The Thesis Committee for Rohan Jayesh Shah
certifies that this is the approved version of the following thesis:

Dynamic Traffic Assignment-Based Modeling Paradigms for Sustainable Transportation Planning and Urban Development

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________
Stephen D. Boyles

____
Jennifer C. Duthie

____
Randy B. Machemehl

Dynamic Traffic Assignment-Based Modeling Paradigms for Sustainable Transportation Planning and Urban Development

by

Rohan Jayesh Shah, B.E.

Thesis

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Dynamic Traffic Assignment-Based Modeling Paradigms for Sustainable Transportation Planning and Urban Development

Rohan Jayesh Shah, M.S.E.
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Supervisor: Stephen D. Boyles

Transportation planning and urban development in the United States have synchronously emerged over the past few decades to encompass goals associated with sustainability, improved connectivity, complete streets and mitigation of environmental impacts. These goals have evolved in tandem with some of the relatively more traditional objectives of supply-side improvements such as infrastructure and capacity expansion. Apart from the numerous federal regulations in the US transportation sector that reassert sustainability motivations, metropolitan planning organizations and civic societies face similar concerns in their decision-making and policy implementation. However, overall transportation planning to incorporate these wide-ranging objectives requires characterization of large-scale transportation systems and traffic flow through them, which is dynamic in nature, computationally intense and a non-trivial problem.

Thus, these contemporary questions lie at the interface of transportation planning, urban development and sustainability planning. They have the potential of being effectively addressed through state-of-the-art transportation modeling tools, which is the main motivation and philosophy of this thesis. From the research standpoint, some of these issues have been addressed in the past typically from the urban design, built-environment, public health and vehicle technology and mostly qualitative

perspectives, but not as much from the traffic engineering and transportation systems perspective—a gap in literature which the thesis aims to fill. Specifically, it makes use of simulation-based dynamic traffic assignment (DTA) to develop modeling paradigms and integrated frameworks to seamlessly incorporate these in the transportation planning process. In addition to just incorporating them in the planning process, DTA-based paradigms are able to accommodate numerous spatial and temporal dynamics associated with system traffic, which more traditional static models are not able to. Besides, these features are critical in the context of the planning questions of this study.

Specifically, systemic impacts of suburban and urban street pattern developments typically found in US cities in past decades of the 20th century have been investigated. While street connectivity and design evolution is mostly regulated through local codes and subdivision ordinances, its impacts on traffic and system congestion requires modeling and quantitative evidence which are explored in this thesis. On the environmental impact mitigation side, regional emission inventories from the traffic sector have also been quantified. Novel modeling approaches for the street connectivity-accessibility problem are proposed. An integrated framework using the Environmental Protection Agency's regulatory MOVES model has been developed, combining it with mesoscopic-level DTA simulation. Model demonstrations and applications on real and large-sized study areas reveal that different levels of connectivity and accessibility have substantial impacts on system-wide traffic—as connectivity levels reduce, traffic and congestion metrics show a gradually increasing trend. As regards emissions, incorporation of dynamic features leads to more realistic emissions inventory generation compared to default databases and modules, owing to consideration of the added dynamic features of system traffic and region-specific conditions. Inter-dependencies among these sustainability planning questions through the common linkage of traffic dynamics are also highlighted.

In summary, the modeling frameworks, analyses and findings in the thesis contribute to some ongoing debates in planning studies and practice regarding ideal urban designs, provisions of sustainability and complete streets. Furthermore, the integrated emissions modeling framework, in addition to sustainability-related contributions, provides important tools to aid MPOs and state agencies in preparation of state implementation plans for demonstrating conformity to national ambient air-quality standards in their regions and counties. This is a critical condition for them to receive federal transportation funding.

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Chapter 1

Introduction and Motivation

The introductory chapter lays the foundations for this thesis. It enumerates the larger motivations behind the current research. It also establishes the premise on which some of the research questions in sustainable transportation and urban planning explored here are based on, and gives an overall background for the work.

The main research goals and contributions of the thesis are addressing some issues transportation planning and urban development sectors face in terms of sustainable growth and policy implementation by means of dynamic traffic assignment (DTA). These questions are contemporary from the point of view of various federal directives and objectives laid out for regional transportation planning process in recent times. Transportation planning inadvertently invokes traffic mechanics and ever-increasing urban congestion dynamics. There is a growing need for methodologies that inform regional planning decisions and policies that effectively account for these inherent traffic characteristics. This thesis develops integrated frameworks that advance that direction and are readily implementable by practitioners.

The planning questions investigated include quantification of traffic-related impacts of street pattern developments and their connectivity-accessibility aspects. These typically manifest in urban and suburban settings in the US. Also, questions related to environmental and air-quality impacts of the transportation sector in the form of emissions are addressed. This sector has emerged as a major contributor to global air pollution. Integrated modeling frameworks for the connectivity-accessibility problem and the traffic emissions modeling problem are proposed, using mesoscopic-level

DTA simulation. The framework applications to realistic study areas reveal substantial impacts street patterns and corresponding connectivity levels have on system-wide traffic and congestion metrics. They show a gradual increase with a reduction in connectivity levels. The emissions modeling framework and its comparison with some conventional planning strategies and wide state-of-practice brings to light the effects of incorporating additional dynamic features of traffic and region-specific conditions. These findings contribute to planning methodologies from the sustainability perspective and provide quantitative support for some of the arguments in favor of sustainable development and 'neo-urbanist' smart-growth. At the same time, DTA-based modeling paradigms developed contribute to transportation modeling practice and research, and are smoothly integrable in long-range planning process. DTA model applications are finding scope in a diverse set of areas in transportation planning and traffic modeling in recent times. More recently, MPOs and other planning agencies have been adopting DTA models to complement their long range planning models. Capital Area Metropolitan Planning Organization (CAMPO, Austin, TX), North Central Texas Council of Governments (NCTCOG, Dallas, TX) and the San Francisco County Transportation Authority (SFCTA, San Francisco, CA) are a few instances. The next step in the evolution of the MPO toolbox is to make traffic dynamics direct the emissions modeling process–DTA based frameworks such as the one in this study advance that direction. However, utilities of DTA in augmenting and realizing sustainability related goals have not been developed extensively in research literature and practice. Also, an amalgamation of newer simulation-based paradigms, overall traffic dynamics and sustainability questions is still in nascent stages.

Sustainable growth and planning have gained momentum in recent years and permeated many diverse areas spanning transportation planning, modeling, urban development, community neighborhood improvements and regional planning. As asserted by Mihyeon and Amekudzi (2005), sustainability in transportation is characterized by system efficiency and environmental impacts of the system. It has been affirmed that communities bettering sustainability features of the transportation networks within them are benefiting the wider goals of creating vibrant and livable urban regions. The frameworks and research insights developed through this thesis lay an essential quantitative groundwork and provide relevant tools for further analyses in these domains.

1.1 Background

1.1.1 Metropolitan Planning Organizations and Regional Transportation Planning in the United States

The Federal-Aid Highway Act of 1962 set the foundations of metropolitan planning organizations (MPOs) for urbanized areas with populations greater than 50,000 in the United States. Federal funding for large-scale and regional transportation projects began to be routed through MPOs, who were mainly responsible for transportation planning and policy-making of the regions under them. Some of the fundamental mandates and functions of MPOs regarding transportation planning and development are the following:

- Setting a base for effective regional planning and decision-making in the metropolitan area;
- Identifying and evaluating regional transportation issues, their nature, magnitude and potential approaches for resolving them;
- Maintaining long-range transportation plans (LRTPs), spread across at least twenty years into future planning horizons. LRTPs must mainly account for smooth mobility and access for people and goods, improving transportation system performance and efficiency and looking at the quality aspects of human life;

- Fostering public, citizen and civic-group involvement; and
- Protecting regional environment and air-quality through conformity to the emissions and pollutant standards and plans, known as state implementation plans (SIPs), for the state under which the urban area geographically lies.

Closely on the heels of the Highway Act of 1962, the National Environmental Policy Act of 1969 (NEPA) was signed into Law. While it did not exclusively aim at the transportation sector, it included the sector in its regulations. NEPA established mandates for federal agencies to account for the potential environmental consequences of their proposals, and exhaustively document the analysis. The Intermodal Surface Transportation Efficiency Act (ISTEA, 1991) brought about landmark changes and developments in the role of MPOs. Additional federal funding was allotted to MPOs and their purview and authority was expanded to include more metropolitan planning initiatives and projects. The underlying motivations were mitigating traffic congestion, increasing both in magnitude and complication in terms of patterns and unpredictability. This was in tandem with robust suburban developments in previous decades. The Transportation Equity Act of the 21st Century (TEA-21) in 1998 reauthorized the ISTEA stipulations. Looking into the future directions of these lines of policy development in transportation, the Moving Ahead for Progress in the 21st Century Act (MAP-21) , which mainly deals with federal funding and authorization for surface transportation in the US was signed into law in 2012. Reforms put forth by MAP-21 spanned a diverse set of areas from tolling to freight, and included an upgraded environmental review procedure and increased programs and budgets for MPOs.

1.1.2 Extracting the Planning and Sustainability Questions

The above discussion on the foundations and core functions of MPOs, and motivations behind ISTEA's 'renaissance' (as noted by Compass Community Planning Association of Southwest Idaho) for the MPO and its competencies bring to fore some important issues that are not just germane to urban transportation planning. These also show potential to be effectively addressed through advanced traffic modeling paradigms. This forms the main motivations of this thesis. These issues particularly include traffic congestion mitigation and the inherent complications associated with predicting congestion patterns, their magnitudes and locations. Federal regulations associated with the above issues and their identification in this context as noted above further build up the motivation. Investigating the synchronous rapid urban development, analyzing its effects and putting forth the mechanics for quantifying environmental impacts of transportation, all this while accounting for inherent variable features of traffic can all be brought together under one umbrella. This is the underlying research philosophy and motivation of this thesis.

1.2 Research Objectives and Contributions

Specific research objectives and approaches to meet the above mentioned philosophies are discussed here. The thesis aims to address some specific questions that were extracted from the context discussed in Subsection 1.1.2. It demonstrates the close interactions occurring in the urban transportation scheme of things, between traffic and local street development patterns, and between traffic and the environment in the form of vehicular emissions. The thesis underscores and makes further use these interactions to answer the planning questions, and professes that they have a good potential of being addressed by advanced traffic modeling. The research questions are germane to regional transportation planning, and the larger areas of urban planning and development. The paradigm change that has occurred in street patterns, their evolution over the past decades has been the subject of many a debate in urban planning literature and practice. The specific arguments for and against these patterns would be discussed in a later chapter. The second component of environmental impacts permeates almost any developmental undertaking such as urban growth, transportation infrastructure development. It is particularly tied closely with the traffic sector since traffic is a direct source of pollution.

