CM²

**Cooperative Mobility for
Competitive Megaregions**

Develop a GIS-based Megaregion Transportation Planning Model

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16. Abstract

Few studies have focused on the development and implementation of megaregional transportation models. It is a big challenge to build such kind of models because they need to ensure theoretical soundness and methodological validity in academic and professional studies while at the same time to meet the expectation of public agency on the models for reliability, efficiency, and user friendliness. This study intends to fill the gaps to develop a GIS-based operational model for megaregion transportation planning. It extends the spatial scale of a regional transportation model to megaregion, which accommodates larger areas, more passenger and freight trips, and more complex transportation networks. It aims to balance the priorities in both academic research setting and operational planning setting. It selects Texas Triangle, including Austin, Dallas, Houston, and San Antonio metropolitan areas, as an empirical case to demonstrate the procedure of analytical framework design, data inventory, model development, and model implementation. This study also estimates both personal access to employment opportunities and truck access to freight facilities in megaregion traffic analysis zone to facilitate transportation policy development in Texas Triangle.

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Chapter 1.

Megaregions or, as the United Nations (UN) refers to them, megacities are large clustered urban areas with more than 10 million inhabitants. The UN reported that there were 31 megacities globally in 2016 and this number is expected to reach 41 by 2030 (UN, 2016). In addition to the requirement of the total population, economic production is also important for the emergence and development of megaregions. Florida et al. (2008) argued that a megaregion must have a certain level of economic production. The megaregion's economic competitiveness in domestic and international markets is a key concern given the increasing connections between the urban areas in globalization.

In the US, a megaregion is considered a contiguous area connecting major cities. Ross (2009a) defined it as a network of metropolitan centers and their surrounding areas that are spatially and functionally connected through environmental, economic, and infrastructure interactions. This definition regards metros as not only the "space of places" but also the "space of flows" such as transportation, information, and business networks (Lang and Dhavale, 2005). The Regional Plan Association (RPA) (2017) identified 11 megaregions in the United States that encompass more than 70 percent of the nation's population and jobs. Between 2015 and 2045, the US population is projected to increase 22% to 390 million while its GDP is projected to grow by 115% to $36.7 trillion, according to "Beyond Traffic 2045". Most of the population and GPD growth will be concentrated in megaregions.

Transportation infrastructure is inherently a megaregion issue because it forms networks within and among regions and municipalities (Monolith Press 2013). The unprecedented urban sprawl made possible by the expansion of transportation infrastructure has certainly increased the size of megaregions and captured more attention in urban planning. Planners need megaregion travel demand models to formulate projects and programs, appraise and prioritize plans and policies, and assess the economic and social impacts of transportation investments (NASEM 2017). However, it has laid great challenges on understanding and modeling the performance of megaregional transportation systems because they have shaped urban development profoundly. Existing

transportation-related issues in urban areas such as congestion, urban sprawl, air pollution, public health, and equitable accessibility may become more serious at the megaregional level than at the local, state, or national levels. It is necessary to develop appropriate integrated urban models (IUMs) to achieve socio-economic and environmental sustainability (Miller 2018).

As emerging economic units, megaregions open a new context for US transportation planning in the 21st century. It is important to advance the existing infrastructures in megaregions to support personal, local, regional, federal, and global mobility needs and address the relevant economic competitiveness and environmental issues (Ross 2009b). However, there are some challenges to developing models and implementing plans for megaregional transportation development. The megaregional transportation study is a complex and largely unexplored issue partially due to the heterogeneity of data sources and the variety of spatial and temporal definitions. For example, no zonal system has been designated for existing megaregions. The boundaries of megaregions are difficult to delineate because the conceptual areas are defined by connections such as interrelated transportation, geographies, socio-economic activities, or demographic backgrounds.

In the available literature, most studies of megaregions are still limited to academic interests. To advance the state of the practice and accelerate the pace of innovation in transportation planning, the Transportation Research Board (TRB) Committee on Transportation Planning Applications has held seventeen biennial conferences showcasing innovative methods since 1987. Based on the presentations given at the first seven conferences, the committee concluded that "those methods and procedures that have served well for the past 40 years seem increasingly unable to address the issues of most concern to decision-makers. On the eve of the third millennium, entirely new transportation planning methods are needed." (Marshment 2000).

Different aspects of the transportation system in a large planning area may be controlled by different public agencies. The Metropolitan Planning Organizations (MPOs) are responsible for the development of a transportation improvement plan (TIP) and the maintenance of a regional transportation plan (RTP). Many state transportation agencies also have a Statewide Transportation Improvement Program (STIP) and a Statewide Long-Range Transportation Plan (SLRTP). Travel forecasting models have become a necessary means of evaluating policies, plans,

and projects at both regional and state levels. A study by the National Academies of Sciences, Engineering, and Medicine (NASEM) (2017) pointed out that the distinction between regional and state models becomes vague as their levels of resolution converge and the pressures for fine-grained analyses are increasing.

However, few states are ready or able to model the entire state or megaregions at the urban level. Most state transportation agencies and MPOs have failed to encourage greater cooperation among individual MPOs (Seedah and Harrison, 2011). They lack analytical methods to estimate travel demands and measure the performance of transportation infrastructure on moving people and goods at the megaregion level. Zhang et al. (2007) argued that a megaregional approach can provide provocative and imaginative answers to growing problems of congestion, development disparity, and air pollution facing individual metropolitan areas or cities that they are unlikely to solve individually.

To address emerging issues such as the impacts of autonomous vehicles, new high-speed rail services, and aging infrastructures on the clustered metropolitan centers and their surrounding areas, advanced megaregional transportation models need to be developed by integrating individual metropolitan transportation plans and by considering the inter-metropolitan movements of people and goods within the megaregion. However, there are few professional programs and academic studies on megaregional transportation models. There are even fewer studies that explore both passenger travel and freight movement at the megaregion level. NASEM (2017) claimed that no operational megaregion model has been developed in the U.S.

IUMs offer the potential to expand the scope of spatial analysis from metropolitan to megaregional level, evaluate transportation performance of both passenger and freight traffic in megaregions, and support decision making and policy analysis for megaregional transportation planning. Miller (2018) pointed out that persistent and important technological improvements in computer software and hardware, advanced GIS techniques and large urban spatial databases, and model estimation software have made the development and implementation of operational IUMs possible. The significant modeling progress has also made it possible to develop and apply operational megaregional transportation models.

By recognizing the problems in existing models and the potential of IUMs, this study intends to develop a GIS-based operational transportation model with an analytical framework for estimating the movement of people and goods in megaregions based on the available datasets. It aims to gain a better understating of megaregional transportation flows and facilitate the improvement of passenger access to employment opportunities and truck access to freight facilities. It also plans to balance the priorities of academic research and the needs of operational planning agencies to support decision making on socio-economic and environmental issues related to megaregional transportation. It focuses on the Texas Triangle as an empirical case to demonstrate the implementation of the megaregional transportation model for both passenger and freight traffic.

