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16. Abstract

This study takes a megaregion approach to project future travel demand and choice of transport modes in the Texas Triangle, which is encompassed by four major metropolitan areas, Dallas-Fort Worth, Houston, San Antonio, and Austin. The model was developed based on three behavioral characteristics of human travel. First, as income grows, demand for more and faster mobility increases. Second, on average, individuals allocate 1-1.5 hours per capita per day for travel. Third, people allocate 10-15% of per capita personal income for transportation related expenses.

Measured by person-kilometers of travel (PKT), the total mobility demand in the Triangle region is projected to grow nearly four times from 480 billion in year 2000 to 1.8 trillion in year 2050. Per capita PKT is expected to increase from 32,700 to 61,000 for the same time period. The projections show that more than 70% of the year 2050 travel demand likely comes from high-speed travel at 600 km per hour..The study results call for serious consideration of investing in high-speed travel in the form of High Speed Rail (HSP) *now* in order to accommodate the future travel demand in the Triangle Region.

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FUTURE TRAVEL DEMAND AND ITS IMPLICATIONS FOR TRANSPORTATION INFRASTRUCTURE INVESTMENTS IN THE TEXAS TRIANGLE

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ABSTRACT

This study takes a megaregion approach to project future travel demand and choice of transport modes in the Texas Triangle, which is encompassed by four major metropolitan areas, Dallas-Fort Worth, Houston, San Antonio, and Austin. The model was developed based on three behavioral characteristics of human travel. First, as income grows, demand for more and faster mobility increases. Second, on average, individuals allocate 1-1.5 hours per capita per day for travel. Third, people allocate 10-15% of per capita personal income for transportation related expenses.

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EXECUTIVE SUMMARY

The Texas Triangle is one of the ten emerging megaregions identified in the continental U.S. It includes 66 counties which all fall within the boundary of Texas. The Triangle has an area of 57,430 square miles and a total population of nearly 15 million in the year 2000. Four core metropolitan areas – Austin, Dallas-Fort Worth, Houston, and San Antonio are encompassed by the Texas Triangle. By the year of 2050, the Texas Triangle is expected to grow by an additional 10 million people as its history suggests. The population growth will impose tremendous pressure on the region's already burdened transportation infrastructure. Transportation planning should take action now in order to be better prepared to accommodate the increasing travel demand.

Understanding the nature of future travel demand in the Triangle is the first critical step towards smart decision-making in transportation investments. This research examines the future travel demand in the Triangle in two parts. Part One projects the total amount of travel demand by year 2050. In Part Two, distribution of the mobility demand is estimated among air, rail, and roadway travel modes. It applies an aggregate model to project total travel demand and shares of different travel modes in the Triangle region. The results of this study will provide valuable references to the decision-makers on future transportation investment needs in Texas.

The model was developed based on three behavioral characteristics of human travel. First, as income grows, demand for more and faster mobility increases. Second, on average, individuals allocate 1-1.5 hours per capita per day for travel. Third, people allocate 10-15% of per capita personal income for transportation related expenses. The study results suggest that the Texas Triangle would experience an enormous amount of mobility growth by year 2050. Measured by person-kilometers of travel (PKT), the total mobility demand in the Triangle region is projected to grow nearly four times from 480 billion in year 2000 to 1.8 trillion in year 2050. Per capita PKT is expected to increase from 32,700 to 61,000 for the same time period, higher than the North American regional average. This study projected that the total travel by all modes would increase. The mode share structure would also change. People would switch to high-speed transport gradually. The high speed share for travel would increase dramatically in the next 40

plus years. By year 2050, more than 70% of travel is likely to be accomplished by high-speed transport.

The expected growth of future travel demand will impose tremendous pressure on the transportation infrastructure in the Triangle area. Currently in Texas, air transportation offers the only high-speed mode of inter-city travel. By 2050, high-speed travel demand would rise to more than 10 times of the 2000 level. It is unlikely that the demand for high-speed travel can all be accommodated by air travel because of the capacity constraints in airway network, gate and runway, and airport operations. Accordingly, planning for megaregional transportation should seriously consider high-speed travel in the form of High Speed Rail (HSP) to accommodate the future travel demand in the Triangle Region. The sooner the HSP is incorporated in the regional transportation plan, the better the Triangle would prepare for the future.

The study has a number of limitations. The modeling framework builds on the assumptions of fixed travel time and money budgets. Future research should re-examine the assumptions with empirical evidence in Texas. The model also assumes an unchanged travel cost (per km) over years. Recent price hike of fuels suggests that travel cost could go up dramatically and thus change the relationship between income and mobility. Furthermore, the model parameters used for the Triangle demand projections are borrowed from published studies at the national/international level. These parameters need to be re-calibrated with Texas data in the future in order to improve projections accuracy and reliability.

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1. Introduction

The Texas Triangle is one of the ten emerging megaregions initially identified in the continental U.S. (Lincoln Institute of Land Policy & Regional Plan Association, 2004). Three interstate highways, I-10, I-35, and I-45 link the apexes of the Triangle, providing intercity connections in this megaregion (figure 1). For analysis purposes, an explicit working definition of the Texas Triangle was given by Zhang, Steiner, & Butler (2007) in their empirical study. By that definition, the Texas Triangle megaregion includes 66 counties with an area of 57,430 square miles and a total population of nearly 15 million in the year 2000. Four core metropolitan areas – Austin, Dallas-Fort Worth, Houston, and San Antonio are encompassed by the Texas Triangle (figure 2).

State population projections indicate that, by the year of 2050, the Texas Triangle is expected to grow by more than ten million people (TSDC 2008). Associated with the population growth is inevitable growth in mobility demand, which will impose tremendous pressure on the region's already burdened transportation infrastructure. Transportation planning should take action now in order to be better prepared to accommodate the increasing travel demand. Past experience has demonstrated that the choices of transportation technologies and decisions on the locations and alignments of transportation infrastructure strongly influence the direction and magnitude of metropolitan expansions. How the metropolitan expansion is directed through smart transportation decision-making has profound implications in regional consumptions of land, water, energy, and other natural resources and shapes the region's sustainability and quality of life for generations to come (Zhang, et al., 2007).

Understanding the nature of future travel demand in the Triangle is the first critical step towards smart decision-making in transportation investments. This research examines the future travel demand in the Triangle in two parts. Part One projects the total amount of travel demand by year 2050. In Part Two, distribution of the mobility demand is estimated among air, rail, and roadway travel modes

The study explores a megaregion approach to address mobility issues in the spatial scale larger than the common practice of Metropolitan Planning Organizations (MPOs). Travel demand analyses by MPOs provide detailed pictures of transportation demand for their individual areas. However, forces of growth from the interactions among metropolitan areas in the Triangle and between the metro areas and their hinterlands are not often accounted for. Travel demand in the megaregion therefore cannot be well understood by simply summing the numbers of individual metropolitan areas. The study applies an aggregate model built upon the work by Schafer and Victor (Schafer & Victor, 2000). The model was developed based on three behavioral characteristics of human travel. First, as income grows, demand for more and faster mobility increases. Second, on average, individuals allocate 1-1.5 hours per capita per day for travel. Third, people allocate 10-15% of per capita personal income for transportation related expenses.
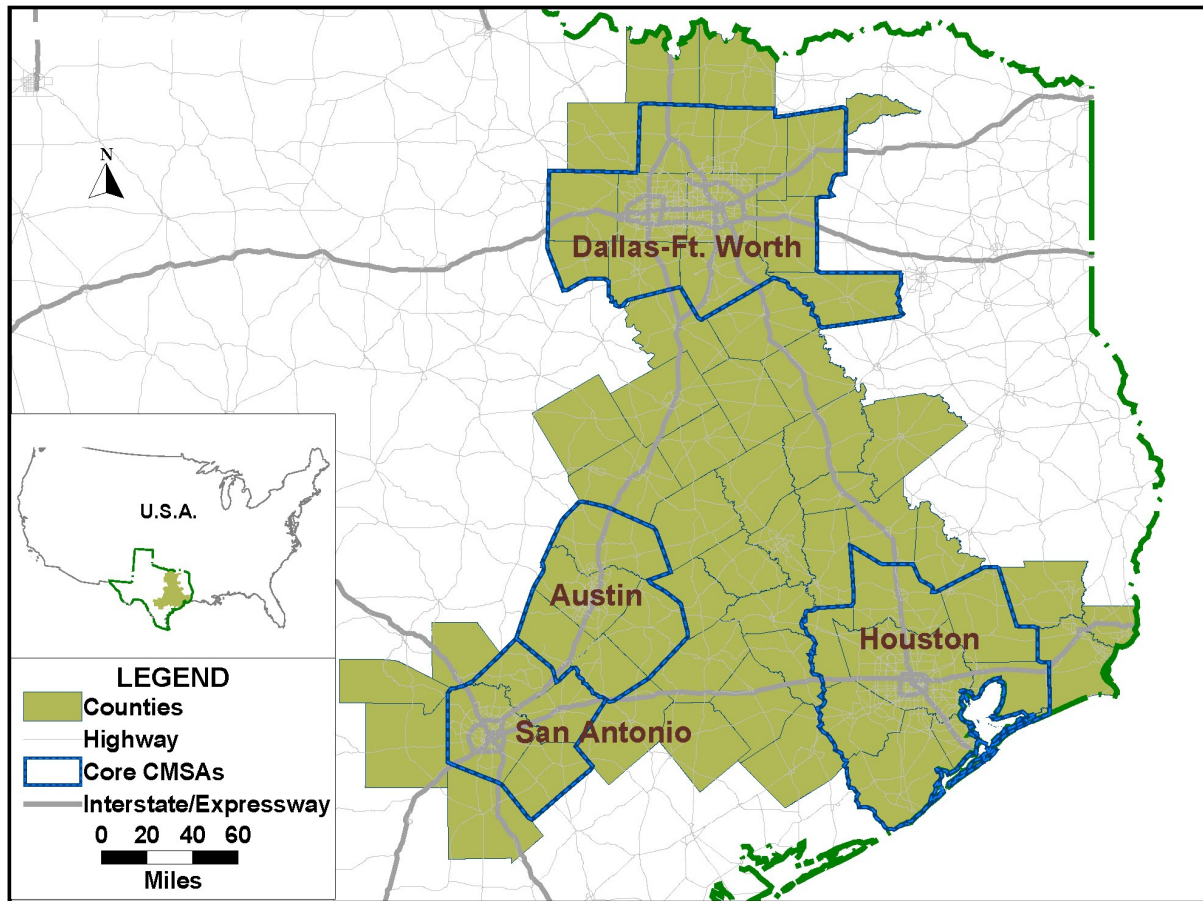
Figure 1. The Texas Triangle delineated by the Interstate Highway Network

