mobile telecommunications among all forms of telecommunications.

Looking at the causal effects in the model, it can be seen that VMT has a positive impact on number of mobile phone subscribers, indicating a complementary relationship. That is, as VMT increases, the number of mobile phone subscribers increases. This is certainly natural, since a main point of mobile phones is to use them while mobile. On the other hand, it is found that 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 it 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. Also, the negative cross effects of prices (i.e. the impacts of CPI for private transportation and gasoline price on number of mobile phone subscribers), although indirect, support that telecommunications and travel are complements.

Table 5.4: Estimated Causal Effects among Personal Vehicle Travel and Mobile Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	use	activity
Endogenous variables								
Travel demand:		0.046						
VMT		(0.046)						
Telecom demand:								
mobile phone subscribers								
Transportation supply:	0.647	0.030			-0.263			
lane miles (urban areas)	(0.584)				(-0.263)			
Telecom supply:		0.762				-0.902		
cell sites		(0.762)				(-0.902)		
Travel costs: CPI for	-0.242	-0.011						
private transportation	(-0.242)							
Telecom costs:								
average monthly revenue								
Land use:	0.327	0.015						
suburbanization rate	(0.327)							
Economic activity:	0.387	0.118		0.132		-0.119		
GDP	(0.387)			(0.132)				

(Table 5.4 continued)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	use	activity
Predetermined variables								
1st lagged travel demand	0.367	0.017	0.566 (0.566)		-0.149			
1st lagged telecom demand		0.155		0.203 (0.203)		-0.183		
1st lagged trans supply	0.132	0.015		0.012		-0.011	0.294 (0.294)	0.092 (0.092)
Gasoline price	-0.145	-0.007			0.602 (0.602)			
Fuel efficiency (MPG)	0.128 (0.128)	0.006						
FRB interest rate	-0.223	-0.010	-0.345 (-0.345)		0.091			
Unemployment rate	-0.321	-0.098		-0.109		0.099		-0.829 (-0.829)
Average HH size	-0.446 (-0.446)	-0.042 (-0.022)						
R^2 (average R^2 = 0.51)	0.52	0.94	0.32	0.06	0.48	0.91	0.09	0.73
Goodness of fit measures	χ^2 = 95.2 (df = 77), Goodness of Fit index (GFI) = 0.83, Normed Fit Index (NFI) = 0.88, Comparative Fit Index (CFI) = 0.97							

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. This is a recursive (having no feedback loop) model, so there is no Stability Index.

Most causal effects among demand, supply, costs, land use, and economic activity are similar to those in the previous models. There is also a positive lagged effect of VMT on mobile phone supply (cell sites), consistent with hypothesis. As expected, economic activity variables (GDP and unemployment rate) significantly affect mobile phone supply with logical signs. 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 more).

5.2.2 Public Transit Travel and Telecommunications

In this section, two structural equation models for public transit travel and telecommunications are presented: one for local and one for mobile telecommunications. Public transit travel mainly involves intra-city travel using mass transit systems, so it is less likely to relate to long-distance telecommunications (toll calls). Thus, a structural equation model for public transit travel and long-distance telecommunications is excluded in this study. As mentioned earlier, since public transit costs including fares are directly controlled and partially subsidized by the government, they are less likely to be affected by supply (or other variables in the model). Accordingly, the travel cost equation was not included in either model.

5.2.2.1 Public Transit Travel and Local Telecommunications

Table 5.5 shows the estimated, standardized causal effects of endogenous and predetermined variables on other endogenous variables, for the final model of public transit travel (number of transit passengers carried) and local telecommunications (number of local telephone calls). The final model is nonrecursive, having a feedback loop between public transit passengers and local telephone calls, and the average R^2 of the model is 0.28, lower than that for the model for personal vehicle travel and local telephone calls.

Looking at the causal effects among endogenous variables, number of transit passengers and number of local telephone calls positively affect each other. That is, as the number of transit passengers increases, the number of local telephone calls increases, and vice versa. Also, the lagged variable of number of transit passengers indirectly positively affects number of local telephone calls. This indicates that the relationship between telecommunications and public transit travel is complementarity. The cross price effects of telecommunications and public transit travel also show, although indirectly, that they are complements. Similar to the VMT and local telephone call model, the magnitude of the total effect of the local telephone calls on public transit is much higher than that in the other direction. This supports the idea that telephone calls motivate people to generate travel, regardless of mode, by creating new activities for various purposes through exchanging information with each other.

Logically, public transportation supply (transit vehicle-miles operated) strongly positively affects its demand, showing the greatest magnitude. Since this supply is directly related to operating service, it is more elastic to demand than general transportation infrastructure such as lane miles. As expected, CPI for public transportation negatively affects its demand, and the cost elasticity of transit demand is

-0.15. This is reasonably consistent with literature (e.g. Hensher and King, 1998; Litman, 2004) on transit price elasticities showing that the elasticity of transit ridership with respect to transit fares ranges from -0.2 to -0.5 in the short term. It is logical that suburbanization rate negatively affects public transit demand. Newman and Kenworthy (1991) and others have also found that the higher density the urban area the greater the transit ridership.

As hypothesized, population positively affects both travel and telecommunications demand. Clearly, measures of economic activity (GDP, unemployment rate, and female proportion of the labor force) logically significantly affect travel demand. The other causal effects among supply, costs, land use, and economic activity are similar to those in the previous models. It makes sense that the lagged variable for total wire length has a negative impact on number of local telephone calls, considering its chained indirect effect: lagged telecommunications supply → (+) suburbanization rate → (−) public transit travel demand → (+) telecommunications demand. As hypothesized, the lagged local call variable indirectly positively affects GDP through telecommunications supply (total wire length).

Table 5.5: Estimated Causal Effects among Public Transit Travel and Local Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	use	activity
Endogenous variables								
Travel demand:	0.251	0.426						
transit passengers		(0.341)						
Telecom demand:	0.738	0.251						
local telephone calls	(0.589)							
Transportation supply:	1.009	0.343						
transit vehicle-miles	(0.806)							
Telecom supply:	0.519	0.849	0.023			-0.263		0.104
total wire length		(0.631)				(-0.263)		(0.104)
Travel costs: CPI for	-0.134	-0.046						
public transportation	(-0.107)							
Telecom costs: CPI for	-0.118	-0.199						
local telephone calls		(-0.159)						
Land use:	-0.699	-0.238						
suburbanization rate	(-0.559)							
Economic activity:	0.222	0.075	0.220					
GDP			(0.220)					

(Table 5.5 continued)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land use	Economic activity
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom		
Predetermined variables								
1st lagged travel demand	0.354	0.120	0.351 (0.351)					
1st lagged telecom demand	0.209	0.343	0.009	0.403 (0.403)		-0.106		0.042
1st lagged telecom supply	-0.233	-0.079					0.333 (0.333)	
Unemployment rate	-0.190	-0.065	-0.189					-0.858 (-0.858)
Population	0.275 (0.220)	0.094						
Female proportion of the labor force	0.119	0.194	0.005	0.229 (0.229)		-0.060		0.024
Average HH size	-0.080	-0.135 (-0.108)						
R^2 (average R^2 = 0.28)	0.19	0.46	0.10	0.30	-	0.07	0.11	0.75
Goodness of fit measures	χ^2 = 187.0 (df = 64), Goodness of Fit index (GFI) = 0.73, Normed Fit Index (NFI) = 0.67, Comparative Fit Index (CFI) = 0.74, Stability Index (SI) = 0.20							

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.

5.2.2.2 Public Transit Travel and Mobile Telecommunications

The final model includes only five equations, for telecommunications and travel demand and supply, and land use, due to the non-identifiability of more complex models. Table 5.6 presents the estimated, standardized (direct and total) effects of endogenous and predetermined variables on other endogenous variables, for the final model of public transit travel (number of transit passengers carried) and mobile telecommunications (number of mobile phone subscribers). The final model is recursive, and the average R^2 value of 0.43 is higher than that of the previous model. The R^2s for the travel and telecommunications demand equations are higher than for the other equations in the model (0.57 and 0.99, respectively). This might indicate that mobile telecommunications is more closely related to travel, regardless of type, than are the other modes of telecommunications.

Turning to the causal effects in the model, interestingly, the number of transit passengers has a negative impact on the number of mobile phone subscribers, indicating a substitutive relationship. That is, as the number of transit passengers increases, the number of mobile phone subscribers decreases. This is probably because transit passengers tend to be lower income (Pucher and Renne, 2003), and hence less able to afford mobile phones, which were very expensive before the mid 1990s. It would be expected, however, that this causal effect may change after 2000, beyond the time period of this study, because recently the costs of mobile phone service have become lower and lower.

Table 5.6: Estimated Causal Effects among Public Transit Travel and Mobile Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)				
	Demand		Supply		Land
RHS variables	Travel	Telecom	Trans	Telecom	use
Endogenous variables					
Travel demand: transit passengers		-0.036 (-0.036)			
Telecom demand: mobile phone subscribers					
Transportation supply: transit vehicle-miles	0.344 (0.344)	-0.012			
Telecom supply: cell sites		0.998 (0.998)			
Land use: suburbanization rate	-0.461 (-0.461)	0.017			
Predetermined variables					
Travel costs: CPI for public transportation	-0.263 (-0.263)	0.010			
Economic activity: GDP		0.227		0.227 (0.227)	
1st lagged travel demand	0.124	-0.004	0.359 (0.359)		
1st lagged telecom demand		0.189		0.189 (0.132)	
1st lagged trans supply	0.359	-0.013			-0.778 (-0.778)
1st lagged telecom supply	-0.150	0.005			0.324 (0.324)
Female proportion of the labor force		0.035 (0.035)			
No. of households	0.222 (0.222)	-0.008			
R^2 (average R^2 = 0.43)	0.57	0.99	0.13	0.09	0.36
Goodness of fit measures	χ^2 = 65.5 (df = 44), Goodness of Fit index (GFI) = 0.86, Normed Fit Index (NFI) = 0.91, Comparative Fit Index (CFI) = 0.97				

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. This is a recursive (having no feedback loop) model, so there is no Stability Index.

On the other hand, similar to the VMT and mobile phone model, there is no significant effect of mobile phone demand on public transit travel. It is plausible that since mobile phone calls can increase or decrease travel, both effects on travel may cancel, resulting in a zero net effect. Logically, the CPI for public transportation negatively affects its demand, showing that the cost elasticity of transit demand is -0.33. The other causal effects among demand, supply, and land use are similar to those in the previous models, and have logical signs.

5.2.3 Ground Travel and Telecommunications

This section presents causal effects between ground travel (personal vehicle travel and public transit travel) and local or mobile telecommunications, separately, because all 14 equations could not be put together in one model due to non-identifiability. As in the individual pairwise models, the public transit cost equation was not included in either structural equation model, and the other two cost equations were not included in the latter model.

5.2.3.1 Ground Travel and Local Telecommunications

Table 5.7 presents the causal effects among endogenous variables, and between predetermined and endogenous variables, for the final model of ground travel (VMT and number of transit passengers) and local telecommunications (number of local telephone calls). The final model is nonrecursive, having a feedback loop among VMT, number of transit passengers, and local telephone calls, and has 10 equations, so the indirect causal effects are a little complicated. The average R^2 is 0.34, which seems relatively strong for a system of this complexity.

Most causal effects among demand, supply, cost, land use, and economic activity are similar to those in the previous pairwise models, showing logical signs. It is reasonable that personal vehicle travel (VMT) and public transit travel (number of transit passengers) have a negative, bi-directional causal relationship, indicating substitution effects between transportation modes. That is, as VMT increases, the number of transit passenger decreases, and vice versa. It is apparent that the effect of public transit travel on VMT is more than double, compared to that in the other direction. Especially to the extent that transit users are captive riders rather than choice ones, increased VMT does not proportionately contribute to reduction in transit use. The results may also be reflecting the well-known tendency that a shift from transit to private vehicles does not simply shift the same distance traveled one mode to another, but is also accompanied by an increase in the distance traveled.

Table 5.7: Estimated Causal Effects among Ground Travel and Local Telecommunications Variables (N = 49)

RHS variables	Endogenous variables (LHS variables)									
	Demand			*Supply*			*Costs*		Land use	Economic activity
	VMT	Transit	Local calls	Lane miles	Transit veh. miles	Total wire length	CPI for PV	CPI for local calls		
Endogenous variables										
Travel demand:										
VMT	0.198	-0.202 (-0.327)	0.453 (0.428)							
transit passengers	-0.532 (-0.458)	0.232	0.140 (0.299)							
Telecom demand:										
local calls	0.057 (0.233)	0.468 (0.418)	0.164							
Transportation supply:										
lane miles (urban areas)	0.312 (0.142)	-0.053	0.118				-0.219 (-0.219)			
transit vehicle-miles	-0.557	1.290 (1.047)	0.146							
Telecom supply:										
total wire length	0.023	0.188	0.469 (0.403)							
Travel costs:										
CPI for private transportation	-0.650 (-0.543)	0.110	-0.246							
Telecom costs:										
CPI for local telephone service	-0.012	-0.095	-0.237 (-0.204)							
Land use:										
suburbanization rate										
Economic activity: GDP	0.410 (0.385)	0.041 (0.097)	0.188							

(Table 5.7 continued)

RHS variables	Endogenous variables (LHS variables)									
	Demand			Supply			Costs		Land use	Economic Activity
	VMT	Transit	Local calls	Lane miles	Transit veh-miles	Total wire length	CPI for PV	CPI for local calls		
Predetermined variables										
CPI for public transportation	0.070	-0.162 (-0.131)	-0.018							
1st lagged VMT	0.172	-0.029	0.065	0.551 (0.551)			-0.120			
1st lagged transit passengers	-0.094	0.218	0.025		0.169 (0.169)					
1st lagged local calls	0.010	0.080	0.198			0.423 (0.423)				
1st lagged lane miles	0.038	0.004	0.018						0.147 (0.147)	0.094 (0.094)
1st lagged wire length	0.002	0.017	0.043					-0.180 (-0.180)	0.500 (0.500)	
Gasoline price	-0.405	0.068	-0.153				0.622 (0.622)			
FRB interest rate	-0.120	0.020	-0.045	-0.384 (-0.384)			0.084			
Unemployment rate	-0.335	-0.034	-0.154							-0.818 (-0.818)
Female proportion of the licensed driver	0.220	-0.510	-0.058		-0.396 (-0.396)					
Population	0.009	0.076	0.188			0.402 (0.402)				
Average HH size	0.040	-0.210 (-0.096)	-0.241 (-0.195)							
R^2 (average R^2 = 0.34)	0.28	0.29	0.33	0.30	0.27	0.34	0.47	0.03	0.32	0.72
Goodness of fit measures	χ^2 = 394.5 (df = 147), Goodness of Fit index (GFI) = 0.68, Normed Fit Index (NFI) = 0.62, Comparative Fit Index (CFI) = 0.70, Stability Index (SI) = 0.52									

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.

Not surprisingly, some of the total effects among the demand variables are less than their direct impacts due to the negative relationship between VMT and number of transit passengers. For example, number of transit passengers indirectly negatively affects local telephone calls through VMT, although its direct effect on local telephone calls is positive. Thus, its total effect, which is the sum of direct and indirect effects, is less than the direct effect.

VMT and number of transit passengers positively affect local telephone calls, and vice versa. This indicates that the relationship between ground travel and telecommunications is complementarity. That is, as VMT or number of transit passengers increases, number of local telephone calls increases. Looking at the magnitudes of the total effects, the effect of VMT on local telephone calls is greater than that of the number of transit passengers. This suggests that the more mobile people are, the more telephone calls they generate. On the other hand, it is found that local telephone calls tend to generate more public transit travel than personal vehicle travel. This may be attributed to the negative relationship between VMT and transit passengers, resulting in a negative (indirect) effect of local telephone calls on VMT.

The induced demand effect of lane miles is similar to those in the previous pairwise models, showing that the lame miles elasticity of VMT is 0.25. All supply equations have the corresponding lagged demand variable with positive signs. The direct effects of economic activity and socio-demographic variables have expected signs, and a few of their indirect effects have opposite but logical signs. For example, the average household size has a positive (indirect) impact on VMT, because it has a positive (direct) impact on number of transit passengers, which is negatively related to VMT. The female proportion of licensed drivers positively affects VMT and negatively affects number of transit passengers. This supports the expectation that the growth in the number of female drivers has significantly contributed to increases in VMT (and, of course, drawn away former transit riders). This trend has been identified in Nationwide Personal Transportation Survey (NPTS) results as well (Pisarski, 1992). Logically, the suburbanization rate is positively affected by the lagged lane miles and total wire length variables, and GDP is positively affected by the lagged lane miles variable.

5.2.3.2 Ground Travel and Mobile Telecommunications

Table 5.8 presents the causal effects among endogenous variables, and between predetermined and endogenous variables, for the final model of ground travel (VMT and number of transit passengers) and mobile telecommunications (number of mobile phone subscribers). The final model is nonrecursive, having a feedback loop between VMT and number of transit passengers, and the average R^2 is 0.41, which is relatively high as for the other mobile telecommunications related models. Most causal effects among demand, supply, cost, land use, and economic activity are similar to those in the previous pairwise or joint models, and all of them have logical signs.

Similar to the individual pairwise model results, VMT has a positive impact on number of mobile phone subscribers (that is, a complementary relationship), whereas number of transit passengers has a negative impact (that is, a substitutive relationship). It is logical that the more mobile people are, the more useful a mobile phone is. Also, there is no significant impact of mobile phones on either VMT or transit passengers. The induced demand impact of lane miles on VMT is similar to the previous model, showing that the lane miles elasticity of VMT is 0.21. Logically, all lagged demand variables positively affect the corresponding supply variables. Economic activity and socio-demographic variables are significant in the demand and supply equations with logical signs. As expected, the female proportion of licensed drivers positively affects VMT and number of mobile phone subscribers, while it negatively affects transit demand and supply variables.

Table 5.8: Estimated Causal Effects among Ground Travel and Mobile Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)							
		Demand			*Supply*		Land	Economic
RHS variables	VMT	Transit	Mobile phone subscribers	Lane miles	Transit vehicle-miles	Cell sites	use	activity
Endogenous variables								
Travel demand:								
VMT	1.217	-2.397 (-1.081)	0.061 (0.028)					
transit passengers	-1.126 (-0.508)	1.217	-0.031					
Telecom demand:								
mobile phone subscribers								
Transportation supply:								
lane miles (urban areas)	0.289 (0.077)	-0.143	0.060			0.054		0.222 (0.222)
transit vehicle-miles	-0.233	0.460 (0.207)	-0.006					
Telecom supply:								
cell sites			0.966 (0.966)					
Land use: suburbanization rate	0.284 (0.128)	-0.307	0.008					
Economic activity: GDP	0.532 (0.627)	0.188 (0.763)	0.249			0.243 (0.243)		

(Table 5.8 continued)

RHS variables	Endogenous variables (LHS variables)							
	Demand			*Supply*				
	VMT	Transit	Mobile phones	Lane miles	Transit vehicle-miles	Cell sites	Land use	Economic activity
Predetermined variables								
CPI for public transportation	0.139	-0.275 (-124)	0.004					
1st lagged VMT	0.184	-0.091	0.038	0.635 (0.635)		0.034		0.141
1st lagged transit passengers	-0.041	0.080	-0.001		0.174 (0.174)			
1st lagged mobile phone subscribers			0.289			0.300 (0.300)		
1st lagged lane miles	0.081	-0.088	0.002				0.287 (0.287)	
Gasoline price	-0.278 (-0.125)	0.300	-0.008					
FRB interest rate	-0.116	0.057	-0.024	-0.401 (-0.401)		-0.022		-0.089
Unemployment rate	-0.452	-0.159	-0.212			-0.207		-0.849 (-0.849)
Female proportion of the licensed driver	0.072	-0.141	0.002		-0.308 (-0.308)			
Average HH size			-0.032 (-0.032)					
R^2 (average R^2 = 0.41)	0.53	0.17	0.99	0.37	0.20	0.15	0.08	0.77
Goodness of fit measures	χ^2 = 224.6 (df = 100), Goodness of Fit index (GFI) = 0.75, Normed Fit Index (NFI) = 0.74, Comparative Fit Index (CFI) = 0.83, Stability Index (SI) = 0.55							

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.

5.3 Causal Relationships between Airline Travel and Telecommunications

This section presents individual structural equation models for telecommunications and domestic or international airline travel, as opposed to ground travel. It is logically assumed that international airline travel and international telephone calls do not affect the suburbanization rate. Thus, the land use equation was not included in the structural equation model for international airline travel and international telephone calls. Also, the telecommunication cost equation was excluded from the model due to non-identifiability. In the final subsection, a combined structural equation model is discussed, using total air travel and total telephone calls.

5.3.1 Domestic Airline Travel and Telecommunications

5.3.1.1 Domestic Airline Travel and Local Telecommunications

Table 5.9 presents the estimated, standardized (direct and total) effects among endogenous variables, and between predetermined and endogenous variables, for the final model of domestic airline travel (domestic airline PMT) and local telecommunications (number of local telephone calls). The final model is recursive, and the average R^2 is 0.37. The R^2s for the travel and telecommunications demand equations are 0.81 and 0.38, which are relatively high.

Turning to the causal effects in the model, local telephone calls and its lagged variable have a positive impact on domestic airline PMT. That is, as local telephone calls increase (in the previous year), domestic airline PMT increases. It supports the idea that telephone calls are more likely to generate air travel than to replace it. In contrast, it is found that there is no significant impact of airline PMT on local telephone calls, differing from the impacts of ground travel on them. Since airline travel is generally long-distance travel, it may be more likely to influence toll calls rather than local calls, considering communications between origin and destination. On the other hand, many of the calls associated with airline travel are local − to/from a travel agent at the origin end, and to/from colleagues or activities at the destination end. Such local calls are too few to detect among *all* local calls, most of which are unrelated to air travel.

As hypothesized, both available seat miles and total wire length positively affect domestic airline PMT and local calls, respectively. Logically, CPI for airline has a negative impact on domestic airline PMT, and GDP has a positive impact on domestic airline PMT. It is also found that other measures of economic activity (such as female proportion of the labor force) logically significantly affect domestic airline PMT and total wire length. As expected, average household size (negatively related to number of households) negatively affects telecommunications and travel demand. Interestingly, number of licensed drivers as a mobility indicator, rather than as an indicator of competitive mode (personal vehicle) use, positively affects airline travel. It implies that the more mobile people are, the more air travel they generate.