The two questions put together form an integral part of issues that are under major ongoing critique, policy-making and active research across a diverse set of areas. These are environmental sciences, transportation planning, urban design, automotive technology and health sciences. These issues are contemporary as they are increasingly manifesting themselves in planning and development decisions at the regional level. At the same time, these are classical owing to their origins in federal directives and MPO regulations beginning the sixties. The essentially 'dynamic' features associated with traffic and congestion are strongly inter-related with them, as would be demonstrated through this thesis by employing advanced traffic assignment modeling, and scientific evidence through rigorous data analysis and computation. These close inter-relations can be very effectively used to answer and technically inform these planning questions. Specifically, simulation-based dynamic traffic assignment (DTA) is used. It is a state-of-the-art technique for simulating vehicular traffic and its propagation through a transportation system. DTA tries to capture the relationship between dynamic route choice behavior of travelers (path and departure time choice) and the characteristics of transportation networks. The thesis develops tools that cogently tie-in these sustainability planning questions with a DTA framework, and propose comprehensive modeling paradigms for analyzing their individual interdependencies with traffic and congestion dynamics. The frameworks are made generic enough to be readily implementable on a variety of test-beds and applications. The discussion on the virtues of using DTA with respect to each of the separate planning questions and its relevance in the current research will be given a separate treatment in the respective sections, where each of these problems would be analyzed individually. At the same time, a more generic background and applicability of DTA will also be provided. The thesis, from an application standpoint, thus lies at the interface of multiple domains of research. These are transportation science and technology, traffic modeling, environmental science and urban planning and policy studies.

1.3 Thesis Organization

Thus, the thesis is organized in the following manner. Chapter 2 gives a detailed background and applicability of DTA for metropolitan planning purposes and the particular modeling framework used in this thesis. Chapter 3 deals with the potential transportation planning and traffic engineering issues associated with street development patterns and the urban form, particularly using the concepts of connectivity and accessibility; a DTA-based modeling methodology is proposed for investigating the same It also covers a policy brief on the state of practice in this domain and its implications. Chapter 4 covers the investigation of emissions and air-quality aspects of the transportation sector at the same time taking into account traffic dynamics and to this end, develops an integrated emissions-DTA modeling framework using the US Environmental Protection Agency's regulatory mobile-source emissions modeling package, MOVES 2010.

For each of these exploratory questions and respective model developments, the essential background, literature review, specific tasks, methodologies, demonstrations and study-area applications, findings and subsequent analyses will all be covered in the respective chapters. This is done mainly to ensure a consistency of ideas and maximum coverage of the individual research aspects. Chapter 5 will cover a general discussion of the research outcomes and discuss the applicability to other contemporary and future planning research. The chapter will conclude with a summary of research contributions and methodologies developed in the thesis, and a discussion on related future research avenues.

Chapter 2

Dynamic Traffic Assignment Modeling Approaches and Applicability

This chapter goes into specific descriptions of DTA models and their underlying concepts. A general discussion on DTA models, its various utilities pertaining to the research questions of the thesis will be presented. Also, the specific DTA modeling package used in this study—VISTA will be introduced and discussed.

2.1 Background and Utilities of DTA

The research questions addressed in the thesis are investigating system-wide traffic impacts of street connectivity and development of an integrated framework for traffic emissions modeling. The needs for accounting traffic dynamics and its potential interactions with these questions were highlighted in the previous chapter. Hence it is critical that the system traffic is realistically characterized and represented. To this end, simulation-based DTA modeling is employed in this study.

DTA is an iterative tool to assign travelers or trips onto the transportation network based on total demand for travel in the system. The underlying principle behind DTA applications is the principle of dynamic user-equilibrium (DUE). A comprehensive discussion on DUE can be found in the Dynamic Traffic Assignment Primer, developed by Chiu et al. (2011), published by Transportation Research Board. The DUE principle states that all trips between the same origin and destination, and departing in the same time period, have approximately the same travel cost. DUE principles, in addition to applicabilities of DTA have been exhaustively described in Peeta and Mahmassani (1995) and Peeta and Ziliaskopoulos (2001), among others. The foundations of DTA were developed in pioneering works by Merchant and Nemhauser (1976, 1978). Users or drivers in the system are assumed to be aware of the network conditions and are assumed to exhibit rational time and cost-saving behavior. Under these assumptions, the DUE principle can then be used to represent a state a system attains over a gradual period of time when drivers have adjusted their route choices and everyone is close enough to the shortest possible paths between the respective origins and destinations.

As the term 'dynamic' suggests, DTA can capture route choices and congestion patterns varying over both time and space, as opposed to the more traditional static traffic assignment models. Static models implicitly assume steady-state conditions and give a highly time-aggregated picture of the network. They are unable to give sufficient insights on congestion locations and times, vehicle queue formations and spill-backs, basically leading to an under-representation of over-saturated network conditions and peak-hour traffic spreading. The last few factors are ones that can have impacts on vehicle emissions, as vehicle operating modes alternate quite rapidly in these processes. This makes the emission rates of pollutants quite rapid. Also, using STA models can sometimes lead to a insufficient predictions of locations of congestion, most commonly downstream of the bottleneck instead of the upstream, and are also unable to account for the fact that bottlenecks will affect downstream traffic conditions. According to the DTA Primer, by Chiu et al. (2011), DTA model analysis results can be used to evaluate many meaningful measures related to individual travel time and cost, as well as system-wide network measures for regional planning decisions such as this study.

Taking a step closer towards finer link-level scenarios, it is understandable that congestion conditions and subsequent travel metrics on a link can be dependent on the conditions of links both upstream and downstream. While static models do not consider these effects, DTA models do. This might neither be too evident nor too influential in free-flow and non-congested conditions. But would under congestion and saturated conditions, these factors are important. DTA is able to account for queue formation and spill-backs during saturated network conditions. As shown in the background example, local connectivity and accessibility can play an important role in travel experience in general, and it is important that traffic congestion be explicitly addressed in the modeling framework. Figure 2.1 illustrates the main steps in the DTA-based modeling approach.

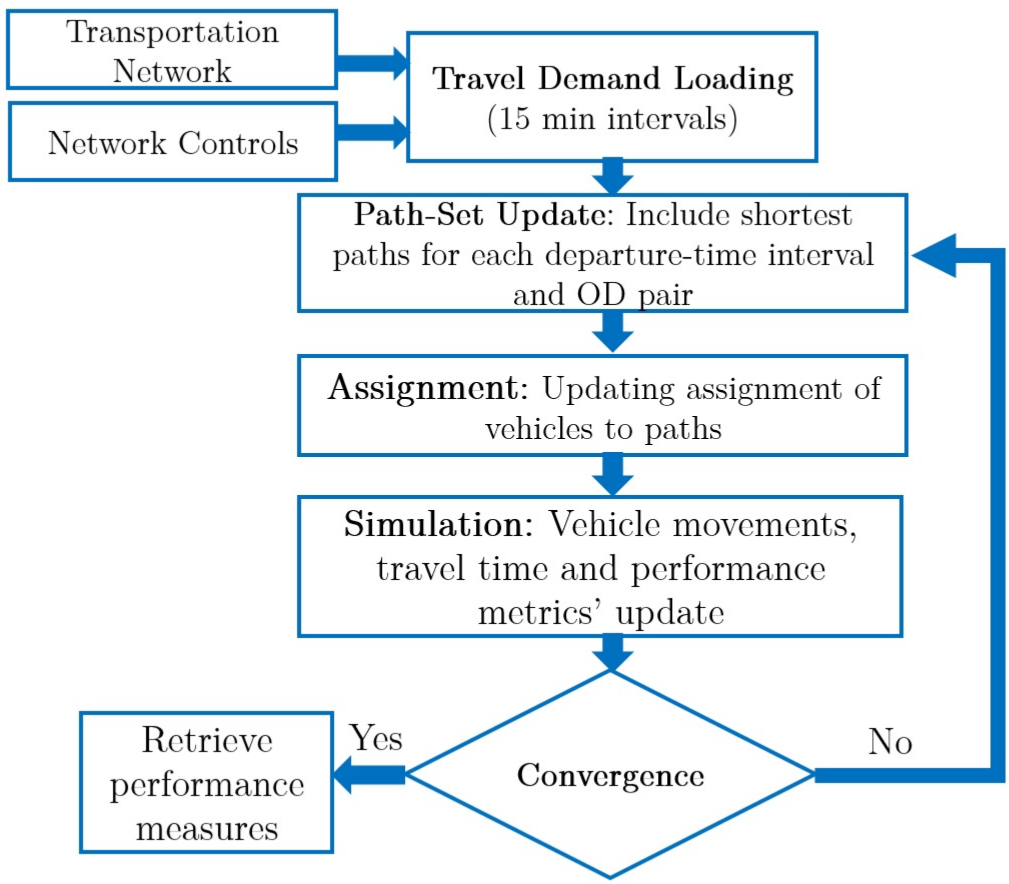

Figure 2.1: DTA methodology flowchart

2.1.1 Applicability to Metropolitan Transportation Planning

DTA is flexible enough to be applied to models of different sizes and resolutions and also to different contexts based on temporal scales of interest. The Traffic Analysis Toolbox Volume XIV: Guidebook on the Utilization of Dynamic Traffic Assignment in Modeling (Report FHWA-HOP-13-015) by Sloboden et al. (2012) is a noteworthy compilation of the virtues and specific factors influencing the applicability of DTA to regional transportation planning models. It provides guidance to practitioners, managers and software developers on DTA methods and potentially helps inform MPOs and state DOTs of the benefits arising from DTA based planning applications. The guidance is aimed at informing appropriate applications of DTA tools for transportation decision making, such as the one in this thesis. The frameworks developed in this thesis are aimed at providing quantitative and empirical support for some of these applications from the sustainability planning standpoint. These factors that have gained much more mileage and importance in recent times as mentioned earlier. Figure 2.2 illustrates the various practical aspects of DTA that may be of interest based on the specific application, problem motivation and the corresponding scope of research.