Source: Zhang, Steiner, and Butler, 2007
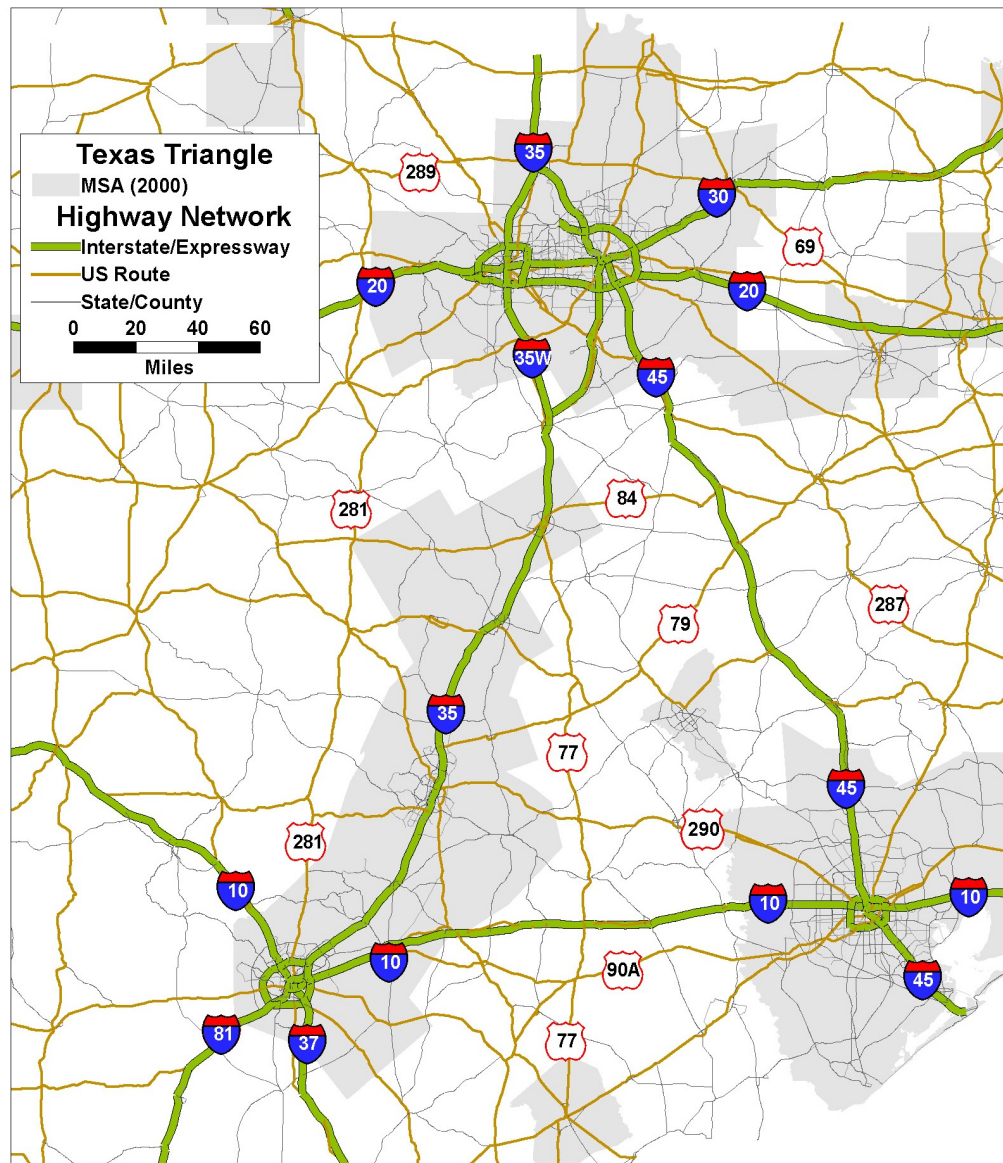
Figure 2. The Texas Triangle Megaregion

Source: Zhang, Steiner, and Butler, 2007

2. Research Context

2.1 Megaregion concept and related studies

The phenomenon of the continuity of an area of metropolitan economy in the U.S. was first captured 50 years ago by Jean Gottmann while analyzing the urban cluster from Boston to Washington – the "northeastern seaboard" named by Gottmann as the "Megalopolis" in the U.S. (Gottmann, 1957). The Megalopolis grew up from the network of sea-trading towns along the coast from Boston to New York, and then from New York to Washington. Gottmann observed that, as a hinge of the American economy and composed of a series of northeastern seaboard cities, the Megalopolis had more rapid growth than many other urban areas in the world. The growth of these individual seaboard cities joined them together, hence ceased the competition among them. In the growth process, the Megalopolis remained its major functions of being manufacturing center, commercial and financial capital, and cultural leader. Gottmann believed that the process of formation of Megalopolis-like clusters would involve considerable changes in the American modes of living. He emphasized that the traffic difficulties and the slums, as well as water supply and local government should receive great attentions in developing Megalopolis. Besides, the coming age of Megalopolis also created new psychological problems: the integration of megalopolis was beyond people's traditional thinking of "common-wealth", and people had also "some difficulty adapting themselves to such a scattered way of life".

Gottmann's Megalopolis concept brought significant impact on urban theory. Researchers in different parts of world recognized the economic importance of large metropolitan networks and started proposing new national strategies for tracking and defining the megalopolis. However, his work mainly influenced the academic field, and had no impact on the way how the U.S. Census Bureau defined spaces. One of the most recent researches was done by Robert Lang and Dawn Dhavale from Metropolitan Institute at Virginia Tech. They started to appeal to the formal acknowledgement of "Megapolitan" geographic concept (It should be noted that researchers use different terms for the metropolitan networks: European researchers use "mega-city region", Lang at Virginia Tech uses "Megapolitan", and America 2050 use "megaregion") by the Census

Bureau (Lang & Dhavale, 2005). In their study, Lang and Dhavale carefully reviewed the evolvement of Megapolitan idea and explained the method of determining Megapolitan locations and boundaries. The method followed the logic of the Census Bureau's Metropolitan Area definition, which looked at both the "place" and "flow" of space. However, Megapolitan Areas are too big to have direct commuting relationship as Metropolitan Areas do; Lang and Dhavale used other forces such as goods movement, business linkages, cultural commonality and physical environment to define the existence of the entity. According to Lang and Dhavale's criteria, ten US "Megapolitan Areas" have come into form, with six located in the eastern half of the U.S., and four in the West.

Lang and Dhavale found that these US Megapolitan Areas made up less than 20% of the land area in the Lower-48 states but captured over two-thirds of the population; the Megapolitan Areas accounted for just over a quarter of the 3,141 US counties, but included more than 43% of all metro/micro counties; and the Megapolitan Areas would account for most new population and job growth in the U.S. from 2005 to 2040 and capture an even bigger share of money spent on construction. According to Lang and Dhavale's analysis, the spectrum of Megapolitan spatial form ranged from "galactic" to "corridor", with the galactic Midwest at one pole and the I-35 corridor at the other pole. The development of the Megapolitan Areas demonstrated different sprawl style –basically a southland style of "dense sprawl" versus Piedmont style of "low-density sprawl"; different strategies were needed to address the sprawl problems in the Megapolitan Areas. Lang and Dhavale suggested that official acknowledgement of Megapolitan Areas by the Census Bureau could spark a discussion on what types of planning would be needed on this scale and could help establishing new super MPOs to plan the infrastructures in Megapolitan Areas.

Another recent voice to attract more attentions to the emerging of megaregions in the U.S. was from America 2050, a committee composed of policy makers, business leaders, scholars and regional planners. The America 2050 definition of megaregions incorporates a wide range of relationships that define common interest among cities, such as environmental system, infrastructure, economic linkage, settlement patterns and land use, and shared culture and history (Regional Plan Association, 2006) Ten megaregions was also identified in the continental U.S.

by the American 2050, and detailed boundaries of each megaregion were defined by individual institutions based on any acceptable approaches. The growing consensus in the American 2050 is that any boundaries need to be appropriate for regional planning purpose, and these boundaries are not constant (Dewar & Epstein, 2007).