Table 5.9: Estimated Causal Effects among Domestic Airline Travel and Local Telecommunications Variables (N = 49)

RHS variables	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land use	Economic activity
	Travel	Telecom	Trans	Telecom	Travel	Telecom		
Endogenous variables								
Travel demand								
domestic airline PMT								
Telecom demand	0.103							
local calls	(0.103)							
Transportation supply	0.719				-0.237			
available seat miles	(0.647)				(-0.237)			
(domestic airline)								
Telecom supply	0.064	0.407						0.108
total wire length		(0.407)						(0.108)
Travel cost	-0.306							
CPI for airline	(-0.306)							
Telecom costs	-0.017	-0.162						
CPI for local telephone		(-0.162)						
Service								
Land use								
suburbanization rate								
Economic activity:	0.203							
GDP	(0.203)							

(Table 5.9 continued)

RHS variables	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land use	Economic activity
	Travel	Telecom	Trans	Telecom	Travel	Telecom		
Predetermined variables								
1st lagged travel demand	0.445		0.619 (0.619)		-0.147			
1st lagged telecom demand	0.022	0.143		0.351 (0.351)				0.038
1st lagged telecom supply	0.003	0.032				-0.195 (-0.195)	0.490 (0.490)	
Unemployment rate	-0.173							-0.850 (-0.850)
Female proportion of the labor force	0.021	0.131		0.322 (0.322)				0.035
Number of licensed drivers	0.165 (0.165)							
Average HH size	-0.024	-0.231 (-0.231)						
R^2 (average R^2 = 0.37)	0.81	0.38	0.38	0.34	0.06	0.04	0.24	0.73
Goodness of fit measures	χ^2 = 156.9 (df = 63), Goodness of Fit index (GFI) = 0.75, Normed Fit Index (NFI) = 0.72, Comparative Fit Index (CFI) = 0.79							

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. This is a recursive (no feedback loop) model, so there is no Stability Index.

As supply and cost variables, the total wire length and CPI for local calls significantly affect local telephone calls in a logical way, similar to the previous models. As hypothesized, lagged demand variables positively affect supply variables, and supply variables negatively affect cost variables. It is reasonable that the suburbanization rate is positively affected by the lagged total wire length. This supports the idea that suburbanization has been accelerated by providing both telecommunications and transportation infrastructure in suburban areas. Other causal effects of socio-demographic and economic activity variables are similar to those in the previous models.

5.3.1.2 Domestic Airline Travel and Long-distance Telecommunications

Table 5.9 presents the estimated, standardized causal effects among endogenous variables, and between predetermined and endogenous variables, for the final model of domestic airline travel (domestic airline PMT) and long-distance telecommunications (number of toll calls). The final model is recursive, and the average R^2 of the model is 0.35, which is higher than that of the model of VMT and number of toll calls.

For the causal effects among endogenous variables, similar to the local calls in the previous model, number of toll calls strongly positively affects domestic airline PMT, indicating a complementary relationship between the two. That is, as number of toll calls increases, domestic airline PMT increases. It is natural that the effect of toll calls on domestic airline PMT is much higher than that of local calls because airline travel is long-distance. However, there is no significant impact of domestic airline PMT on toll calls. It may indicate that the net effect of airline travel on generating and replacing toll calls is zero, rather than no impact of domestic airline PMT on toll calls. Alternatively, it may indicate that any generation effect of airline travel on toll calls contributes such a small proportion of total toll calls as to be non-detectable. As expected, supply variables positively affect demand variables and negatively affect cost variables. It is logical that total wire length has a positive impact on suburbanization rate, by enhancing the network capacity of telecommunications infrastructure through its extension to suburban areas. Clearly, CPI for airline and GDP should logically affect airline PMT, and they do so in the expected ways (negatively and positively, respectively).

Similar to the previous models, there are lagged causal effects between demand and supply or costs, with logical signs. As hypothesized, the lagged variable of telecommunications demand indirectly positively affects economic growth. That is, as number of toll calls in the previous year increases, total wire length increases, then GDP increases. Other economic activity variables (unemployment rate and female proportion of the labor force) logically significantly affect demand, supply, and cost. It is reasonable that average household size negatively affects telecommunications and travel demand. As seen in the previous structural equation models relating to toll calls, it makes sense that the dummy variable of 1950-1983 significantly affects the CPI for inter-state toll calls due to the divestiture of AT&T in 1984.

Table 5.10: Estimated Causal Effects among Domestic Airline Travel and Long-distance Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	use	activity
Endogenous variables								
Travel demand:								
domestic airline PMT								
Telecom demand:	0.647							
toll calls	(0.647)							
Transportation supply:	0.696				-0.232			
available seat miles	(0.610)				(-0.232)			
(domestic airline)								
Telecom supply:	0.218	0.300				-0.490		0.130
total wire length		(0.300)				(-0.490)		(0.130)
Travel costs:	-0.372							
CPI for airline	(-0.372)							
Telecom costs: CPI for inter-state telephone service								
Land use:								
suburbanization rate								
Economic activity:	0.188							
GDP	(0.188)							

(Table 5.10 continued)

RHS variables	Demand: Travel	Demand: Telecom	Supply: Trans	Supply: Telecom	Costs: Travel	Costs: Telecom	Land use	Economic activity
	Endogenous variables (LHS variables)							
Predetermined variables								
1st lagged travel demand	0.427		0.613 (0.613)		-0.142			
1st lagged telecom demand	0.060	0.082		0.273 (0.273)		-0.134		0.036
1st lagged telecom supply							0.203 (0.203)	
Unemployment rate	-0.162							-0.861 (-0.861)
Female proportion of the labor force	0.098	0.135		0.450 (0.450)		-0.221		0.059
Average HH size	-0.092	-0.143 (-0.143)						
Dummy (1950-1983)						0.725 (0.725)		
R^2 (average R^2 = 0.35)	0.58	0.09	0.38	0.28	0.05	0.60	0.04	0.77
Goodness of fit measures	χ^2 = 153.0 (df = 76), Goodness of Fit index (GFI) = 0.78, Normed Fit Index (NFI) = 0.75, Comparative Fit Index (CFI) = 0.84							

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. This is a recursive (no feedback loop) model, so there is no Stability Index.

5.3.1.3 Domestic Airline Travel and Mobile Telecommunications

Table 5.11 presents the causal effects among the variables in the final model of domestic airline travel (domestic airline PMT) and mobile telecommunications (number of mobile phone subscribers). The final model is nonrecursive, having a feedback loop between available seat miles and GDP. The average R^2 of the model is 0.58, which is the highest among all models. Further, the R^2s for the travel and telecommunications demand equations are 0.84 and 0.93, respectively. This may indicate that mobile telecommunications is more closely related to airline travel than ground travel. The land use equation was not included in the model due to non-identifiability.

Turning to the causal effects in the model, interestingly, domestic airline PMT has a positive impact on number of mobile phone subscribers, indicating a complementary relationship. That is, as domestic airline PMT increases, the number of mobile phone subscribers increases. There are two possible explanations for this relationship: income and mobility. The first explanation is one of third-party correlation: those who travel a lot by air tend to have high incomes, so they can afford a mobile phone, considering its expensiveness in the earlier years. The other explanation is a more behavioral one: the more people travel, the more important it becomes to be reachable while traveling, and to be able to make calls while traveling. Not surprisingly, there is no significant relationship in the other direction, meaning that the net impact of mobile communications on domestic airline travel is zero.

As expected, supply variables strongly positively affect their demand variables and negatively their cost variables, while lagged demand variables positively affect their current supply variables. Available seat miles and GDP significantly affect all endogenous variables directly or indirectly, in logical ways. The other economic activity variables (the FRB interest rate and unemployment rate) have logical signs on all endogenous variables. As hypothesized, CPI for airline has a negative impact on domestic airline PMT. As found in the earlier model of domestic airline PMT, number of licensed drivers, as a mobility indicator, positively affects airline travel. Also, average household size negatively affects number of mobile phone subscribers, which is logical.

Table 5.11: Estimated Causal Effects among Domestic Airline Travel and Mobile Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)						
	Demand		Supply		Costs		Economic
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	activity
Endogenous variables							
Travel demand:		0.029					
domestic airline PMT		(0.029)					
Telecom demand:							
mobile phone subscribers							
Transportation supply:	0.845	0.036	0.041	0.015	-0.248	-0.013	0.140
available seat miles	(0.725)				(-0.238)		(0.134)
(domestic airline)							
Telecom supply:		0.740				-0.908	
cell sites		(0.740)				(-0.908)	
Travel costs:	-0.252	-0.007					
CPI for airline	(-0.252)						
Telecom costs:							
average monthly revenue							
Economic activity:	0.450	0.094	0.305	0.109	-0.073	-0.099	0.041
GDP	(0.203)		(0.293)	(0.105)			

(Table 5.11 continued)

	Endogenous variables (LHS variables)						
	Demand		Supply		Costs		Economic activity
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	
Predetermined variables							
1st lagged travel demand	0.555	0.023	0.684 (0.657)	0.010	-0.163	-0.009	0.092
1st lagged telecom demand	0.086 (0.086)	0.140		0.185 (0.185)		-0.168	
FRB interest rate	-0.067	-0.014	-0.046	-0.016	0.011	0.015	-0.155 (-0.149)
Unemployment rate	-0.402	-0.084	-0.272	-0.097	0.065	0.088	-0.928 (-0.892)
Number of licensed drivers	0.189 (0.189)	0.006					
Average HH size		-0.025 (-0.025)					
R^2 (average $R^2 = 0.58$)	0.84	0.93	0.55	0.04	0.06	0.91	0.76
Goodness of fit measures	$\chi^2 = 59.5$ (df = 49), Goodness of Fit index (GFI) = 0.86, Normed Fit Index (NFI) = 0.92, Comparative Fit Index (CFI) = 0.99, Stability Index (SI) = 0.04						

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.

5.3.2 International Airline Travel and International Telecommunications

As mentioned earlier, logically, the land use (suburbanization rate) equation was not included in the structural equation model for international airline PMT and international telephone calls. The telecommunication cost equation was excluded from the model due to non-identifiability. Table 5.12 presents the estimated, standardized (direct and total) effects among the variables in the model. The final model is recursive, and the average R^2 is 0.35, which is similar to or somewhat lower than those in the models of domestic airline travel and telecommunications.

For the causal effects between travel and telecommunications demand, interestingly, there are no contemporaneous effects between international airline travel and international calls. It may indicate that substitutive and complementary effects between the two are canceled out contemporaneously. However, it is found that there is a significantly positive impact of lagged international calls on international airline PMT. That is, as international airline travel increases in the previous year, international calls increase in the current year. It makes sense that after people make international trips, they keep communicating with their colleagues, families or friends visited, or maintain or update information via telephone calls. It is also found that the lagged variable of international calls has an indirect positive, albeit small, effect on international airline PMT through its supply and GDP. That is, as international calls increase in the previous year, total wire length increases, GDP increases, then international airline PMT increases.

Table 5.12: Estimated Causal Effects among International Airline Travel and Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)						
	Demand		Supply		Costs		Economic
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	activity
Endogenous variables							
Travel demand:							
international airline PMT							
Telecom demand:							
no. of international calls							
Transportation supply:	0.360						
available seat miles	(0.360)						
(international airline)							
Telecom supply:	0.058						0.181
total wire length							(0.181)
Travel costs:	-0.070						
average air fare for	(-0.070)						
international travel							
Telecom costs:		-0.402					
average cost per		(-0.402)					
international calls							
Economic activity:	0.322						
GDP	(0.322)						

(Table 5.12 continued)

	Endogenous variables (LHS variables)						
	Demand		Supply		Costs		Economic activity
RHS variables	Travel	Telecom	Trans	Telecom	Travel	Telecom	
Predetermined variables							
1st lagged travel demand	0.167	0.174 (0.174)	0.462 (0.462)				
1st lagged telecom demand	0.005			0.094 (0.094)			0.017
1st lagged travel supply	0.025				-0.355 (-0.355)		
1st lagged telecom supply		0.184 (0.184)					
Unemployment rate	-0.279						-0.868 (-0.868)
Population	0.099 (0.074)			0.427 (0.427)			0.077
Average HH size		-0.133 (-0.133)					
R^2 (average R^2 = 0.35)	0.60	0.20	0.21	0.18	0.13	-	0.75
Goodness of fit measures	χ^2 = 102.3 (df = 54), Goodness of Fit index (GFI) = 0.83, Normed Fit Index (NFI) = 0.77, Comparative Fit Index (CFI) = 0.86						

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. This is a recursive (no feedback loop) model, so there is no Stability Index.

As expected, available seat miles and GDP strongly positively affect international air travel demand, and average air fare negatively affects the demand. Similarly, average cost per international call negatively affects number of international calls. As a measure of telecommunications supply, logically, the lagged variable of total wire length positively affects number of international calls. As expected, unemployment rate has a negative impact on international air travel. Two socio-demographic variables, population and average household size, significantly affect both demand and telecommunications supply in logical ways. It is reasonable that total wire length positively affects GDP, whereas the lagged variable of available seat miles negatively affects the average international air fare.

5.3.3 Total Airline Travel and Telecommunications

This section presents the structural equation model for total airline travel and telecommunications (total telephone calls). Two demand variables were calculated: total airline travel and total telephone calls. The former is the sum of domestic and international airline PMT, and the latter is the sum of local, toll, and international telephone calls. Logically, the transportation supply variable is the sum of domestic and international available seat miles, and the cost variables for travel and telecommunications are the CPIs for airline and telephone service, respectively. Together with the other variables described in Chapter 4, the final model was developed. As shown in Table 5.13, the final model is recursive, and the average R^2 is 0.4, which is relatively higher than those of the individual models for airline travel and telecommunications, except for the mobile telecommunications-related model.

Table 5.13: Estimated Causal Effects among Total Airline Travel and Telecommunications Variables (N = 49)

RHS variables	Endogenous variables (LHS variables): Demand		Supply		Costs		Land use	Economic activity
	Travel	Telecom	Trans	Telecom	Travel	Telecom		
Endogenous variables								
Travel demand								
total airline PMT								
(domestic + international)								
Telecom demand	0.187							
telephone calls	(0.187)							
(domestic + international)								
Transportation supply	0.675				-0.179			
total available seat miles	(0.633)				(-0.179)			
(domestic + international)								
Telecom supply	0.211	1.129				-0.699		
total wire length		(0.930)				(-0.699)		
Travel cost	-0.234							
CPI for airline travel	(-0.234)							
Telecom costs	-0.053	-0.284						
CPI for telephone		(-0.284)						
service								
Land use								
suburbanization rate								
Economic activity:	0.400		0.236		-0.042			
GDP	(0.241)		(0.236)					

(Table 5.13 continued)

RHS variables	Demand: Travel	Demand: Telecom	Supply: Trans	Supply: Telecom	Costs: Travel	Costs: Telecom	Land use	Economic activity
	Endogenous variables (LHS variables)							
Predetermined variables								
1st lagged travel demand	0.467		0.692 (0.692)		-0.124			
1st lagged telecom demand	0.041	0.218		0.193 (0.193)		-0.135		
1st lagged telecom supply	0.044		0.026		-0.005		0.420 (0.420)	0.111 (0.111)
Unemployment rate	-0.351		-0.207		0.037			-0.876 (-0.876)
Female proportion of the labor force	0.083	0.441		0.391 (0.391)		-0.274		
Number of licensed drivers	0.099 (0.099)							
Population	0.151		0.224 (0.224)		-0.040			
Average HH size	-0.025	-0.136 (-0.136)						
Dummy (1950-1983)	-0.035	-0.186				0.654 (0.654)		
R^2 (average R^2 = 0.40)	0.81	0.20	0.58	0.24	0.05	0.36	0.18	0.75
Goodness of fit measures	χ^2 = 227.0 (df = 81), Goodness of Fit index (GFI) = 0.73, Normed Fit Index (NFI) = 0.71, Comparative Fit Index (CFI) = 0.77							

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. This is a recursive (no feedback loop) model, so there is no Stability Index.

Turning to the causal effects among the endogenous variables, similar to the individual model for air travel and local telephone calls, number of total telephone calls has a positive impact on total airline PMT. It indicates a complementary relationship between air travel and telecommunications. That is, as number of total telephone calls increases, airline PMT increases. Its lagged effect is also positive in the model. Again, however, the opposite relationship (of airline travel on telecommunications) is not significant. As hypothesized, cost variables positively affect their demand variables, whereas they are negatively affected by their supply variables. Furthermore, CPI for telephone service indirectly negatively affects air travel demand. This also supports that air travel and telephone calls are complementary. As expected, GDP has positive impacts on air travel demand and supply, and an indirect, negative impact on costs through transportation supply.

Similar to the individual models of airline travel and telecommunications, the lagged demand variables positively affect their contemporaneous supply variables. In addition, logically, the lagged variable of total wire length positively affects land use and economic activity (impact of infrastructure on suburbanization and economic development). Its indirect impacts on total seat miles and the CPI for airline are positive and negative, respectively. That is, as total wire length increases in the previous year, GDP increases, then total seat miles increase (it also tends to decrease the CPI for airline). Other economic activity variables (unemployment rate and female proportion of the labor force) logically affect demand, supply, or costs. Three socio-demographic variables (number of licensed drivers, population, and average household size) affect travel demand, supply, and costs in logical ways. Among them, population has an indirect, negative impact on travel costs through transportation supply. That is, as population increases, available seat miles increase, then CPI for airline decreases. As expected, the dummy variable of 1950-1983 is significant in the telecommunications cost equation, together with its supply.

5.4 Comparisons of Causal Relationships between Telecommunications and Travel by Mode

This section compares causal relationships between telecommunications and travel, identified by the individual and joint mode-specific structural equation models in the previous sections. Table 5.14 summarizes the causal relationships between the two by mode. Most significant causal relationships between telecommunications and travel (17 out of 19 significant or 28 altogether) are complementarity either uni-directionally or bi-directionally. That is, as telecommunications increases, travel increases, and/or vice versa. The only exceptions are the two causal relationships between number of transit passengers and number of mobile phone subscribers, which are substitution. That is, as public transit travel increases, the number of mobile phone subscribers decreases. This is probably because transit passengers tend to be lower income, and hence less able to afford mobile phones, which were very expensive before the mid 1990s. Further, it is found that there are a number (9 out of 28) of neutral (net zero) effects of telecommunications on travel or vice versa. That is, telecommunications can generate or replace travel, but both effects on total amount of travel may cancel, resulting in a zero net effect. The other direction (net zero impact of travel on telecommunications) is possible too − the zero effects were fairly balanced, with five from telecommunications to travel and four in the opposite direction. Zero effects were never present for both directions in the same model, indicating that there was always a dominant relationship in at least one direction.

Table 5.14: Causal Relationships between Telecommunications and Travel Demand by Mode

Models	Telecommunications → travel	Travel → telecommunications
Ground travel & telecommunications		
VMT − local calls	0.329	0.246
VMT − toll calls	0.804	
VMT − mobile phone subscribers		0.046
transit passengers − local calls	0.738	0.426
transit passengers − mobile phone subscribers		-0.036
VMT − local calls / transit passengers − local calls	0.057 / 0.468	0.453 / 0.140
VMT − mobile phone subscribers / transit passengers − mobile phone subscribers		0.061 / -0.031
Airline travel & telecommunications		
domestic − local calls	0.103	
domestic − toll calls	0.647	
domestic − mobile phone subscribers		0.029
international − international calls	0.005*	0.174*
total − total telephone calls	0.187	

Note: All coefficients are standardized. A positive coefficient means complementarity, a negative coefficient substitution, "* " a lagged effect, and a blank an insignificant effect.

For ground travel and telecommunications, local calls and VMT or transit passengers have a bi-directional, complementary relationship. However, VMT and toll calls or mobile phone subscribers have a uni-directional, complementary relationship from telecommunications to travel. That is, as number of toll calls increases, VMT increases. On the other hand, as indicated above, the causal effect of number of transit passengers on number of mobile phone subscribers is substitution. The joint structural equation models for ground travel and telecommunications show the same causal effects as found in the individual models, together with a substitutive relationship between VMT and transit passengers. Figure 5.1 displays all relationships between ground travel and telecommunications.

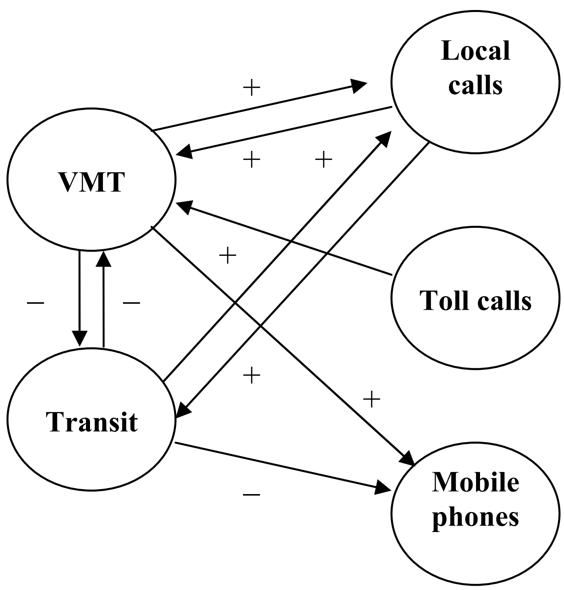


Figure 5.1: Causal Relationships between Ground Travel and Telecommunications

For airline travel and telecommunications, all causal relationships are complementarity. Figure 5.2 shows these relationships graphically. Domestic airline PMT is positively affected by number of local calls or number of toll calls, and it positively affects number of mobile phone subscribers. That is, as number of local calls or toll calls increases, domestic airline PMT increases. Also, as domestic airline PMT increases, number of mobile phone subscribers increases. Interestingly, international airline PMT and international calls have a bi-directional, lagged, complementary relationship. That is, as number of international calls (international airline PMT) increases in the previous year, international airline PMT (number of international calls) increases in the current year. Further, the number of total telephone calls significantly positively affects total airline travel, but not the reverse.

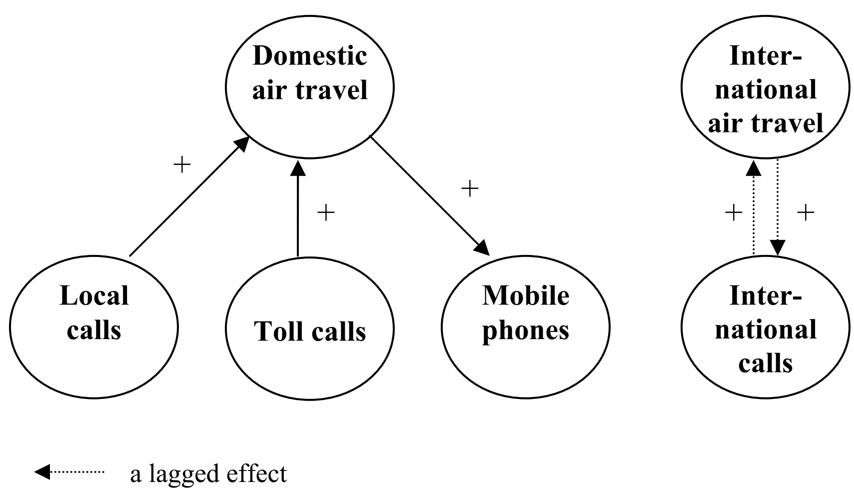


Figure 5.2: Causal Relationships between Airline Travel and Telecommunications

Looking at the magnitudes of the causal relationships between travel and telecommunications, the impact of telecommunications on travel is generally stronger than the converse, although magnitudes are not exactly comparable across the models due to their different specifications.