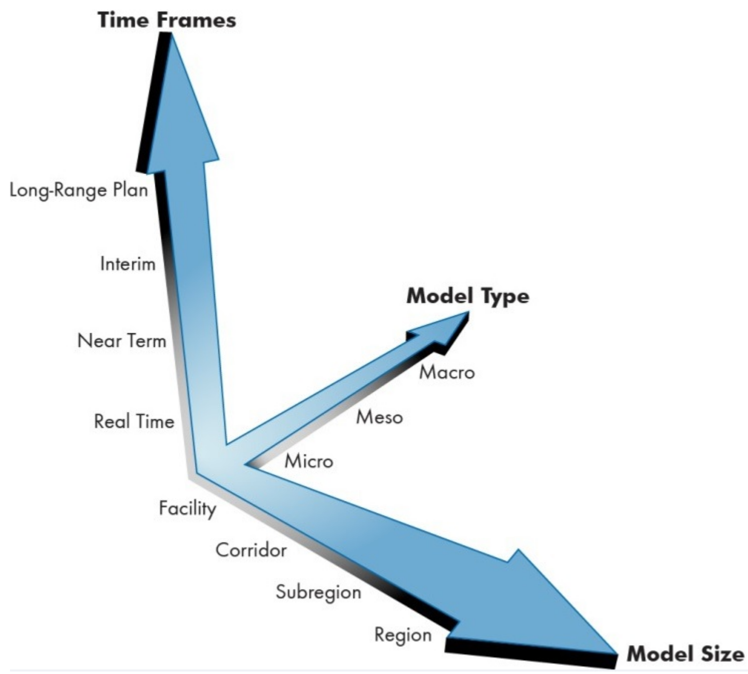

Figure 2.2: DTA modeling considerations during different applications. *Adapted from FHWA-HOP-13-015, by Sloboden et al. (2012)*

It can be seen that there is a flexibility in model network size, a feature relevant to the current research since the frameworks developed are meant to serve regional transportation planning whose areas of operations can be variable depending on the region. Other points of interest are flexibility in levels of detail and the associated ease of data management, variability in modeling time frames and modeling sizes which are crucial practical considerations for MPOs and DOTs.

2.2 The VISTA DTA Modeling Package

In order to meet the DTA modeling needs for this study, VISTA (Visual Interactive System for Transport Algorithms) network modeling package is used. It has a GUI, that integrates spatio-temporal data and models for a wide range of transport applications in planning and engineering. VISTA's DTA approach is based on the cell transmission model (CTM), originally proposed by Daganzo (1994) and developed as a discrete version of the hydrodynamic traffic flow model. The CTM is a simulation-based model which divides network links into shorter ‘cells’, the number of vehicles in each ‘cell’ are then computed through a series of discrete time steps of small values such as six seconds. There is a restraint on the maximum number of vehicles in each cell and also on the maximum number of vehicles that can move from one cell to the other by taking into account the link capacity. Since link capacity plays an important role of restricting movement of additional vehicles, both per cell and a number of cells taken together (a link), vehicle flows are sort of strictly prohibited from exceeding cell and link capacities. But if in case, (and this occurs too often in real-life situations too) the demand for a cell exceeds the available capacity of it, queuing sets in in front of the cell, and this helps maintain vehicle flows less than available capacity.

The VISTA model, an extension of the CTM model, is able to model scenarios in a realistic fashion and it is an extension to CTM in the sense that the cell size is made adjustable, based on the number of vehicles that need to be accommodated. This makes it more flexible and helps in terms of computational effort as well. The scale of modeling is mesoscopic, which makes it the most effective in conducting regional level analysis from the point of view of accuracy and computation time considerations. The mesoscopic scale is able to draw a reasonable trade-off between the level of detail and its tractability, thus making it suitable to be applicable to networks and study-areas of varying proportions unlike relatively finer micro-simulation traffic flow models. This feature is of significant practical interest, as is enables DTA to be applicable to larger regional level study areas like the one in this study.In the context of the integrated emissions modeling framework, the mesoscopic scale is compatible well with the MOVES county-domain selection.

VISTA uses an SQL-based database management system, where all the tables related to the regional demand data, network characteristics and model-run outputs are stored, and can be easily accessed via queries or directly via the GUI. Thus, the

VISTA model provides good capabilities to run both regional-level and finer local-level DTA analysis, and is suited well for integration with an highway source emissions modeling software package in a smooth and compatible manner.

Chapter 3

The Street Connectivity-Accessibility Problem

This chapter covers the first planning question noted in the previous chapter, relating to urban and suburban development patterns and their influences on traffic, congestion aspects, and overall regional transportation planning.

3.1 Background and Motivations

Research into street connectivity has focused primarily on its impacts on non-motorized users or active transportation, as appears in Saelens et al. (2003), Dill (2004), Oakes et al. (2007), Frank and Engelke (2001). It has also focused on health outcomes, as in Saelens et al. (2003), Takano et al. (2002), Oakes et al. (2007), Maibach et al. (2009), and even injury incidents in youth, as in Mecredy et al. (2012). In parallel, Leck (2006), Crane (1996), Crane and Crepeau (1998), Ewing and Cervero (2001), Cervero and Radisch (1996) conducted studies that linked urban forms and designs with travel behavior. Accessibility is the ability to connect people to services and activities, while mobility represents the amount of travel actually occurring. Accessibility can be influenced by system connectivity, mobility substitutes, and land use patterns, as postulated by Litman (2008). Parthasarathi and Levinson (2010) extended the research in quantifying mobility, and Levinson (1998) and Handy and Niemeier (1997) in quantifying accessibility. Xie and Levinson (2007) and Parthasarathi et al. (2012) examined road network structures to conduct related analyses such as spatial separation. However, not a lot of research has extended into drawing direct correlations between accessibility and mobility. Traditionally, transportation and regional planning have focused on improving mobility through roadway capacity improvements and road-network expansions. Planning decisions often involve trade-offs between different types and levels of connectivity, as propounded by Litman (2008). Neo-traditional neighborhood designs intend to improve accessibility through basic changes in land-use patterns and street geometries, thus improving efficiency in travel and activity patterns as reported by McNally (1993). Ben-Joseph (1997) and Kulash et al. (1990) report that supporters of these designs assert that a highly interconnected street network in a continuous grid-format helps travel distance and time, extend public transit accessibility and reduce automobile dependency. A set of studies established relations between connectivity and VMT using discrete and neighborhood-specific metrics such as intersection density, road density, 4-way intersection percentage, and so on. These include Boarnet et al. (2003), Ewing and Cervero (2001) and Cervero and Kockelman (1997). Dumbaugh and Rae (2009) show that better connected grid networks face fewer accident occurrences than cul-de-sac dominated neighborhoods surrounded by high-speed arterials. A synthesis of motivations for providing better street connectivity and arguments from various different perspectives can be found in Handy et al. (2003). This synthesis also reports that a many cities across the US are adopting subdivision ordinances that promote higher street connectivity.

The thesis researches the impacts network connectivity and accessibility can have on a transportation systems performance. Accordingly, it studies the relationship between network connectivity and mobility, using advanced techniques like DTA. DTA accounts for the spatial and temporal variations in network traffic . The main contribution is to present a modeling strategy to evaluate the impact that changing a networks connectivity can have on travel-related performance metrics. Since impacts on traffic and travel metrics have to be quantified, it becomes imperative to make use of tools that are able to exhaustively incorporate characteristics of traffic and the underlying user (driver) behavior in transportation systems. DTA integrates these effectively and realistically. Further, unlike much previous research on connectivity, this research quantifies system-wide and large-scale impacts, as opposed to local impacts on certain neighborhoods or intersections. The new method is demonstrated on a study area in Austin, Texas, but the approach is generic and can be applied to any region.

The remainder of this chapter on street connectivity progresses as follows–Section 3.2 illustrates the influence street connectivity and design can have on the actual accessibility it provides. The methodology is discussed in Section 3.3, along with modeling strategies for three different levels of connectivity. Specific virtues of a DTA-based modeling paradigm are also discussed. The model application to the Austin study area is described in Section 3.4, which also includes the findings and subsequent analysis. Section 3.5 concludes by highlighting the implications of the study and a general discussion on the current and future research aspects.

3.2 Street Connectivity Trends: Policy Briefing

Street designs are a key variable in accessibility evaluations, as suggested by Oakes et al. (2007). Historically, most cities were laid out in densely interconnected networks that enabled people to get around before cars became ubiquitous. Starting around the time of World War II, opinion toward grid-like networks shifted; as publicized by the Federal Housing Authority in the 1930s, they were monotonous, unsafe and "characterless" (The Atlantic Cities, online, 2011). These designs gave way to more dispersed and less-connected cul-de-sac like designs, in tandem with the public adaptation to the car mode. The street car and its inclusion in the civic life was thus the major determinant in the paradigm shift in street network designs. The conventional street grid provided optimal accessibility and made most use of the available land. The transition towards more curvilinear patterns caused a significant reduction in connectivity and at the same time, reduced the actual meaningful usage of the land.

The reasons for this evolution of patterns are slightly more subtle, historical and in a sense, self-contradictory–automobiles provided more mobility but they also brought with them risks of accidents involving pedestrians and children playing on the street, lack of privacy to homes and so on. Some studies have reported the related ideologies, discussed later in this section. These cul-de-sac patterns were thus intended to keep the automobiles away from most local houses and provide more privacy by restricting their free and fast passage anywhere at will as it would have occurred in a grid-like structure. These patterns, as a whole, restricted the vehicle through-fare on local streets. All of this contributed to the prevalence of rather dispersed, dendritic pattern in the middle of the 20th century and henceforth. While the privacy and safety concerns that arose then cannot be discounted, these restrictive patterns can have significant effects on traffic and accessibility, and regional transportation system performance as a whole. This would become evident by a small motivational example in this section and showcased through this study on the system level.

To put this discussion on historical emergence of street patterns in perspective, Figure 3.1 illustrates the changing trends in designs over the decades, through sub-figures from left to right. The thicker lines represent arterial roads and the thinner ones represent local connecting streets. Beginning from the conventional grid-like patterns in the 1900s (extreme left), the trend transformed towards more curvilinear loop-like patterns during the 1930-1950s, (second and third from the left) thus setting a background and marking the introduction of more pronounced cul-de-sac like patterns. The one on the extreme right shows the dendritic cul-de-sac like patterns prevalent post-1950-1960s that continued more or less until recent times.