Of the ten megaregions in the U.S., the megaregions in Texas have invited probably the most discussion. The America 2050 defined the Triangle area determined by Dallas-Fort Worth, Houston, and San Antonio metro areas as one megaregion, which is largely based on the cultural cohesion and the Texas growth history (Meinig, 2004). However, Lang broke the link between Dallas and Houston, and defined two corridor format megaregions: I-35 corridor, the "high tech corridor" including Austin, Dallas-Fort worth and San Antonio metro areas, and Gulf Coast corridor, the "energy corridor" including the Houston metro area. However, Lang did point out that Megapolitan areas do not exist in isolation, and they could link to one another. He thus indicated the I-35 corridor and the Gulf Coast corridor could form "the greater Texas pairs" based on physical proximity, economic connectivity, and shared history.

According to local studies, the above four large metropolitan areas operate as one large economic unit, and the interconnection between Dallas and Houston is significant (Gilmer, 2003, 2004a, 2004b). Based on economic, ecological and infrastructure criteria, the research team from the community and regional planning program in the University of Texas at Austin defined a detailed boundary of the Texas Triangle megaregion in the 2006 international megaregional planning workshop. In their study, 66 counties including the four core metropolitan areas constitute the Texas Triangle region, which will be the study area for this research.

Various studies of the trans-metropolitan clusters (from the first Megalopolis to the 40 Mega Regions in the world) all emphasized the importance of economic connections among cities in the networks. These connections can be better understood by reviewing Peter Taylor and Robert Lang's report "U.S. cities in the 'world city network'" (Taylor & Lang, 2005). As Taylor and Lang pointed out, a new economic globalization was emerging based upon cities and their regions, thus the network of flows between cities provided a skeletal spatial organization of contemporary globalization. Taylor and Lang studied the intercity economic relationship by

focusing on one type of economic connection, the connection between advanced producer services firms.

Through a series of comparisons and analyses, Taylor and Lang found that except that New York, Chicago, and Los Angeles functioned as leaders in global connectivity, San Francisco, Miami, Atlanta and Washington were also important nodes in the world city network. However, U.S. cities overall were less globally connected than their European Union and Pacific Asian counterparts. For example, Dallas and Houston ranked the eighth and ninth in the global network connectivity of U.S. cities, but ranked the sixty first and the sixty second in the global network connectivity of world cities. The U.S. cities had stronger links to other U.S. cities than to cities around the globe, and were more locally oriented than cities in the European Union. Taylor and Lang concluded that globalization had made cities and their networks more complex; although global connections were not necessary for success; the increased complexity brought by globalization was crucial to city vibrancy and could make cities best able to weather the economic storms.

Taylor and Lang's study revealed one important justification for addressing Mega Region planning – joint development of U.S. cities could increase the global connectivity of these cities as an integrated region and bring more successful opportunities. While all the Mega Region related studies provide reasons of studying this new geographic unit and general background, more detailed studies still remain a larger undertaking. Transportation connection among cities in the Mega Regions is one of the important fields to embank on, which requires appropriate regional modeling methods.

2.2 Urban modeling methods

Norbert Oppenheim conducted a critical survey of the development in urban and regional modeling (Oppenheim, 1995). Although the paper was written in 1986, it still provides rich information of the nature and extent of progress in urban and regional modeling. First, Oppenheim pointed out that there was a strong tendency to adopt a top-down approach for urban

modeling. Such an approach may develop models that would reflect the prior assumptions built into the formulation, more than observable reality. The top-down approach tended to focus on the effects, not the causes of urban systems evolution. Second, Oppenheim believed that since urban systems were ultimately social systems, regional modeling should have more behavioral content. The traditional concepts such as pure rationality and system equilibrium do not always hold, hence models based on these concepts may not represent significant progress. Oppenheim suggested modeling process should incorporate multiple criteria, qualitative as well as quantitative to make models more realistic. Urban models should integrate the micro/disaggregate level of analysis and the macro/aggregate level of analysis, and introduce different time scales, which could develop models' sensitivity to contextual change.

Oppenheim listed various available general conceptual approaches, such as the mathematical programming school, the dynamic modeling school, the travel budget school, the disaggregated behavioral school and so on, as well as many fully developed operational urban models, including the TOPAZ model, the UMOT model, the ITPM model, and the TRANSLOC model, etc. However, Oppenheim indicated there's a lack of common theory and criteria for developing these models, and called on a greater unification of urban and regional theory together with greater coordination in the associated methodological work.

Travel demand modeling work has been mostly conducted in Metropolitan Area level to capture intra-metropolitan travel demand. Under federal law, metropolitan planning organizations (MPOs) are charged with estimating future travel demand and analyzing the impacts of alternative transportation investment scenarios. In 2007, a Transportation Research Board (TRB) study (National Research Council (U.S.), 2007)was funded by the Federal Highway Administration (FHWA), the Federal Transit Administration (FTA), and the Office of the Secretary of Transportation (OST) to evaluate the travel modeling practice, and to determine the national state of this practice. The detailed information on travel modeling practice was gathered by a web-based survey among all MPOs. 60% of all MPOs responded the survey, and 84% of the responding MPOs had a population exceeding 1 million.

The TRB study found that the four-step model remained the most used approach by MPOs. This approach has been in use since the 1950s. Although refinements and incremental improvements have been made to the process over years, the basic structure of the process has stayed unchanged. There're more advanced travel models adopted by a few MPOs; some models are based on tours of travel or the representation of human activity, some include joint transportation-land use models, and some combine travel demand forecasting with detailed traffic simulation models.

As the TRB report summarized, the four-step model performs well in forecasting aggregate system, but yields less satisfactory results in more disaggregate problems which are more linked to individual behavior. It can be seen that Oppenheim's evaluation of urban and regional modeling are also applicable to the four-step model. Because of the inherent weakness, the four-step model cannot well capture the choices made by travelers in response to congestion and other indicators of transportation system performance; the aggregate manner of the four-step modeling process neglects travel behavioral factors, hence makes it difficult to reflect traveler's responses to changes in public policies. The four-step model usually does not model walking or bicycle travel, and is not able to evaluate the impact of sustainable transportation designs such as transit-oriented development. Besides, the four-step model focuses on modeling passenger travel, so freight movement and commercial truck activities lack concern.

2.3 Inter-city Travel

Although the conventional travel modeling method has such-and-such weaknesses, people have gained the most experience in applying this method in modeling travel demand. When the inquiry focus extends from intra-city travel demand as concerned by all MPOs to inter-city travel demand, which has gone out of one MPO boundary, the four-step method still provides the basic structure for researchers and planners.

Common used intercity travel model has quite similar structure as the four-step model, except that it combines the trip generation and trip distribution into one step. However, comparing to

urban model systematically maintained by MPOs, intercity travel models have received much less attention from both practitioners and scholars. Many reasons were hypothesized by Eric Miller (Miller, 2004): first, there were fewer intercity travel corridors of policy interest than urban regions, which stunted the intercity travel modeling market; second, intercity travel analyses often cross boundaries of the political jurisdiction of a single planning agency, and thus are performed on an ad hoc, project specific basis; third, intercity models are usually not owned by a single public agency who would otherwise spend a great effort to maintain, use and make improvement to the model; lastly, studying intercity travel model has more difficulties in study area defining, behavioral representation, data collection.

One example of modeling intercity travel demand is a study done by Enjian Yao and Takayuki Morikawa (Yao & Morikawa, 2005). Yao and Morikawa developed an integrated intercity travel model including the process of trip generation, destination choice, mode choice, and route choice. In their study, Yao and Morikawa made improvements to the conventional four-step model by considering the 4 step decision making as an integrated process, hence capturing induced travel by changes in service level. The Tokyo – Nagoya – Osaka corridor in Japan was studied by the model to forecast the travel need of a proposed high speed rail (HSR) project.

The integrated intercity travel model was based on a hierarchical structure of sub-models for each sub-choice. Yao and Morikawa assumed trip generation model as the top level, destination choice model as the second level, mode choice model as the third level and route choice model as the fourth level in the hierarchical structure. Each travel choice is made conditionally on the higher level choices, while the higher level choice is influenced by the expected maximum utility of lower level choices. Yao and Morikawa combined aggregate OD trip data and disaggregate data which were obtained from revealed preference (reflect current intercity travel choice) and stated preference (reflect the preference for proposed HSR system) questionnaire in modeling mode and route choice. In the trip generation model, Yao and Morikawa measured the accessibility to make the model become sensitive to the changes in travel condition. Yao and Morikawa estimated that by 2020 when the HSR would be put into operation, the induced travel accounted for 16.5% of the travel demand. It's clear that Yao and Morikawa improved the

conventional travel model by considering the underlying intercity travel behavioral factors and incorporating aggregate and disaggregate data in the model.

The trans-metropolitan clusters started emerging in the continental U.S. about 50 years ago, and will have significant effect on American's economy and people's life. This new geographical unit needs more detailed studies in various aspects. From transportation planning point of view, travel demand among cities is an important factor to define the formation of a Mega Region and determine its future infrastructure investment. Currently, although with various weakness, the conventional four-step travel demand model are still providing basic knowledge and structure for both intra and inter city travel demand projection. However, Researchers have been improving the model aiming to those weaknesses. Further research and more efforts are needed to study the travel demand in Mega Regions.