Chapter 2. Previous Studies

In the available literature on megaregional transportation planning, most studies are limited to qualitative descriptions and case study research, which address policy issues and governance frameworks for megaregions. Few academic studies or professional programs focus on the development and implementation of operational megaregional transportation models. There are even fewer studies that explore both passenger and freight movement within a megaregion.

Ross (2009a) used knowledge of current regional and statewide transportation planning structures to conceive a framework for governing megaregional transportation planning based on a review of the organizational structures and finance of multijurisdictional initiatives in the U.S. and around the world. Dewar and Epstein (2007) also did pioneer work on megaregional planning by reviewing the relevant planning work for megaregions in the U.S. through 2050. They explored the data available for the public to analyze commute flows and truck flows, but their studies were conceptual and descriptive without any quantitative analysis.

As a follow-up study of Ross (2009a), Read et al. (2017) reviewed local and regional long-range plans to determine the extent of megaregional planning. They also conducted case-study research on Cascadia and the Texas Triangle by reviewing the long-range transportation plans of their largest Metropolitan Planning Organizations (MPOs), and the comprehensive plans of the most- and second-most-populous cities as well as a peripheral city within the MPOs. They reported that there remains a lack of clear guidance for the planning agencies on addressing megaregional issues in planning practice. They also pointed out an increasing level of interregional collaboration around large-scale issues of transportation, air and water quality, and resilience across local jurisdictional borders. The increase of accessibility and mobility for people and freight is one of the key planning factors of the regional long-range planning framework.

In the past decades, statewide modeling has made some important advances in expanded detail and capacities, wider diversities of demands, more robust freight models, larger investments in data collection, more sophisticated forecasting modeling for mode choice of high-speed rail, incremental model enhancement for passenger travel, and the extension of modeling with GPS

tracking data. However, this progress in statewide modeling has not been accompanied by similar advances in megaregional modeling. Existing megaregion studies are either research-driven or project-based, such as high-speed rail projects. No agency is responsible for the development of megaregional transportation models except for some federal initiatives because megaregions have no institutionalized governance structures in place (NASEM 2017).

Moeckel et al. (2015) concluded that little research has been conducted to model megaregions after a review of a considerable body of literature on megaregions. In a synthesis report compiled for the National Cooperative Highway Research Program (NCHRP), NASEM (2017) asserted that there is no operational megaregional model in the U.S. as of 2016 except for a prototype called the Chesapeake Bay Megaregional Model. The few published studies tend to focus on one aspect of megaregional planning, rather than integrating transportation, land use, demographic, economic, and environmental components.

An operation freight model developed as a collaborative effort of the Maricopa Association of Governments (MAG), the Pima Association of Governments (PAG), the Arizona Department of Transportation (ADOT), and the Federal Highway Administration (FHWA) stands as one of the few megaregional transportation models. It can be integrated with regional and statewide travel forecasting models to support decision making and transportation analysis across the Arizona Sun Corridor megaregion, the metropolitan areas served by MAG and PAG (Maricopa Association of Governments 2017). The model consists of several major components, including firm synthesis, supply chain, mode choice and transport, and truck tour sub-models. The firm synthesis and the supply chain sub-models account for an evolving market of buyers and sellers, and the mode choice and the truck touring sub-models captured trip chaining activities of freight deliveries of differing classes. Although this model aims to support transportation analysis at the megaregion level, it is limited to freight movement.

Zhang et al. (2013) developed a microlevel traffic simulation for a megaregion evacuation, which incorporates the transportation processes of the Gulf Coast region from Houston to New Orleans. These researchers simulated a regionwide evacuation event using a traffic demand generation process, which yields a spatial-temporal distribution of traffic flows in a hurricane threat scenario.

The model focused on the traffic assignment step and only measured transportation performance in a hurricane evacuation.

As the outcome of a case study and demonstration project funded by FHWA about assembling analysis tools to evaluate scenarios and impacts in megaregions, the Chesapeake Bay Megaregion (CBM) Model was developed for the megaregion around Washington, D.C. NASEM (2017) highlighted it as a prototype of an operational megaregional transportation model in the U.S. The CBM model fully integrates economic, land-use, transportation, and environmental modules in two geographic layers. A megaregional layer with 2,075 zones represents more details of economic activities, land-use changes, environmental impacts, and travel demands in MPOs, while a national layer with 126 zones captures relevant activities and flows outside of the main study area (Moeckel et al. 2015). The CBM model uses a vertical integration approach to enable data exchange across the two geographic layers while a horizontal integration function facilitates the integration of different modules within a geographic layer.

Although researchers employed the CBM model to analyze the effects of a high energy price on the megaregion's land use and transportation systems, they implemented it only as a prototype, and there has been no detailed model validation outside of the state of Maryland (NASEM 2017). Another limitation of the CBM is that the Chesapeake Bay area spans the area from the southern border of Pennsylvania through Maryland and eastern Virginia to Norfolk and Virginia Beach, which is only a part of the most populous Northeast megaregion of the Boston–Washington corridor extending from the northern suburbs of Boston, Massachusetts, to the southern suburbs of Washington, D.C., in northern Virginia. Therefore, the CBM model does not cover an entire megaregion.

To fill a gap in the practice of modeling megaregions, this study intends to develop an operational transportation planning model to gain a better understanding of the movement of persons and freight within megaregions. The model relies on two geographic layers, i.e., the intra-metropolitan and inter-metropolitan layers. It develops a series of functions to facilitate data exchange or integration in the same geographic layer or between the two different layers on a GIS-based platform.

Chapter 3. Methodology

It is a substantial challenge to build integrated models for analyzing passenger and freight movement in megaregions because they need to have theoretical soundness and methodological validity in academic and professional studies while at the same time meeting the expectations of public agencies for reliability, efficiency, and user-friendliness.

This research focuses on the development of a transportation model at the megaregion level. It proposes an analytical framework to address this issue. This model aims to assist policymakers and facilitate the planning process for megaregional development. It is built on the base of the transportation module developed in the Southern California Planning Model (SCPM), which is a regional planning model initially developed at the University of Southern California (USC) in the early 1990s to address the problems of spatial economic impact analysis within the five counties of the Los Angeles Metropolitan area (Richardson et al. 1993). This model has been widely applied in Los Angeles, Houston, and other cities and regions to estimate the effects of natural or manmade disasters and steadily updated over the years as new and revised data sources became available (Richardson et al. 2015).

SCPM is a regional input-output model that reports results in considerable spatial detail. The first version of SCPM (SCPM1) employed an origin-destination (OD) matrix to trace all economic impacts, including those of intra- and interregional shipments, usually at a certain level of sectoral and geographical disaggregation. It did not include transportation network and travel demand modeling. The second version (SCPM2) endogenizes traffic flows including freight deliveries and, therefore, indirect interindustry effects by including an explicit representation of the transportation network. It incorporates a transportation network model with gravity models to allocate indirect and induced impacts generated by the input-output model to the traffic analysis zones (TAZs). The latest version (SCPM3) adds time-of-day functions to the capabilities of SCPM to model AM peak, PM peak, and off-peak traffic. It facilitates an understanding of the effects of peak-load pricing on a complex land use-transportation system, including impacts on transportation network performance at the link level and activity effects at the TAZ level.