In sum, it is found that causal effects between telecommunications and travel are different among their modes. However, most of them are complementarity regardless of a causal direction. These results are opposed to the substitutive relationships found between the two in Selvanathan and Selvanathan's study (1994), although their study focused on consumers' expenditures on transportation and communications goods, rather than on measures of actual activity as in this study. In the next chapter, structural equation models, using composite indices for endogenous categories, are discussed to explore even more comprehensively the relationships between telecommunications and travel.

CHAPTER 6. CAUSAL RELATIONSHIPS BETWEEN COMPOSITE INDICES OF TELECOMMUNICATIONS AND TRAVEL

In the previous chapter, individual and joint structural equation models for telecommunications and ground travel or airline travel were developed, 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 since it necessarily ignores a number of variables and relationships that may be important to obtaining a complete picture of the relationships shown in Figure 3.1. On the other hand, there are more than 30 different endogenous variables in the eight categories described in Table 4.1. Building a structural equation model with, say, 30 equations, one for each variable, is not possible given that we have 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.

In this chapter, a different approach is taken: using confirmatory factor analysis to combine the variables of a given category into a single composite indicator for that category. While 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. In the first section, composite indices for endogenous variable categories (telecommunications and travel demand, supply, and costs; land use; and economic activity) are constructed. In the second sections, structural equation models for travel and wired (telephone calls) or mobile, called wireless, (mobile phone subscribers) telecommunications are estimated, using the composite indices and socio-demographic variables, and then the estimated results for the models are discussed. In the final section, both estimated results of the structural equation models are compared with those of the single-equation approach.

6.1 Composite Indices

Focused on domestic travel and telecommunications, composite indices for the endogenous category variables were constructed, using the key variables in the conceptual categories described in Chapter 4. Initially, exploratory factor analysis was conducted on the 26 (log-transformed and first-order differenced, $\log(X_t) - \log(X_{t-1})$) endogenous variables remaining after excluding international travel and telecommunications, gasoline price, and fuel efficiency variables, but the resulting factor solutions did not coincide well with the conceptual categories. Thus, confirmatory factor analysis was employed to create the composite indices. That is, a single-factor solution was obtained through factor analysis of each category, based on the set of variables in that category. It should be noted that in reality, the composite indices are measures of latent variables, and that in the ideal application, both confirmatory factor analysis (the "measurement model") and structural modeling are conducted simultaneously in the structural equation context (Kline, 1998). However, as Golob (2003) points out, both a measurement model and a structural model are seldom estimated together in practice, and the current situation is no exception. In view of the sample size limitations (resulting in the under-identification of structural equation models), two-step modeling is used in this study. That is, the composite indices 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, 2002).

Ultimately, factor score variables for all endogenous variable categories except land use were developed. Because there is only one individual variable (suburban proportion of total metropolitan population) in the land use category, the suburbanization rate will be entered directly into the models as the variable representing the land use factor. The FRB interest rate variable was excluded from the economic activity category due to the counter-intuitive sign in its factor loading. Additionally, mobile phone-related variables did not work in the corresponding factor categories, also showing counter-intuitive 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 are developed: for travel and wired telecommunications (telephone calls), and for travel and mobile (wireless) telecommunications (mobile phone subscribers). Table 6.1 presents the component variables and their score coefficients for each composite index. All component variables are natural log-transformed, first-order differenced, (i.e. $\log[X_t] - \log[X_{t-1}]$). The composite indices account for 40 - 70% of the total variances in the variables for their categories. Table 6.2 shows pairwise Pearson correlation coefficients of all composite indices. They are consistent with the hypothesized causal relationships.

Table 6.1: Composite Indices

Composite Index	Component Variables (natural-log form, 1st differenced, $\log(X_t) - \log(X_{t-1})$)	Component Score Coefficient
Travel Demand (59%)	Passenger VMT	0.485
	Revenue transit passengers carried	-0.376
	Revenue domestic airline PMT	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 Cost (64%)	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 toll calls	0.660
	Number of mobile phone subscribers*	Single-variable factor
Telecommunications Supply (63%)	Number of telephone residential access lines	0.506
	Number of telephone business access lines	0.461
	Total telephone wire length	0.243
	Number of cell sites*	Single-variable factor
Telecommunications Costs (56%)	CPI for local telephone calls	0.384
	CPI for intra-state toll calls	0.533
	CPI for inter-state toll calls	0.406
	Real average monthly revenue from mobile call services*	Single-variable factor
Land Use	Suburban population ratio to total metropolitan populations	Single-variable factor
Economic Activity (67%)	Real GDP	0.466
	Unemployment rate	-0.473
	Female proportion of the labor force	0.245

Notes: 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.

Table 6.2: Pairwise Correlation Coefficients of Composite Indices (N = 50)

	Travel demand	Trans supply	Travel costs	Telecom demand	Telecom supply	Telecom costs	Mobile phone subscribers	Mobile phone supply	Mobile phone costs	Land use	Economic activity
Travel demand	1										
Trans supply	.795***	1									
Travel costs	-.401***	-.281**	1								
Telecom demand	.222	.251*	.002	1							
Telecom supply	.335**	.429***	.002	.435***	1						
Telecom costs	-.069	-.163	.206	-.090	-.405***	1					
Mobile phone subscribers	-.134	-.336**	-.052	-.357**	-.585***	.193	1				
Mobile phone supply	-.161	-.371***	-.079	-.372***	-.585***	.178	.995***	1			
Mobile phone costs	.102	.346**	.096	.263*	.537***	-.198	-.941***	-.953***	1		
Land use	.672***	.770***	-.117	-.057	.341*	-.047	-.166	-.202	.183	1	
Economic activity	.453***	.241*	-.205	.087	.075	-.216	.175	.169	-.165	.139	1

Notes: *** correlation is significant at α = 0.01, ** correlation is significant at α = 0.05, * correlation is significant at α = 0.1.

6.2 Causal Relationships between Travel and Telecommunications

Based on the conceptual model, two structural equation models were developed (for travel and telephone calls, and travel and mobile phone subscribers), using composite indices and (natural log-transformed, first-order differenced) socio-demographic variables. Through the same estimation procedure described in Section 5.1, 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 telecommunications due to non-identifiability. Thus, this model does not include the mobile phone cost equation.

6.2.1 Structural Equation Model of Travel and Wired Telecommunications

Table 6.3 presents the estimated, standardized (direct and total) effects among endogenous variables, and between predetermined and endogenous variables, for the final model of travel and wired telecommunications (telephone calls). The final model is nonrecursive, having a feedback loop between travel and telecommunications demand, and the average R^2 of the model is 0.32, which is moderate compared to the individual and joint models. The ratio of the χ^2 statistic to the degrees of freedom of the final model is less than three, and the other measures of goodness of fit are greater than 0.7. These indicate the model has a good fit. Figure 6.1 graphically summarizes the identified causal effects, based on the conceptual model

Turning to the causal effects in the model, both travel and telecommunications (telephone call) demand variables positively significantly affect each other. That is, as travel demand increases, telecommunications increases, 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 appear, telephone calls more often occur as a kind of derived demand from travel than as a means of generating travel. This seems consistent with anecdotal observation, in that a much higher proportion of trips seem to involve telecommunications (before the trip to prepare for it, during the trip to coordinate activities and communicate with "home base", 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) 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. However, telecommunications cost is not significant in the model. This may suggest that the demand for telephone calls is relatively inelastic, at least within the range of experienced costs.

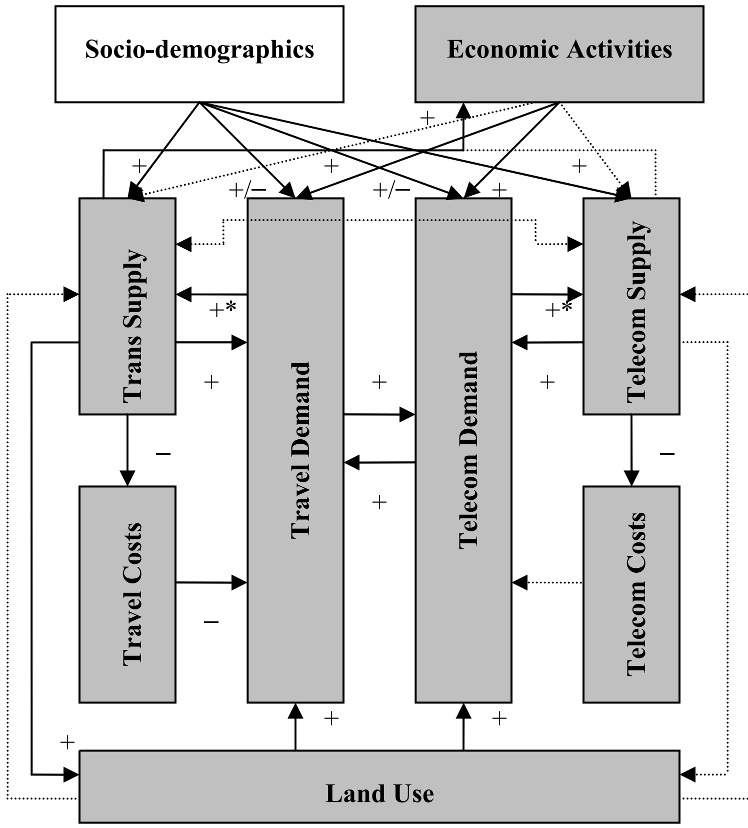
Table 6.3: Estimated Causal Effects among Travel and Wired Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Travel	Telecom	Travel	Telecom	use	activity
Endogenous variables								
Travel demand	0.081	0.364						
		(0.336)						
Telecommunications demand (wired telephone calls)	0.242	0.081						
	(0.224)							
Transportation supply	0.795	0.267			-0.176		1.262	0.173
	(0.513)				(-0.176)		(1.262)	(0.173)
Travel costs	-0.248	-0.083						
	(-0.229)							
Land use	0.130	0.044						
	(0.120)							
Economic activity	0.189	0.064						
	(0.175)							

(Table 6.3 continued)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Travel	Telecom	Travel	Telecom	use	activity
Predetermined variables								
1st lagged travel demand	0.090	0.030	0.114 (0.114)		-0.020		0.143	
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 proportion of licensed drivers	0.484	0.163	0.609 (0.609)		-0.107		0.768	0.106
Dummy (1950-1983)						0.460 (0.460)		
R^2 (average = 0.32)	0.72	0.36	0.48	0.26	0.05	0.31	0.36	0.03
Goodness of fit measures	χ^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							

Notes: Socio-demographic 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.



Notes: '+' = a positive causal effect (total), '–' = a negative causal effect (total). '*' = a lagged effect. A dotted line means a hypothesized but insignificant causal relationship.

Figure 6.1: Identified Causal Relationships between Travel and Wired Telecommunications

Additionally, land use and economic activity have positive impacts on both travel and telecommunications demand, but stronger 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. Logically, the supply variables strongly positively affect the corresponding demand variables. Similar to the individual and joint models relating to toll calls, the dummy variable of

1950-1983 is significant in the telecommunications cost equation, together with telecommunications supply, due to the 1984 AT&T divestiture. 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 socio-demographic 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 been identified in Nationwide Personal Transportation Survey (NPTS) results as well (Pisarski, 1992).

6.2.2 Structural Equation Model of Travel and Mobile Telecommunications

Table 6.4 shows the estimated, standardized causal effects among the variables for the final model of travel and mobile telecommunications (mobile phone subscribers). The final model is recursive (having no feedback loop), differing from the previous model. The average R^2 of the model is 0.38, which is slightly lower than those of the individual models, but greater than the previous model. All goodness-of-fit measures show that the model has a good fit. As mentioned earlier, there is no telecommunication cost equation in the model due to non-identifiability.

Table 6.4: Estimated Causal Effects among Travel and Mobile Telecommunications Variables (N = 49)

	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
RHS variables	Travel	Telecom	Travel	Telecom	Travel	Telecom	use	activity
Endogenous variables								
Travel demand		0.043						
		(0.043)						
Transportation supply	0.943	0.055		0.018	-0.338		1.255	0.167
	(0.536)				(-0.338)		(1.255)	(0.167)
Telecommunications		0.779						
supply (no. of cell sites)		(0.779)						
Travel costs	-0.160	-0.007						
	(-0.160)							
Land use	0.249	0.011						
	(0.249)							
Economic activity	0.246	0.096		0.110				
	(0.246)			(0.110)				

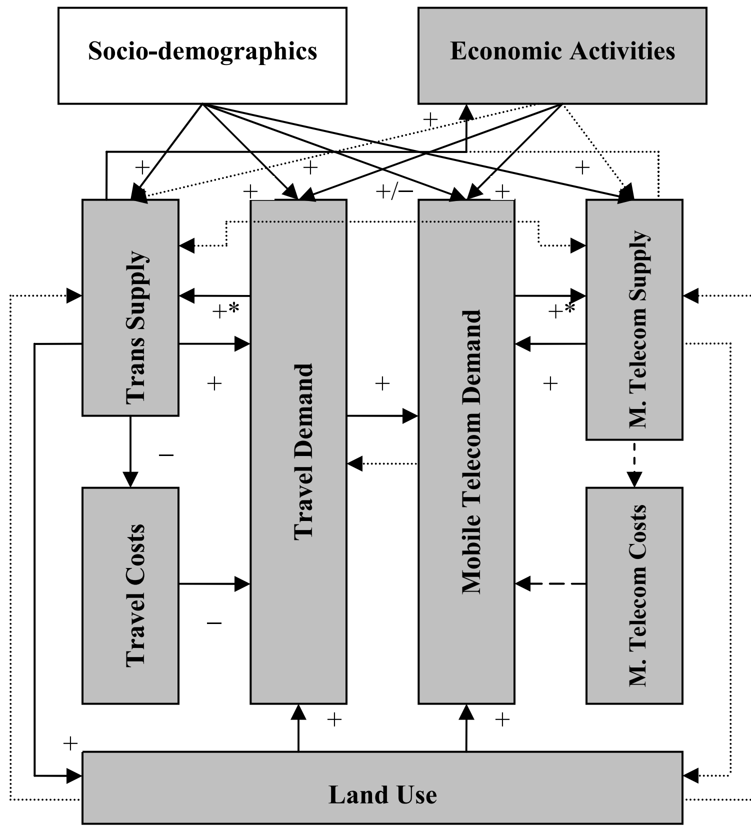
(Table 6.4 continued)

RHS variables	Endogenous variables (LHS variables)							
	Demand		Supply		Costs		Land	Economic
	Travel	Telecom	Travel	Telecom	Travel	Telecom	use	activity
Predetermined variables								
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 HH 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 (average = 0.38)	0.71	0.95	0.49	0.05	0.14	-	0.32	0.03
Goodness of fit measures	χ^2 = 75.5 (df = 38), Goodness of Fit index (GFI) = 0.82, Normed Fit Index (NFI) = 0.91, Comparative Fit Index (CFI) = 0.95							

Notes: Socio-demographic 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. This is a recursive (having no feedback loop) model, so there is no Stability Index.

For the causal effects in the model, it can be seen 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, since a main point of mobile phones is to use them while mobile. On the other hand, it is found that 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 it may save travel by facilitating more efficient scheduling and routing of trips. At least during the time frame of this study, 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 rather than subscribers as the measure of demand, if those data should become available. Interestingly, the telecommunications cost variable is not significant in the telecommunications demand equation. The reason is that the mobile phone cost variable is highly correlated with the mobile phone supply (number of cell sites) variable (their correlation coefficient is -0.95, see Table 6.2), resulting in a multicollinearity problem.

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 hypothesis. As expected, economic activity positively affects mobile phone supply. This supports the well-established principle that economic growth stimulates further infrastructure expansion. Similarly, the female driver proportion strongly affects all categories. All identified causal relationships are summarized in Figure 6.2.



Notes: '+' = a positive causal effect (total), '–' = a negative causal effect (total). '*' = a lagged effect.
A dashed line means a hypothesized but non-identifiable causal relationship. A dotted line means a hypothesized but insignificant causal relationship.

Figure 6.2: Identified Causal Relationships between Mobile Telecommunications and Travel

6.3 Comparisons of Causal Relationships between Travel and Telecommunications

This section examines the single-equation models for travel and telecommunications demand to explore their unidirectional relationships and compare their coefficients with those in the structural equation models. That is, three structural equation model specifications were re-estimated as single equations so as to enable an appropriate comparison with the structural equation models. Since 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.

Table 6.5 shows 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 call index 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^2s, 0.73 and 0.99, respectively, while the telephone call model has a moderate R^2 of 0.30. The Durbin-Watson statistics show that there are no autocorrelations among the residuals of the models.

The coefficients of the explanatory variables are similar to those in the structural equation models. 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 if the single equation models were viewed in isolation it would have to be cautioned that endogeneity bias and correlations among included and excluded variables in each equation could greatly affect the results).

Table 6.5: Single-equation Demand Models (N = 49)

Variables	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		-0.350 (-2.81)	-0.027 (-1.88)
R^2	0.73	0.36	0.99
Durbin-Watson statistic	1.58	1.53	1.38

Notes: All coefficients are standardized. Numbers in parentheses indicate t-statistics.
Socio-demographic variables are (natural) log-transformed first-order differenced (i.e. $\log[X_t] - \log[X_{t-1}]$) variables. All composite variables were already developed base on the first-order differenced (natural) log-transformed individual variables.

Also, 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. The single equation model results suggest 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 is likely to generate an endogeneity bias, suggesting that simultaneous equation modeling is superior in this context.

The models relating to telephone calls are selected to compare bi-directional causal effects between telecommunications and travel demand among the single-equation models, the restricted structural equation models (see Appendix D for the estimated results of these models), and the full structural equation models. As shown in Table 6.6, the magnitudes of the causal effects are bigger in the structural equation models than in the single-equation models. The average total effect of telephone call demand on travel demand in the structural equation models is 0.236 and that of the other direction is 0.327, compared to 0.136 and 0.277 in the single-equation models, respectively. Similarly, although the subject is different, gasoline demand studies (e.g. Dahl, 1986) have found higher coefficient magnitudes in simultaneous equation models, compared to single-equation models.

Table 6.6: Comparison of Direct and Total Causal Effects among the Restricted and Full Models (N = 49)

Model Type	Telecom (telephone calls) demand → travel demand	Travel demand → telecom (telephone calls) demand
Single-equation models	0.136	0.277
Structural equation models		
Demand*	0.185 (0.173)	0.386 (0.361)
Demand/Supply*	0.300 (0.278)	0.278 (0.258)
Demand/Supply/Cost*	0.261 (0.244)	0.278 (0.261)
Demand/Supply/Land use*	0.207 (0.195)	0.313 (0.295)
Demand/Supply/Cost/Land use*	0.247 (0.229)	0.356 (0.329)
Demand/Supply/Land use/Econ*	0.210 (0.197)	0.315 (0.296)
Full (conceptual)	0.242 (0.224)	0.364 (0.336)
Average	0.236 (0.220)	0.327 (0.305)

Notes:
All coefficients are standardized. Open coefficients indicate total effects; those enclosed in parentheses indicate direct effects. The estimated effects for the single-equation models are not purely direct *or* total effects, since they are partially reflecting the influence of the multi-directional relationships that are necessarily omitted from the single-equation models.
* All other endogenous variable(s) are treated as exogenous. For example, only travel and telecommunications demand variables are endogenous in the demand model, whereas both demand and supply variables for travel and telecommunications are endogenous in the demand/supply model.

In most cases except one, however, the causal effects of travel demand on telephone call demand are bigger than those of the converse, regardless of the type of model. Overall, these results suggest that the aggregate relationship between actual amounts of telecommunications and travel is complementarity in a more comprehensive system, albeit asymmetric in directional weight. That is, as travel demand increases, telecommunications demand increases, and (to a lesser extent) vice versa. This finding is consistent with those of the individual and joint models discussed in the previous chapter. Thus, it can be concluded that the overall relationship between travel and telecommunications is complementarity, not substitution, in either a comprehensive system or an individual system.

CHAPTER 7. CONCLUSIONS

7.1 Summary

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.

This study first presents a conceptual model in Chapter 3, considering causal relationships among travel, telecommunications, land use, economic activity, and socio-demographics. To my knowledge, this is the first time a model incorporating all these categories has been developed. Then, based on the conceptual model, the aggregate relationships between telecommunications (local telephone calls, toll calls, and mobile phone subscribers) and travel (VMT, transit passengers, and airline PMT) are explored in a comprehensive framework, using structural equation modeling of national time series data spanning 1950-2000 in the U.S. 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, after testing a nested series of constrained alternatives of the conceptual model, by successively switching more and more exogenous variables to endogenous (by adding more equations to the system), the final models (full models or alternative models that have the most possible endogenous variable categories, when full models were not identifiable) were achieved. The estimated structural equation models support the hypothesized causal directions in the conceptual model.

At a more detailed level, individual and joint structural equation models for telecommunications and ground travel or airline travel were developed in Chapter 5, 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), and then the causal relationships between the two were compared by mode. The model results suggest that most significant causal relationships between telecommunications and travel (17 out of 19 significant or 28 pairwise relationships altogether) are complementarity either uni-directionally or bi-directionally. That is, as telecommunications increases, travel increases, and/or vice versa. The only exceptions are the two causal relationships between number of transit passengers and number of mobile phone subscribers, which are substitution. That is, as public transit travel increases, the number of mobile phone subscribers decreases. This is probably because transit passengers tend to be lower income, and hence less able to afford mobile phones, which were very expensive before the mid 1990s. Further, there are a number (9 out of 28) of neutral (zero net) effects of telecommunications on travel or vice versa. That is, telecommunications can generate or replace travel, but both effects on the total amount of travel may cancel, resulting in a zero net effect. The other direction (zero net impact of travel on telecommunications) is possible too − the zero effects were fairly balanced, with five from telecommunications to travel and four in the opposite direction. Zero effects were never present for both directions in the same model, indicating that there was always a dominant relationship in at least one direction. Overall, causal effects between telecommunications and travel differ by mode. However, most of them are complementarity regardless of the causal direction.

At a coarser level of measurement, composite indices for endogenous variable categories (telecommunications and travel demand, supply, and costs, land use, and economic activity) were first constructed by combining the variables of a given category into a single composite indicator for that category through confirmatory factor analysis (Chapter 6). Then, structural equation models for travel and wired (telephone calls) or mobile, called wireless (mobile phone subscribers), telecommunications were estimated, using the composite indices and socio-demographic variables. Although this approach necessarily sacrifices specificity in the relationships it identifies, it can capture a more complete view of the overall relationships among the set of variables of interest. The estimated models show that telephone calls and travel demand relationships 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). It is suspected that the absence of the converse relationship is due to positive and negative effects canceling, rather than to a lack of any effect. Comparing these results with those in the single equation approach and restricted models, the effects of travel demand on telephone call demand are bigger than those of the converse, regardless of the type of model. In sum, these results also support 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.