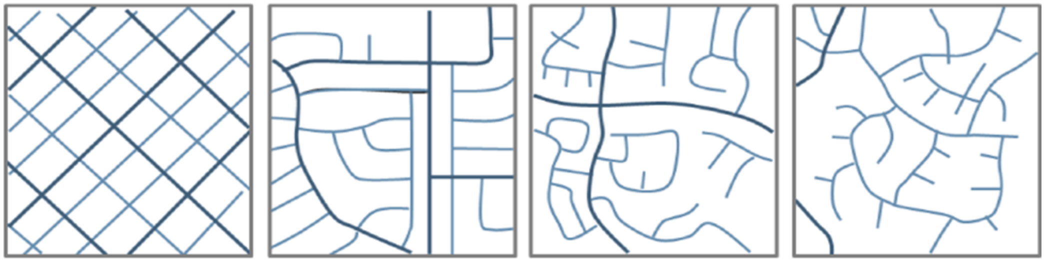

Figure 3.1: Street pattern trends over the decades. *Adapted from Marshall and Garrick (2010)*

These changing trends in the patterns in which these local streets are designed and laid-out represent varying degrees of connectivity. They can have significant impacts on the accessibility to arterials, major roads and consequently to services and opportunities. Figure 3.2 illustrates two street pattern design extremes, one the grid-like pattern, other the cul-de-sac pattern, and the accessibility impacts they can have in the present context.

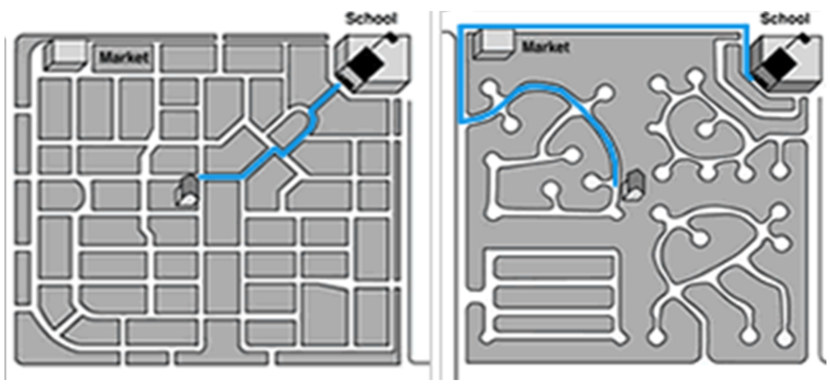

Figure 3.2: Grid (left) and cul-de-sac (right) patterns and their accessibility impacts. *Adapted from Safe Routes Information.org*

It can be seen that for the same trip, the two network patterns lead to much different experiences in terms of travel distance. This simple but insightful example puts this research in perspective. This difference in the 'amount of travel required can affect individuals decisions to walk, bike or use an automobile. All of this when considered at an aggregated scale, that is at the regional street-pattern scale can have significant community health and environmental impacts such as higher mobile source emissions from vehicles and more incidences of ailments occurring due to lack of physical activity. However, there have also been have been arguments in favor of cul-de-sac like street patterns by suggesting that they are relatively safer for children and provide more privacy, such as the one in Sanoff and Dickerson (1971). The dead-end like situation ensured that automobiles cannot pass through at high speeds and provided a sense of safety. It has also been claimed in studies such as Bookout (1992) that realty demand and prices for the most isolated cul-de-sac lots are often higher. Suburban home dwellers might even pay a premium to be located on such cul-de-sacs. While these are some of the other dimensions of the street design debate, the lack of many interconnected pathway systems between cul-de-sacs, adjacent streets, and neighborhoods substantially affects accessibility. They do not turn out to be favorable for active transportation. The cul-se-sac designs have thus created high dependence on the automobile, and according to Southworth and Ben-Joseph (2004), come to symbolize all problems of suburbia. From the travel standpoint, connectivity is important not just for the accessibility to destinations as described in the motivational example above, but also from the point of view of spreading traffic more evenly through the network by making alternate routes available. While network connectivity, especially for local streets is mainly regulated through local codes and subdivision ordinances, its standalone impacts on traffic and system congestion requires modeling exercises and quantitative evidence.

3.3 Experiment Methodology

The methodology is focused on a novel modeling strategy that helps quantify the large-scale and system-level impacts of connectivity features. This section discusses the framework and the scenario generation for different connectivity levels.

3.3.1 The Traffic Analysis Zone (TAZ) Paradigm

The discussion of the experiment methodology is initiated by providing a brief description of the TAZ paradigm, common in transportation modeling exercises. TAZ constructs, as presented here, are germane to this experiment. Regional transportation models typically divide a study area into smaller geographical units called TAZs, whose spatial extent varies with models. A conceptual development and a detailed discussion regarding TAZs can be found in de Dios Ortúzar and Willumsen (2001). Within each TAZ is a centroid, which represents the point of origin and/or point of destination. Centroids are artificial constructs used to load trips onto and off of the network. Each centroid is connected to a node in the actual network via one or more centroid connectors, another artificial construct for the purpose of loading or offloading trips.

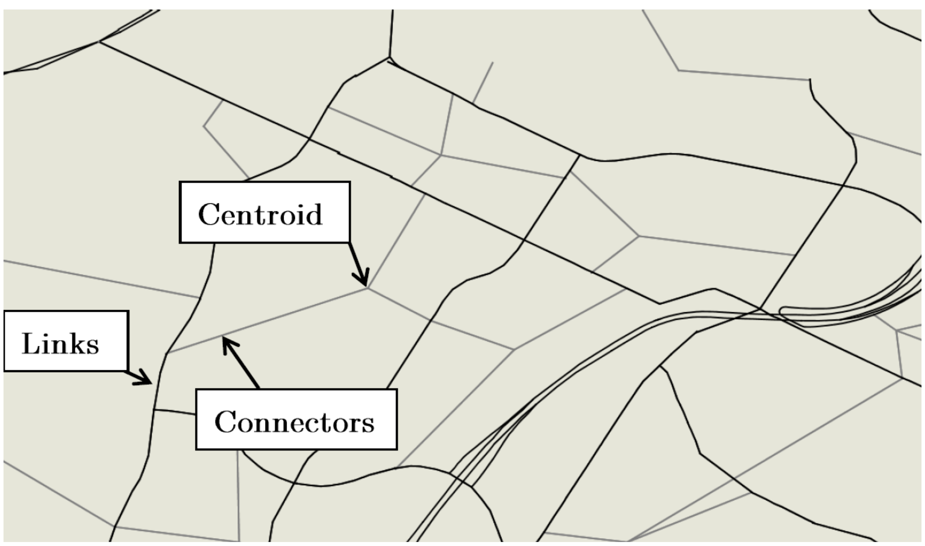

Figure 3.3: The TAZ paradigm and high connectivity scenario

3.3.2 High Connectivity Scenario

The connectivity scenarios are modeled by using the TAZ and centroid-connector notions described in the previous subsection. A centroid that is connected to multiple connectors represents high network connectivity in the sense that vehicles have the freedom to choose multiple entry points onto the larger network (Figure 3.3). Traffic demand originates from the centroid and tries to get onto the main links of the network by means of connectors. This potentially represents the period when vehicles right after the start of their trip navigate through local streets before getting on to the main arterials. The multiple-connector option TAZ-structure is modeled to resemble a grid-like local street network where vehicles experience more connectivity and more accessibility to arterials.

3.3.3 Low Connectivity Scenario

The approach from the high connectivity scenario is continued to model a comparatively low connectivity scenario. Under this strategy, the earlier larger TAZ is further sub-divided into a number of smaller TAZs, called sub-zones for ease of understanding. Subsequently, the original centroid is also further split into a number of sub-centroids corresponding to each sub-zone. The number of these sub-centroids to be formed is determined by the number of connectors from the original centroid (from which they are created). In this case, the sub-centroids are connected to the main links in the network only by means of a single connector (per sub-centroid) and not multiple ones as in the earlier high-connectivity case. This reduces the number of available options to get on to the network links, and is the main point of difference between the previous scenario and this. It relates to some real-life patterns of local streets set out in dispersed cul-de-sacs where accessibility of traffic to arterial roads is limited, mostly in the form of single dispersed type local streets to get on to them. The original zonal demand associated with the centroid is equally split among the sub-centroids, reflecting a scenario where the entire zonal traffic is subjected to low connectivity environments. It represents less-connected topologies such as suburban subdivisions, in which drivers have a limited number of access points to the main roadway network. The Figure 3.4 represents this modeling experiment of splitting the zones, centroids and connectors. Thus, this and the previous high-connectivity scenario reflect different degrees of connectivity and accessibility observed in street patterns.

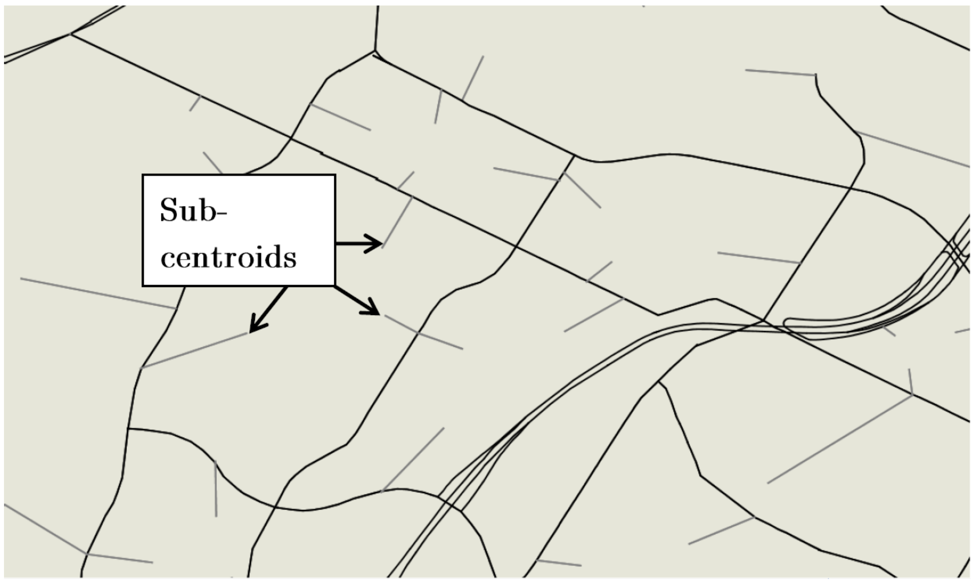

Figure 3.4: Low connectivity scenario

3.3.4 Medium Connectivity Scenario

The medium connectivity scenario uses centroids and sub-centroids from both high and low connectivity scenarios respectively. Recall that under high connectivity, demand was concentrated at a single centroid with multiple access points to the network. Under low connectivity, it was evenly distributed among sub-centroids each with just a single access point to the network. Under medium connectivity, both these types of demand are included, meaning some fraction of the original demand rests with the original centroid with multiple access points, but the remaining fraction is split among the smaller sub-centroids with single access points. Thus, the system contains half the demand or population experiencing high connectivity and the other half experiencing low connectivity, representing an intermediate between the two previous connectivity extremes. In terms of accessibility, it is a scenario with 50% of the demand having higher accessibility and 50% having relatively lower network accessibility. In terms of local street patterns, the original zones now have bothsub-zones with a high local street connectivity with multiple options and sub-zones with low connectivity with limited options to access the arterials. The number of sub-centroids is determined once again by the number of original connectors attached to the centroid. Figure 3.5 illustrates this modeling exercise, where both multiply-connected centroids and singly-connected sub-centroids co-exist.