To extend the SCPM transportation module from the regional level to a megaregion, it is important to incorporate passenger and freight trips between metropolitan areas into the modeling process. Similar to the framework of intraregional and interregional data processing in Pan (2006) and Giuliano et al. (2010) as well as the two-layer structure of the Chesapeake Bay Megaregion Model described by Moeckel et al. (2015), this study has adopted a framework of two geographic layers to examine intra-metropolitan and inter-metropolitan transportation flows.

In comparison to passenger flows, freight movement is a much more complex and largely unexplored issue mainly because of the costs of data collection, the heterogeneity of data sources, the ambiguity of classifications, and the lack of adequate methodologies (Pan 2006). Giuliano et al. (2010) employed reliable secondary data sources, including small-area employment data, and derived estimates of commodity flows when vehicle (trip)-based freight data were not available. However, truck movement data including OD trip matrices have become available in the past decade at more and more local, state, and federal transportation agencies.

This study develops an analytical framework for a megaregional transportation model, which involves four major research steps: (1) Megaregion transportation data processing, including (a) intra-metropolitan and (b) inter-metropolitan transportation data processing; (2) Transportation data tool functions; (3) Megaregion transportation data integration, including the combination of intra-metropolitan and inter-metropolitan passenger trips and the combination of intra-metropolitan and inter-metropolitan freight trips; and (4) Megaregion network modeling.

As the analytical framework in Figure 1 illustrates, the model separates megaregional transportation into two geographic layers, i.e., intra-metropolitan and inter-metropolitan parts for both passenger and freight trips. Intra-metropolitan transportation represents passenger and freight flows among traffic analysis zones (TAZs) within each metropolitan area of a megaregion, and inter-metropolitan transportation represents passenger and freight movements that do not begin and end within the same metropolitan area of a megaregion.

The local MPOs within a megaregion are expected to provide intra-metropolitan transportation data for their metropolitan planning areas, including passenger and freight trip ODs, traffic analysis zones (TAZs), and network link files, etc.

Inter-metropolitan transportation includes passenger and freight movement between two different metropolitan areas of a megaregion, trips originating in or destined for areas outside of the metropolitan areas within the megaregion, or trips to areas outside of the megaregion. Usually, the state or federal transportation agencies have inter-metropolitan transportation data available. For example, the Bureau of Transportation Statistics (BTS) and the Federal Highway Administration (FHWA) have incorporated data from Commodity Flow Surveys (CFSs), the US Census Bureau's international trade data, and a variety of data sources to develop a Freight Analysis Framework (FAF) to describe freight movement among states and major metropolitan areas by all modes of transportation.[1] The US Census Bureau also provides data about commuting trips between workers' residence location and workplace at the county level through its American Community Survey (ACS).[2]

FAF data for freight shipments are available in tonnage, value, and ton-miles by origin and destination, commodity type, and mode. However, data conversion is necessary, for example, from tons to dollars to jobs to trucks to passenger-car-equivalents (PCEs). This study develops the necessary tool functions for data unit transformations.

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[1] https://ops.fhwa.dot.gov/freight/freight_analysis/faf/
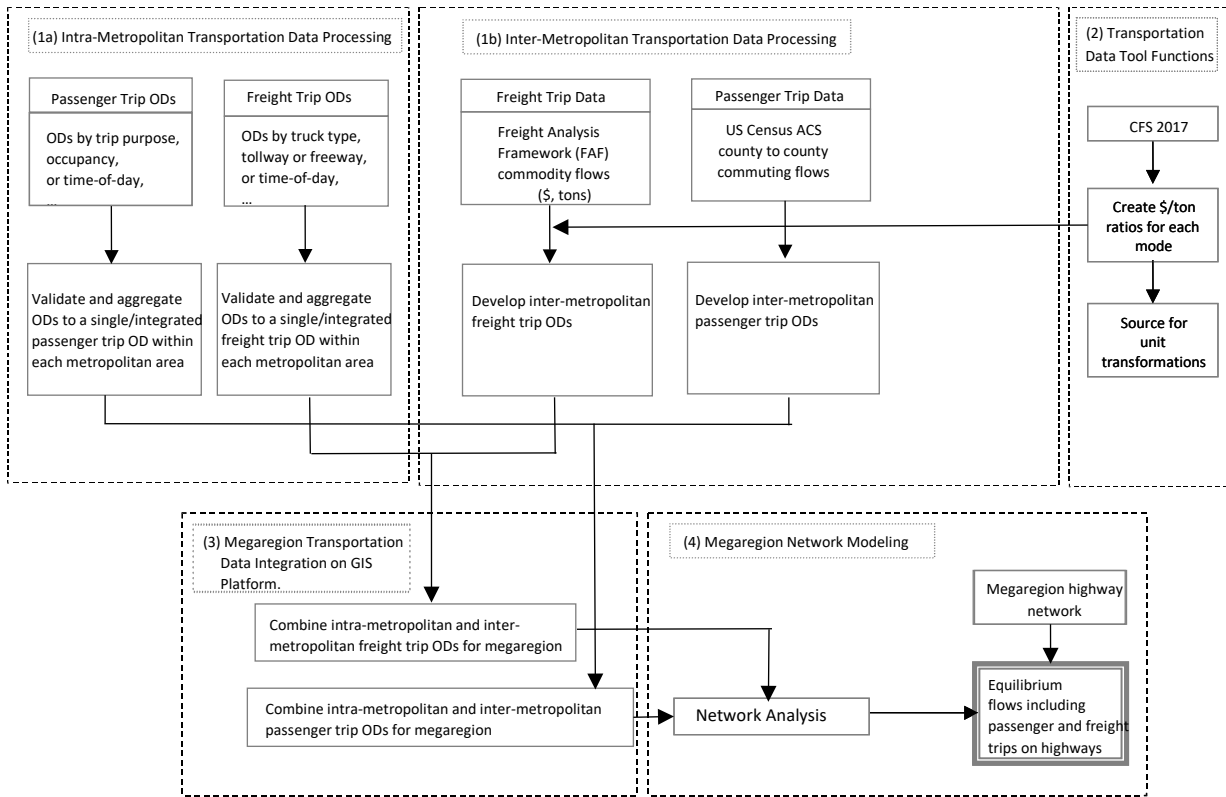[2] https://www.census.gov/topics/employment/commuting/guidance/flows.html

Figure 1. An analytical framework for a megaregional transportation model

The framework also shows that the intra-metropolitan and inter-metropolitan transportation data will be incorporated into the megaregional transportation system on a GIS-based platform. GIS functions combine the TAZs in metropolitan areas and the zones outside of metropolitan areas into megaregion analysis zones (MAZs). The megaregional transportation system has passenger and freight trips originating in or destined for the MAZs that move through megaregional transportation networks.