In consequence, the empirical results from both levels of structural equation modeling strongly suggest that the aggregate relationship (or system-wide net effect) between actual amounts of travel and telecommunications is complementarity, not substitution. That is, as telecommunications demand increases, travel demand increases, and vice versa. It is noteworthy that the largest portions of the effects in each direction are direct rather than indirect. This finding of complementarity contrasts with that in the previous aggregate study of Selvanathan and Selvanathan (1994), using consumer expenditures on communications and travel over time, but appears to be a faithful representation of observed trends in activity measures (rather than monetary measures) of the two concepts. On the other hand, it is similar to the relationship between the two in Plaut's study (1999) for the U.S., using input-output analysis, although her study focuses on industry.

There are several ways by which the current results could be reconciled with those of Selvanathan and Selvanathan. First, their study involved a different geographic area (Australia and the United Kingdom), and a time frame that is only a subset of ours (1960-

1986, compared to 1950-2000 here). It is possible that application of their methodology to the U.S. for the years 1950-2000 would return a result of complementarity.

Second, they addressed only consumer expenditures on travel and communications, while the data used in the current study comprise industrial as well as consumer activity. As mentioned, Plaut's findings of complementarity with respect to industrial inputs are consistent with ours, and since, as Plaut points out, about two thirds of total expenditures on telecommunications and travel are attributable to industrial purchases, the current results may simply represent something of a weighted average between complementarity with respect to industry and substitution with respect to consumers.

Finally, however, it is possible that application of the Selvanathan and Selvanathan method to the identical area and times as our study would still yield a result of substitution. That is because they focus on monetary expenditures, while the present study is based on measures of actual activity. It is possible for activity measures of both travel and telecommunications to increase over time, even while expenditures on the one increase only at the expense of expenditures on the other. This could be true even if prices of each remained relatively stable, but could especially be true if travel prices are rising more rapidly than those of telecommunications, which is the case for much of the study period. Thus, although the two sets of results are not *necessarily* contradictory, it would be fruitful in future research to ascertain more specifically the source of the difference.

In view of the comprehensiveness of the conceptual model and its empirical realizations, it is of interest to examine what the empirical results have to say with respect to conventionally-modeled influences on travel demand. As shown in Table 7.1, the final models for domestic travel indicate that transportation supply measures, such as lane miles and domestic airline seat miles (considering telephone calls and mobile phones, total effects range from 0.38 to 1.01, and from 0.34 to 0.95, respectively), have a stronger impact than economic activity measures (total effects range from 0.17 to 0.40, and from 0.24 to 0.45) on travel demand. In fact, transportation supply has generally been less paid attention in traditional travel demand models (which use mainly socio-economic variables). These results suggest that transportation supply variables should be considered key factors in forecasting travel demand. It is not surprising that the effects of transportation supply on travel demand are bigger when mobile phone demand is not included in the demand model, because to some extent the shared (interacted) effects of excluded variables may be absorbed into the estimated effects of the other explanatory variables. Also, considering that transit and airline supply variables (transit VMT and available seat miles) are more operation-oriented, those supply impacts on travel demand are bigger than those of lane miles. Overall, these results suggest that the induced demand impacts of transportation supply are strong and significant − for transit and air travel as well as the more-often studied passenger car travel.

The effect of travel costs (a composite including gasoline price) on travel demand is relatively low (total effects range from -0.13 to -0.37) but significant. This supports the conventional wisdom that any policy strategy related to increasing gasoline prices can help reduce VMT (even if only modestly). In addition, suburbanization rate, as a land use indicator, significantly affects transportation demand as well (total effects range from -0.46 to -0.70 for transit passengers and from 0.16 to 0.33 for VMT). The implication is that land use policies need to be more focused on reducing further decentralization to curb the continuous growth in VMT, emphasizing growth-control measures (e.g. urban growth boundaries).

Table 7.1: Total Effects of Key Variables on Travel Demand

Travel demand	Telecom demand		Trans supply	Travel costs	Economic activity (or GDP)	Land use
VMT	Local	0.33	0.38	-0.29	0.40	0.18
	Toll	0.80	0.53	-0.29	0.43	0.16
	Mobile		0.65	-0.24	0.39	0.33
Transit passengers	Local	0.74	1.01	-0.13	0.22	-0.70
	Mobile		0.34	-0.26		-0.46
Domestic air travel	Local	0.10	0.72	-0.31	0.20	
	Toll	0.65	0.70	-0.37	0.19	
	Mobile		0.85	-0.25	0.45	
Composite travel demand	Wired	0.24	0.81	-0.30	0.17	0.13
	Mobile		0.95	-0.21	0.24	0.25

Note: All coefficients are standardized.

Although this study has provided considerable insight into the relationships among the many variables measured, and between travel and telecommunications demand in particular, it has some limitations. First, due to the scope (national level) of this study, it relies on secondary sources for the data analyzed. Thus, the quality control exercised by other data collection agents with regard to issues such as sampling, analysis of non-response, and missing data, is not always clearly-specified (and when it is, such control is not always to the desired level). Secondly, aggregate time series data often has a relatively smaller sample size than other types of data, depending on the time unit (e.g. month, quarter, or year). In this study, only annual nationwide time series data are available for both telecommunications and travel, resulting in a small sample size of 51. Thirdly, the relationships between telecommunications and travel identified in this study could not consider the impacts of the Internet on travel because there are too few years of data during the Internet era. The same is true to a lesser extent for mobile phones, where the time series (1984-2000) is longer than for the Internet but for shorter than for the other variables in the model.

Lastly, 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 unit increases VMT by 0.3 units, we will not know whether the 0.3 is the net of 0.3 unit generation and no substitution, or of 2 units generation and 1.7 units substitution, etc. Thus, in particular, as indicated at several places earlier, we are unable to determine whether a zero net impact means both generation and substitution are negligible, or means both are considerable but cancel each other out. 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 (reviewed in Chapter 2) 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.

7.2 Future Research

The conceptual model and the identified relationships between telecommunications and travel suggest some directions for future research.

First, it is desirable to replicate the approach used in this study with a larger sample. This may improve the stability of estimates and allow even more complex models. A larger sample can be obtained (1) by waiting for more years to go by (this approach is obviously disadvantageous but will be critical for exploring the impact of mobile phones and the Internet); (2) by using quarterly data (this approach is not available for many variables, and also needs to correct for seasonality); or (3) by using smaller geographical units such as state, metropolitan area, or county (this approach is probably the most practical, but measurement error will be more pronounced at a lower level). The latter approach also permits segmentation by geographical area, to determine whether the relationships identified here differ by area.

Secondly, this study found that telecommunications impacts on travel are strong and significant, so future studies of travel demand should consider how to incorporate telecommunications demand into travel demand forecasting. For example, together with traditional economic and socio-demographic variables, telecommunications demand indicators such as the amount of telecommunications use (e.g. number of telephone calls or frequencies of Internet use) can be considered as key explanatory variables in aggregate travel demand forecasting models. At the disaggregate level, we are severely hampered by a lack of data on both ICT and travel activities of the same individuals. No nationwide survey in the U.S. has collected data on both ICT and travel. However, this kind of household survey has been conducted, focusing on physical travel and telecommunications activities, in Germany (Zumkeller, 2002). It is strongly recommended that telecommunications-related questions be added to national or regional travel-related (travel or activity diary) surveys to obtain more detailed information about telecommunications demand.

Lastly, it is found that if other transportation-related factors, such as land use, the economy, and travel cost, are considered in this context, the induced demand effects are even higher than those of (traditional) single equation models, due to their indirect impacts on each other. As a result, the total induced impacts of transportation infrastructure on travel in various contexts are considerable. Thus, further research on this topic, using regional or statewide data, would considerably contribute to the traditional travel demand and supply forecast methods.

REFERENCES

Arbuckle, James L. and Werner Wothke (1999) *Amos 4.0 User's Guide*. Chicago, IL: SmallWaters Corporation.

Bennison, David J. (1988) Transport/telecommunication interactions: Empirical evidence from a videoconferencing field trial in the United Kingdom. *Transportation Research A* **22(4)**, pp. 291-300.

Bentler, P. M. (1990) Comparative fit indexes in structural models. *Psychological Bulletin* **107**, pp. 238-246.

Bentler, P. M. and D. G. Bonett (1980) Significances tests and goodness of fit in the analysis of covariance structures. *Psychological Bulletin* **88**, pp. 588-606.

Bentler, P. M. and E. H. Freeman (1983) Tests for stability in linear structural equation systems. *Psychometrika* **45**, pp. 143-145.

Blum, Ulrich C. H. and Marc J. I. Gaudry (1988) Aggregate time series gasoline demand models: Review of the literature and new evidence for West Germany. *Transportation Research A* **22(2)**, pp. 75-88.

Bureau of Transportation Statistics (1998) *Transportation Statistics Annual Report 1998.* US DOT, Bureau of Transportation Statistics, Washington, DC.

Bureau of Transportation Statistics (2001) *Air Traffic Statistics and Airline Financial Statistics.* US DOT, Bureau of Transportation Statistics, the Office of Airline Information, Washington, DC. Available at http://www.bts.gov/oai/indicators/top.html.

Cairncross, Frances (1995) The death of distance. *The Economist* **336(7934)**, pp. SS5-6.

Cairncross, Frances (2001) *The Death of Distance: How the Communications Revolution is Changing Our Lives*. Boston, MA: Harvard Business School Press.

Casas, Jesse, Johanna Zmud and Stacey Bricka (2001) Impact of shopping via Internet on travel for shopping purposes. TRB ID No. 01-3393, Presented at the 80th Annual Meeting of the Transportation Research Board, Washington, DC.

Castells, Manuel (1989) *The Informational City: Information Technology, Economic Restructuring, and the Urban-regional Process*. Cambridge, MA: Basil Blackwell Inc.

Cellular Telecommunications Industry Association (2002) *Semi-annual Wireless Industry Survey*. Washington, DC. Available at www.wow-com.com/pdf/wireless_survey_2002a.pdf.

Cervero, Robert and John Landis (1996) Why the transportation-land use connection is still important. *TR News* **187**, pp. 9-13.

Cervero, Robert and Mark Hansen (2002) Road supply-demand relationships: Sorting out causal linkages. *Journal of Transport Economics and Policy* **36(3)**, pp. 469-490.

Choo, Sangho, Patricia L. Mokhtarian and Ilan Salomon (2001) *Impacts of Home-based Telecommuting on Vehicle-miles Traveled: A Nationwide Time Series Analysis*. Publication No. P600-01-020, the California Energy Commission, Sacramento, CA, December.

Chou, Chih-Ping and Peter M. Bentler (1995) Estimates and tests in structural equation modeling. In Rick H. Hoyle, ed., *Structural Equation Modeling: Concepts, Issues, and Applications* (pp. 37-55), Thousand Oaks, CA: Sage Publications.

Costantino, James (1992) The IVHS strategic plan for the United States. *Transportation Quarterly* **46(4)**, pp. 481-490.

Dahl, Carol A (1986) Gasoline demand survey. *The Energy Journal* **7(1)**, pp. 67-82.

Denstadli, Jon Martin (forthcoming) Impacts of videoconferencing on business travel: the Norwegian experience. *Journal of Air Transport Management*.

Downs, Anthony (2004) *Still Stuck in Traffic: Coping with Peak-hour Traffic Congestion*. Washington, D.C.: The Brookings Institution.

Federal Communications Commission (2000) *Trends in Telephone Service*. Industry Analysis Division, Common Carrier Bureau, Washington, DC. Available at ftp.fcc.gov/Bureaus/Common_Carrier/Reports/FCC-State_Link/IAD/trend100.pdf

Federal Highway Administration (2001) *Highway Statistics 1999*. U.S. DOT, Federal Highway Administration, Office of Highway Information, Policy Washington, DC. Available at www.fhwa.dot.gov/ohim/ohimstat.htm

Ferrell, Christopher E. (2004) Home-based teleshoppers and shopping travel: Do teleshoppers travel less? Presented at Transportation Research Board, the 83rd Annual Meeting, Washington, D.C.

Fox, John (1980) Effect analysis in structural equation models: Extension and simplified methods of computation. *Sociological Methods & Research* **9(1)**, pp. 3-28.

Fulton, Lewis M., Daniel J. Meszler, Robert B. Noland and John V. Thomas (2000) A statistical analysis of induced travel effects in the U.S. mid-Atlantic region. *Journal of Transportation and Statistics* **3(1)**, pp. 1-14.

Gately, Dermot (1990) The U.S. demand for highway travel and motor fuel. *The Energy Journal* **11(3)**, pp. 59-73.

Giuliano, Genevieve and Andrew Gillespie (1997) Research issues regarding societal change and transport. *Journal of Transport Geography* **5(3)**, pp. 165-176.

Goldberger, Arthur S. (1972) Structural equation methods in the social sciences. *Econometrica* **40(6)**, pp. 979-1001.

Golob, Thomas F. (2003) Structural equation modeling for travel behavior research. *Transportation Research B* **37(1)**, pp. 1-25.

Golob, Thomas F. and Amelia C. Regan (2001) Impacts of information technology on personal travel and commercial vehicle operations: Research challenges and opportunities. *Transportation Research C* **9(2)**, pp. 87-121.

Gordon, Peter and Harry W. Richardson (1997) Are compact cities a desirable planning goal? *Journal of the American Planning Association* **63(1)**, pp. 95-106.

Gould, Jane and Thomas F. Golob (1997) Shopping without travel or travel without shopping? An investigation of electronic home shopping. *Transport Reviews* **17(4)**, pp. 355-376.

Gould, Jane, Thomas F. Golob and Patrick Barwise (1998) Why do people drive to shop? Presented at the 77th Annual Meeting of the Transportation Research Board, Washington, DC.

Graham, Stephen and Simon Marvin (1996) *Telecommunications and the City: Electronic Spaces, Urban Spaces*. London: Routledge.

Greene, David L. (1992) Vehicle use and fuel economy: How big is the "rebound" effect? *The Energy Journal* **13(1)**, pp. 117-143.

Greene, William H. (2000) *Econometric Analysis*, 4th ed. Upper Saddle River, NJ: Prentice Hall.

Hamer, Rebecca, Eric Kroes and Harry van Ooststroom (1991) Teleworking in the Netherlands: An evaluation of changes in travel behaviour. *Transportation* **18(4)**, pp. 365-382.

Hansen, Mark and Yuanlin Huang (1997) Road supply and traffic in California urban areas. *Transportation Research A* **31(3)**, pp. 205-218.

Harkness, Richard C. (1977) Selected results from a technology assessment of telecommunication-transportation interactions. *Habitat* **2(1/2)**, pp. 37-48.

Henderson, Dennis K. and Patricia L. Mokhtarian (1996) Impacts of center-based telecommuting on travel and emissions: Analysis of the Puget Sound demonstration project. *Transportation Research D* **1(1)**, pp. 29-45.

Hensher, David and Jenny King (1998) Establishing fare elasticity regimes for urban passenger transport: Time-based fares for concession and non-concession market segmented by trip length. *Journal of Transportation Statistics* **1(1)**, pp.43-57.

Horowitz, J. L., F.S. Koppelman and S. R. Lerman. (1986) *A Self-instructing Course in Disaggregate Mode Choice Modeling*. Publication No. IA-11-0006, U.S. DOT, Urban Mass Transportation Administration, Washington, DC.

Hu, Li-tze, Peter M. Bentler and Yutaka Kano (1992) Can test statistics in covariance structure analysis be trusted? *Psychological Bulletin* **112(2)**, pp. 351-362.

Hu, Patricia S. and Jennifer R. Young (1999) *Summary of Travel Trends: 1995 Nationwide Personal Transportation Survey*. Publication No. FHWA-PL-00-006, US Department of Transportation, Federal Highway Administration, Washington, DC.

Jones, Clifton T. (1993) Another look at U.S. passenger vehicle use and the "rebound" effect from improved fuel efficiency. *The Energy Journal* **14(4)**, pp. 99-110.

Jöreskog, Karl G. (1973) A general method for estimating a linear structural equation system. In A. S. Goldberger and O. D. Duncan, eds., *Structural Equations Models in the Social Sciences* (pp. 85-112), New York: Seminar Press.

Jöreskog, Karl G. (1977) Structural equation models in the social sciences: Specification, estimation and testing. In Paruchuri R. Krishnaiah, ed., *Applications of Statistics* (pp. 265-287), Amsterdam: North-Holland.

Jöreskog, Karl G. and Dag Sörbom (1976) *LISREL III: Estimation of Linear Structural Equation Systems by Maximum Likelihood Methods*. National Educational Resources, Inc., Chicago.

Keane, Thomas F. (1996) The economic importance of the national highway system. *Public Roads On-line*, U.S. DOT, Federal Highway Administration, Washington, DC. Available at www.tfhrc.gov/pubrds/pubrds.htm

Keesling, J. Ward (1972) *Maximum Likelihood Approaches to Causal Analysis*. Unpublished Ph.D. Dissertation. Department of Education, University of Chicago.

Kennedy, Peter (1998) *A Guide to Econometrics*, 4th ed. Cambridge, MA: MIT Press.

Kmenta, Jan (1997) *Elements of Econometrics*, 2nd ed. Ann Arbor: University of Michigan Press.

Kline, Rex B. (1998) *Principles and Practice of Structural Equation Modeling*. New York, NY: The Guilford Press.

Koenig, Brett E., Dennis K. Henderson and Patricia L. Mokhtarian (1996) The travel and emissions impacts of telecommuting for the state of California telecommuting pilot project. *Transportation Research C* **4(1)**, pp. 13-32.

Litman, Todd (2004) Transit price elasticities and cross-elasticities. *Journal of Public Transportation* **7(2)**, pp. 37-58.

Mankiw, N. Gregory (2003) *Macroeconomics*, 5th ed. New York, NY: Worth Publishers.

Manski, Charles F. and Ilan Salomon (1987) The demand for teleshopping: An application of discrete choice models. *Regional Science and Urban Economics* **17**, pp. 109-121.

Marvin, Simon (1997) Environmental flows: Telecommunications and the dematerialisation of cities? *Futures* **29(1)**, pp. 47-65.

Mokhtarian, Patricia L. (1988) An empirical evaluation of the travel impacts of teleconferencing. *Transportation Research A* **22(4)**, pp. 283-289.

Mokhtarian, Patricia L. (1990) A typology of relationships between telecommunications and transportation. *Transportation Research A* **24(3)**, pp. 231-242.

Mokhtarian, Patricia L. (1991) Defining telecommuting. *Transportation Research Record* **1305**, pp. 273-281.

Mokhtarian, Patricia L. (1998) A synthetic approach to estimating the impacts of telecommuting on travel. *Urban Studies* **35(2)**, pp. 215-241.

Mokhtarian, Patricia L. (2000) Telecommunications and travel. In: *Transportation in the New Millennium*, Transportation Research Board, National Research Council, National Academy of Science, Washington, DC. Available at www.nationalacademies.org/trb/publications/millennium/00115.pdf.

Mokhtarian, Patricia L. (2002) Telecommunications and travel: The case for complementarity. *Journal of Industrial Ecology* **6(2)**, pp. 43-57.

Mokhtarian, Patricia L. (2004) A conceptual analysis of the transportation impacts of B2C e-commerce. *Transportation* **31(3)**, pp. 257-284.

Mokhtarian, Patricia L. and Ilan Salomon. (2002) Emerging travel patterns: Do telecommunications make a difference? In Hani S. Mahmassani, ed., *In Perpetual Motion: Travel Behaviour Research Opportunities and Application Challenges* (pp. 143-182). Oxford, UK: Pergamon Press/Elsevier.

Mokhtarian, Patricia L. and Krishna V. Varma (1998) The trade-off between trips and distance traveled in analyzing the emissions impacts of center-based telecommuting. *Transportation Research D* **3(6),** pp. 419-428.

Mokhtarian, Patricia L. and Ravikumar Meenakshisundaram (1999) Beyond tele-substitution: Disaggregate longitudinal structural equations modeling of communication impacts. *Transportation Research C* **7(1),** pp. 33-52.

Mokhtarian, Patricia L., Susan L. Handy and Ilan Salomon (1995) Methodological issues in the estimation of the travel, energy, and air quality impacts of telecommuting. *Transportation Research A* **29A(4)**, pp. 283-302.

Mueller, Ralph O. (1996) *Basic Principles of Structural Equation Modeling: An Introduction to LISREL and EQS*. New York: Springer.

Niles, John S. (1994) *Beyond Telecommuting: A New Paradigm for the Effect of Telecommunications on Travel*. Prepared for the US Department of Energy, Offices of Energy Research and Scientific Computing, Washington, DC 20585, Report No. DOE/ER-0626, September. Available at http://www.lbl.gov/ICSD/Niles.

Nilles, Jack M. (1988) Traffic reduction by telecommuting: A status review and selected bibliography. *Transportation Research A* **22(4)**, pp. 301-317.

Nilles, Jack M., F. Roy Carlson Jr., Paul Gray and Gerhard J. Hanneman (1976) *The Telecommunications-Transportation Tradeoff: Options for Tomorrow*. New York: John Wiley and Sons.

Noland, Robert B. (2001) Relationships between highway capacity and induced vehicle travel. *Transportation Research A* **35(1)**, pp. 47-72.

Novak, David C. and Matthew McDonald (1998) A general overview of the potential macroeconomic impacts of ITS investment in the United States. Presented at the 77th Annual Meeting of the Transportation Research Board, Washington, DC.

Owen, Wilfred (1962) Transportation and technology. *The American Economic Review* **52(2)**, pp. 405-413.

Pendyala, Ram, Konstadinos G. Goulias and Ryuichi Kitamura (1991) Impact of telecommuting on spatial and temporal patterns of household travel. *Transportation* **18(4)**, pp. 383-409.

Pickrell, Don (1999) Transportation and land use. In José Gómez-Ibáñez, William B. Tye and Clifford Winston, eds., *Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer* (pp. 403-435), Brookings Institution Press, Washington, DC.

Pisarski, Alan E. (1992) *New Perspectives in Commuting: Based on Early Data from the 1990 Decennial Census and the 1990 Nationwide Personal Transportation Study*. U.S. DOT, Federal Highway Administration, Washington, DC.

Plaut, Pnina O. (1997) Transportation - communication relationships in industry. *Transportation Research A* **31A(6)**, pp. 419-429.

Plaut, Pnina O. (1999) Do telecommunications reduce industrial uses of transportation? An international comparison of Israel, Canada, U.S.A. & Europe. *World Transport Policy & Practice* **5/4**, pp. 42-49.

Pucher, John and John L. Renne (2003) Socioeconomics of urban travel: Evidence from the 2001 NHTS. *Transportation Quarterly* **57(3)**, pp. 49-77.

Salomon, Ilan (1985) Telecommunications and travel: Substitution or modified mobility? *Journal of Transport Economics and Policy* **19(3)**, pp. 219-235.

Salomon, Ilan (1986) Telecommunications and travel relationships: A review. *Transportation Research A* **20A(3)**, pp. 223-238.