Figure 3.5: Medium connectivity scenario

Some real-life developments where such a setting may be visible are ones containing some areas with grid-like street patterns and some with more dispersed cul-de-sac like patterns, thus making fractions of the total travel demand experience each. One such development in present times can be found in suburban Sacramento, CA, as presented in Handy et al. (2005), and illustrated in Figure 3.6. Relating this scenario to the timeline of different street patterns as they emerged over decades in from Figure 3.1, it represents the curvilinear loop-like patterns during the 1930-1950s, (second and third from the left) that marked the advent of more pronounced cul-de-sac like patterns of modern times. In all these scenarios modeled above, the total demand from each original origin zone to each original destination zone remains the same.

Figure 3.6: Sacramento suburban network a practical occurrence of the medium connectivity scenario. *Adapted from Handy et al. (2005)*

The main research question to be addressed in this study is investigating the system-wide traffic impacts street connectivity can have, hence it is critical that the system traffic is realistically characterized and represented. Simulation-based DTA captures these characteristics. As shown in the background example, local connectivity and accessibility can play an important role in travel experience in general, and it is important that traffic congestion be explicitly addressed in the modeling framework.

DTA is able to more realistically represent and model real-life traffic conditions in the system. The VISTA DTA framework introduced earlier is used in this study. This mesoscopic-scale feature of VISTA is of significant practical interest, as is enables DTA to be applicable to larger regional level study areas like the one in this study. Thus, the DTA procedure is exercised on the three varying connectivity level systems described in the previous sections, as part of the experiment. Each of these scenarios are examined for system performance, presented in the next section.

3.4 Study Area Application, Findings and Analysis

This section describes the study area used for the experimental analysis and the resulting system performance metrics.

3.4.1 Study Area Description

The study area selected is approximately six miles south of downtown Austin, the capital city of Texas, and is highlighted in Figure 3.7 along with its network representation (shown in green) in the DTA tool. This area primarily contains suburban development types and many residents travel north to work. The area is flanked by Interstate 35 on the east and the US 290 highway on the north. The DTA model was run for the three hour evening peak period (4 PM to 7 PM), under a travel demand of 254,864 vehicles. The following subsections give the results for the system-wide impacts of varying the level of connectivity. The study area contains 2440 links, 1318 nodes and 121 TAZs.

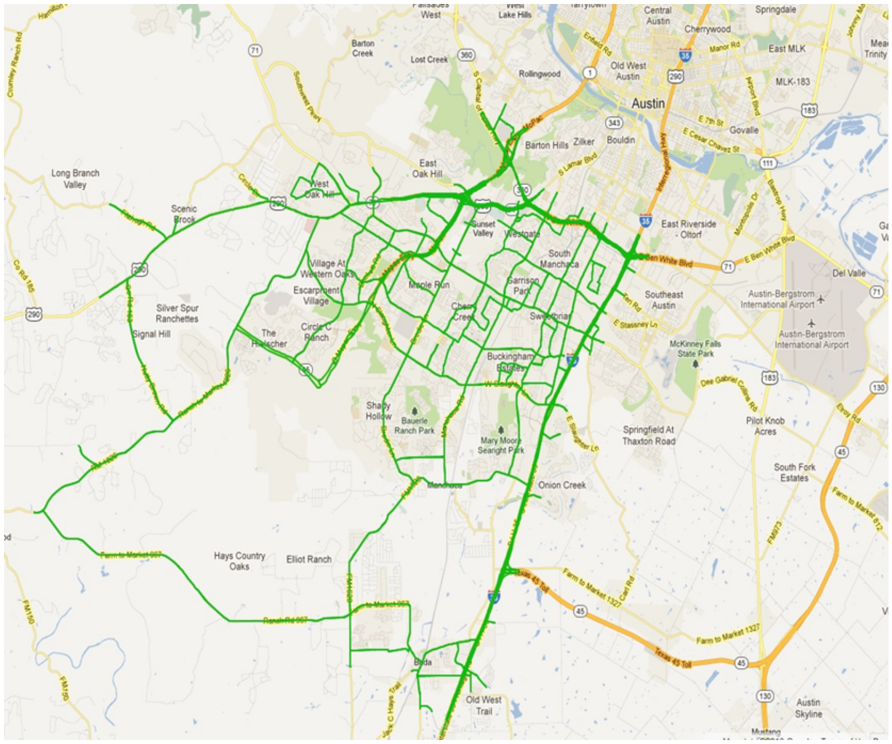

Figure 3.7: Study area for the connectivity study: region and network representation

The travel and system performance metrics emerging from the DTA modeling on the different connectivity level scenarios are presented in the following subsections.

3.4.2 Travel Time

Travel time is perhaps the most intuitive and the most 'directly' experienced metric of travel, and is also a common performance metric for evaluating transportation systems. This subsection explores travel time metrics at the system level and the origin-destination (OD) pair level. Table 3.1 gives the system-wide travel time performance measures for each scenario. Total system travel time (TSTT) is an aggregated total of the travel times of all the vehicles or users in the system or the network. It is found from this table that the total system travel time increases from the high-connectivity scenario to the medium and then to the low-connectivity scenario; the percentage increase as one moves gradually from the high connectivity to the low connectivity scenario is also presented in the right-most column.

Table 3.1: System-wide travel time performance

Connectivity level	*TSTT (hours)*	*Increase in TSTT over high connectivity case*
High	36326	-
Medium	43262	19.09%
Low	55647	53.18%

Further into the travel time analysis, moving towards the OD levels, Figures 3.8 and 3.9 illustrate the distribution of average path travel times across all OD pairs in the network for each level of connectivity. The time average is taken across all possible paths between an OD pair.

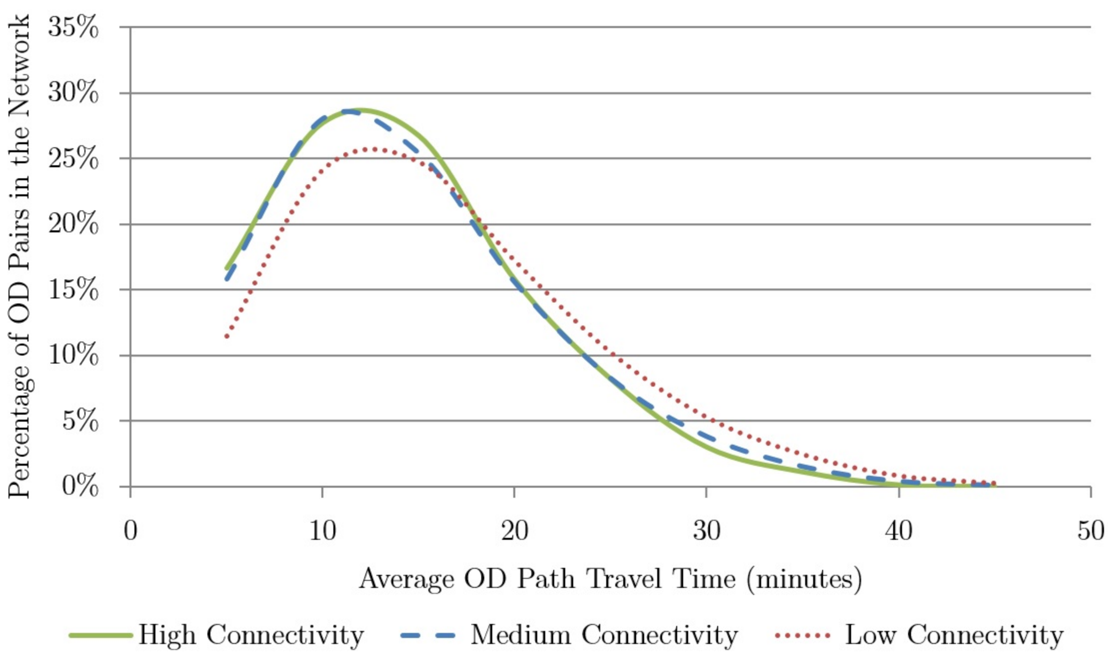

Figure 3.8: Distribution of average OD path travel time

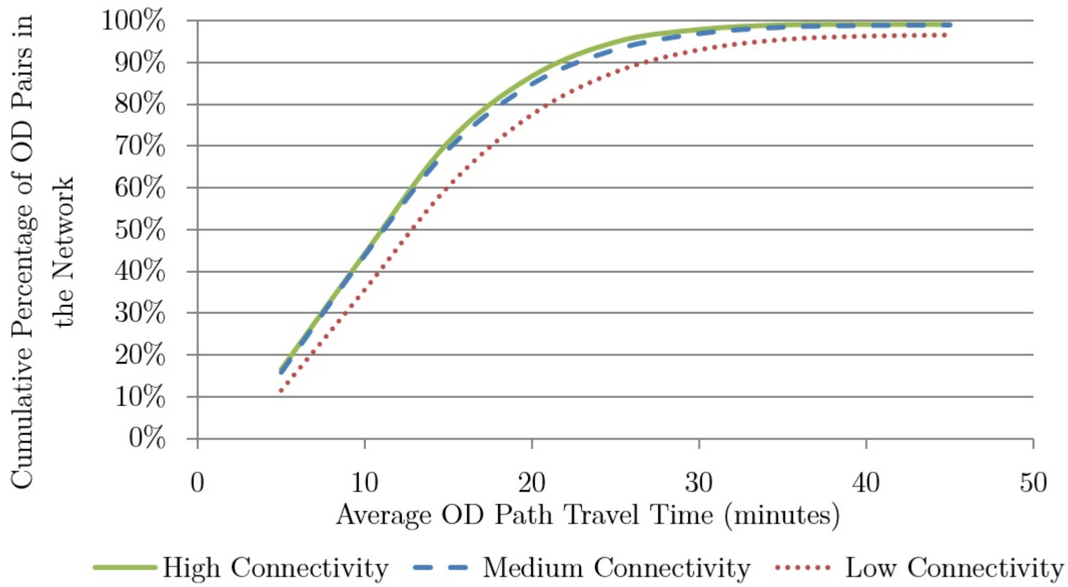

Figure 3.9: Cumulative distribution of average OD path travel time

As shown in Figure 3.8, there is a much larger percentage of OD pairs with higher average path travel times than in the high and medium-connectivity scenarios. This is also indicated by the rightward shift in the curve for the low-connectivity case. (This shift is even more obvious in Figure 3.9) The high and medium connectivity scenario curves are very similar except that the high connectivity scenario has more OD pairs in the 15 to 20 minute range, and the medium connectivity scenario has more OD pairs in the 30 to 35 minute range. Figure 3.9 illustrates the cumulative distribution functions of the OD travel time, and from these we observe a higher value of travel time for the low-connectivity network over the entire range of cumulative percentages of OD pairs. Also, the medium-connectivity case shows a similar trend as the high-connectivity case, except for a few higher ranges of travel time values, indicating the connectivity-effects to be well evident only in cases of higher travel time consumption. Thus, a dominance of the cumulative distribution for average OD travel time of the low-connectivity network over the high-connectivity one across all percentiles of available OD pairs is observed.