The megaregional network models described in the framework load megaregional passenger and freight trip ODs onto megaregional highway networks through network assignment functions. The passenger and freight trips are assigned together in an equilibrium-based model by considering the network overloading condition, which is presented as follows,

$$\text{Min} \sum_a \int_0^{x_a} C_a(x)\,dx \qquad\qquad (3.1)$$

$$\text{subject to } x_a = \sum_o \sum_d \sum_p \delta_{a,p}^{od} h_p^{od} \qquad \forall a \qquad\qquad (3.2)$$

$$\sum_p h_p^{od} = T_{od} \qquad\qquad \forall o,d \qquad\qquad (3.3)$$

$$h_p^{od} = P_p^{od} + F_p^{od} \qquad\qquad \forall o,d \qquad\qquad (3.4)$$

$$h_p^{od},\ P_p^{od},\ F_p^{od} \geq 0 \qquad\qquad \forall p,o,d \qquad\qquad (3.5)$$

where x_a is the total flow on link a,

$C_a(t)$ is the cost-flow function to calculate average travel cost on link a,

$\delta_{a,p}^{od}$ is the link-path incidence variable; equal to one if link a belongs to path p connecting

OD pair o and d,

h_p^{od} is the flow on path p connecting OD pair o and d, including both passenger flow P_p^{od} and

freight flow F_p^{od},

T_{od} is total trips between origin node o and destination node d, including both passenger and

freight trips,

p is a network path, and o and d are two end nodes on the network.

This assignment model for both passenger and freight flows adopts the equations described by Sheffi (1985) that Beckman et al. (1956) used to formulate a mathematical model for Wardrop's first principle of route choice ("user equilibrium"). The objective function (3.1) aims to minimize the overall travel costs of transportation networks, which are constrained by link flows and zonal demands. Giuliano et al. (2010) employed this model to load freight traffic onto regional highway

networks and Pan (2003) and Pan (2006) utilized it to assign both passenger and freight trips in regional transportation models.

The implementation of the model requires the solution of all feasible values to be generated in iterations. The total travel costs of the network are minimized to satisfy the objective function (3.1) when the model reaches convergence. The procedure can be described as follows,

Step 0: **Initialization**. Perform an all-or-nothing approach for assigning both passenger and freight trips simultaneously using free-flow travel costs $C_a = C_a(0)$, for each link a on the empty network. Link flows x_a are obtained.

Step 1: **Update link travel times**. The travel time on link a is updated as $C_a = C_a(x_a)$.

Step 2: **Find a feasible descent direction**. Use the updated travel time $\{C_a\}$ for an all-or-nothing assignment for passenger and freight trips, which yields a set of auxiliary link flows $\{u_a\}$ combining passenger trips with freight trips in PCEs.

Step 3: **Find the optimal parameter**. A linear approximation algorithm (LPA) such as the Golden section or Bisection method described in Sheffi (1985) is applied to obtain optimal parameter α satisfying the following equation:

$$\text{Min} \sum_a \int_0^{x_a + \alpha(u_a - x_a)} C_a(x)dx$$

Step 4: **Update link flows**. Link flows x_a are changed to be $x_a + \alpha(u_a - x_a)$

Step 5: **Test Convergence.** The process stops when a convergence criterion is satisfied and link flows are the optimal link flows at the equilibrium condition. Otherwise, go back to Step 1 and continue the process.

Pan (2003) and Pan (2006) adopted this approach to load both passenger and freight flows onto a congested regional highway network under a user equilibrium condition. A similar procedure can also be utilized to load both passenger and freight trips onto megaregional highway networks with congestion.

Chapter 4. Analysis

4.1. Study Area

The megaregional transportation model described by the analytical framework in Figure 1 will analyze passenger and freight flows in the Texas Triangle, which contains the state's four largest metropolitan areas, i.e., Austin, Dallas-Fort Worth, Houston, and San Antonio, connected by major interstate highways, including I-10, I-45, and I-35. The total population of the four metropolitan areas within the Texas Triangle was 16.2 million in 2010, which increased 19.7% to a total of 19.4 million in 2019[3] making it one of the fastest-growing megaregions in the U.S.

The boundaries of the four large metropolitan areas in the Texas Triangle are different from those of the Freight Analysis Framework, version 4 (FAF4) zones defined in the Commodity Flow Survey (CFS). Figure 2 shows that the areas of the FAF4 zones are larger than the traffic analysis zones (TAZs) of the metropolitan areas determined by their local MPOs. It also illustrates the coverage of the Texas Triangle based on the passenger job accessibility calculated in this study.
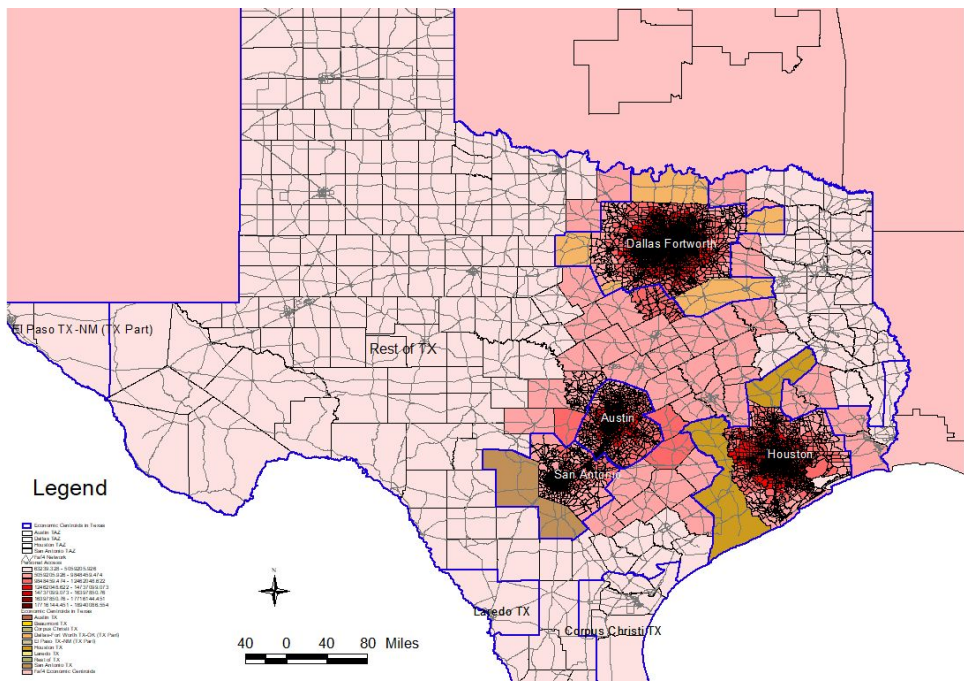

Figure 2. The study area – the Texas Triangle with its megaregion analysis zones (MAZs).