3. Theory and Model

The aggregate model developed by Schafer and Victor (Schafer & Victor, 2000) was built on findings from Yacov Zahavi's research (Zahavi & Talvitie, 1980) of travel time and travel money expenditure. Zahavi found that the behavior of travelers was largely determined by two fundamental constraints: on average, fixed budgets of time and money are devoted to travel (Schafer & Victor, 2000). This characteristic of travel time and money budget has been studied extensively. Some researchers supported the stability of travel time expenditure (Barnes & Davis, 2001; Chumak & Braaksma, 1981; Hupkes, 1982), and the positive relationship between travel money expenditure and motorization (Gunn, 1981). There're also researchers who obtained different findings that didn't support the existence of fixed travel time and money expenditure (Levinson & Kumar, 1995; Mokhtarian & Chen, 2004; Osula & Adebisi, 2001) concluded that although constant travel time and money budget in time and space does not exist definitively, travel expenditures appear to have some stability at aggregate level.

3.1 Travel time budget (TTB)

As Zahavi observed, on average, humans spend a fixed amount of their daily time budget on traveling, i.e., the travel time budget (TTB). Time-use and travel surveys from different cities and countries throughout the world suggest that TTB is approximately 1.1 hours per person per day (Schafer and Victor 2000). This TTB applies not only for motorized mobility, but also for non-motorized mobility. Thus, Schafer and Victor studied the relationship between the time spent in motorized modes (TTB_{mot}) and motorized mobility to get accurate prediction of motorized travel. They described the relationship as shown in equation (1a).

$$TTB_{mot} = a + \frac{b}{(TV - c)^d} \qquad (1a)$$

where TV is the total traffic volume per capita per year in km.

TTB_{mot} rises as motorized level increases and could reach 1.1 hours when people's mobility is highly motorized. This concept was used by Schafer and Victor to estimate the parameters in equation (1a). The TTB_{mot} curve was forced to pass through the zero-point and through a hypothetical future point with a TTB_{mot} of 1.1 hours per capita per day at a traffic volume of 240,000 km/cap (Schafer and Victor 2000). Equations (1b) and equation (1c) show the results:

$$a = \frac{b}{(-c)^d} \tag{1b}$$

$$b = \frac{1.1}{\dfrac{1}{(240,000 - c)^d} - \dfrac{1}{(-c)^d}} \tag{1c}$$

Figure 3 shows the graphic relationship between mobility and $TTB_{mot.}$

Figure 3. TTB_{mot} as a function of motorized mobility

Source: Schafer and Victor, 2000
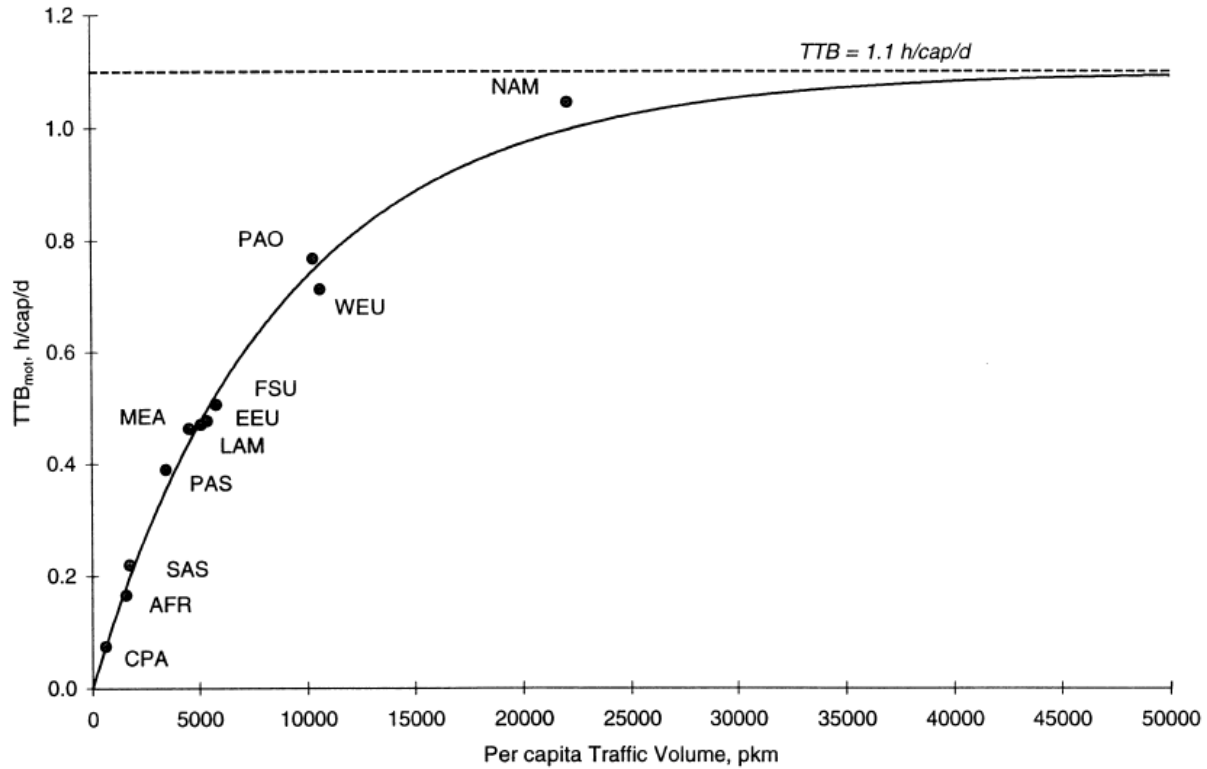
3.2 Travel money budget (TMB) and total mobility

Zahavi also proposed that individuals devote a fixed proportion of income to traveling, the travel money budget (TMB), which rises with motorization. Schafer (1998) collected data from twelve OECDs and three low-income countries, and found that TMB increases from about 5% at a motorization rate of almost zero passenger cars per 1000 capita to 10-15% at about 200 cars per 1000 capita, and remains approximately constant at higher ownership rates. In the United States, 2005 car ownership was 776 cars per 1000 capita (UNECE, 2005). So, TMB in the US should be relatively stable, which is manifested in Figure 4.

Figure 4. Transport-related indicators in the US

Source: Schafer and Victor, 2000
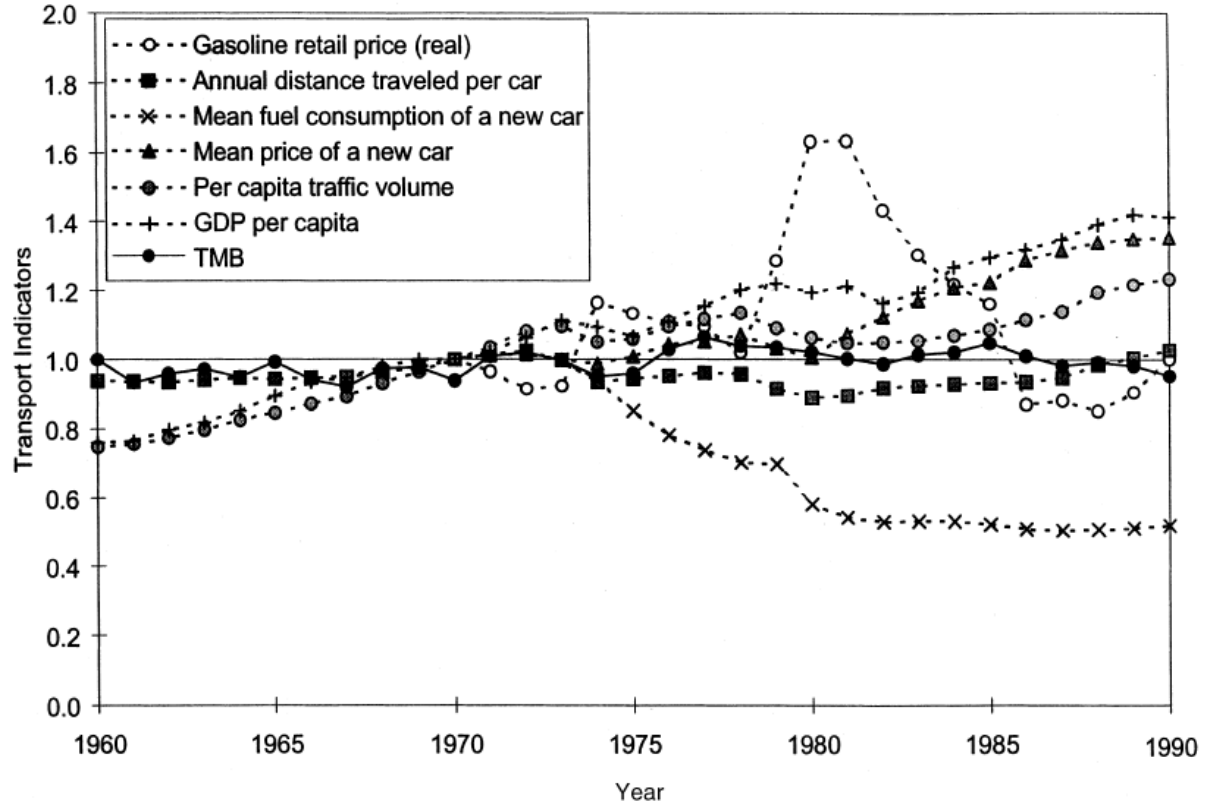
Based on the characteristic of TMB, Schafer and Victor (2000) posited a strong relationship between income and the total demand for mobility. As income increases, spending on travel must also increase (the TMB defines the proportion), which allows greater mobility. Schafer and Victor described the relationship between GDP per capita and traffic volume (TV) per capita by equation (2a).

$$\frac{TV}{cap} = \log\left(\frac{GDP/cap}{g} - h\right) * \left(\frac{GDP}{cap}\right)^e * f^*$$

(2a)

In the equation, f^* accounts for the money people spend on transport (the TMB) and the inverse unit cost of transport (pkm/USD); and $\log\left(\frac{GDP/cap}{g} - h\right)$ is a dimensionless log factor for

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better fitting with the data curves (Schafer and Victor 2000). Instead of purely using historical data to calibrate f^*, Schafer and Victor used the hypothetical future point again, where the total annual distance traveled per capita would be 240,000 km and the corresponding per capita income is 240,000 USD. Equation (2b) shows their calibration result.

$$f^* = \frac{240,000^{1-e}}{\log\left(\dfrac{240,000}{g} - h\right)} \tag{2b}$$

Equations (2a) and (2b) were used to project the future total mobility in the Triangle.