In the low connectivity scenario, vehicles have only one option to enter the roadway network. For this case, the percentage of the total vehicles experiencing lower travel times of 2-15 minutes is lower, whereas the ones experiencing longer times to complete their trips is higher. On the other hand, travel times are significantly lower in the high connectivity network, with a higher proportion of vehicles experiencing lower travel times. In this high connectivity scenario, drivers have multiple options to enter the network. The curve for the medium connectivity is observed to lie in between the curves for the high and low connectivity ones. Providing very restricted choice options to access the network gives rise to a situation where a high proportion of the traffic gets loaded on to some segments, leading to congestion and higher system-wide travel times. In the medium connectivity scenario, a fraction of the vehicles have more options to access the arterials while a fraction does not. The latter fraction can get loaded onto specific arterials that could be oversaturated, thus contributing to higher travel times overall. Thus under the travel time metrics for this system, the total system travel time, average path travel time distribution across OD pairs and the distribution of time spent in the network over the total demand (number of vehicles) display similar trends as we transition from high to medium to the low connectivity scenarios.

3.4.3 Volume to Capacity Ratio

Volume to capacity (V/C) ratio is a metric that is widely used to represent congestion in transportation systems. It quantifies congestion on a single roadway segment (or 'link'). Detailed information on this metric can be found in the Highway Capacity Manual, published by the Transportation Research Board, Manual (2000). It is quantitatively defined as the total traffic volume (vehicles per hour) on the link divided by the maximum traffic handling capacity of the link. The capacity of a link, as defined here, does not take into account delays due to intersection controls. For this reason, the maximum V/C on many links in the study area will be a value less than one.

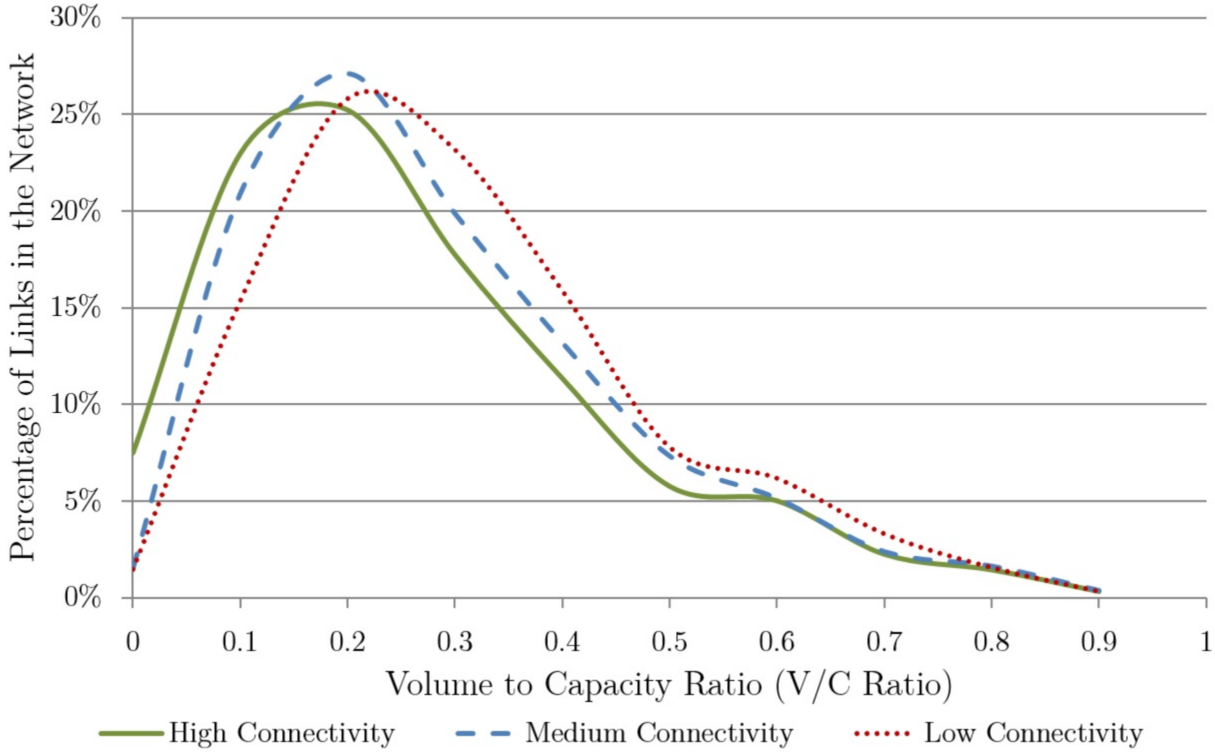

Figure 3.10: V/C ratio distribution

The plots in Figure 3.10 show the percentage of links in the entire network having different each value of the V/C ratio, for each different connectivity level system. While the distributions are not drastically different, the medium connectivity results are shifted to the right of the high connectivity results, and the low connectivity results are shifted even further to the right. This indicates as expected–that the most congestion is occurring in the low connectivity scenario, followed by medium, and then high. A similar consistency of the effects of connectivity levels on system traffic is observed in translating from the high to low connectivity levels.

3.4.4 Travel Distance

Distance traveled is the last among the system performance metrics used to assess travel experience for the three differently connected systems. Two system-wide metrics were used to assess changes in travel distance. The first, vehicle miles of travel (VMT), is a measure of total distanced traveled on the roadway system by motor vehicles. It is another aggregated system-wide metric like the total system travel time and its unit is vehicle-miles. The second is the average distance traveled, taken across all vehicles. Both results are shown in Table 3.2.

Table 3.2: System-wide travel distance performance

Connectivity Level	*Total VMT* ($*10^9$ vehicle-miles)	*VMT increase over high connectivity case*	*Average path length* (miles)	*Path length increase over high connectivity case*
High	7.27	-	5.40	-
Medium	7.66	5.36%	5.79	7.22%
Low	8.30	14.11%	6.10	12.96%

The distribution of the path lengths traversed by all the vehicles using the network is also plotted, as shown in the Figure 3.11.

Table 3.2 shows, as expected, both total VMT and average trip distance increase as vehicles are subjected to worsening levels of connectivity from high to medium to low. Note that the number of vehicles in each of the scenarios is the same (since the total travel demand for the system has not been changed across connectivity scenarios), so it indicates an increase in the total distance they have traveled.

Travel distance in general shows an increase because we modify the centroid connectors in such a way that the vehicle movement is more restrictive, and there are only a few limited places where drivers originating from a particular location can enter the main network. In the high-connectivity scenario, where drivers have the liberty to choose the location to enter the network based on their final destinations, drivers are able to choose a shorter path. Thus, it can be seen that network connectivity variations can have significant impacts on the driving patterns and motorized travel

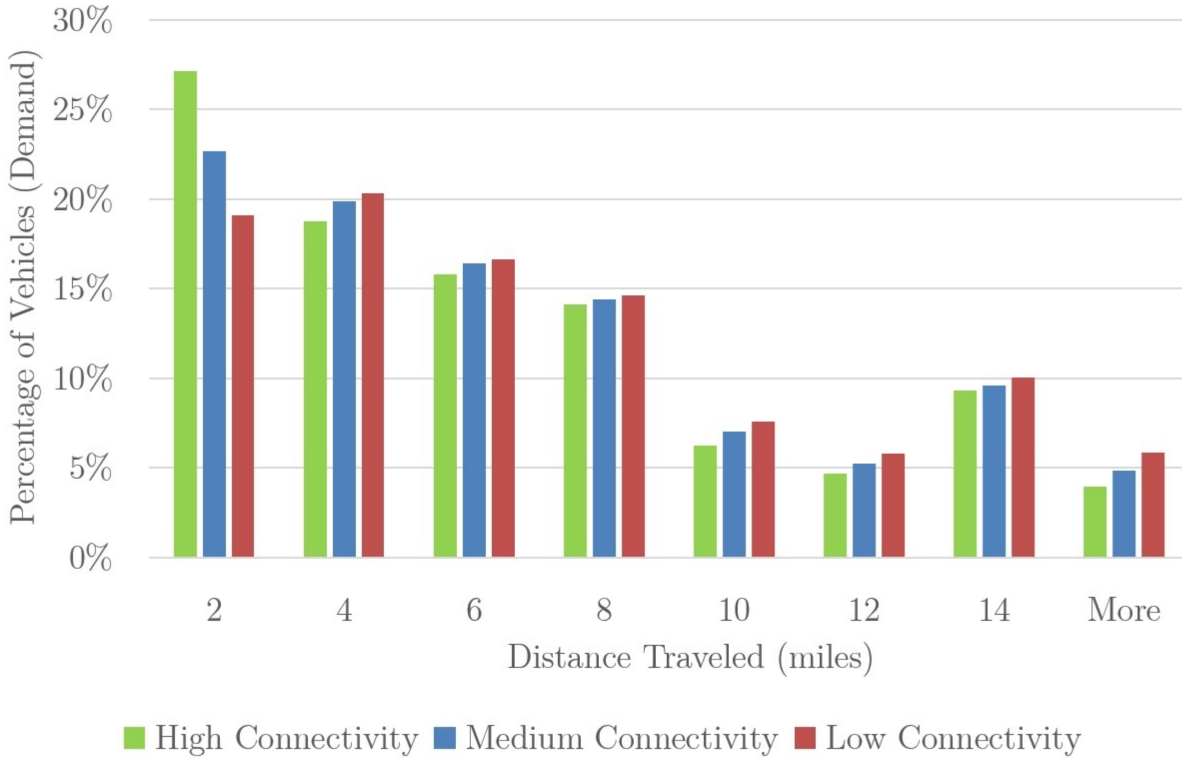

Figure 3.11: Path length distribution across the entire demand in the network

in general as a whole. When vehicles are forced to use only one roadway to enter and egress the network, as opposed to choosing the roadway that will make their travel time the least, additional delay is added to the network in terms of both travel distance and travel time. We see that as the connectivity in the network worsens, the accessibility to ideal paths or routes reduces and vehicles have to travel longer distances in order to get on to their destinations. A set of trip start and end points might have the same straight line distances between them in all scenarios, but the actual traversed distance to get from one point to the other is much higher in networks that face poor connectivity. This may lead to increased driver stress due to a longer driving effort and more road congestion, as well as environmental impacts in the form of higher fuel consumption and increased mobile-source emissions, thus affecting regional air quality. This highlights the potential system-wide, and consequently regional impacts street connectivity and designs can have.