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[3] Author calculation using the US Census Bureau's data for Metropolitan and Micropolitan Statistical Areas Population Totals and Components of Change: 2010-2019, https://www.census.gov/newsroom/press-kits/2020/pop-estimates-county-metro.html

4.2. Data

Researchers obtained data from a variety of agencies at two geographic levels: the intra-metropolitan level and the inter-metropolitan level. One of the most important sources of metropolitan-level data was the metropolitan planning organizations (MPOs). As federally mandated and funded organizations, the MPOs are required to develop transportation plans and policies for the country in their areas with a population of 50,000 or more, including a long-term transportation plan, i.e., Regional Transportation Plan (RTP), and a four-year plan called the Transportation Improvement Program (TIP). Our traffic analysis zones, origin-destination matrix, and transportation network data of metropolitan areas were obtained from local MPOs.

The Austin MPO, or the Capital Area Metropolitan Planning Organization (CAMPO), is responsible for transportation planning for Bastrop, Burnet, Caldwell, Hays, Travis, and Williamson counties. CAMPO provided transportation modeling data in 2018 that it had developed for its 2040 regional transportation plan, including passenger and freight trip ODs for 2,102 internal TAZs plus 59 external zones, a master road network with 17,169 links and 6,533 miles, 396 existing and planned transit routes, etc. A total of 11,678,748 daily passenger vehicle trips and 1,031,178 freight truck trips were generated in the metropolitan areas, of which 320,610 passenger vehicle trips and 51,333 freight truck trips were external trips with one end out of the CAMPO region (Table 1). The passenger trip tables were available for different trip purposes, occupancy, and time-of-day. The TAZ system completely covers the six-county CAMPO region, which is consistent with the FAF4 zone designated for the Austin metropolitan area (Figure 3a).

The Transportation Department at the North Central Texas Council of Governments (NCTCOG) serves as the MPO for the Dallas-Fort Worth region. It provided transportation data for Collin, Dallas, Denton, Ellis, Hill, Hood, Hunt, Johnson, Kaufman, Parker, Rockwall, Tarrant, and Wise counties. The NCTCOG data include passenger and freight trip ODs for 5,386 TAZs, including 5,303 internal TAZs and 83 external zones, and a road network with 41,454 links in 19,404 miles. The passenger trip tables were categorized by time-of-day and occupancy, and the freight trip tables were also available for different times-of-day. There were a total of 19,843,163 passenger trips and 758,006 freight trips generated in the NCTCOG area per day, including 331,914 external

passenger trips and 95,528 external freight trips (Table 1). The NCTCOG's TAZs cover an area smaller than the FAF4 zone designated for the Dallas metropolitan area, which includes seven more counties, i.e., Cooke, Henderson, Hopkins, Grayson, Palo Pinto, Navarro, Somervell (Figure 3b).

The Houston-Galveston Area Council (H-GAC) cooperates with local governments in the Houston metropolitan area to address regional planning issues. Its transportation plans cover an eight-county area, including Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties. -H-GAC provided passenger and freight trip ODs for 2,954 internal TAZs and 46 external zones, and a road network with 68,314 links and 30,167 miles. The passenger trip tables were available for different trip purposes. A total of 15,726,515 passenger trips and 1,154,140 freight trips were generated every day in the H-GAC region, including 181,121 passenger trips and 31,924 freight trips entering or leaving the region through its external zones (Table 1). The FAF4 zone designated for Houston metropolitan area includes Austin, Matagorda, Walker, Washington, and Wharton counties in addition to the eight-county H-GAC region (Figure 3c).
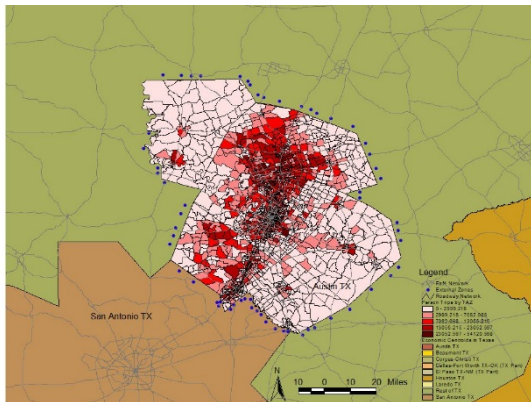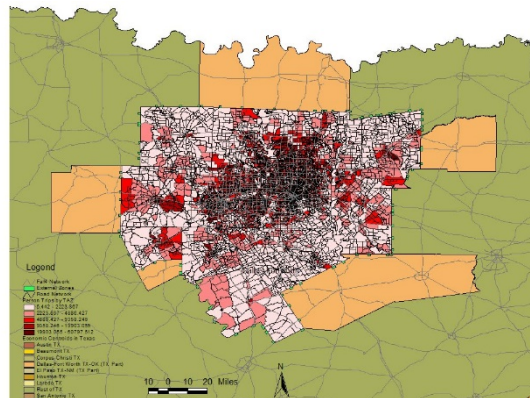
| a. Austin | b. Dallas-Fort Worth |

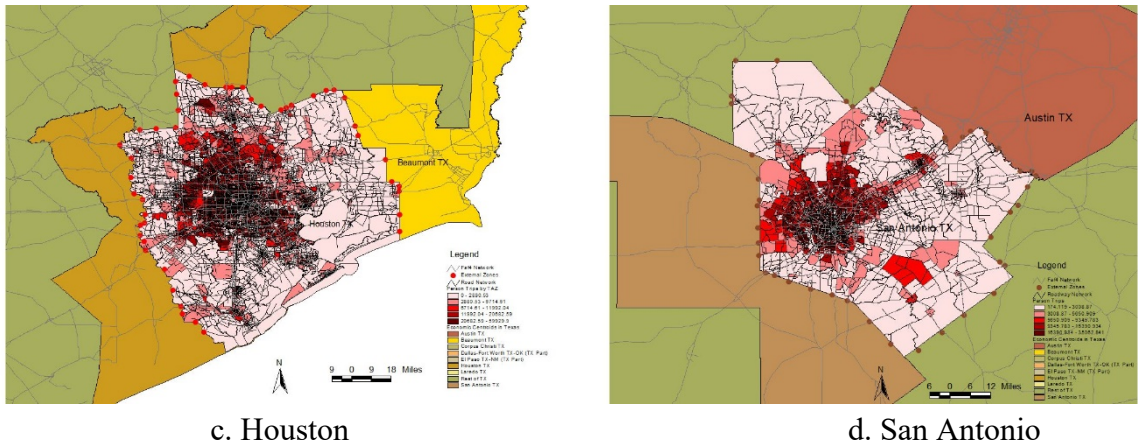| c. Houston | d. San Antonio |

Figure 3. Transportation data collected for Austin, Dallas-Fort Worth, Houston, and San Antonio

The Alamo Area Metropolitan Planning Organization (AAMPO) develops transportation plans and programs to address the needs of the greater San Antonio area, including Bexar, Comal, Kendall, Guadalupe, and Wilson counties, which is smaller than the FAF4 zone designated for the San Antonio metropolitan area. Atascosa, Bandera, and Medina County are a part of the FAF4 zone but are not included in the AAMPO transportation region (Figure 3d). AAMPO provided the passenger and freight trip ODs for 1,248 internal zones and 42 external zones, and a road network with 16,140 links and 6,256 miles. There were a total of 6,610,887 passenger trips and 621,961 freight trips, and 175,658 passenger trips and 31,509 freight trips were external trips (Table 1).