Salomon, Ilan and Frank S. Koppelman (1988) A framework for studying teleshopping versus store shopping. *Transportation Research A* **22(4)**, pp. 247-255.

Salomon, Ilan and Frank S. Koppelman (1992) Teleshopping or going shopping? An information acquisition perspective. *Behavior & Information Technology* **11(4)**, pp. 189-198.

Salomon, Ilan and Joseph L. Schofer (1988) Forecasting telecommunications-travel interactions: The transportation manager's perspective. *Transportation Research A* **22(3)**, pp. 219-229.

Salomon, Ilan, Helen Nancy Schneider and Joseph Schofer (1991) Is telecommuting cheaper than travel? An examination of interaction costs in a business setting. *Transportation* **18(4)**, pp. 291-318.

Satorra, Albert and Peter M. Bentler (1988) *Scaling Corrections in Covariance Structural Analysis*. UCLA Statistics Series 2, Los Angeles: University of California, Department of Psychology.

Satorra, Albert and Peter M. Bentler (1994) Corrections to test statistics and standard errors in covariance structural analysis. In Alexander von Eye and Clifford C. Clogg, eds., *Latent Variables Analysis: Applications for Developmental Research* (pp. 399-419), Thousand Oaks, CA: Sage Publications.

Saunders, Robert J., Jeremy J. Warford and Björn Wellenius (1994) *Telecommunications & Economic Development*, 2nd ed. Published for The World Bank, Baltimore, MD: The John Hopkins University Press.

Schafer, Andreas (1998) The global demand for motorized mobility. *Transportation Research A* **32(6)**, pp. 455-477.

Schimek, Paul (1996) Gasoline and travel demand models using time series and cross-section data from United States. *Transportation Research Record* **1558**, pp. 83-89.

Selvanathan, E. A. and Saroja Selvanathan (1994) The demand for transport and communication in the United Kingdom and Australia. *Transportation Research B* **28(1)**, pp. 1-9.

Senbil, Metin and Ryuichi Kitamura (2003) Simultaneous relationships between telecommunications and activities. Presented at the 10th International Conference on Travel Behaviour Research, Lucerne, August 2003.

Small, Kenneth A. and Clifford Winston (1999) The demand for transportation: Models and applications. In José Gómez-Ibáñez, William B. Tye and Clifford Winston, eds., *Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer* (pp. 11-55), Brookings Institution Press, Washington, DC.

Simon, Samuel A., Henry Geller, Joshua L. Mindel, and Richard P. Adler (2003) *Reflections and Directions: Twenty Years After the Divestiture of AT&T.* New Millennium Research Council, Washington, DC. Available at http://www.newmillenniumresearch.org/archive/divestiture-report.pdf.

Springer, Robert K. and Robert W. Resek (1981) An econometric model of gasoline consumption, vehicle miles traveled, and new car purchases. *Energy Systems and Policy* **5(1)**, pp. 73-87.

Tacken, M. (1990) Effects of teleshopping on the use of time and space. *Transportation Research Record* **1285**, pp. 89-91.

Transportation Research Board (1995) *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*. Special Report 245, Transportation Research Board, National Research Council, Washington, DC.

Ullman, Jodie B. (1996) Structural equation modeling. In Barbara G. Tabachnick and Linda S. Fidell, *Using Multivariate Statistics*, 3rd ed. (pp. 709-811), New York: HarperCollins College Publisher.

United States Department of Commerce (1995) *The U.S. Telecommunications Services Industry*. Publication No. ESA/OPD 95-4, Economics and Statistics Administration, Office of Policy Development. Available at www.esa.doc.gov/de2k814.htm.

United States Department of Commerce (2000) *Digital Economy 2000*. Economics and Statistics Administration, Office of Policy Development. Available at www.esa.doc.gov/de2k814.htm.

West, Stephen G., John F. Finch and Patrick J. Curran (1995) Structural equation models with nonnormal variables: Problems and remedies. In Rick H. Hoyle, ed., *Structural Equation Modeling: Concepts, Issues, and Applications* (pp. 56-75), Thousand Oaks, CA: Sage Publications.

Wheaton, William C. (1982) The long-run structure of transportation and gasoline demand. *The Bell Journal of Economics* **13(2)**, pp. 439-454.

Wiley, David E. (1973) The identification problem for structural equation models with unmeasured variables. In A. S. Goldberger and O. D. Duncan, eds., *Structural Equations Models in the Social Sciences* (pp. 69-83). New York: Seminar Press.

Wright, Sewall (1934) The method of path coefficients. *Annals of Mathematical Statistics* **5(3)**, pp. 161-215.

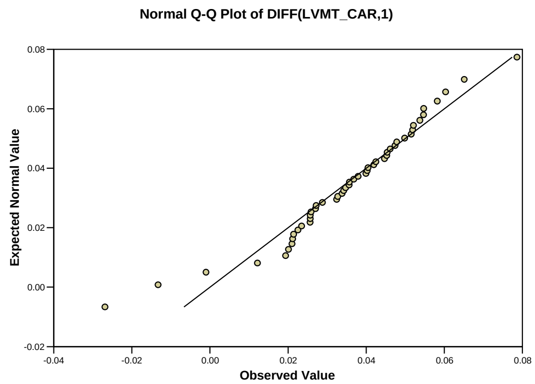
Zumkeller, Dirk (2002) Transportation and telecommunication: First comprehensive surveys and simulation approaches. In Hani S. Mahmassani, ed., *In Perpetual Motion: Travel Behaviour Research Opportunities and Application Challenges* (pp. 183-207). Oxford, UK: Pergamon Press/Elsevier.

APPENDICES

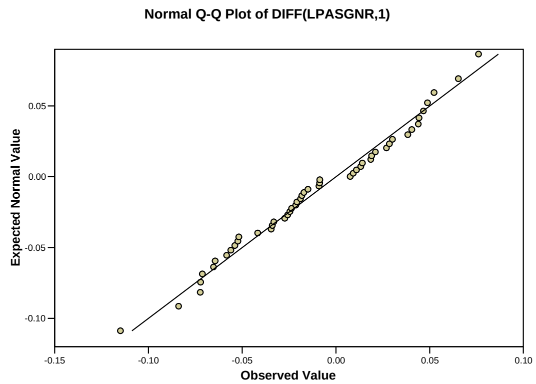
A. Normal Q-Q Plots for Individual Variables (natural log form, 1st order differenced)

1. Travel Demand

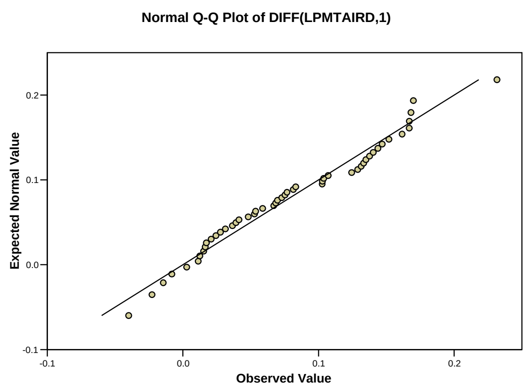
- Passenger VMT



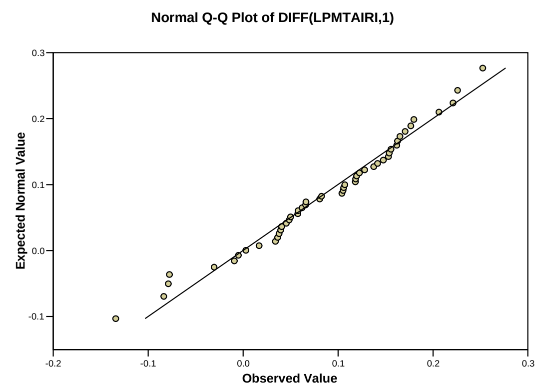
- Transit passengers carried



- Airline PMT (domestic travel)

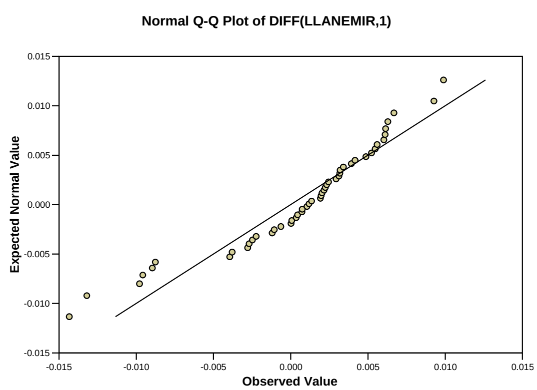


- Airline PMT (international travel)

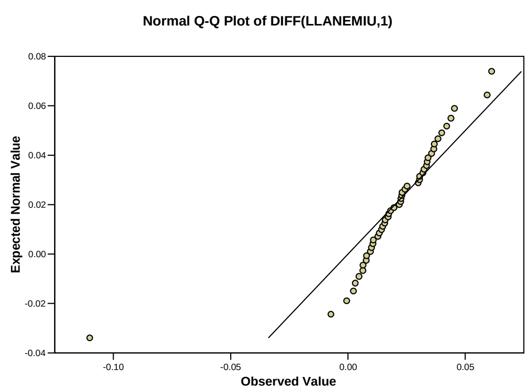


2. Transportation Supply

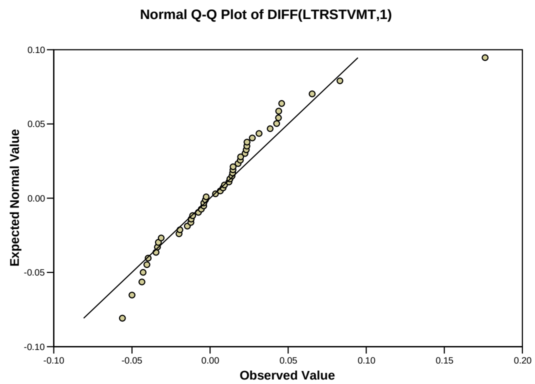
- Lane miles (rural areas)



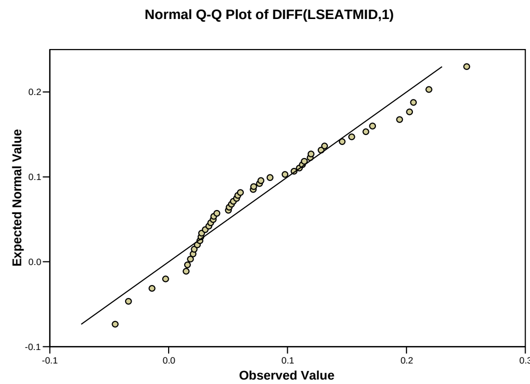
- Lane miles (urban areas)



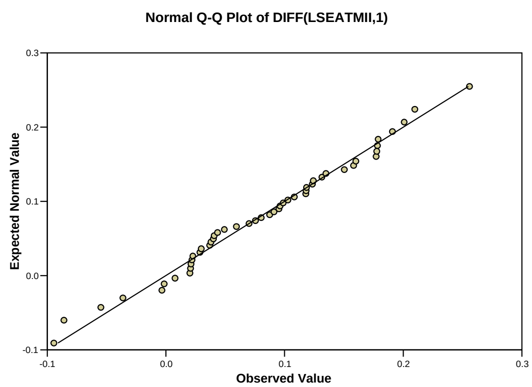
- Transit vehicle-miles operated



- Available seat miles (domestic travel)

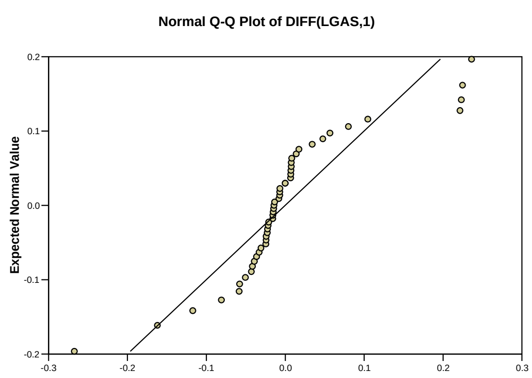


- Available seat miles (international travel)

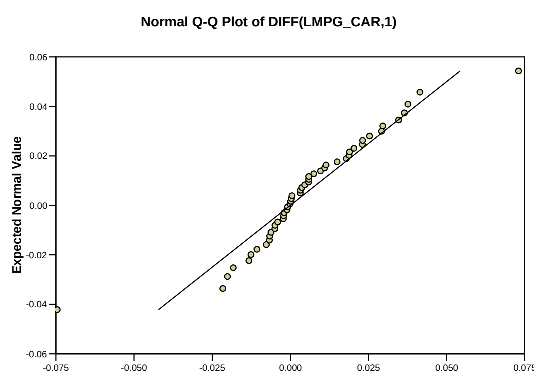


3. Travel Costs

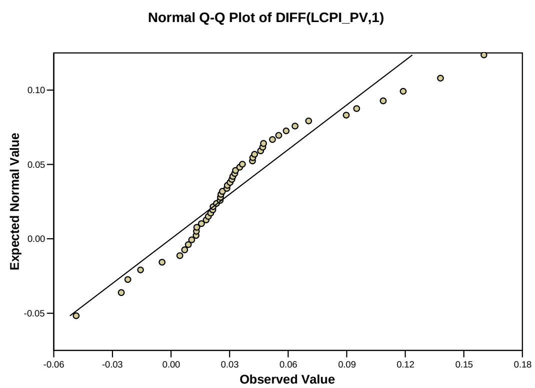
- Gasoline price



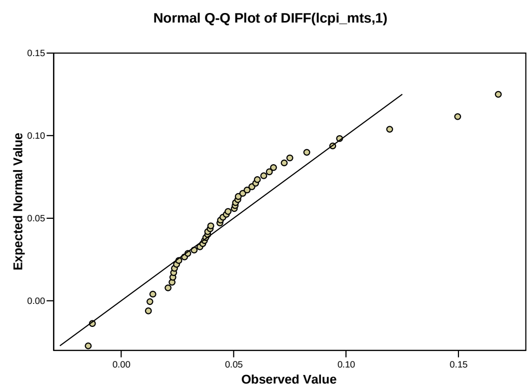
- Fuel efficiency (MPG)



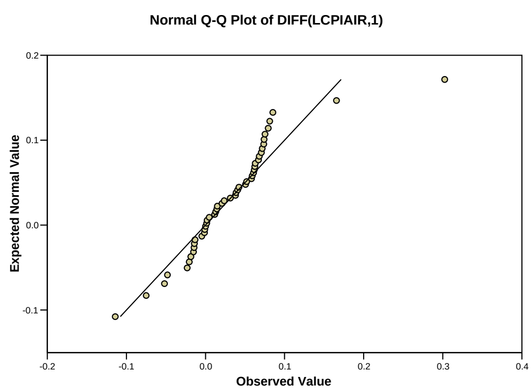
- CPI for private transportation



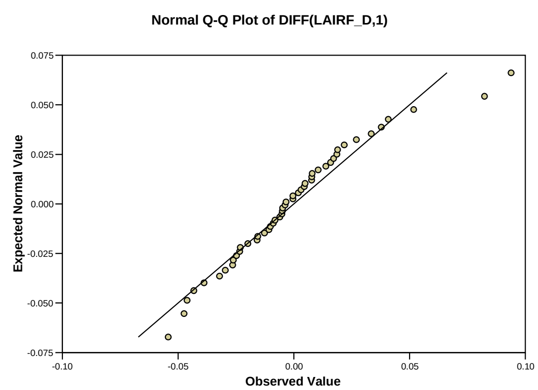
- CPI for public transportation



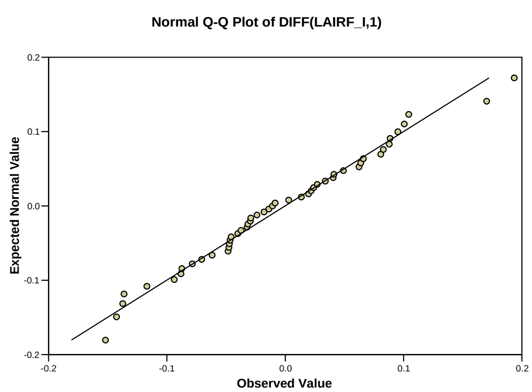
- CPI for airline



- Average air fare (domestic travel)

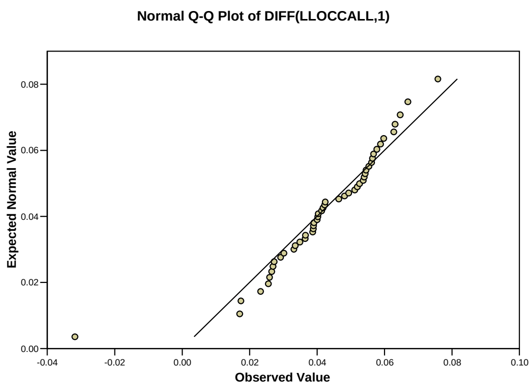


- Average air fare (international travel)

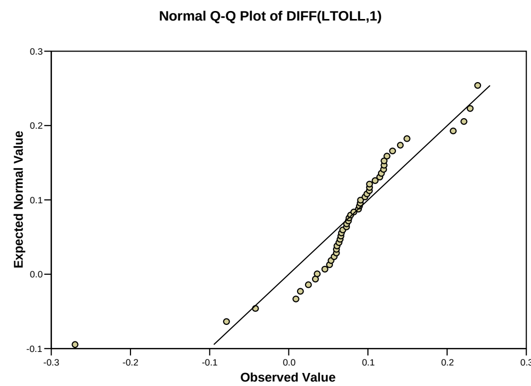


4. Telecommunications Demand

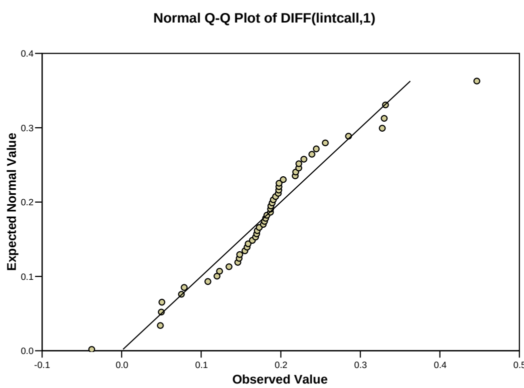
- Local telephone calls



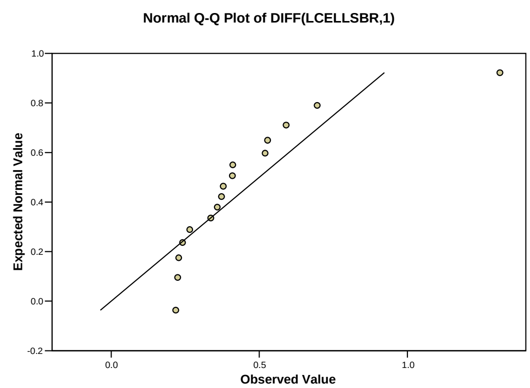
- Toll calls



- International calls

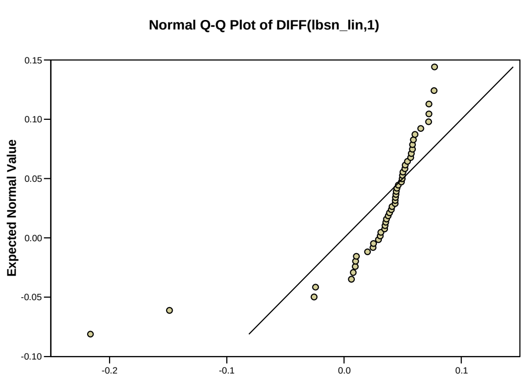


- Mobile phone subscribers

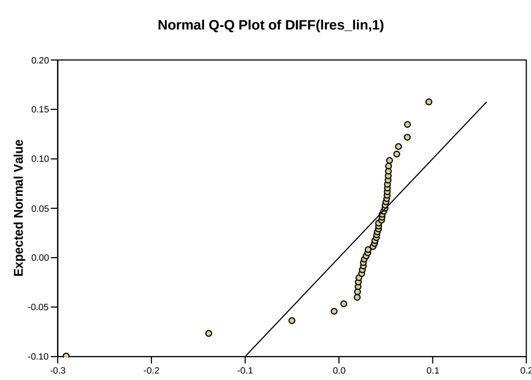


5. Telecommunications Supply

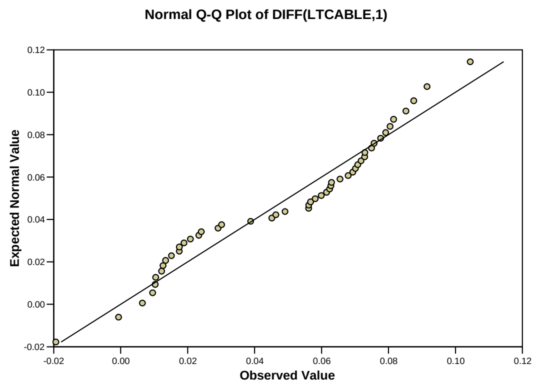
- Telephone access lines (business)

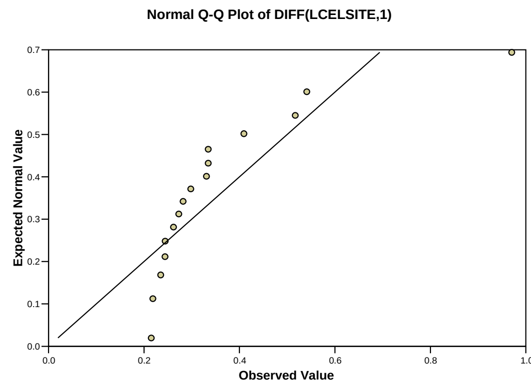


- Telephone access lines (residence)