3.5 Discussion and Concluding Remarks

This connectivity study investigates the influence of connectivity features on automobile traffic dynamics, at the system-wide level. It makes use of centroid-connector modifications to model various degrees of connectivity, applies this strategy to a suburban network, performs DTA and compares variations in system-wide traffic metrics under these varying connectivity scenarios. It is found that connectivity levels are indeed interrelated with traffic and congestion metrics, and low connectivity can have negative impacts on the same. A medium connectivity scenario where a fraction of the population have high connectivity access and the other half does not also gives rise to some insights as to how gradually depraving population to more access options affects the system. The low connectivity scenario impacts network traffic the most in terms of more movement required, higher travel times on an average and more congestion. The experiment considers the network structure and possible spatial and temporal variations in traffic characteristics via DTA and takes a quantitative approach as a whole. It sets a formal background for deeper networks and traffic modeling-based connectivity analyses at the larger system and regional levels, at a wider perspective than local community levels. The study can augment policy reasoning in favor of providing better network connectivity.

While this study considers only vehicle dynamics, it could be extended to incorporate impacts on other modes and their movements particularly when there are intermodal interactions. One way in which this could be done is by using the traffic flow outputs on the links to estimate the network effects on bicycling and walking, since several indices to address the quality of these modes like the Bicycle Environmental Quality Index (BEQI) (San Francisco Department of Public Health) depend on vehicle volume as an input. An attempt in this direction has been made in Duthie et al. (2013). Also, only inter-zonal trips were considered in the study and not intra-zonal trips in either connectivity scenarios. While structural components of the built environment do play the major role in travel experience, of course apart from personal taste-variations and socio-demographics, network connectivity also has tangible and non-trivial impacts. These are quantified and demonstrated through this experiment. The study brings up yet another set of effects of having poor street connectivity, this time on regional travel and congestion, and highlights the need to holistically analyze from different perspectives and pay closer attention to network design and connectivity aspects in the planning domain.

Chapter 4

Mobile-Source Emissions Modeling

The second set of planning questions addressed in this chapter relates to environmental impacts of transportation in the form of emissions, the regulatory aspects and the inclusion of inherent traffic dynamics into the emissions modeling process.

4.1 Background and Motivations

4.1.1 Air Quality and Emissions: A Global Concern

Air pollution is a major health concern and in recent times, a policy issue in many countries across the world, particularly in developed ones like the US after the inception of the Kyoto Protocol. Within the larger issue of global air-quality, pollution from vehicular sources have had some of the highest proportions in the total air pollution, most importantly in urban settings where they operate in large volumes. As a whole, the transportation sector leads to a substantial amount of emissions, affecting regional air quality and subsequent ozone layer depletion and pernicious health impacts on inhabitants of the region. As per recent findings of the United Nations Framework Convention on Climate Change (UNFCCC), the transportation sector represented 27% of the total U.S. greenhouse gas (GHG) emissions in 2010. To put the matter in perspective, Colvile et al. (2001), among other researchers, conduct a seminal review on the role of the transportation sector in air pollution impacts across the European and North American continents.

4.1.2 Transportation Air-Quality Related Federal Regulations in the United States

The transportation planning sector in the US has seen many regulations in this regard both at the federal level and the regional planning level. The Clean Air Act of 1970 required all states in the US to adopt state implementation plans (SIPs). SIPs include an emissions inventory for all regions in the state and a 'plan' that includes policies and mechanisms for demonstrating attainment of all the ambient air quality standards as determined by federal guidelines. The Clean Air Act also requires the United States Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) (40 CFR Part 50) for pollutants considered harmful to public health and the environment. The Clear Air Act Amendments (1977) strengthened these stipulations, requiring all transportation plans to show attainment of vehicle emission-reduction targets (at least until the NAAQS levels) specified in SIPs. In relatively recent years, the Clean Air Act Amendments (1990) have been a milestone policy advance in transportation, cementing the federal air-quality requirements more than ever, indicating that federal funding for regional transportation projects can be withheld from regions failing to demonstrate ambient pollutant level attainment. More specifically, from the transportation standpoint, what is crucial is 'transportation conformity' – a section under the Clean Air Act, specifically section 176(c), subsection 42 U.S.C. 7506(c). It attempts to ensure that federal funding and approval are given to transportation (mainly highway and transit) projects that are consistent with or 'conform to' the air quality goals charted out in SIPs.

A paradigm shift in the objectives of transportation planning can be observed from these federal regulations and their continued emission-target attainment requirements. Transportation planning and development evolved from simple capacity expansion and infrastructure building to managing systems well, achieving sustainability and reducing emissions and mitigating the environmental impacts. Keeping up with these federal regulations, the thesis extends the DTA-based modeling paradigms to address transportation emissions and NAAQS compliance issues. The specific utilities associated with using a DTA-based approach for these purposes will be discussed in subsequent sections.

4.2 Need for Accurate Traffic Emissions Predictions and Current State of Practice

As described under the previous subsection, state departments of transportation (DOTs) and MPOs have to study the environmental impacts of major infrastructure projects which may require capital investments and funds from federal or state sources directly or indirectly. These essentially are all activities that involve transportation-related developments and decision-making. This requires unifying models from the transportation planning and air-quality planning domains. The current methods used to estimate vehicle emissions for conducting conformity analyses require the implementation of two separate modeling processes:

1. Estimation of traffic activities and prediction of the traffic state in the region, typically based on travel demand models;

2. Computation of associated emission factors using mobile source emission models; and

3. Using the outcome of the two models to obtain pollutant estimates.

In light of this, developing accurate emission estimates is thus dependent not only on the individual accuracy of the two modeling exercises, but also on the consistent and seamless interface and interdependence among them. This is also professed in the CAAA Amendments – Transportation Conformity Rule Amendments: Flexibility and Streamlining (1997). The CAAA in a recent statement reports the benefits of emission control programs aimed at reducing pollution from smokestacks and tailpipes produce enormous air quality and health benefits; they reckon that by 2020, these amendments if fully incorporated, will prevent nearly 230,000 early deaths". Despite the recent attention that has been drawn to SIPs and attempts to incorporate them into the planning process have been manifold, a seamless integration of all these modeling components remains a task that has not been fully accomplished, barring a few attempts where a modeling exercise involving both traffic state prediction models and emissions models has been undertaken. These shall be discussed in detail in the subsequent literature review, and this research is an attempt in that direction.

The National Research Council (NRC) in 1995 defined certain categories of variables potentially influencing mobile source emissions and fuel consumption: driver behavior, travel-related factors, highway network characteristics, and vehicle characteristics. Most earlier practices in estimating vehicular emissions for a regional transportation network were based solely on demand forecasting models, as explained by Deakin and Harvey (1993). However they are unable to capture user route choice behavior in any form, and can lead to inaccuracies in predicting the actual vehicle hours traveled (VHT) or VMT and other traffic characteristics in the network. An actual traffic assignment exercise where these demand models are further used to assign vehicles onto actual paths based on link attributes, driver behavior and equilibrating algorithms becomes necessary. This results in more accurate emissions estimates based on more detailed and realistic traffic data in the form of flow per link in the network as opposed to single-step forecasting models, which give a singular and highly aggregated metric of traffic demand over the entire network.

However, some recent literature has addressed these issues. Traffic assignment models which could use the demand model to give a better indication of the traffic via metrics such as volumes on individual links, VMT and average speeds were introduced to be used in conjunction with the emissions models. These will be covered in detail in the literature review in Section 4.3. While this was an improvement in the traffic inputs, by way of having more intuitive and more representative metrics, these traffic assignment models typically have been 'static' in nature, in the sense that they inherently assume a steady state behavior of traffic, and use a time-scaled average values of these parameters. Besides, they do not model congestion explicitly and do not consider real-life phenomena like queue-spillback from one link onto the following links under saturated traffic conditions. Such drawbacks with static traffic assignment can have implications on the emissions estimates from them as congestion and saturation results in a heightened vehicle activity and more rapid alternating cycles in vehicle operations. This can lead to a much higher rate of emissions. Thus in reality, the traffic state in any particular region, or at a finer scale on any link or a road segment is essentially 'dynamic' in nature. Driver route choices, dynamic route switching, congestion locations and congestion time, all these space and time-dependent factors that come into play. This study makes an attempt to do so via the usage of a dynamic traffic assignment model and demonstrates a descriptive framework of the analysis and the applications of the same, at the same time making the entire methodology generic enough to be applicable in all kinds of regional and local conformity analyses and at more aggregated levels in SIPs.

Thus, the larger motivation behind the study is to address some of these temporally *and* spatially variable factors in the assignment process by introducing DTA models in highway source emissions modeling exercises. In a way, the purpose is to fill-in the gaps in the literature on incorporating DTA models with emission modeling tools, and becoming a versatile methodology in doing the same. Thus, characterizing and actually including spatio-temporal variables via DTA modeling is critical for evaluating accurate traffic prediction strategies and consequently estimating more realistic emissions is crucial from an environmental and energy-consumption perspectives. Besides, with regard to the emissions model that is used in this study, there have been even more limited research efforts in incorporating traffic dynamics into it. MOtor Vehicle Emission Simulator (MOVES), developed by the EPA's Office of Transportation and Air Quality (OTAQ) and regulated by EPA to be used in all SIPs is considered in this study.