Table 1. Passenger and freight trips in the four metropolitan areas of the Texas Triangle

Metropolitan area	Passenger Trips			Freight Trips		
	Intra-metropolitan	External	Total	Intra-metropolitan	External	Total
Austin	11,358,138	320,610	11,678,748	979,844	51,333	1,031,178
Dallas-Fort Worth	19,511,249	331,914	19,843,163	662,478	95,528	758,006
Houston	15,545,394	181,121	15,726,515	1,122,215	31,924	1,154,140
San Antonio	6,435,229	175,658	6,610,887	590,453	31,509	621,961

Source: Author calculation based on data from local MPOs.

In addition to the transportation data at the metropolitan level, the project also obtained data for the inter-metropolitan level from federal agencies, including the passenger commuting data from

the US Census Bureau and freight transportation data from FAF4. The US Census Bureau's 2011-2015 5-Year ACS Commuting Flows data provided the commuting trips from workers' residence county to workplace county. The FAF4 provided commodity flow OD matrices in tonnage and dollar value for 132 pre-defined domestic regions, which are called economic centroids. Nine FAF4 economic centroids are located in Texas, including Austin, San Antonio, Dallas-Fort Worth, Houston, Laredo, Beaumont, Corpus Christi, El Paso, and the rest of Texas. Four of these nine economic centroids—Austin, Dallas-Fort Worth, Houston, and San Antonio—are located within the Texas Triangle. The Census ACS commuting flow data and the FAF4 commodity flow data fill the gaps in the passenger and freight trips that have at least one end outside of the four metropolitan areas of the megaregion.

A benefit of this research is that the heterogeneous transportation data we collect from a variety of sources were in similar formats and from almost the same base-year, i.e., H-GAC provided data from its 2015 base year model, and the US Census commuting tables were 5-Year ACS commuting flows from 2011 to 2015.

4.3. Data Analysis and Modeling Results

After data collection, the study followed the analytical framework in Figure 1 to process the intra-megaregion and inter-megaregion data for passenger and freight flows. The first step was to validate the data by comparing the passenger trips with population and employment at the TAZ or county level, checking the calculated freight ratios in the total vehicle fleet, and comparing freight trip data obtained from local MPOs and FAF4, etc. Researchers also examined passenger and freight trip densities and checked whether their distribution patterns matched the urban forms. The dollar value or tonnage of commodity flows for inter-metropolitan freight movement was converted to the number of trucks and further to PCEs by adopting the ratios estimated from the transportation data tool functions.

In addition to data validation, researchers aggregated the passenger trip ODs by trip purpose, occupancy, or time-of-day to a daily passenger trip OD for each of the four metropolitan areas, i.e., Austin, Dallas-Fort Worth, Houston, and San Antonio. Similarly, they also combined the

freight trip ODs categorized by truck type, highway type, or time-of-day into a daily freight trip OD for each of the four metropolitan areas.

As for the inter-metropolitan transportation data, passenger commuting data at the county level and freight truck flow data in the FAF4 zonal system were not compatible in geographic locations. Researchers developed a zonal system for the megaregion on a GIS platform, including the intra-metropolitan zonal systems adopted from MPOs, the counties outside of metropolitan areas but within the state, and the external zones out of the state. It has a total of 12,436 MAZs for the Texas Triangle, as listed in Table 2.

Table 2. The transportation megaregional analysis zones (MAZs) for the Texas Triangle

Name	TAZs	Internal Zones	External Zones	Descriptions
Ext-Tex	391	N/A	N/A	External zones located out of Texas
Austin	2,161	2,102	59	TAZs in Austin
Dallas	5,386	5,303	83	TAZs in Dallas
Houston	3,000	2,954	46	TAZs in Houston
San Antonio	1,290	1,248	42	TAZs in San Antonio
TexCounty-OutMetro	208	N/A	N/A	Texas counties out of the four metropolitan areas defined by FAF4
Total	12,436	N/A	N/A	Total number of zones for the megaregion

Source: Author preparation based on data from local MPOs and FAF4.

The megaregion zonal system for the Texas Triangle includes 391 external stations located outside of the state of Texas, which are identified through the FAF4 zonal system, the border entries, and other geographic information. It also incorporates the internal and external zones of the four metropolitan areas in the megaregion, which are exactly the same TAZ systems defined by their respective MPOs. It also includes the counties located outside of the four metropolitan areas but within the boundaries defined by FAF4. The design principle of the megaregion zonal system is

similar to the development of the TAZ system in regional transportation analysis or the census tract in socio-demographic analysis. The higher the population density, the smaller the size of the zones. There are a large number of intra-metropolitan transportation zones that usually have a smaller size and a much smaller number of inter-metropolitan transportation zones that have a much larger size due to differences in density. Figure 2 shows the megaregion zonal system, and Figure 3 illustrates the internal and external zones for each metropolitan area in the megaregion.

Following the analytical framework in Figure 1, the intra-metropolitan passenger trip tables for the four metropolitan areas in the Texas Triangle are combined with inter-metropolitan passenger trip ODs to build a megaregion passenger trip OD. Similarly, the intra-metropolitan freight trip tables for the metropolitan areas in the Texas Triangle are also incorporated with inter-metropolitan freight trip tables to create a megaregion freight trip OD.

To facilitate network analysis of megaregion passenger and freight movement, researchers adopted the transportation network from FAF4, which has 39,160 network links in Texas. Based on an assumption that all the network links have two ways or two directions, the number of network links based on the FAF4 data set becomes 78,320. Researchers also added two-way centroid connectors to each of the 12,436 network centroids. The total number of network links for the megaregion transportation system is 103,192 by incorporating 24,872 centroid connectors and 78,320 FAF4 network links.

In this study, the 103,192 highway network links were reorganized in the forward star data structure described by Sheffi (1985) to save space in computer memory and facilitate the management of the sequence list of links. In addition to from-node, to-node, length, and lanes, the network link attributes also include link capacity, speed, and link type attributes. The link capacity is obtained from the FAF4 data set, which estimates capacity using the methodology in the Highway Capacity Manual (HCM). The speed of a link is estimated based on the type of the link.