3.3 The hypothetical future condition

Except the two key assumptions of fixed travel time and money budget, Schafer and Victor also applied a hypothetical future condition in calibrating their model. Basically, rising mobility within a fixed travel time budget requires a shift to faster modes – more distance must be covered within the same period of time; hypothetically, at very high levels of income and mobility the highest speed mode must supply all mobility (Schafer and Victor 2000). In the hypothetical future, all demand would be supplied by aircraft at today's gate-to gate mean speed of 600 km/h, the travel time budget would be fixed at 1.1 hours per capita per day, the total annual distance traveled would be 240,000 km/cap, and the corresponding income would be 240,000 USD/cap. The hypothetical future condition was applied to calibrate equations to project both total mobility and mode share.

3.4 Mode share

Four transport modes – bus, rail, cars, and high-speed transport (including aircraft and high speed train) were considered for people's travel demand. The projection of travel mode choice was based on four constraints: the fixed TTB, path dependence, land use patterns, and a balancing equation (Schafer and Victor 2000).

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- Ordinary railway

The use of ordinary passenger rail has been declining. Schafer and Victor assumed that future railway would reach a zero-share at a traffic volume of 240,000 pkm/cap, and expressed the share of rail use as a function of the total mobility shown in equation (3).

$$S_{Rail} = i * \left(\frac{1}{(TV - j)^k} - \frac{1}{(240,000 - j)^k} \right) \tag{3}$$

- Bus

Schafer and Victor applied the concept of land use constraints to the estimation of the share for low-speed transport travel. Data from three industrialized regions (North America, West Europe, and Pacific OECD) which have three different types of land use defined the envelope for the trajectory of low-speed public transport (Schafer and Victor 2000), as shown by equation (4).

$$S_{LS} = l * \left(\frac{1}{(TV - m)} - \frac{1}{(240,000 - m)} \right) \tag{4}$$

Then the share for bus travel can be calculated using equation (5).

$$S_{Bus} = S_{LS} - S_{Rail} \tag{5}$$

- High-speed transport

The share for high-speed transport travel was derived based on the constraint that the traffic volume of each motorized mode must sum to the total projected traffic volume, and the sum of the daily motorized per capita travel time over all modes of transport which move daily traffic volume at their mean speed, must equal the travel time budget for motorized modes (TTB$_{mot}$).

Thus, an important factor that will affect the share for high-speed travel in this relationship is the speed of each mode. Schafer and Victor assumed in 2050 the speed for each mode is: rail as 30km/h, bus as 20km/h, car as 55km/h, and high-speed transport as 600km/h. The share for high speed transport in 2050 was then derived as equation (6a):

$$S_{HST,2050} = \frac{1 - S_{Bus} * (1 - V_{Auto}/V_{Bus}) - S_{Rail} * (1 - V_{Auto}/V_{Rail}) - V_{Auto} * TTB_{mot} * 365/TV}{(1 - V_{Auto}/V_{HST})} \tag{6a}$$

Then, the continuous share over the 1990-2050 time period could be projected following a Gompertz regression equation shown in equation (6b):

$$S_{HST} = s * \exp\{-\exp[-t * (TV/cap - u)]\} + v \tag{6b}$$

The parameter s and v were specified to force the trajectory through the projected 2050-value, as shown in equations (6c) and (6d):

$$s = \frac{S_{HST,2050} - 1}{\exp\{-\exp[-t * (TV_{2050}/cap - u)]\} - \exp\{-\exp[-t * (240{,}000 - u)]\}} \tag{6c}$$

$$v = 1 - s * \exp\{-\exp[-t * (240{,}000 - u)]\} \tag{6d}$$

- Automobile

$$S_{Auto} = 1 - S_{Rail} - S_{Bus} - S_{HST} \tag{7}$$

3.5 Model Parameters

Equations (1a) – (6d) will be used to project the future travel demand and mode shares in the Texas Triangle. There're a number of parameters in the equations. Schafer and Victor estimated these parameters for the world-regional level. Some parameters were derived by iteration

(equations 1a, 1b, and 1c); some parameters were estimated by least-square regression (equations 2-6).

The best way to apply these equations to the Triangle would be first estimating the Triangle's parameters using corresponding data. However, there're no available historical data of total passenger traffic volume and travel mode share in the Triangle, which are needed to estimated the parameters specifically for the Triangle. Due to this, the second best solution was chose for this study: since the Triangle is part of North America, the parameters derived by Schafer and Victor for North America region were used directly without modification. The parameters' values are shown in table 1.

Table 1. Model parameters

Equation 2a, 2b		
e = 0.776	g = 40.2	h = 61.19
Equation 1a, 1b, 1c		
c = -176.083	d = 20	
Equation 3		
i = 122.7	j = 6262	k = 1
Equation 4		
l = 1195	m = -3248	
Equation 6b, 6c, 6d		
$t = 4.82*10^{-5}$	u = 35684	

4. Data

The model defines that the levels of mobility are mainly a function of GDP value. To understand the future travel demand in the Triangle, future population and GDP value of the Triangle need to be obtained.

4.1 Population projection

The Texas State Data Center (TxSDC) has projected population at county level until 2040. The projection applies a cohort-component technique and provides four scenarios which assume the same set of mortality and fertility rates but different net migration scenarios. The net migration assumptions were derived from 1990-2000 patterns which have been altered relative to expected future population trends (during 1990-2000, Texas experienced the most rapid growth overall). Scenario 0 assumes zero net migration and population growth is only through natural increase; Scenario 0.5 assumes half of the net migration of those in the 1990s; Scenario 1 assumes the net migration rates of the 1990s will characterize those occurring in the future; Scenario 2 uses 2000-2004 estimates of net migration.

The TxSDC's projection stops at 2040; this study estimated the 2050 population by assuming that population growth from 2040 to 2050 would keep the same rate as growth from 2030 to 2040. Figure 5 shows the four scenarios of Triangle Population from 2000 to 2050, and figure 6 shows the percentage share of Triangle population in Texas under these four scenarios. Under scenario 0, which assumes zero net migration, the Triangle population increases in a very slow rate and the growth almost stops after 2030; the percentage share of the Triangle population continues dropping. Under the other three scenarios, both the absolute number of the Triangle population and the percentage share of the Triangle population increase. So, it could be concluded that migration is a major source for the Triangle population growth. It is the economic development in the Triangle that attracted a large number of people during the 1990s period, and obviously, the migration won't suddenly stop as the scenario 0 assumes.

Comparing scenarios 0.5, 1 and 2 which have different net migration assumptions, scenario 0.5 has the most modest population growth. Under scenario 0.5, by 2050, 74% of the Texas population would concentrate in the Triangle, while under scenario 1 and scenario 2, more than 80% population would live in the Triangle by 2050. Scenario 1 and 2 posit a much faster population agglomeration pattern in the Triangle region.

Figure 5. Triangle population (2000-2050)