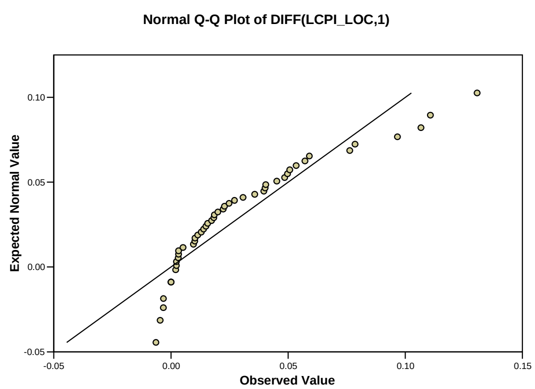
- Telephone wire length
- Cell sites

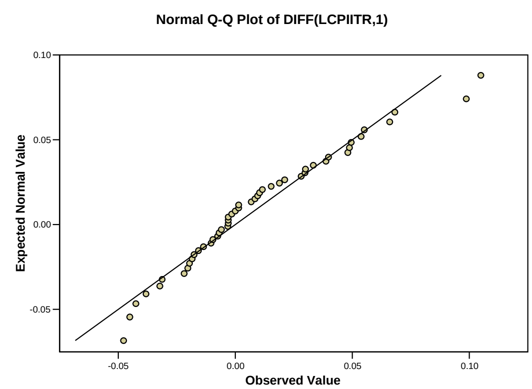




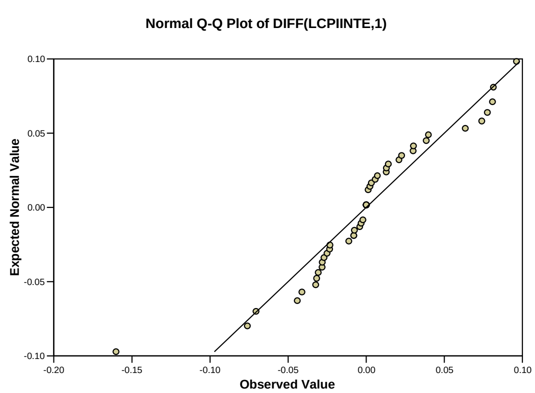
6. Telecommunications Costs

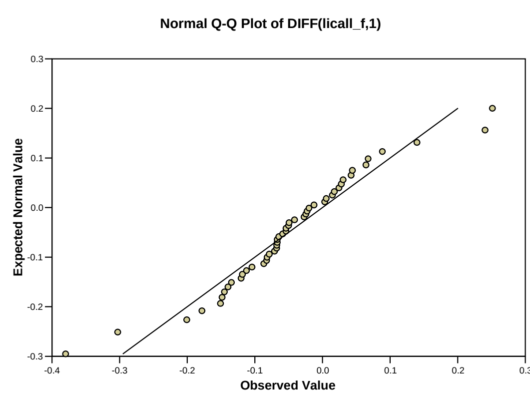
- CPI for local telephone service
- CPI for intra-state toll service



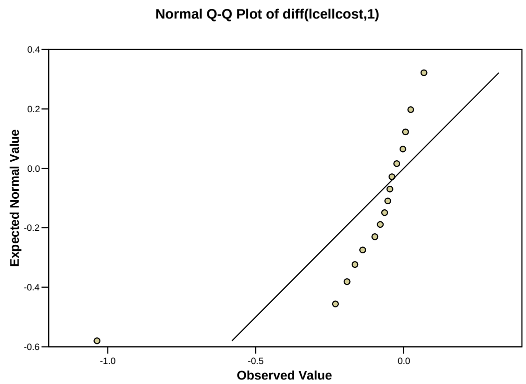


- CPI for inter-state toll service
- Average cost per international call



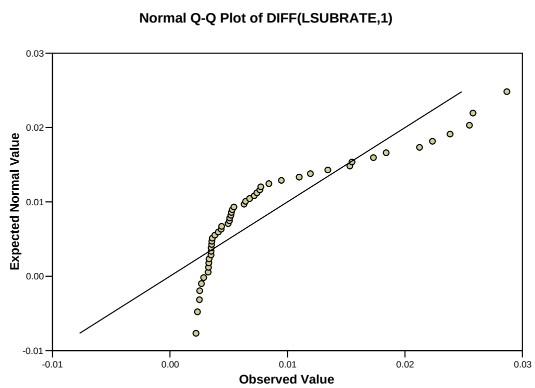


- Average monthly revenue from mobile call service

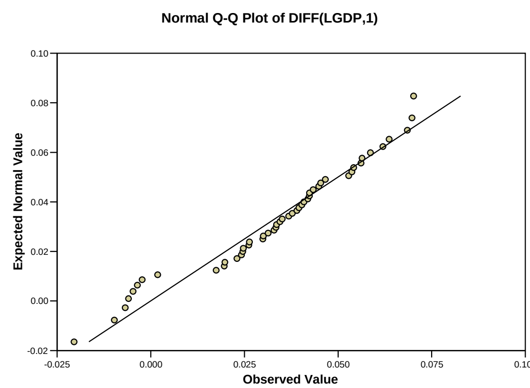


7. Land Use/Economic Activity

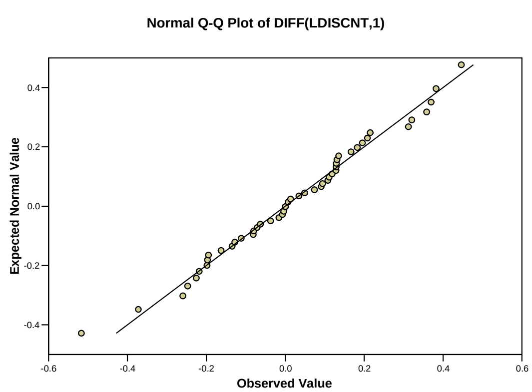
- Suburbanization rate



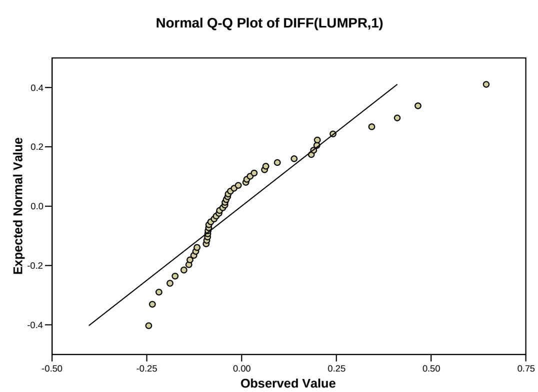
- GDP



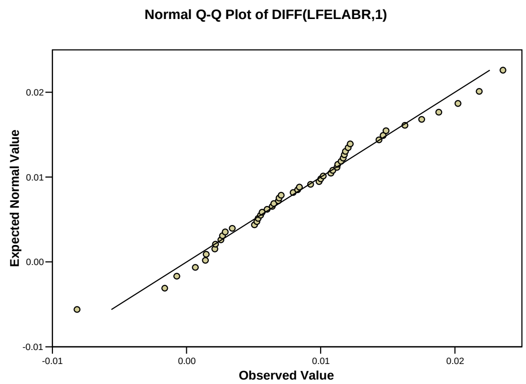
- FRB interest rate



- Unemployment rate

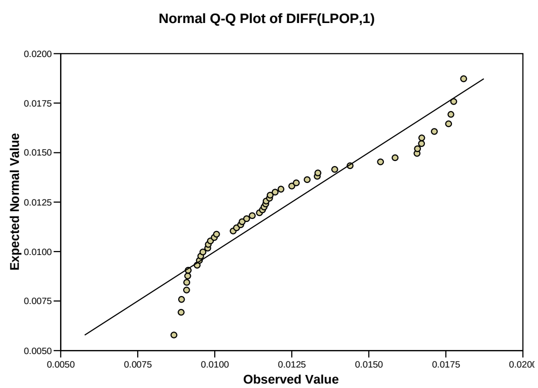


• Female proportion of the labor force

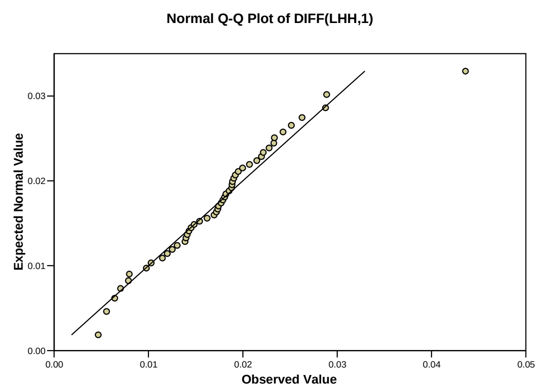


8. Socio-demographics

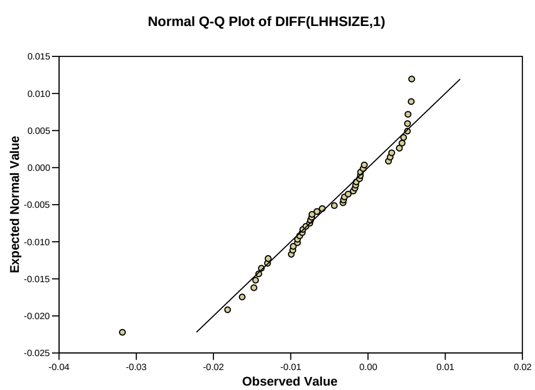
• Population



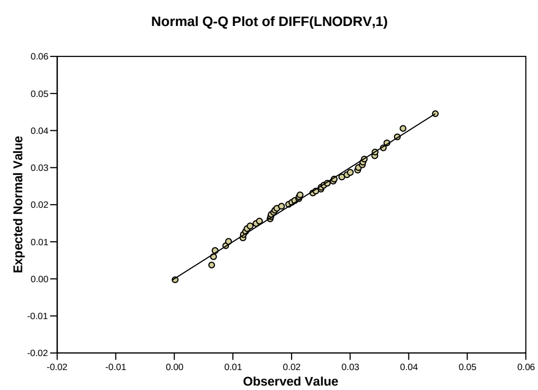
• Households



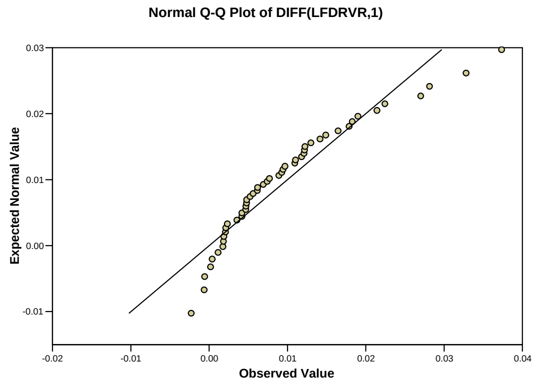
• Average household size



• Licensed drivers



- Female proportion of licensed drivers



B. Pairwise Correlation Tests

1. Variable list

Variable	Descriptions
DLVMTCAR	Passenger vehicle-miles traveled
DLPASGNR	Revenue transit passengers carried
DLPMTA_D	Revenue airline passenger-miles traveled (domestic travel)
DLPMTA_I	Revenue airline passenger-miles traveled (international travel)
DLLMI_R	Lane miles (rural areas)
DLLMI_U	Lane miles (urban areas)
DLTRSVMT	Revenue transit vehicle-miles operated
DLSITM_D	Revenue airline available seat-miles (domestic travel)
DLSITM_I	Revenue airline available seat-miles (international travel)
DLGAS	Real gasoline price
DLMPGCAR	Fuel efficiency (miles per gallon)
DLCPI_PV	CPI for private transportation
DLCPIMTS	CPI for public transportation
DLCPIAIR	CPI for airline
DLAIRF_D	Real average air fares (domestic travel)
DLAIRF_I	Real average air fares (international travel)
DLLOCAL	Number of local telephone calls
DLTOLL	Number of toll calls
DLINTCAL	Number of international calls
DLCELSBR	Number of mobile phone subscribers
DLBS_LIN	Number of telephone access lines (business lines)
DLRS_LIN	Number of telephone access lines (residential lines)
DLTCABLE	Telephone wire length
DLCELSIT	Number of cell sites
DLCPILOC	CPI for local telephone calls
DLCPITIN	CPI for intra-state toll calls
DLCPITBT	CPI for inter-state toll calls
DLICALLF	Real average cost per international call
DLCELL_C	Real average monthly revenue from mobile call services
DLSUB_R	Suburbanization rate
DLGDP	Real Gross Domestic Product (GDP)
DLDISCNT	Federal Reserve Bank (FRB) interest rate
DLUMPR	Unemployment rate
DLFELABR	Female proportion of the labor force
DLPOP	Population
DLHH	Number of households
DLHHSIZE	Average household size
DLNODRV	Number of licensed drivers
DLFDRVR	Female proportion of licensed drivers

2. Correlation Coefficient Table (N = 50)

	DLVMTCAR	DLPASGNR	DLPMTA_D	DLPMTA_I	DLLMI_R	DLLMI_U	DLTRSVMT
DLVMTCAR	1.00						
DLPASGNR	**-0.41**	1.00					
DLPMTA_D	**0.52**	-0.22	1.00				
DLPMTA_I	**0.39**	-0.15	**0.48**	1.00			
DLLMI_R	-0.07	-0.13	0.15	0.07	1.00		
DLLMI_U	**0.51**	**-0.36**	**0.34**	0.10	-0.15	1.00	
DLTRSVMT	**-0.34**	**0.65**	**-0.31**	**-0.28**	-0.19	**-0.27**	1.00
DLSITM_D	**0.47**	**-0.30**	**0.84**	**0.48**	0.20	**0.23**	**-0.31**
DLSITM_I	**0.25**	-0.22	**0.39**	**0.86**	0.07	0.14	**-0.30**
DLGAS	**-0.50**	0.22	-0.15	0.07	**0.29**	**-0.44**	0.00
DLMPGCAR	**-0.38**	**0.32**	**-0.52**	-0.19	-0.07	**-0.43**	**0.37**
DLCPI_PV	**-0.46**	**0.29**	**-0.24**	-0.17	0.10	**-0.46**	0.19
DLCPIMTS	-0.02	-0.16	-0.07	-0.10	0.11	**-0.33**	-0.02
DLCPIAIR	**-0.28**	0.16	**-0.46**	-0.12	0.08	**-0.47**	0.06
DLAIRF_D	0.00	0.05	0.18	-0.13	0.07	0.06	0.19
DLAIRF_I	-0.15	0.07	0.10	-0.12	0.05	0.03	**0.39**
DLLOCAL	0.21	0.00	0.22	0.20	-0.05	0.19	-0.17
DLTOLL	0.13	-0.14	0.07	0.01	-0.05	0.03	**-0.30**
DLINTCAL	-0.18	0.12	-0.05	-0.15	**0.26**	-0.04	0.02
DLCELSBR	0.01	**0.31**	-0.05	0.01	-0.11	0.01	**0.67**
DLBS_LIN	0.08	**-0.28**	0.09	0.06	0.03	-0.06	**-0.48**
DLRS_LIN	0.17	**-0.30**	0.15	0.20	0.12	0.03	**-0.42**
DLTCABLE	**0.37**	**-0.37**	**0.39**	**0.36**	**0.26**	**0.30**	**-0.56**
DLCELSIT	-0.01	**0.33**	-0.07	-0.01	-0.13	0.00	**0.69**
DLCPILOC	-0.10	0.08	**-0.24**	**-0.40**	-0.17	-0.11	**0.52**
DLCPITIN	0.07	0.01	-0.09	**-0.36**	0.00	0.21	0.11
DLCPITBT	-0.02	-0.09	-0.04	**-0.37**	0.14	-0.04	-0.10
DLICALLF	0.12	-0.11	-0.01	**0.34**	-0.02	-0.10	**-0.34**
DLCELL_C	0.01	**-0.24**	0.02	0.00	0.21	0.00	**-0.63**
DLSUB_R	**0.40**	**-0.66**	**0.54**	**0.40**	**0.37**	**0.30**	**-0.63**
DLGDP	**0.59**	0.12	**0.54**	**0.37**	-0.09	**0.31**	-0.02
DLDISCNT	-0.02	0.14	**0.28**	0.21	0.20	-0.19	-0.05
DLUMPR	**-0.34**	**-0.25**	**-0.48**	**-0.30**	0.16	-0.13	-0.15
DLFELABR	**0.29**	-0.12	**0.55**	**0.24**	0.09	0.14	-0.18
DLPOP	0.23	**-0.63**	**0.30**	**0.37**	**0.40**	0.21	**-0.65**
DLHH	0.12	0.06	0.07	0.04	0.13	**-0.32**	-0.14
DLHHSIZE	-0.02	**-0.30**	0.05	0.11	0.04	**0.38**	-0.12
DLNODRV	**0.45**	**-0.39**	**0.50**	0.18	**0.40**	**0.32**	**-0.55**
DLFDRVR	**0.43**	**-0.59**	**0.52**	**0.32**	**0.36**	**0.26**	**-0.53**

Notes:
All variables are first-order differenced, natural log-transformed.
Bold correlation coefficients are significant at $\alpha = 0.1$

	DLSITM_D	DLSITM_I	DLGAS	DLMPGCAR	DLCPI_PV	DLCPIMTS	DLCPIAIR
DLVMTCAR							
DLPASGNR							
DLPMTA_D							
DLPMTA_I							
DLLMI_R							
DLLMI_U							
DLTRSVMT							
DLSITM_D	1.00						
DLSITM_I	**0.52**	1.00					
DLGAS	-0.12	0.01	1.00				
DLMPGCAR	**-0.44**	-0.19	**0.30**	1.00			
DLCPI_PV	-0.21	**-0.26**	**0.68**	**0.43**	1.00		
DLCPIMTS	0.01	-0.11	0.12	**0.28**	**0.51**	1.00	
DLCPIAIR	**-0.25**	-0.15	**0.54**	**0.41**	**0.72**	**0.48**	1.00
DLAIRF_D	0.18	-0.10	-0.05	-0.14	-0.16	-0.09	**-0.36**
DLAIRF_I	-0.03	-0.12	-0.09	0.02	-0.11	-0.08	**-0.43**
DLLOCAL	0.23	0.12	-0.15	**-0.30**	-0.01	0.05	0.02
DLTOLL	-0.01	-0.03	-0.05	-0.09	0.04	0.02	0.07
DLINTCAL	-0.07	-0.23	0.15	-0.04	**0.27**	0.17	0.19
DLCELSBR	0.02	-0.02	-0.12	0.12	-0.01	-0.04	-0.02
DLBS_LIN	0.02	0.11	0.04	-0.16	-0.15	-0.05	-0.09
DLRS_LIN	0.17	0.23	0.14	-0.21	-0.03	-0.01	0.02
DLTCABLE	**0.50**	**0.37**	0.03	**-0.37**	0.01	0.14	0.15
DLCELSIT	-0.02	-0.04	-0.13	0.13	-0.03	-0.06	-0.04
DLCPILOC	**-0.23**	**-0.38**	-0.21	**0.30**	0.19	**0.37**	0.11
DLCPITIN	-0.10	**-0.31**	-0.18	-0.06	0.19	**0.33**	0.10
DLCPITBT	-0.04	**-0.36**	-0.04	-0.07	**0.27**	**0.35**	0.11
DLICALLF	0.08	**0.40**	0.19	0.05	-0.07	-0.23	0.13
DLCELL_C	0.00	0.02	0.16	-0.10	0.03	0.05	0.08
DLSUB_R	**0.59**	**0.45**	-0.04	**-0.33**	-0.18	0.04	-0.15
DLGDP	**0.37**	0.15	-0.17	**-0.36**	**-0.24**	**-0.30**	-0.23
DLDISCNT	**0.24**	0.03	**0.38**	0.00	**0.25**	-0.08	0.13
DLUMPR	**-0.28**	-0.07	0.08	0.20	0.09	**0.28**	0.19
DLFELABR	**0.38**	0.22	-0.06	**-0.32**	0.08	0.20	0.02
DLPOP	**0.39**	**0.44**	-0.03	**-0.29**	**-0.27**	-0.09	-0.17
DLHH	0.15	0.07	0.15	0.01	**0.33**	**0.36**	**0.54**
DLHHSIZE	0.01	0.11	-0.15	-0.12	**-0.41**	**-0.36**	**-0.56**
DLNODRV	**0.44**	0.16	0.00	**-0.35**	-0.04	0.09	-0.10
DLFDRVR	**0.58**	**0.35**	-0.02	**-0.30**	-0.10	0.16	-0.08

Notes:
All variables are first-order differenced, natural log-transformed.
Bold correlation coefficients are significant at α = 0.1

	DLAIRF_D	DLAIRF_I	DLLOCAL	DLTOLL	DLINTCAL	DLCELSBR	DLBS_LIN
DLVMTCAR							
DLPASGNR							
DLPMTA_D							
DLPMTA_I							
DLLMI_R							
DLLMI_U							
DLTRSVMT							
DLSITM_D							
DLSITM_I							
DLGAS							
DLMPGCAR							
DLCPI_PV							
DLCPIMTS							
DLCPIAIR							
DLAIRF_D	1.00						
DLAIRF_I	0.20	1.00					
DLLOCAL	0.00	-0.06	1.00				
DLTOLL	**-0.58**	0.00	0.15	1.00			
DLINTCAL	**-0.28**	0.08	**0.27**	0.12	1.00		
DLCELSBR	**0.45**	0.18	0.07	**-0.61**	-0.11	1.00	
DLBS_LIN	-0.13	-0.13	-0.03	**0.46**	-0.04	**-0.69**	1.00
DLRS_LIN	-0.11	-0.10	0.17	**0.35**	0.05	**-0.43**	**0.79**
DLTCABLE	-0.10	-0.19	**0.59**	0.22	0.11	-0.22	0.06
DLCELSIT	**0.44**	0.19	0.04	**-0.60**	-0.12	**0.99**	**-0.66**
DLCPILOC	0.16	0.20	**-0.23**	**-0.24**	-0.13	**0.48**	**-0.58**
DLCPITIN	0.16	0.10	0.18	-0.13	-0.08	0.13	**-0.33**
DLCPITBT	-0.03	-0.11	0.14	-0.08	0.11	-0.15	-0.09
DLICALLF	0.00	**-0.31**	0.12	0.01	**-0.30**	-0.15	**0.31**
DLCELL_C	**-0.41**	-0.21	-0.08	**0.48**	0.22	**-0.94**	**0.59**
DLSUB_R	0.16	-0.15	0.01	-0.10	-0.22	-0.17	0.11
DLGDP	0.09	-0.16	0.14	-0.10	-0.06	0.22	-0.05
DLDISCNT	0.12	-0.17	0.17	0.01	0.18	-0.03	0.17
DLUMPR	-0.10	0.10	-0.05	0.08	-0.03	-0.20	-0.01
DLFELABR	-0.03	0.00	**0.30**	0.22	0.05	-0.09	0.14
DLPOP	0.10	-0.20	0.01	-0.15	-0.16	**-0.24**	0.22
DLHH	-0.13	**-0.33**	**0.33**	0.17	0.07	-0.07	0.17
DLHHSIZE	0.16	0.23	**-0.30**	-0.22	-0.12	-0.02	-0.07
DLNODRV	0.09	0.10	0.20	0.14	-0.08	**-0.31**	0.11
DLFDRVR	0.22	-0.15	0.14	-0.08	-0.21	-0.14	0.13

Notes:
All variables are first-order differenced, natural log-transformed.
Bold correlation coefficients are significant at α = 0.1