Once the megaregion passenger and freight trip ODs were prepared and the network links were developed, researchers adopted the user-equilibrium-based model with capacity constraints and the iterative procedure described in the methodology section to load both passenger and freight

flows into the megaregional transportation network. The model has run multiple iterations (more than 10 in this study) to reach convergence in 6 iterations (Figure 4).
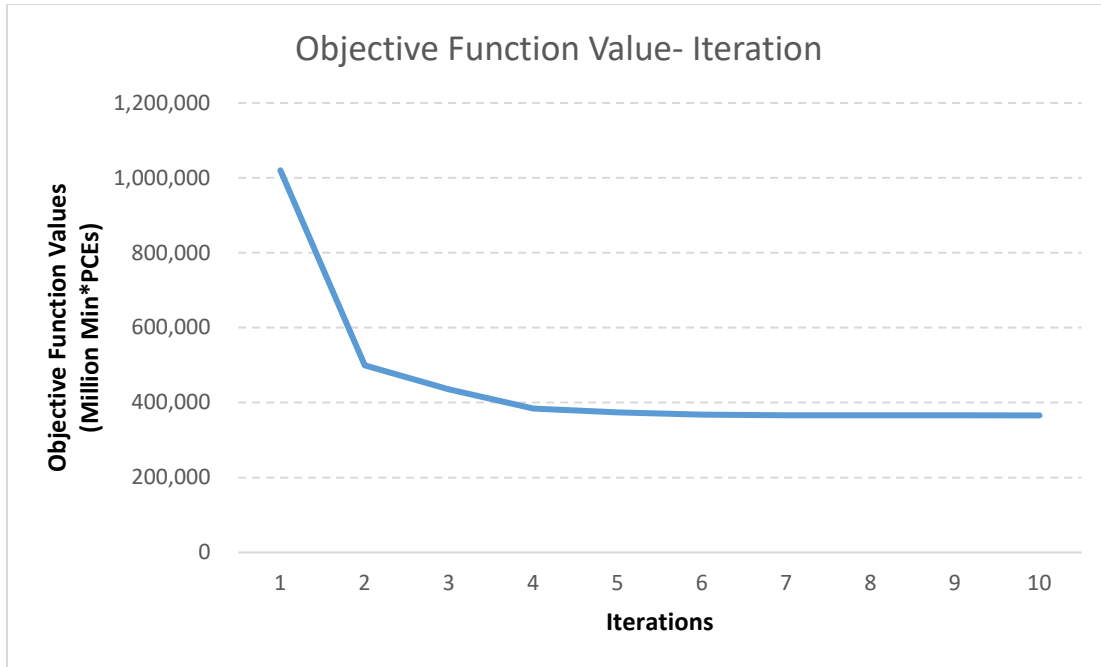

Figure 4. Objective function values vs. iterations using user-equilibrium assignment.

To be compatible with passenger trips, the freight trips are measured in PCE, which was converted from freight tonnage in the FAF4 database using the ton-per-PCE ratio estimated by Giuliano et al. (2010). Figure 5a and Figure 5b show the link volumes estimated by the user equilibrium assignment with link capacity constraints for passenger flows and freight flows, respectively.

Figure 5a and Figure 5b clearly show that passenger and freight flows have similar distributions in the Texas Triangle. The intra-metropolitan trips have much higher volumes than the inter-metropolitan trips. The inter-metropolitan trips have high volumes on the major highways, such as I-20, I-35, I-45, I-10, and I-37, etc. Fewer trips cross the state's borders than cross the boundaries of metropolitan areas in the Texas Triangle.

To facilitate transportation policy-making, researchers also estimated passenger accessibility to employment opportunities and freight accessibility in the northern and southern parts of the megaregion, which are shown in Figures 6a, 6b, 6c, and 6d. Due to the discrepancies between the

metropolitan boundaries defined by FAF4 and those defined by local MPOs, accessibility has not been calculated for a few counties outside of the boundaries of MPOs for transportation planning but within FAF4 zones designated for the four major metropolitan areas.
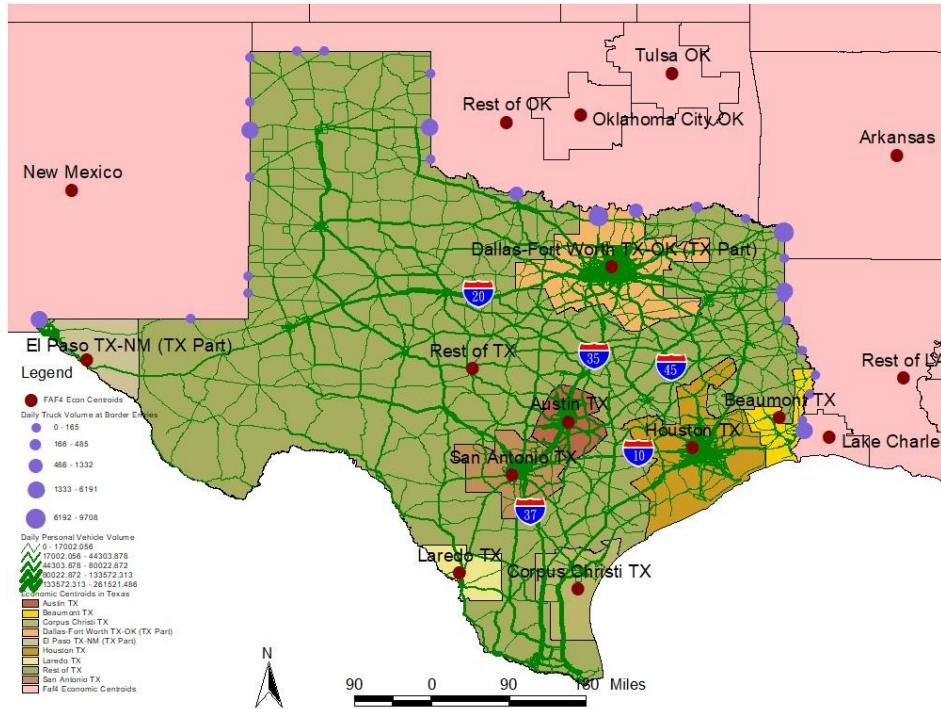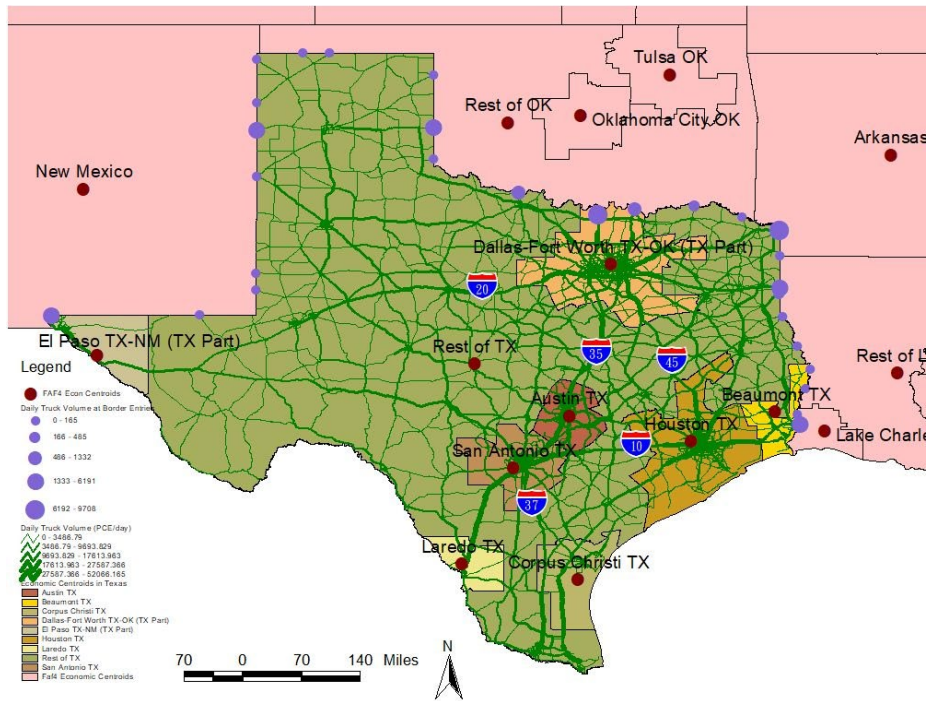