Data Source: The Texas State Data Center
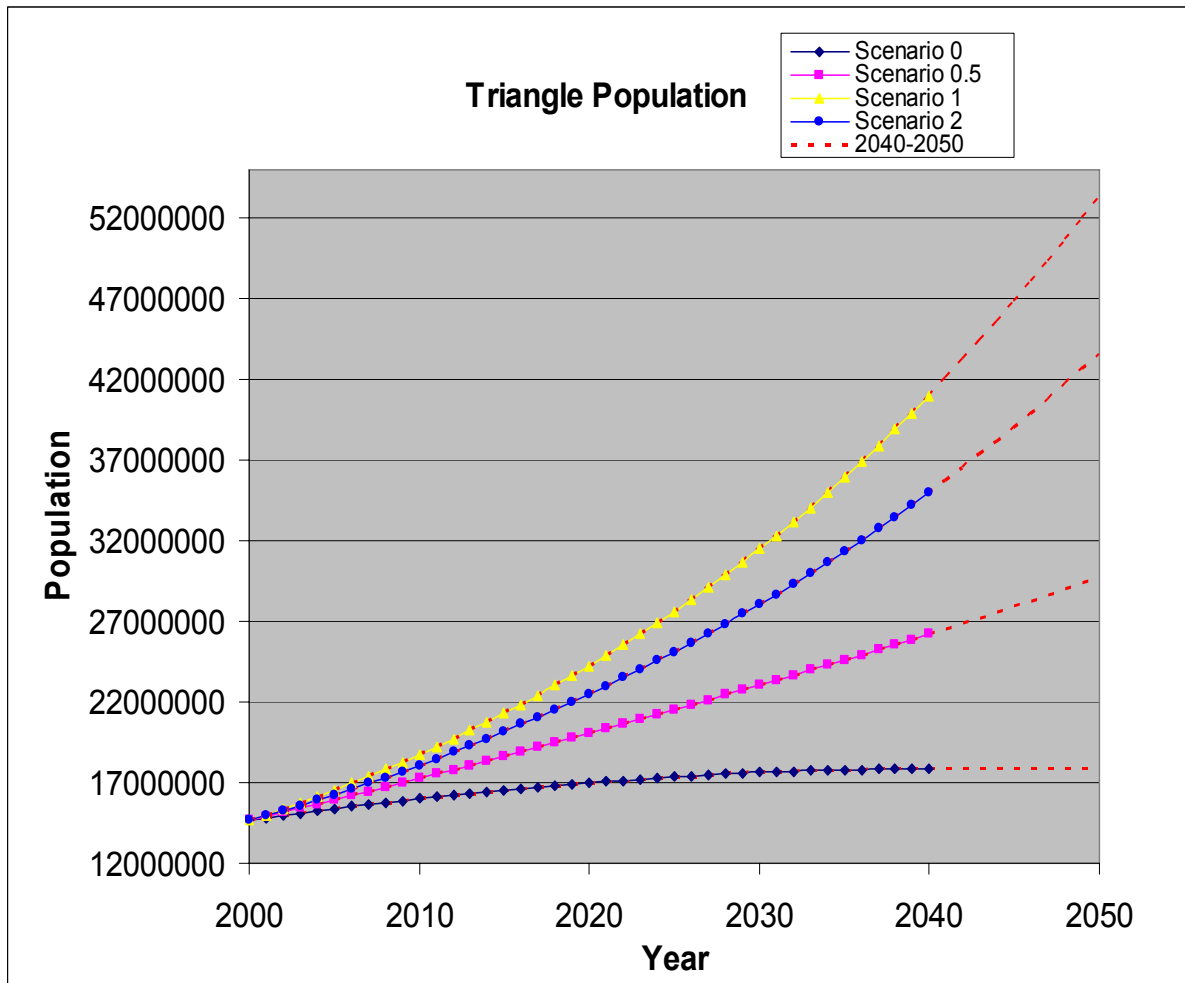
Figure 6. Triangle population share (2000-2050)

Data Source: The Texas State Data Center
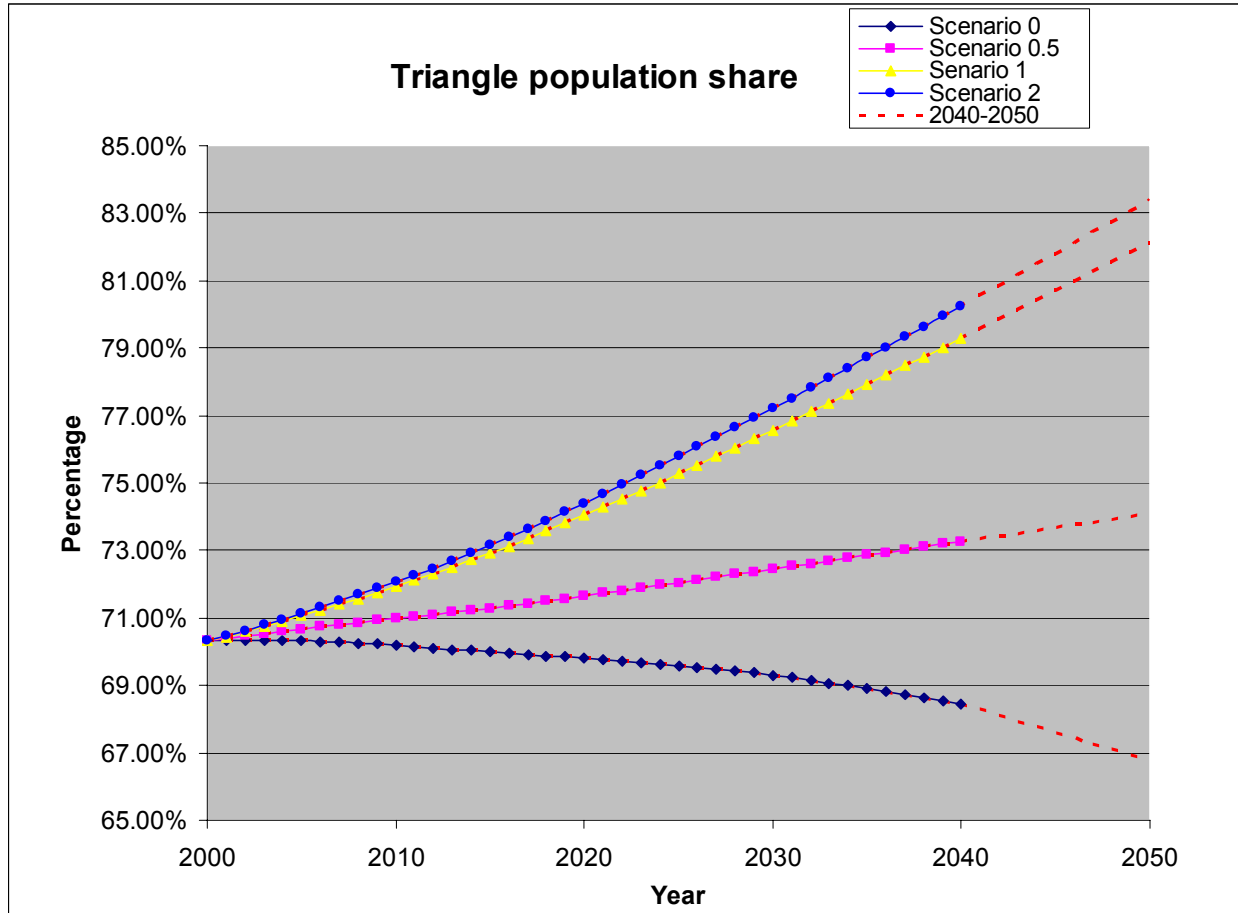
4.2 GDP projection

Long-range GDP projection is a quite complex process and considered by many economists lack of accuracy because of the rapidly changing economic conditions. Bureau of Economic Analysis (BEA) stopped projecting long-range GDP in the 1980s. The Texas Comptroller of Public Account (TCPA) is the only agency that provides projected GDP data for Texas and makes it available to the public. The Texas GDP projection was completed using the State of Texas Economic Model, which used multiple linear regression equations and was based on the assumption that the historical relationships of the past would continue over the projection period.

The TCPA projected the Texas GDP by 2035. In this study, the 2050 GDP was then extrapolated using a best curve fitting method. Figure 7 shows the Texas GDP from 2000 to 2050.

Figure 7. Texas GDP (2000-2050)

Data Source: The Texas Comptroller of Public Account
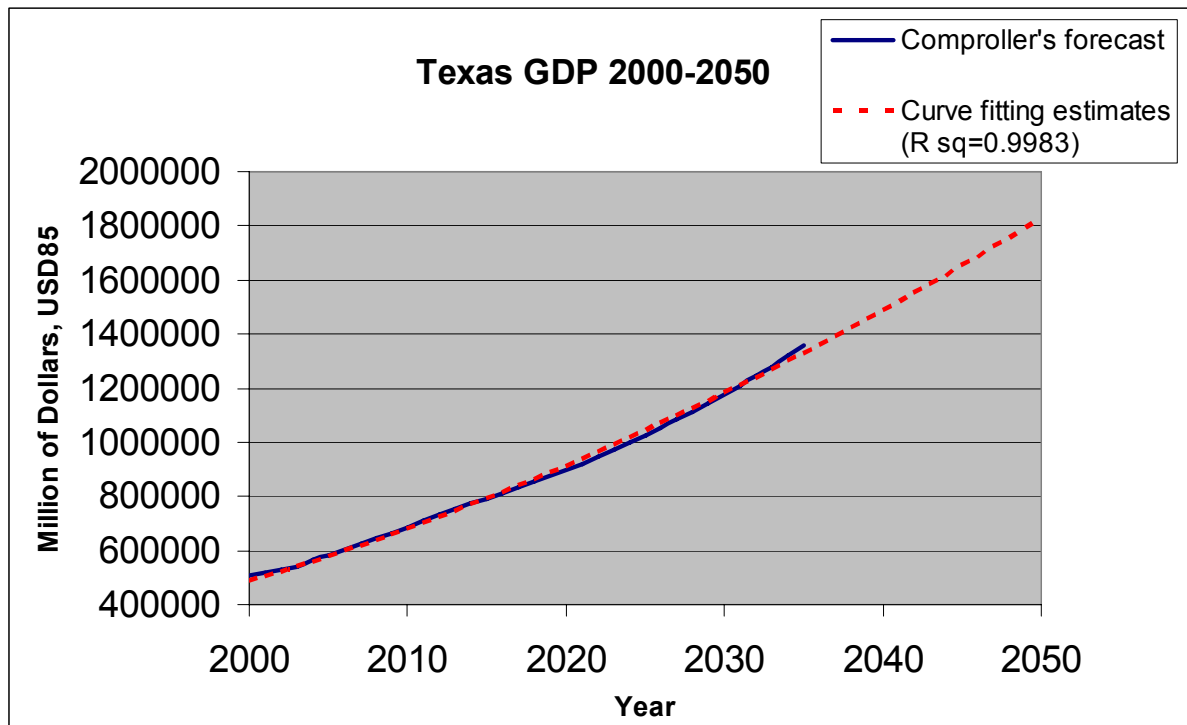
The above GDP values are only available for the entire Texas. The Triangle GDP needs to be extracted from the Texas GDP. Since BEA provides historical income data at county level, the percentage share of the Triangle income relative to the state as a whole can be calculated, which could be taken as an approximation of the percentage GDP share of the Triangle in Texas.