	DLRS_LIN	DLTCABLE	DLCELSIT	DLCPILOC	DLCPITIN	DLCPITBT	DLICALLF
DLVMTCAR							
DLPASGNR							
DLPMTA_D							
DLPMTA_I							
DLLMI_R							
DLLMI_U							
DLTRSVMT							
DLSITM_D							
DLSITM_I							
DLGAS							
DLMPGCAR							
DLCPI_PV							
DLCPIMTS							
DLCPIAIR							
DLAIRF_D							
DLAIRF_I							
DLLOCAL							
DLTOLL							
DLINTCAL							
DLCELSBR							
DLBS_LIN							
DLRS_LIN	1.00						
DLTCABLE	**0.38**	1.00					
DLCELSIT	**-0.42**	**-0.28**	1.00				
DLCPILOC	**-0.55**	**-0.26**	**0.48**	1.00			
DLCPITIN	**-0.31**	0.14	0.12	**0.44**	1.00		
DLCPITBT	-0.09	0.11	-0.18	0.06	**0.47**	1.00	
DLICALLF	**0.28**	0.13	-0.16	**-0.45**	**-0.41**	**-0.30**	1.00
DLCELL_C	**0.40**	**0.25**	**-0.95**	**-0.51**	-0.14	0.18	0.12
DLSUB_R	**0.30**	**0.57**	-0.20	-0.19	-0.01	0.08	0.21
DLGDP	0.00	0.12	0.22	-0.18	-0.13	-0.15	0.10
DLDISCNT	**0.26**	**0.32**	-0.05	**-0.26**	**-0.31**	-0.02	0.08
DLUMPR	-0.01	0.04	-0.20	0.11	**0.26**	0.19	-0.05
DLFELABR	**0.24**	**0.43**	-0.13	-0.13	0.03	0.09	0.10
DLPOP	**0.36**	**0.41**	**-0.26**	**-0.42**	-0.15	0.09	**0.28**
DLHH	**0.32**	**0.45**	-0.11	0.06	0.02	0.12	0.16
DLHHSIZE	-0.16	**-0.26**	0.00	-0.22	-0.08	-0.07	-0.04
DLNODRV	0.20	**0.63**	**-0.36**	-0.14	**0.30**	**0.24**	0.06
DLFDRVR	**0.34**	**0.63**	-0.18	-0.11	0.10	0.19	0.12

Notes:
All variables are first-order differenced, natural log-transformed.
Bold correlation coefficients are significant at $\alpha = 0.1$

	DLCELL_C	DLSUB_R	DLGDP	DLDISCNT	DLUMPR	DLFELABR	DLPOP
DLVMTCAR							
DLPASGNR							
DLPMTA_D							
DLPMTA_I							
DLLMI_R							
DLLMI_U							
DLTRSVMT							
DLSITM_D							
DLSITM_I							
DLGAS							
DLMPGCAR							
DLCPI_PV							
DLCPIMTS							
DLCPIAIR							
DLAIRF_D							
DLAIRF_I							
DLLOCAL							
DLTOLL							
DLINTCAL							
DLCELSBR							
DLBS_LIN							
DLRS_LIN							
DLTCABLE							
DLCELSIT							
DLCPILOC							
DLCPITIN							
DLCPITBT							
DLICALLF							
DLCELL_C	1.00						
DLSUB_R	0.18	1.00					
DLGDP	-0.20	0.11	1.00				
DLDISCNT	0.08	0.13	**0.37**	1.00			
DLUMPR	0.18	-0.01	**-0.86**	**-0.50**	1.00		
DLFELABR	0.07	**0.34**	**0.24**	**0.23**	**-0.28**	1.00	
DLPOP	**0.26**	**0.86**	0.01	0.06	0.08	0.14	1.00
DLHH	0.08	0.14	0.09	**0.29**	-0.09	**0.41**	0.00
DLHHSIZE	0.03	0.20	-0.08	**-0.24**	0.11	**-0.32**	**0.39**
DLNODRV	**0.34**	**0.66**	0.13	0.10	0.03	**0.38**	**0.45**
DLFDRVR	0.16	**0.90**	0.08	**0.23**	-0.02	**0.34**	**0.72**

Notes:
All variables are first-order differenced, natural log-transformed.
Bold correlation coefficients are significant at α = 0.1

	DLHH	DLHHSIZE	DLNODRV	DLFDRVR
DLVMTCAR				
DLPASGNR				
DLPMTA_D				
DLPMTA_I				
DLLMI_R				
DLLMI_U				
DLTRSVMT				
DLSITM_D				
DLSITM_I				
DLGAS				
DLMPGCAR				
DLCPI_PV				
DLCPIMTS				
DLCPIAIR				
DLAIRF_D				
DLAIRF_I				
DLLOCAL				
DLTOLL				
DLINTCAL				
DLCELSBR				
DLBS_LIN				
DLRS_LIN				
DLTCABLE				
DLCELSIT				
DLCPILOC				
DLCPITIN				
DLCPITBT				
DLICALLF				
DLCELL_C				
DLSUB_R				
DLGDP				
DLDISCNT				
DLUMPR				
DLFELABR				
DLPOP				
DLHH	1.00			
DLHHSIZE	**-0.92**	1.00		
DLNODRV	**0.30**	-0.10	1.00	
DLFDRVR	**0.30**	0.01	**0.71**	1.00

Notes:
All variables are first-order differenced, natural log-transformed.
Bold correlation coefficients are significant at $\alpha = 0.1$

C. Unstandardized Direct and Total Effects between Telecommunications and Travel

1. Personal Vehicle Travel and Local Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLLMI_U	<---	DLVMTL1*	.643	.131	4.921	***
DLLMI_U	<---	DLDISCNT	-.045	.012	-3.855	***
DLTCABLE	<---	DLLCALL1*	.576	.199	2.899	.004
DLTCABLE	<---	DLFELABR	1.190	.439	2.711	.007
DLCPI_PV	<---	DLLMI_U	-.353	.172	-2.050	.040
DLCPI_PV	<---	DLGAS	.265	.046	5.799	***
DLCPILOC	<---	DLTCABLE	-.314	.153	-2.054	.040
DLSUB_R	<---	DLLMIUL1*	.047	.025	1.869	.062
DLGDP	<---	DLLMIUL1*	.085	.063	1.356	.175
DLGDP	<---	DLUMPR	-.098	.009	-11.525	***
DLVMTCAR	<---	DLLMI_U	.217	.114	1.902	.057
DLVMTCAR	<---	DLCPI_PV	-.122	.047	-2.584	.010
DLVMTCAR	<---	DLGDP	.295	.083	3.548	***
DLVMTCAR	<---	DLSUB_R	.364	.247	1.477	.140
DLLOCAL	<---	DLTCABLE	.179	.095	1.885	.059
DLLOCAL	<---	DLCPILOC	-.060	.055	-1.090	.276
DLLOCAL	<---	DLHHSIZE	-.698	.266	-2.630	.009
DLVMTCAR	<---	DLLOCAL	.308	.183	1.681	.093
DLLOCAL	<---	DLVMTCAR	.228	.183	1.244	.214

* 1st order lagged demand variables (local calls, DLLCALL1, and VMT, DLVMTL1)

- Total effects

LHS	DLUMPR	DLLMIUL1	DLFELABR	DLLCALL1	DLHHSIZE	DLGAS	DLDISCNT	DLVMTL1	DLTCABLE	DLLMI_U	DLCPILOC	DLSUB_R	DLGDP	DLCPI_PV	DLLOCAL	DLVMTCAR
DLTCABLE			1.190	.576												
DLLMI_U							-.045	.643								
DLCPILOC			-.374	-.181					-.314							

LHS	DLUMPR	DLLMIUL1	DLFELABR	DLLCALL1	DLHHSIZE	DLGAS	DLDISCNT	DLVMTL1	DLTCABLE	DLLMI_U	DLCPILOC	DLSUB_R	DLGDP	DLCPI_PV	DLLOCAL	DLVMTCAR
DLSUB_R		.047														
DLGDP	-.098	.085														
DLCPI_PV						.265	.016	-.227		-.353						
DLLOCAL	-.007	.010	.253	.122	-.751	-.008	-.003	.041	.212	.064	-.065	.089	.072	-.030	.075	.245
DLVMTCAR	-.031	.045	.078	.038	-.231	-.035	-.013	.180	.065	.280	-.020	.392	.318	-.131	.331	.075

2. Personal Vehicle Travel and Long-distance Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLLMI_U	<---	DLVMTL1	.581	.138	4.214	***
DLLMI_U	<---	DLDISCNT	-.046	.013	-3.539	***
DLTCABLE	<---	DLTOLLL1*	.096	.034	2.846	.004
DLTCABLE	<---	DLFELABR	1.799	.420	4.287	***
DLCPI_PV	<---	DLLMI_U	-.353	.176	-2	.045
DLCPI_PV	<---	DLGAS	.265	.046	5.783	***
DLTOLL	<---	DLTCABLE	.641	.448	1.429	.153
DLTOLL	<---	DLHHSIZE	-2.418	1.304	-1.854	.064
DLTOLL	<---	DLCPBWL1*	-.214	.193	-1.111	.267
DLSUB_R	<---	DLLMIUL1*	.037	.031	1.217	.224
DLGDP	<---	DLLMIUL1	.098	.064	1.536	.125
DLGDP	<---	DLUMPR	-.097	.009	-11.382	***
DLVMTCAR	<---	DLTOLL	.187	.085	2.208	.027
DLVMTCAR	<---	DLLMI_U	.376	.134	2.817	.005
DLVMTCAR	<---	DLCPI_PV	-.139	.046	-3.045	.002
DLVMTCAR	<---	DLGDP	.358	.079	4.542	***
DLVMTCAR	<---	DLMPGCAR	.142	.083	1.715	.086
DLVMTCAR	<---	DLSUB_R	.420	.302	1.391	.164
DLCPITBT	<---	DLTCABLE	-.927	.189	-4.905	***
DLCPITBT	<---	D50_83	.083	.011	7.408	***

* 1^{st} order lagged variables (toll calls, DLTOLLL1, lane miles (urban areas), DLLMIUL1, and CPI for interstate toll calls, DLCPBWL1)
D50_83 = time dummy (1950 -1983: 1; otherwise 0).

- Total effects

LHS	DLUMPR	DLLMIUL1	D50_83	DLFELABR	DLTOLLL1	DLCPBWL1	DLHHSIZE	DLGAS	DLDISCNT	DLVMTL1	DLMPGCAR	DLTCABLE	DLLMI_U	DLSUB_R	DLGDP	DLCPI_PV	DLTOLL
DLTCABLE				1.799	.096												
DLLMI_U									-.046	.581							
DLSUB_R		.037															
DLGDP	-.097	.098															
DLCPI_PV								.265	.016	-.205			-.353				
DLTOLL				1.152	.062	-.214	-2.42					.641					
DLCPITBT			.083	-1.67	-.089							-.927					
DLVMTCAR	-.035	.051		.215	.011	-.040	-.452	-.037	-.019	.247	.142	.120	.425	.420	.358	-.139	.187

* 1^{st} order lagged demand variables (toll calls and VMT)

3. Personal Vehicle Travel and Mobile Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLLMI_U	<---	DLVMTL1	.717	.120	5.988	***
DLLMI_U	<---	DLDISCNT	-.041	.013	-3.205	.001
DLCPI_PV	<---	DLLMI_U	-.408	.157	-2.597	.009
DLCPI_PV	<---	DLGAS	.260	.040	6.524	***
DLSUB_R	<---	DLLMIUL1	.087	.041	2.147	.032
DLGDP	<---	DLLMIUL1	.082	.060	1.361	.174
DLGDP	<---	DLUMPR	-.100	.008	-11.776	***
DLVMTCAR	<---	DLLMI_U	.428	.121	3.545	***
DLVMTCAR	<---	DLCPI_PV	-.114	.050	-2.307	.021
DLVMTCAR	<---	DLGDP	.318	.087	3.648	***
DLVMTCAR	<---	DLSUB_R	.805	.237	3.394	***
DLVMTCAR	<---	DLHHSIZE	-.963	.299	-3.220	.001
DLVMTCAR	<---	DLMPGCAR	.108	.082	1.319	.187
DLCELSIT	<---	DLCELSL1*	.105	.060	1.744	.081

			Estimate	S.E.	C.R.	P
DLCELSIT	<---	DLGDP	5.071	3.412	1.486	.137
DLCELSBR	<---	DLVMTCAR	4.177	1.853	2.254	.024
DLCELSBR	<---	DLCELSIT	1.476	.279	5.283	***
DLCELSBR	<---	DLHHSIZE	-4.218	2.112	-1.997	.046
DLCELL_C	<---	DLCELSIT	-.382	.008	-44.990	***

* 1st order lagged demand variable (mobile phone subscribers, DLCELSL1)

- Total effects

LHS	DLUMPR	DLLMIUL1	DLCELSL1	DLGAS	DLDISCNT	DLVMTL1	DLMPGCAR	DLHHSIZE	DLLMI_U	DLSUB_R	DLGDP	DLCPI_PV	DLCELSIT	DLVMTCAR
DLLMI_U					-.041	.717								
DLSUB_R		.087												
DLGDP	-.100	.082												
DLCPI_PV				.260	.017	-.292			-.408					
DLCELSIT	-.506	.416	.105								5.071			
DLVMTCAR	-.032	.096		-.030	-.020	.341	.108	-.963	.475	.805	.318	-.114		
DLCELL_C	.193	-.159	-.040								-1.938		-.382	
DLCELSBR	-.878	1.016	.156	-.124	-.082	1.423	.452	-8.241	1.985	3.364	8.810	-.478	1.476	4.177

4. Public Transit Travel and Local Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLTCABLE	<---	DLLCALL1	.847	.220	3.850	***
DLTCABLE	<---	DLFELABR	1.088	.471	2.312	.021
DLGDP	<---	DLTCABLE	.077	.067	1.151	.250
DLGDP	<---	DLUMPR	-.105	.009	-11.931	***
DLTRSVMT	<---	DLPSNGL1*	.298	.098	3.043	.002
DLTRSVMT	<---	DLGDP	.372	.223	1.665	.096

			Estimate	S.E.	C.R.	P
DLCPILOC	<---	DLTCABLE	-.290	.153	-1.890	.059
DLSUB_R	<---	DLTCABL1*	.075	.024	3.087	.002
DLPASGNR	<---	DLTRSVMT	.836	.231	3.628	***
DLPASGNR	<---	DLCPIMTS	-.121	.090	-1.339	.180
DLPASGNR	<---	DLSUB_R	-3.384	1.032	-3.278	.001
DLPASGNR	<---	DLPOP	3.375	2.366	1.426	.154
DLLOCAL	<---	DLTCABLE	.398	.078	5.106	***
DLLOCAL	<---	DLCPILOC	-.091	.040	-2.265	.024
DLLOCAL	<---	DLHHSIZE	-.276	.189	-1.458	.145
DLPASGNR	<---	DLLOCAL	1.215	.418	2.906	.004
DLLOCAL	<---	DLPASGNR	.165	.074	2.241	.025

* 1st order lagged demand variables (transit passengers, DLPSNGL1, and total wire length, DLTCABL1)

- Total effects

LHS	DLUMPR	DLTCABL1	DLFELABR	DLLCALL1	DLHHSIZE	DLPSNGL1	DLPOP	DLCPIMTS	DLTCABLE	DLGDP	DLCPILOC	DLSUB_R	DLTRSVMT	DLLOCAL	DLPASGNR
DLTCABLE			1.088	.847											
DLGDP	-.105		.084	.066					.077						
DLCPILOC			-.316	-.246					-.290						
DLSUB_R		.075													
DLTRSVMT	-.039		.031	.024		.298			.029	.372					
DLLOCAL	-.007	-.053	.584	.455	-.345	.051	.697	-.025	.537	.064	-.114	-.699	.173	.251	.207
DLPASGNR	-.041	-.319	.736	.573	-.419	.311	4.222	-.151	.676	.389	-.139	-4.234	1.046	1.521	.251

5. Public Transit Travel and Mobile Telecommunications

- Direct effects

			ESTIMATE	S.E.	C.R.	P
DLTRSVMT	<---	DLPSNGL1	.309	.083	3.726	***
DLSUB_R	<---	DLTSVML1*	-.138	.025	-5.404	***

			ESTIMATE	S.E.	C.R.	P
DLSUB_R	<---	DLCLSTL1*	.003	.001	2.286	.022
DLPASGNR	<---	DLTRSVMT	.388	.171	2.277	.023
DLPASGNR	<---	DLCPIMTS	-.329	.122	-2.701	.007
DLPASGNR	<---	DLSUB_R	-2.826	.778	-3.633	***
DLPASGNR	<---	DLHH	1.381	.617	2.239	.025
DLCELSIT	<---	DLCELSL1	.098	.051	1.916	.055
DLCELSIT	<---	DLGDP	8.562	3.417	2.506	.012
DLCELSBR	<---	DLPASGNR	-1.398	.813	-1.718	.086
DLCELSBR	<---	DLCELSIT	1.947	.040	49.005	***
DLCELSBR	<---	DLFELABR	9.114	3.344	2.726	.006

* 1^{st} order lagged demand variables (transit VMT, DLTSVML1, and cell sites, DLCLSTL1)

- Total effects

LHS	DLCLSTL1	DLTSVML1	DLGDP	DLCELSL1	DLFELABR	DLPSNGL1	DLHH	DLCPIMTS	DLSUB_R	DLTRSVMT	DLCELSIT	DLPASGNR
DLSUB_R	.003	-.138										
DLTRSVMT						.309						
DLCELSIT			8.562	.098								
DLPASGNR	-.008	.389				.120	1.381	-.329	-2.826	.388		
DLCELSBR	.011	-.543	16.672	.190	9.114	-.168	-1.931	.460	3.950	-.543	1.947	-1.398

6. Ground Travel and Local Telecommunications

- Direct effects

			ESTIMATE	S.E.	C.R.	P
DLLMI_U	<---	DLVMTL1	.644	.129	4.992	***
DLLMI_U	<---	DLDISCNT	-.044	.012	-3.682	***
DLTRSVMT	<---	DLPSNGL1	.149	.102	1.469	.142
DLTRSVMT	<---	DLFDRVR	-1.771	.583	-3.036	.002
DLTCABLE	<---	DLLCALL1	.874	.232	3.764	***
DLTCABLE	<---	DLPOP	4.280	1.201	3.564	***

			ESTIMATE	S.E.	C.R.	P
DLCPI_PV	<---	DLLMI_U	-.353	.171	-2.066	.039
DLCPI_PV	<---	DLGAS	.265	.045	5.882	***
DLCPILOC	<---	DLTCABL1	-.211	.161	-1.314	.189
DLGDP	<---	DLLMIUL1	.079	.060	1.314	.189
DLGDP	<---	DLUMPR	-.097	.009	-11.404	***
DLVMTCAR	<---	DLLMI_U	.114	.111	1.023	.306
DLVMTCAR	<---	DLCPI_PV	-.270	.087	-3.115	.002
DLVMTCAR	<---	DLGDP	.334	.076	4.409	***
DLPASGNR	<---	DLTRSVMT	1.242	.301	4.133	***
DLPASGNR	<---	DLCPIMTS	-.176	.106	-1.652	.099
DLPASGNR	<---	DLGDP	.206	.210	.983	.325
DLPASGNR	<---	DLHHSIZE	-.585	.552	-1.059	.289
DLLOCAL	<---	DLTCABLE	.239	.065	3.696	***
DLLOCAL	<---	DLCPILOC	-.106	.044	-2.394	.017
DLLOCAL	<---	DLHHSIZE	-.445	.204	-2.184	.029
DLSUB_R	<---	DLLMIUL1	.042	.036	1.174	.240
DLSUB_R	<---	DLTCABL1	.129	.032	3.992	***
DLVMTCAR	<---	DLPASGNR	-.187	.048	-3.865	***
DLVMTCAR	<---	DLLOCAL	.254	.176	1.447	.148
DLPASGNR	<---	DLVMTCAR	-.802	.442	-1.815	.070
DLPASGNR	<---	DLLOCAL	1.119	.492	2.275	.023
DLLOCAL	<---	DLVMTCAR	.393	.158	2.489	.013
DLLOCAL	<---	DLPASGNR	.112	.064	1.738	.082

- Total effects

LHS	DLUMPR	DLLMIUL1	DLTCABL1	DLGAS	DLPOP	DLLCALL1	DLFDRVR	DLPSNGL1	DLDISCNT	DLVMTL1	DLHHSIZE
DLLMI_U									-.044	.644	
DLCPILOC			-.211								
DLTCABLE					4.280	.874					
DLTRSVMT							-1.771	.149			
DLGDP	-.097	.079									
DLCPI_PV				.265					.015	-.227	
DLLOCAL	-.015	.012	.026	-.030	1.190	.243	-.115	.010	-.004	.056	-.549

LHS	DLUMPR	DLLMIUL1	DLTCABL1	DLGAS	DLPOP	DLLCALL1	DLFDRVR	DLPSNGL1	DLDISCNT	DLVMTL1	DLHHSIZE
DLPASGNR	-.009	.007	.028	.035	1.281	.262	-2.710	.228	.005	-.067	-1.279
DLVMTCAR	-.035	.028	.001	-.086	.063	.013	.477	-.040	-.011	.161	.099
DLSUB_R		.042	.129								

LHS	DLCPIMTS	DLLMI_U	DLCPILOC	DLTCABLE	DLTRSVMT	DLGDP	DLCPI_PV	DLLOCAL	DLPASGNR	DLVMTCAR
DLLMI_U										
DLCPILOC										
DLTCABLE										
DLTRSVMT										
DLGDP										
DLCPI_PV		-.353								
DLLOCAL	-.009	.087	-.123	.278	.065	.150	-.112	.164	.052	.415
DLPASGNR	-.217	-.104	-.133	.299	1.531	.088	.134	1.253	.232	-.496
DLVMTCAR	.038	.251	-.007	.015	-.269	.356	-.323	.062	-.217	.198
DLSUB_R										

7. Ground Travel and Mobile Telecommunications

- Direct effects

			ESTIMATE	S.E.	C.R.	P
DLLMI_U	<---	DLVMTL1	.766	.148	5.166	***
DLLMI_U	<---	DLDISCNT	-.047	.014	-3.258	.001
DLTRSVMT	<---	DLPSNGL1	.148	.108	1.365	.172
DLTRSVMT	<---	DLFDRVR	-1.285	.517	-2.485	.013
DLSUB_R	<---	DLLMIUL1	.083	.040	2.079	.038
DLGDP	<---	DLLMI_U	.203	.064	3.187	.001

			ESTIMATE	S.E.	C.R.	P
DLGDP	<---	DLUMPR	-.102	.008	-12.213	***
DLVMTCAR	<---	DLLMI_U	.057	.056	1.008	.313
DLVMTCAR	<---	DLGAS	-.025	.018	-1.357	.175
DLVMTCAR	<---	DLGDP	.503	.093	5.401	***
DLVMTCAR	<---	DLSUB_R	.308	.224	1.374	.169
DLPASGNR	<---	DLTRSVMT	.222	.163	1.362	.173
DLPASGNR	<---	DLCPIMTS	-.143	.109	-1.309	.191
DLPASGNR	<---	DLGDP	1.386	.397	3.494	***
DLCELSIT	<---	DLCELSL1	.153	.047	3.233	.001
DLCELSIT	<---	DLGDP	9.302	3.618	2.571	.010
DLCELSBR	<---	DLVMTCAR	2.565	1.720	1.491	.136
DLCELSBR	<---	DLCELSIT	1.874	.039	48.592	***
DLCELSBR	<---	DLHHSIZE	-6.843	2.807	-2.438	.015
DLVMTCAR	<---	DLPASGNR	-.224	.092	-2.433	.015
DLPASGNR	<---	DLVMTCAR	-2.452	.646	-3.794	***