Figure 5a. Passenger Flows in the Texas Triangle.

Figure 5b. Freight Flows in the Texas Triangle.

The figures illustrate that the Texas Triangle, including the four major metropolitan areas and the clustered counties between them, has higher passenger accessibility and freight accessibility than do the other parts of the state. It is also interesting to observe different patterns of passenger and freight accessibility in the northern and southern parts of the Texas Triangle. Freight accessibility is more concentrated than passenger accessibility in the central part of the Dallas-Fort Worth metropolitan area while passenger accessibility is more concentrated than freight accessibility in the core of the Austin, Houston, and San Antonio metropolitan areas.
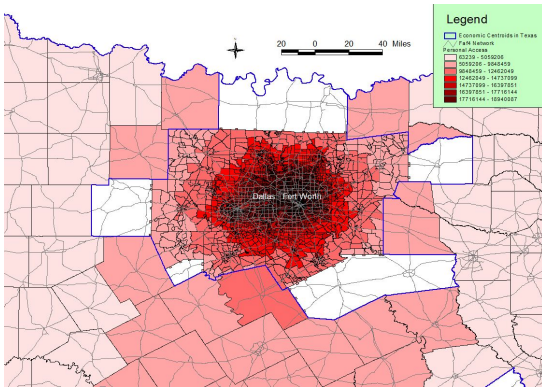
Figure 6a. Passenger accessibility in the northern part of the Texas Triangle.
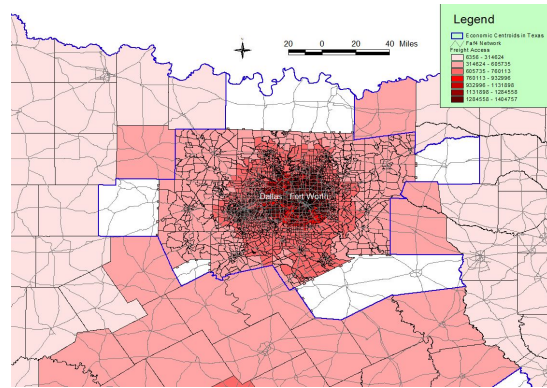

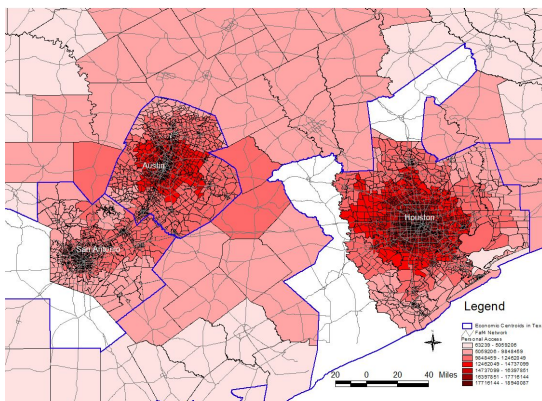Figure 6b. Freight accessibility in the northern part of the Texas Triangle.

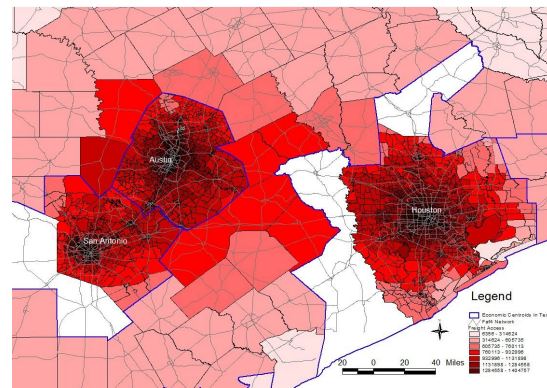Figure 6c. Passenger accessibility in the southern part of the Texas Triangle.

Figure 6d. Freight accessibility in the southern part of the Texas Triangle.

Chapter 5. Conclusions

Few studies have focused on the development and implementation of megaregional transportation models. It is a substantial challenge to build such models because they need to have both theoretical soundness and methodological validity in academic and professional studies, while at the same time they must meet the expectations of public agencies in terms of reliability, efficiency, and user-friendliness. NASEM (2017) highlighted that there is no operational megaregional model in the U.S. except for a prototype model developed for a part of a megaregion.

This study fills the gap by developing an operational model on a GIS platform for megaregional transportation planning. It extends the spatial scale of a regional transportation model to the megaregion, which accommodates larger areas, more passenger and freight trips, and more complex transportation networks. It illustrates the development of a megaregional transportation model in an analytical framework with four steps: megaregional transportation data processing, transportation data tool functions, megaregional transportation data integration, and megaregional network modeling. The Texas Triangle serves as an empirical case to demonstrate the procedures of framework design, data inventory, model development, and model implementation.

One of the outcomes of this study is that this model bridges the separation of passenger and freight movement in a megaregional transportation network. It provides an integrated framework and a design for megaregional analysis zones (MAZs) that breaks the spatial barriers between transportation planners and decision-makers in transportation planning agencies at the federal, state, and local levels and allows them to work together to coordinate projects and policies in megaregions.

This model also provides a base for the development of advanced application scenarios. This capability allows decision-makers and planners to gain a better understanding of the potential impacts of policies, plans, and events in megaregion. For example, it has provided insights into passenger and freight accessibility in megaregions. It is capable of estimating the economic and transportation impacts of high-speed rail connecting Dallas-Fort Worth and Houston. It also

enables planners to study the effects of autonomous vehicles in megaregional transportation systems.

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