The income shares of the Triangle region from 1980 to 2005 are shown in figure 8, which indicates the Triangle income shares kept increasing over time. Figure 8 also shows the population share of the Triangle region during the same time period. It can bee seen from figure 8, from 1980 to 2005, the Triangle population share and income share increased at approximately same pace; which indicates that the Triangle income share was highly related to its population share. As shown in figure 9, the Triangle income share could be expressed as a second order polynomial function of the Triangle population share. Thus the income share of the Triangle from 2006 to 2050 was estimated from the population share of the Triangle.

The regression equation estimates that, under population projection scenario 0.5, when the Triangle population share reaches 74.09% in 2050, the Triangle income share will become 86.36%. However, under population projection scenario 1 and 2, when the Triangle population share reaches more than 80%, the Triangle income share will be larger than 100%, which can not happen in the reality. This implies that when the Texas population becomes overly concentrated (near 80%) in the Triangle region, the Triangle income share will not be able to keep the same growth pace as before and the Triangle region will start losing its attraction to immigrates from other parts of Texas. Based on this, population projection scenario 0.5 was considered as more appropriate, and used in the following analysis.

Figure 8. Triangle population/income share (1980-2005)

Data Source: Income data from BEA; population data from Census Bureau
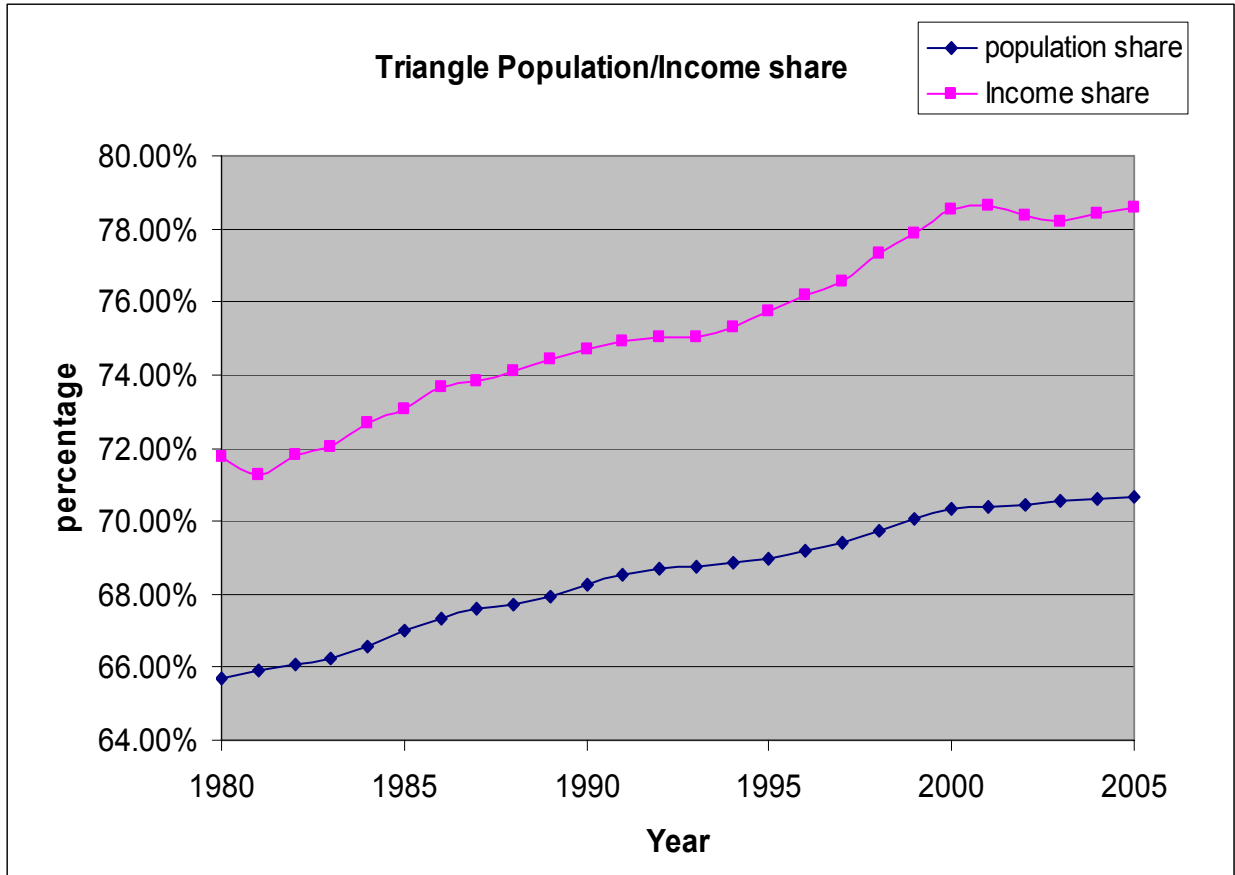
Figure 9. Triangle income share as a function of population share

Data Source: Income data from BEA; population data from Census Bureau

Triangle income share and population share

$y = 9.1167x^2 - 10.974x + 3.9898$

$R^2 = 0.9881$

Income share (vertical axis): 70.00%, 75.00%, 80.00%, 85.00%, 90.00%

population share (horizontal axis): 65.00%, 67.00%, 69.00%, 71.00%, 73.00%, 75.00%
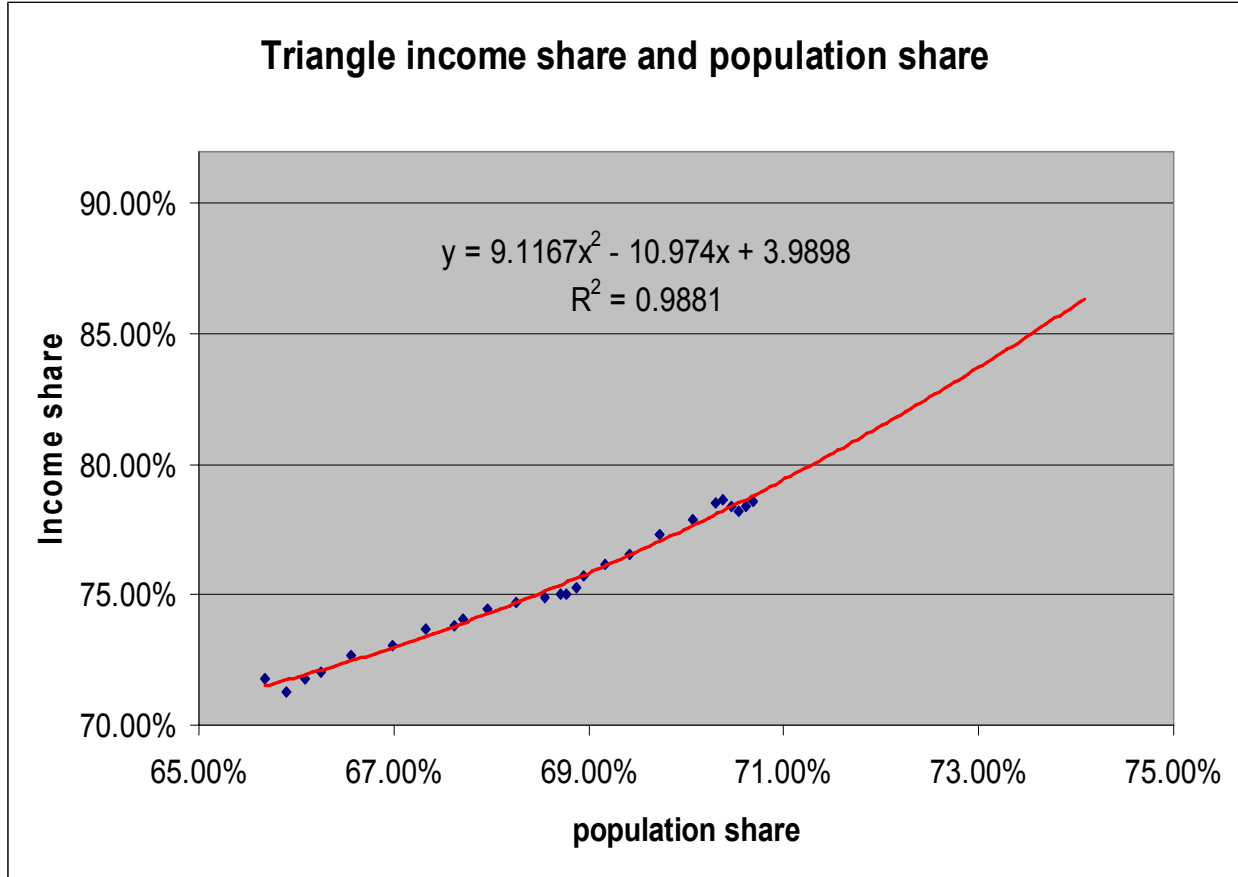
The GDP per capita value in the Triangle was thus calculated by dividing GDP by population. Table 2 shows the GDP/cap values for 1990, 2000, 2020, and 2050.

Table 2. Estimated GDP/cap in the Triangle (USD 85)

Year	GDP (millions)	Population	GDP/cap
1990	240685	11593003	20761
2000	398266	14660393	27166
2020	723912	20065099	36078
2050	1577409	29766964	52992

5. Projection Results

5.1 Total mobility

The mobility in the Texas Triangle was projected using the model and data described above. Table 3 shows the projection results. Table 3 also includes per capita travel demand of the entire North American region in the corresponding years. The estimated average (per capita) travel demands in the Triangle are generally higher than the North American regional average during all these years.