- Total effects

LHS	DLUMPR	DLLMIUL1	DLCELSL1	DLFDRVR	DLPSNGL1	DLDISCNT	DLVMTL1	DLHHSIZE
DLLMI_U						-.047	.766	
DLTRSVMT				-1.285	.148			
DLSUB_R		.083						
DLGDP	-.102					-.009	.155	
DLPASGNR	-.035	-.139		-.633	.073	.011	-.183	
DLVMTCAR	-.044	.057		.142	-.016	-.010	.162	
DLCELSIT	-.950		.153			-.088	1.445	
DLCELSBR	-1.892	.146	.287	.364	-.042	-.190	3.124	-6.843

LHS	DLCPIMTS	DLGAS	DLLMI_U	DLTRSVMT	DLSUB_R	DLGDP	DLPASGNR	DLVMTCAR	DLCELSIT
DLLMI_U									
DLTRSVMT									
DLSUB_R									
DLGDP			.203						
DLPASGNR	-.316	.136	-.238	.493	-1.674	.341	1.217	-5.435	
DLVMTCAR	.071	-.055	.212	-.110	.683	.426	-.496	1.217	
DLCELSIT			1.885			9.302			
DLCELSBR	.182	-.142	4.076	-.283	1.751	18.528	-1.273	5.686	1.874

8. Domestic Airline Travel and Local Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLSITM_D	<---	DLAIRDL1*	.584	.098	5.932	***
DLTCABLE	<---	DLLCALL1	.728	.250	2.914	.004
DLTCABLE	<---	DLFELABR	1.568	.579	2.706	.007
DLCPILOC	<---	DLTCABL1	-.235	.164	-1.432	.152
DLCPIAIR	<---	DLSITM_D	-.232	.197	-1.176	.240
DLLOCAL	<---	DLTCABLE	.233	.083	2.818	.005
DLLOCAL	<---	DLCPILOC	-.084	.063	-1.339	.181
DLLOCAL	<---	DLHHSIZE	-.505	.278	-1.814	.070
DLGDP	<---	DLTCABLE	.076	.060	1.274	.203
DLGDP	<---	DLUMPR	-.099	.008	-11.695	***
DLPMTA_D	<---	DLLOCAL	.332	.320	1.036	.300
DLPMTA_D	<---	DLSITM_D	.562	.087	6.433	***
DLPMTA_D	<---	DLCPIAIR	-.272	.057	-4.749	***
DLPMTA_D	<---	DLGDP	.529	.166	3.189	.001
DLPMTA_D	<---	DLNODRV	.910	.361	2.518	.012
DLSUB_R	<---	DLTCABL1	.123	.030	4.107	***

* 1st order lagged demand variable (domestic airline PMT, DLAIRDL1)

• Total effects

LHS	DLUMPR	DLTCABL1	DLFELABR	DLLCALL1	DLHHSIZE	DLAIRDL1	DLNODRV	DLCPILOC	DLTCABLE	DLSITM_D	DLGDP	DLCPIAIR	DLLOCAL
DLCPILOC		-.235											
DLTCABLE			1.568	.728									
DLSITM_D						.584							
DLGDP	-.099		.120	.056					.076				
DLCPIAIR						-.135				-.232			
DLLOCAL		.020	.365	.169	-.505			-.084	.233				
DLSUB_R		.123											
DLPMTA_D	-.053	.007	.184	.086	-.168	.365	.910	-.028	.118	.625	.529	-.272	.332

9. Domestic Airline Travel and Long-distance Telecommunications

• Direct effects

			Estimate	S.E.	C.R.	P
DLSITM_D	<---	DLAIRDL1	.566	.090	6.302	***
DLTCABLE	<---	DLTOLLL1	.101	.036	2.830	.005
DLTCABLE	<---	DLFELABR	2.089	.475	4.397	***
DLCPIAIR	<---	DLSITM_D	-.229	.139	-1.652	.099
DLTOLL	<---	DLTCABLE	.815	.391	2.085	.037
DLTOLL	<---	DLHHSIZE	-1.496	1.010	-1.481	.139
DLGDP	<---	DLTCABLE	.102	.073	1.393	.164
DLGDP	<---	DLUMPR	-.106	.009	-12.388	***
DLPMTA_D	<---	DLTOLL	.481	.172	2.796	.005
DLPMTA_D	<---	DLSITM_D	.568	.088	6.424	***
DLPMTA_D	<---	DLCPIAIR	-.350	.054	-6.482	***
DLPMTA_D	<---	DLGDP	.483	.171	2.821	.005
DLCPITBT	<---	DLTCABLE	-.974	.187	-5.198	***
DLCPITBT	<---	D50_83	.087	.011	7.788	***
DLSUB_R	<---	DLTCABL1	.046	.026	1.777	.076

- Total effects

LHS	DLUMPR	DLTCABL1	D50_83	DLFELABR	DLTOLLL1	DLHHSIZE	DLAIRDL1	DLTCABLE	DLSITM_D	DLGDP	DLCPIAIR	DLTOLL
DLTCABLE				2.089	.101							
DLSITM_D							.566					
DLGDP	-.106			.213	.010			.102				
DLCPIAIR							-.130		-.229			
DLTOLL				1.702	.082	-1.496		.815				
DLSUB_R		.046										
DLCPITBT			.087	-2.034	-.099			-.974				
DLPMTA_D	-.051			.921	.045	-.719	.367	.441	.648	.483	-.350	.481

10. Domestic Airline Travel and Mobile Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLSITM_D	<---	DLAIRDL1	.659	.097	6.796	***
DLGDP	<---	DLUMPR	-.109	.010	-10.574	***
DLGDP	<---	DLDISCNT	-.016	.009	-1.856	.063
DLCPIAIR	<---	DLSITM_D	-.219	.105	-2.078	.038
DLPMTA_D	<---	DLCELSL1	.003	.002	1.455	.146
DLPMTA_D	<---	DLSITM_D	.635	.080	7.983	***
DLPMTA_D	<---	DLCPIAIR	-.241	.056	-4.263	***
DLPMTA_D	<---	DLGDP	.542	.172	3.147	.002
DLPMTA_D	<---	DLNODRV	1.150	.365	3.152	.002
DLCELSIT	<---	DLCELSL1	.097	.066	1.458	.145
DLCELSIT	<---	DLGDP	3.969	3.195	1.242	.214
DLCELSBR	<---	DLPMTA_D	.804	.376	2.138	.033
DLCELSBR	<---	DLCELSIT	1.438	.365	3.939	***
DLCELSBR	<---	DLHHSIZE	-5.376	2.175	-2.472	.013
DLCELL_C	<---	DLCELSIT	-.387	.008	-49.008	***
DLSITM_D	<---	DLGDP	.895	.339	2.641	.008
DLGDP	<---	DLSITM_D	.044	.034	1.295	.195

- Total effects

LHS	DLDISCNT	DLUMPR	DLHHSIZE	DLAIRDL1	DLNODRV	DLCELSL1	DLGDP	DLSITM_D	DLCPIAIR	DLCELSIT	DLPMTA_D
DLGDP	-.017	-.113		.030			.041	.046			
DLSITM_D	-.015	-.101		.686			.932	.041			
DLCPIAIR	.003	.022		-.150			-.204	-.228			
DLCELSIT	-.068	-.450		.120		.097	4.132	.182			
DLPMTA_D	-.020	-.131		.488	1.150	.003	1.204	.740	-.241		
DLCELL_C	.026	.174		-.046		-.037	-1.600	-.070		-.387	
DLCELSBR	-.113	-.752	-5.376	.565	.925	.142	6.909	.857	-.193	1.438	.804

11. International Airline Travel and Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLTCABLE	<---	DLINTCL1*	.034	.048	.715	.475
DLTCABLE	<---	DLPOP	4.361	1.346	3.240	.001
DLSITM_I	<---	DLAIRIL1	.420	.110	3.830	***
DLAIRF_I	<---	DLSMIIL1*	-.368	.133	-2.756	.006
DLGDP	<---	DLTCABLE	.134	.126	1.067	.286
DLGDP	<---	DLUMPR	-.106	.009	-11.924	***
DLPMTA_I	<---	DLSITM_I	.399	.215	1.859	.063
DLPMTA_I	<---	DLAIRF_I	-.076	.061	-1.247	.213
DLPMTA_I	<---	DLGDP	1.267	.245	5.173	***
DLPMTA_I	<---	DLPOP	2.203	1.815	1.214	.225
DLINTCAL	<---	DLAIRIL1	.170	.142	1.192	.233
DLINTCAL	<---	DLTCABL1	.521	.400	1.304	.192
DLINTCAL	<---	DLICALLF	-.303	.099	-3.059	.002
DLINTCAL	<---	DLHHSIZE	-1.457	1.435	-1.015	.310

* 1st order lagged demand variables (international calls, DLINTCL1, and international seat miles, DLSMIIL1)

- Total effects

LHS	DLUMPR	DLINTCL1	DLHHSIZE	DLICALLF	DLTCABL1	DLSMIIL1	DLAIRIL1	DLPOP	DLTCABLE	DLGDP	DLAIRF_I	DLSITM_I
DLTCABLE		.034						4.361				
DLGDP	-.106	.005						.585	.134			
DLAIRF_I						-.368						
DLSITM_I							.420					
DLINTCAL			-1.457	-.303	.521		.170					
DLPMTA_I	-.135	.006				.028	.168	2.944	.170	1.267	-.076	.399

12. Total Airline Travel and Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
DLTCABLE	<---	DLTIDCL1*	.363	.197	1.845	.065
DLTCABLE	<---	DLFELABR	1.831	.531	3.449	***
DLGDP	<---	DLTCABL1	.093	.062	1.502	.133
DLGDP	<---	DLUMPR	-.108	.009	-11.809	***
DLTSITM	<---	DLTAIRL1*	.610	.082	7.430	***
DLTSITM	<---	DLPOP	4.115	1.707	2.411	.016
DLTSITM	<---	DLGDP	.608	.273	2.225	.026
DLCPICAL	<---	DLTCABLE	-.818	.239	-3.418	***
DLCPICAL	<---	D50_83	.048	.008	5.730	***
DLTIDCA	<---	DLTCABLE	.590	.162	3.633	***
DLTIDCA	<---	DLCPICAL	-.154	.087	-1.763	.078
DLTIDCA	<---	DLHHSIZE	-.337	.277	-1.217	.224
DLCPIAIR	<---	DLTSITM	-.192	.165	-1.165	.244
DLTAIRT	<---	DLTIDCA	.557	.270	2.060	.039
DLTAIRT	<---	DLTSITM	.595	.089	6.722	***
DLTAIRT	<---	DLCPIAIR	-.206	.055	-3.737	***
DLTAIRT	<---	DLGDP	.584	.161	3.618	***
DLTAIRT	<---	DLNODRV	.534	.347	1.538	.124

			Estimate	S.E.	C.R.	P
DLSUB_R	<---	DLTCABL1	.106	.025	4.234	***

DLTICCA = total telephone calls, DLTAIRT = total airline PMT, DLTSITM = total seat miles.
* 1st order lagged demand variables (total calls, DLTIDCL1, and airline PMT, DLTAIRL1)

- Total effects

LHS	DLUMPR	DLTCABL1	D50_83	DLFELABR	DLTIDCL1	DLPOP	DLTAIRL1	DLHHSIZE	DLNODRV	DLTCABLE	DLGDP	DLCPICAL	DLTSITM	DLCPIAIR	DLTIDCA
DLTCABLE				1.831	.363										
DLGDP	-.108	.093													
DLCPICAL			.048	-1.498	-.297					-.818					
DLTSITM	-.065	.056				4.115	.610				.608				
DLCPIAIR	.013	-.011				-.789	-.117				-.117		-.192		
DLTIDCA			-.007	1.311	.260			-.337		.716		-.154			
DLSUB_R		.106													
DLTAIRT	-.104	.090	-.004	.731	.145	2.612	.387	-.188	.534	.399	.970	-.086	.635	-.206	.557

13. Travel and Wired Telecommunications

- **Additional Variable List**

Variable	Description
TD	Travel demand (composite index)
TELE_D	Telecommunications demand (composite index)
TS	Transportation supply (composite index)
TELE_D	Telecommunications supply (composite index)
TC	Travel costs (composite index)
TELE_C	Telecommunications costs (composite index)
LU	Land use (suburbanization rate)
ECON	Economic activity (composite index)
TDL1	1st order lag of travel demand

TELE_DL1	1st order lag of telecommunications demand
D50_83	Time dummy (1950 -1983: 1; otherwise 0)

- Direct effects

			Estimate	S.E.	C.R.	P
TS	<---	TDL1*	.109	.071	1.550	.121
TS	<---	DLFDRVR	67.076	11.447	5.860	***
TC	<---	TS	-.179	.141	-1.264	.206
TELE_S	<---	TELE_DL1*	.288	.133	2.166	.030
TELE_S	<---	DLPOP	161.595	45.143	3.580	***
LU	<---	TS	.009	.001	8.160	***
ECON	<---	TS	.162	.137	1.181	.238
TD	<---	TS	.493	.115	4.280	***
TD	<---	TC	-.218	.070	-3.114	.002
TD	<---	LU	15.528	14.696	1.057	.291
TD	<---	ECON	.180	.074	2.421	.015
TELE_D	<---	TELE_S	.256	.114	2.241	.025
TELE_D	<---	DLHHSIZE	-47.240	14.995	-3.150	.002
TELE_C	<---	TELE_S	-.706	.236	-2.988	.003
TELE_C	<---	D50_83	.976	.270	3.616	***
TD	<---	TELE_D	.212	.153	1.389	.165
TELE_D	<---	TD	.354	.152	2.338	.019

- Total effects

LHS	D50_83	DLPOP	TELE_DL1	DLHHSIZE	DLFDRVR	TDL1	TS	TELE_S	ECON	LU	TC	TELE_D	TD
TS					67.076	.109							
TELE_S		161.595	.288										
ECON					10.860	.018	.162						
LU					.630	.001	.009						
TC					-11.975	-.020	-.179						
TELE_D		44.745	.080	-51.086	18.185	.030	.271	.277	.069	5.952	-.083	.081	.383
TD		9.503	.017	-10.850	51.304	.084	.765	.059	.195	16.792	-.236	.230	.081

LHS	D50_83	DLPOP	TELE_DL1	DLHHSIZE	DLFDRVR	TDL1	TS	TELE_S	ECON	LU	TC	TELE_D	TD
TELE_C	.976	-114.093	-.204					-.706					

14. Travel and Mobile Telecommunications

- Direct effects

			Estimate	S.E.	C.R.	P
TS	<---	TDL1	.085	.065	1.320	.187
TS	<---	DLFDRVR	69.446	11.078	6.269	***
TC	<---	TS	-.351	.126	-2.778	.005
LU	<---	TS	.009	.001	7.641	***
ECON	<---	TS	.157	.134	1.171	.242
TD	<---	TS	.520	.117	4.434	***
TD	<---	TC	-.149	.076	-1.957	.050
TD	<---	LU	32.894	15.941	2.063	.039
TD	<---	ECON	.253	.079	3.206	.001
DLCELSIT	<---	DLCELSL1	.107	.065	1.654	.098
DLCELSIT	<---	ECON	.100	.071	1.418	.156
DLCELSBR	<---	TD	.075	.026	2.884	.004
DLCELSBR	<---	DLCELSIT	1.515	.279	5.433	***
DLCELSBR	<---	DLHHSIZE	-7.050	2.289	-3.080	.002

- Total effects

LHS	DLCELSL1	DLHHSIZE	DLFDRVR	TDL1*	TS	ECON	LU	TC	DLCELSIT	TD
TS			69.446	.085						
ECON			10.933	.013	.157					
LU			.639	.001	.009					
TC			-24.357	-.030	-.351					

LHS	DLCELSL1	DLHHSIZE	DLFDRVR	TDL1*	TS	ECON	LU	TC	DLCELSIT	TD
DLCELSIT	.107		1.098	.001	.016	.100				
TD			63.521	.078	.915	.253	32.894	-.149		
DLCELSBR	.162	-7.050	6.444	.008	.093	.171	2.476	-.011	1.515	.075

D. Estimated Restricted Models of Composite Indices of Telecommunications and Travel

1. Variable List

Variable	Description
TD	Travel demand (composite index)
TELE_D	Telecommunications demand (composite index)
TS	Transportation supply (composite index)
TELE_D	Telecommunications supply (composite index)
TC	Travel costs (composite index)
TELE_C	Telecommunications costs (composite index)
LU	Land use (suburbanization rate)
ECON	Economic activity (composite index)
TDL1	1st order lag of travel demand
TELE_DL1	1st order lag of telecommunications demand
DLPOP	Population (natural log and 1st order differenced)
DLHHSIZE	Average household size (natural log and 1st order differenced)
DLFDRVR	Female proportion of licensed drivers (natural log and 1st order differenced)
D50_83	Time dummy (1950 -1983: 1; otherwise 0)

2. Demand Model

- Standardized Total Effects (Direct Effects)

LHS (R^2)	**RHS**							
	DLHHSIZE	TELE_S	ECON	LU	TC	TS	TELE_D	TD
TELE_D	-.382	.282	.077	.096	-.093	.172	.067	**.386**
(0.34)	(-.358)	(.265)						**(.361)**
TD	-.066	.049	.214	.266	-.258	.476	**.185**	.067
(0.71)			(.200)	(.249)	(-.242)	(.447)	**(.173)**	
Avg. R^2 = 0.53, χ^2 = 2.1 (df = 7), GFI = 0.99, NFI = 0.99, CFI = 1.00, SI = 0.06								

3. Demand/Supply Model

- Standardized Total Effects (Direct Effects)

LHS (R^2)	RHS										
	DLPOP	TELE_DL1	DLHHSIZE	TDL1	ECON	LU	TC	TELE_S	TS	TELE_D	TD
TELE_S	.408	.289									
(0.22)	(.408)	(.289)									
TS				.728							
(0.53)				(.728)							
TELE_D	.143	.102	-.374	.099	.049	.051	-.074	.351	.135	.078	**.278**
(0.32)			(-.347)					(.326)			**(.258)**
TD	.040	.028	-.104	.381	.188	.199	-.285	.098	.524	**.300**	.078
(0.67)					(.174)	(.184)	(-.264)		(.486)	**(.278)**	
Avg. R^2 = 0.44, χ^2 = 51.0 (df = 26), GFI = 0.87, NFI = 0.85, CFI = 0.91, SI = 0.07											

4. Demand/Supply/Cost Model

- Standardized Total Effects (Direct Effects)

LHS (R^2)	RHS												
	D50_83	DLPOP	TELE_DL1	DLHHSIZE	DLFDRVR	TDL1	ECON	LU	TS	TELE_S	TC	TELE_D	TD
TS					.333	.492							
(0.59)					(.333)	(.492)							
TELE_S		.415	.296										
(0.23)		(.415)	(.296)										
TC					-.099	-.145			-.296				
(0.08)									(-.296)				
TELE_D		.144	.103	-.363	.058	.086	.043	.036	.175	.347	-.070	.068	**.278**
(0.34)				(-.340)						(.325)			**(.261)**
TD		.035	.025	-.088	.224	.330	.164	.140	.672	.085	-.268	**.261**	.068
(0.71)							(.154)	(.131)	(.555)		(-.251)	**(.244)**	
TELE_C	.535	-.420	-.300							-1.012			
(0.13)	(.535)									(-1.012)			
Avg. R^2 = 0.35, χ^2 = 114.1 (df = 51), GFI = 0.80, NFI = 0.79, CFI = 0.86, SI = 0.06													

5. Demand/Supply/Land use Model

- Standardized Total Effects (Direct Effects)

LHS (R^2)	DLPOP	TELE_DL1	DLHHSIZE	DLFDRVR	TDL1	ECON	TC	TS	TELE_S	LU	TELE_D	TD
TS				.644	.057							
(0.47)				(.644)	(.057)							
TELE_S	.420	.244										
(0.24)	(.420)	(.244)										
LU				.824	.074			1.280				
(0.33)								(1.280)				
TELE_D	.128	.074	-.382	.145	.013	.063	-.077	.225	.305	.044	.061	**.313**
(0.34)			(-.360)						(.287)			**(.295)**
TD	.025	.015	-.075	.491	.044	.213	-.260	.762	.060	.148	**.207**	.061
(0.69)						(.200)	(-.245)	(.539)		(.140)	**(.195)**	

Avg. $R^2 = 0.41$, $\chi^2 = 60.9$ (df = 35), GFI = 0.84, NFI = 0.86, CFI = 0.93, SI = 0.06

6. Demand/Supply/Cost/Land use Model

- Standardized Total Effects (Direct Effects)

LHS (R^2)	RHS												
	D50_83	DLPOP	TELE_DL1	DLHHSIZE	DLFDRVR	TDL1	ECON	TS	TELE_S	LU	TC	TELE_D	TD
TS					.597	.128							
(0.49)					(.597)	(.128)							
TELE_S		.439	.252										
(0.26)		(.439)	(.252)										
LU					.752	.161		1.259					
(0.36)								(1.259)					
TC					-.121	-.026		-.202					
(0.06)								(-.202)					
TELE_D		.124	.071	-.386	.154	.033	.063	.257	.283	.043	-.083	.081	**.356**
(0.36)				(-.357)					(.261)				**(.329)**
TD		.028	.016	-.088	.467	.100	.191	.782	.065	.132	-.253	**.247**	.081
(0.71)							(.177)	(.522)		(.122)	(-.234)	**(.229)**	
TELE_C	.463	-.317	-.182						-.723				
(0.30)	(.463)								(-.723)				
Avg. R^2 = 0.36, χ^2 = 128.4 (df = 53), GFI = 0.77, NFI = 0.77, CFI = 0.84, SI = 0.08													

7. Demand/Supply/Land use/Econ Model

- Standardized Total Effects (Direct Effects)

LHS (R^2)	**RHS**											
	DLPOP	TELE_DL1	DLHHSIZE	DLFDRVR	TDL1	TC	TS	TELE_S	ECON	LU	TELE_D	TD
TS				.634	.066							
(0.47)				(.634)	(.066)							
TELE_S	.420	.245										
(0.24)	(.420)	(.245)										
ECON				.120	.012		.189					
(0.03)							(.189)					
LU				.816	.085		1.286					
(0.32)							(1.286)					
TELE_D	.128	.074	-.384	.150	.016	-.077	.236	.304	.059	.043	.062	**.315**
(0.33)			(-.362)					(.287)				**(.296)**
TD	.025	.015	-.076	.505	.053	-.261	.796	.060	.199	.144	**.210**	.062
(0.69)						(-.246)	(.540)		(.187)	(.135)	**(.197)**	
Avg. R^2 = 0.35, χ^2 = 69.6 (df = 37), GFI = 0.82, NFI = 0.84, CFI = 0.91, SI = 0.06												