According to the projection results, both average and total travel demand in the Triangle would increase rapidly. The per capita mobility would grow 31% from 2000 to 2020 and 87% from 2000 to 2050, while the 2020 total mobility would be almost two times as much as the 2000, and the 2050 total mobility would be almost three times greater than the 2000.

Table 3. Projected mobility in the Texas Triangle Area

Year	TV/cap (km)		Texas Triangle Total mobility (millions of km)
	Texas Triangle	North America[*]	
1990	25318	22078	293517
2000	32722	27353	479718
2020	42737	40432	857526
2050	61081	58149	1818205

* 1990, 2020 and 2050 values are from Schafer and Victor (2000), 2000 values are from Bureau of Transportation Statistics (2006)

5.2 Mode shares

Table 4 shows the estimated mileage traveled by the four modes and the percentage share of the four modes in the Triangle. Although the total travel by rail and bus would keep increasing from 2000 to 2050, their share would decrease; on the other hand, both the total travel and the share of high-speed transport would increase. By 2050, the share of high-speed transport would reach 73%, and the mileage traveled by high-speed would be more than 10 times as much as 2000. The total travel by car would increase from 2000 to 2020 and then decrease between 2020 and 2050. The percentage share of car for travel would drop from 70% in 2000 to 64% in 2020, and then to 26% in 2050. The projection results strongly suggest the importance of the use of high-speed transport in the future in the Triangle.

Table 4. Estimated mode share and total travel by mode in the Texas Triangle

Year		Rail	Bus	Car	High speed
2000	Total (millions of km)	1973	11608	336386	129751
	Per cap (km)	135	792	22945	8850
	Share	0.41%	2.42%	70.12%	27.05%
2020	Total (millions of km)	3079	18766	549516	286166
	Per cap (km)	153	935	27387	14262
	Share	0.36%	2.19%	64.08%	33.37%
2050	Total (millions of km)	3115	21728	468739	1324622
	Per cap (km)	105	730	15747	44500
	Share	0.17%	1.20%	25.78%	72.85%

5.3 Alternative analysis

In the projection process, the level of mobility is strictly defined by the GDP value. So, the variance in GDP estimation will affect the projection results of future mobility. However, as mentioned above, long-range GDP projection is filled with uncertainties because of the ever-changing economic condition. In the above analysis, the future per capita GDP was estimated based on two separated population and GDP projection processes. In the following analysis, an alternative method was used to estimate the future per capita GDP, i.e., using growth rate of GDP/cap. The results from the alternative analysis can be used to compare with the previous analysis and possibly provide a range for future mobility.

From the previous analysis, the compound annual GDP/cap growth rate in the Triangle can be calculated as 1.9% from 1990 to 2020 and 1.3% from 2020 to 2050, while Schafer and Victor (2000) defined the annual GDP/cap growth rate of North America as 2.3% from 1990 to 2020, and 1.4% from 2020 to 2050, based on the IS92a baseline scenario of the Intergovernmental Panel on Climate Change (IPCC). Assuming that the IPCC GDP/cap growth rates would apply in the Triangle, the 2020 and 2050 GDP/cap values can be estimated using the 1990 GDP/cap as base year, and are shown in table 5.

Table 5. Estimated 2020 and 2050 GDP/cap using IPCC growth rate (in USD 85)

Year	1990	2020	2050
Triangle GDP/capita	20761	41070	62325

The IPCC GDP/cap growth rates are higher than the previous analysis and lead to higher per capital GDPs in 2020 and 2050, which in turn correspond to higher travel demand. As shown in Tables 6 and 7, in the IPCC growth scenario, the average mobility in 2020 and 2050 is 13% and 16% higher than that estimated previously, respectively. Under the IPCC growth scenario, people shift to faster mode earlier – in 2020, 44% travel would be carried out by high-speed transport, compared with a mere 33% of high-speed share in the preceding analysis. These two analyses project that by 2050, high-speed transport will take 73% to 78% travel in the Triangle.

Table 6. Estimate 2020 and 2050 travel demand using IPCC growth rate

Year	TV/cap (km)	Total mobility (millions of km)
2020	48230	967748
2050	70920	2111084

Table 7. Estimated mode shares and total travel by mode using IPCC growth rate

Year		Rail	Bus	Car	High speed
2020	Total (millions of km)	2321	15389	521402	428636
	Per cap (km)	116	767	25986	21362
	Share	0.24%	1.59%	53.88%	44.29%
2050	Total (millions of km)	2898	20745	443520	1643921
	Per cap (km)	97	697	14900	55226
	Share	0.14%	0.98%	21.01%	77.87%

5.4 Sensitivity of results

The model used in this study is not fully deterministic. The projection results could be affected by different assumptions. Thus, possible changes on some assumed values were made to test the sensitivity of our results.

In the study, the fixed TTB of 1.1 h/d/cap were used, which were obtained by surveys mostly done in 1970s and 1980s. Now people may allocate longer time to travel because they may have been used to congestion, or they could make more frequent longer trips. In Texas that has great land, it's quite possible that people spend longer time in traveling. If the TTB is increased by 10% to 1.2 h/d/cap, the projected share of high speed transport for travel in 2050 will decrease by 5%. This shows that greater TTB could impede the process of people shifting to faster travel mode, but the effect is mild.

The mean speeds of transport modes could also affect the projection results. Transport speed can be changed by applying different techniques. For example, bus speed could be largely increased by using dedicated bus way. Increasing bus speed by 50% would reduce the 2050 high speed transport share by one percentage point, and increase the 2050 car share by one percentage point. Car speed can also vary depending on road condition and technologies (for example, congestion could greatly decrease the mean vehicle speed, but the intelligent transportation system could reduce congestion and increase the mean vehicle speed). Increasing car speed by 20% could reduce the 2050 high speed transport share by six percentage points and increase the 2050 car share by six percentage points, while decreasing car speed by 20% would have the opposite effect. These results suggest that variance in the mean speeds would only have minor effect on the future mode shares.

6. Conclusions and Direction for Future Research

The study results suggest that the Texas Triangle would experience an enormous amount of mobility growth by year 2050. Measured by person-kilometers of travel (PKT), the total mobility demand in the Triangle region is projected to grow nearly four times from 480 billion in year 2000 to 1.8 trillion in year 2050. Per capita PKT is expected to increase from 32,700 to 61,000 for the same time period, higher than the North American regional average. This study projected that the total travel by all modes would increase. The mode share structure would also change. People would switch to high-speed transport gradually. The share for high speed travel would increase dramatically in the next 40 plus years. By year 2050, more than 70% of PKT is likely to be accomplished by high-speed transportation averaging 600 km per hour.

The expected growth of future travel demand will impose tremendous pressure on the transportation infrastructure in the Triangle area. Currently in Texas, air transportation offers the only high-speed mode of inter-city travel. By year 2050, high-speed travel demand would rise to more than 10 times of the year 2000 level. It is unlikely that the demand for high-speed travel can all be met by air travel because of the capacity constraints in airway network, gate and runway, and airport operations. Accordingly, planning for megaregional transportation should seriously consider high-speed travel in the form of High Speed Rail (HSP) to accommodate the future travel demand in the Triangle Region. The sooner the HSP is incorporated in the regional transportation plan, the better the Triangle would prepare for the future.

This study is an experiment of using megaregion approach – applying an aggregate model to project future travel demand in the Texas Triangle. While the study results offer insights to future travel demand, a number of limitations exists. The modeling framework builds on the assumptions of fixed travel time and money budgets. Future research should re-examine the assumptions with empirical evidence in Texas. The model also assumes an unchanged travel cost (per km) over the projection period. Recent price hike of fuels suggests that travel cost could go up dramatically and thus change the relationship between income and mobility. Furthermore, the model parameters used for the Triangle demand projections are borrowed from published studies

at the national/international level. These parameters need to be re-calibrated with Texas data in the future in order to improve projection accuracy and reliability.

The limitations of this study point to the direction for future research for better understanding long-term travel demand in the Texas Triangle. An important topic warranting further research is intercity travel in the Triangle. For this purpose, data on intercity travel connections must be gathered and assembled through coordination with various public and private sectors. For instance, the Census Bureau provides journey to work data in the county level for auto mode; the Bureau of Transportation Statistics maintains and reports airline activity data; rail service information is available from Amtrak's achieves; the Greyhound Bus Line furnishes major intercity bus service for which data on bus passenger travel can be collected. Once a detailed intercity travel database is established, the relationship between income and mobility in the Triangle can be calibrated empirically. Travel demand forecast can then be improved. Moreover, the current trends of escalating fuel price and possible global warming will all affect the relationship between income and mobility; hence, these factors need to be incorporated into the future study.

Travel demand projections from the megaregion approach can be cross-checked and refined with the statewide travel models. The Texas Statewide Analysis Model (SAM) for statewide multi-modal travel demand analysis includes two major components, passenger and freight. Developed as a customized module with TransCAD GIS, SAM applies the traditional four-step travel demand modeling techniques. For passenger component, SAM contains 4,600 Traffic Analysis Zones (TAZ) within Texas, and 142 external zones which construct one-county buffer around the State. The SAM passenger component models auto, air, rail travel modes, as well as potential high-speed rail model. For freight component, 254 counties in Texas are used as TAZs along with 35 external county zones. Freight component models auto and rail travel modes. SAM provides a framework to study both intra-city travel demand and inter-city travel demand in the entire Texas state. Its application however remains a challenge due to the high cost in computing time and data input.

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