Traditionally, MPOs have used their transportation planning models to generate input for emissions analysis in MOVES. More recently, MPOs and other planning agencies have been adopting DTA to complement their planning models. As mentioned in Chapter 1, CAMPO in Austin, TX, NCTCOG in Dallas, TX, and SFCTA in San Francisco, CA are a few examples of such planning agencies. DTA is a bridge between regional and microscopic models for simulating traffic patterns at a sub-regional or corridor level. Since vehicular emissions are directly impacted by traffic dynamics of vehicular speed, acceleration, stops, operating cycles, the next step in the evolution of the MPO toolbox is to make traffic dynamics direct the emissions modeling process. The contribution of this component of the thesis is developing a framework to integrate DTA into the MOVES emission modeling process at the county-scale. This integration framework will enable MPOs and other planning agencies to achieve attainment through more accurate TC analyses and SIPs.

The rest of this chapter is organized as follows. Section 4.3 will conduct a comprehensive literature review on this and related research. Section 4.4 will cover a description of the MOVES emissions model. This will lay the groundwork for Section 4.5 following that, which covers the entire integration methodology and the underlying procedures. Section 4.5 will also conduct a case-study based development of the methodology, where the integrated framework is developed at the same time demonstrated on the study area, which is an entire county in the south-central region in Texas. A analysis of the obtained results will follow that and section 4.6 will conclude with a discussion of future research avenues and some remarks.

4.3 Literature Review

In modeling atmospheric pollution from the transportation sector, in particular from highway attributable mobile sources, there has been extensive past research conducted in the two individual components–first the traffic state estimation using demand forecasting models and second in the estimation of emissions factors using standard emissions models. So instead of focusing on them individually, a review is conducted of research that addresses both in series, complementing one another to produce a complete mobile source emissions model. In particular, works that take into account dynamic aspects of traffic models have been the main focus. In general, there have been a limited attempts in integrating traffic assignment and emissions models and among them, even fewer ones applied exclusively to the United States-based conformity and SIP developments.

Some recent studies which include congestion and highlight the effects it can have on pollutant emissions include ones by André and Hammarström (2000), and De Vlieger et al. (2000). Another study by Hallmark et al. (2002) found that driving patterns at different intersections are significantly influenced by queue position, downstream and upstream lane volumes, incidences and posted link speeds. All of these factors can be effectively captured via the DTA modeling approach. Rakha et al. (2000) reported that proper signal co-ordination can reduce emissions by up to 50%. One of the earliest works which included junction effects and vehicle operating modes in modeling air pollution from road traffic was by Matzoros (1990). Later, LeBlanc et al. (1995) introduced many characteristics such as geometric design characteristics, traffic characteristics, traffic delay characteristics, driver behavior, weather, and roadway environmental characteristics into the emissions modeling process. Qu et al. (2003) propose that road design features such as grade, alignment and quality can have significant impacts on vehicle speeds and emissions, as driving patterns change based on them.

In addition to these road-related characteristics, weather related attributes such as temperature, humidity and visibility influence emissions estimates as well, both by way of influencing driver behavior Kilpeläinen and Summala (2007), and atmospheric reactions of certain primary chemical pollutants. Nesamani et al. (2007) define 'emission specific characteristics' (ESCs), which are the various factors that can affect emissions, not only traffic related variables, but a host of other variables representing road and weather conditions and driver characteristics and examine their effects on vehicle speeds, which in turn affect emission estimates.

Coming to the specific integration of traffic simulation and emission models, Stathopoulos and Noland (2003) conduct a simulation of two traffic-improvement scenarios using the traffic simulation model VISSIM and the comprehensive model emissions model (CMEM). In another study, Noland and Quddus (2006) examine whether road schemes that improve traffic capacity or smooth the traffic flow result in an increased vehicle pollution, and employ a simulation methodology similar to the previous research, via integration of VISSIM and CMEM. Abou-Senna and Radwan (2013) propose a VISSIM and MOVES framework, however this micro-simulation based approach does not account for network equilibrium and user behavior representation. Xie et al. (2012) propose a PARAMICS and MOVES for evaluating emissions from alternately fueled vehicles. However, these are essentially micro-simulation models that consider dynamic network loading without taking into account network equilibrium states. DTA-based models such as VISTA are able to address these gaps. Bai et al. (2007) analyze the suitability of trip-based and link-based data for mobile source emissions using a mesoscopic DTA model, and recently, Lin et al. (2011) demonstrate the integration of a microscopic DTA model with emissions modeling for fine-grained air quality analysis. However, utilities for SIP analyses that aid the metropolitan planning process were not developed. A common set of guidelines regarding air quality impacts of improving traffic flow can be found in the National Cooperative Highway Research Program (NCHRP) Report 535 by Dowling (2005). Smit et al. (2008) address the concerns about consideration of average speed distributions on roads as opposed to single mean speeds and apply their methodology to emissions of large road networks, and report that inclusion of speed distributions led up to 24% higher emissions estimations of CO, HC, NOx, PM10, CO2. On similar lines, van Beek et al. (2007) examine the effects of speed measures on air pollution and traffic safety. Most recently, Wismans et al. (2013) conduct a comparison of static and dynamic traffic assignment approaches to conduct local air and noise pollution analysis for a congested highway corridor near Amsterdam, The Netherlands. Ahn and Rakha (2008) conduct an analysis of how motorists' route choice decisions in trying to minimize their travel times impact the air quality in the region, and demonstrate that macroscopic emission estimation tools can produce erroneous outcomes if they ignore transient vehicle behavior along a route.

The current research tries to fill in the gaps in literature on integration of a more coarse dynamic traffic assignment model, which provides mesoscopic-scale capabilities, with the EPA-regulated emissions modeling package MOVES, which can be seamlessly tied-in with the county-domain capabilities of MOVES. According to the regulations, SIPs have to be performed at the county-level of analysis.

4.4 Emissions Modeling and USEPA's Motor Vehicles Emissions Simulator (MOVES) 2010

Recent years have seen numerous developments of energy and emission models from vehicular sources, both at the academic and commercial levels. Generally, emission models are of two types, macroscopic and microscopic. Macroscopic models use average aggregate network parameters to estimate network-wide energy consumption and emission factors. The primary macroscopic emission models used in the United States developed for regulatory purposes have been the U.S EPA's MOBILE and the California Air Resources Board's (CARB) EMFAC model and both use the average speed computations as inputs to emission factors (EFs) for each pollutant and for each activity. EFs when multiplied by vehicle activities, such as VMT or VHT, give the total emission estimates (in the form of emission inventories). Thus, notice that it eventually uses a single traffic-related variable, an average value of speed, to estimate emissions, thereby ignoring other important explanatory variables that can significantly affect emission estimates as discussed in the previous sections.

According to Vallamsundar and Lin (2011), to overcome these drawbacks of macroscopic models and also meet the growing need for developing emission estimates on a local scale, microscopic emission models were developed. These models are enabled to incorporate the effects of instantaneous speed and acceleration profiles on vehicle emissions, their effects having been discussed in Sections 4.1 through 4.3, thereby better representing real network conditions. MOVES is EPA's next-generation microscopic and mesoscopic analysis-enabled mobile source emission model which significantly improves on the capability of the other microscopic and mesoscopic emission tools. The EPA officially released the MOtor Vehicle Emission Simulator (MOVES), a regulatory mobile source emissions model for computing EFs officially in March 2010, primarily for use in SIPs. The MOVES model replaces the earlier EPA models developed for similar purposes–MOBILE (last version 6.2) and NONROAD based on an extensive review of in-use vehicle data. MOVES can be used effectively not only for developing SIPs, but also for regional and project-level analyses and generally conducting analyses pursuant to the National Environmental Policy Act (NEPA). This study uses the latest version, MOVES2010b, that was released in June 2012. A brief exploration of the basic methodology which MOVES employs within itself is presented in the next sub-section. The capability of MOVES to conduct emissions analysis at various spatial scales, macroscopic (US National-Domain), mesoscopic (County or Regional Domain) and microscopic (Project-Domain) makes it an ideal model to integrate a mesoscopic DTA model like the VISTA with for a county-scale analysis.

4.4.1 The MOVES Approach to Emission Computations

MOVES has a *modal based* approach for emission factor estimation, meaning it computes emission inventories by using a set of modal functions. A modal approach means computing emission factors based on various operating modes of vehicles which are functions of speed, acceleration and road grade. These operating modes are stored as *bins*, created based on second-by-second speed and vehicle specific power (VSP). VSP is an estimate of the power demand on the engine during driving and is calculated using the second-by-second speed values in a driving schedule, along with information about the type of vehicle being operated. Conventionally, it is reported in kilowatts per ton, the instantaneous power demand of the vehicle divided by its mass. The VSP is used by MOVES to determine the amount of time a vehicle spends in each of the 23 operating mode bins. VSP was originally developed by Jiménez et al. (1999), but newer models for it with minor revisions have evolved since then and MOVES uses one of the newly evolved VSP models, but the essence remains the same. For each driving cycle mapped, the VSP is computed on a second-by-second basis using the following relation,

$$VSP = v(a(1+\epsilon) + g\phi + gC_R) + \frac{2\rho C_D A v^3}{m} \tag{4.1}$$

where,

v = Speed of the vehicle (without head-wind) (m/s)

a = Acceleration of the vehicle (m/s^2)

ϵ = Mass factor that accounts for rotational masses (equal to the equivalent transnational mass of rotating components such as wheels, gears, shafts, etc.)

g = Acceleration due to gravity (9.8 m/s^2)

ϕ = Road grade (vertical rise/slope length)

C_R = Rolling resistance coefficient

ρ = Air density (kg/m^3)

C_D = Aerodynamic drag coefficient

A = Frontal area of the vehicle (m^2)

m = Mass of the vehicle (kg)

The modal-emissions methodology then estimates VSP values for every discrete operating mode, and modal average emission rates are estimated for each VSP mode. The total emissions occurring over the course of a trip is then estimated by the following relation,

$$E_{trip} = \sum_{i}^{I} T_i^{VSP} ER_i \tag{4.2}$$

where,

i = VSP mode index $= 1, 2, ..., I$ ($I = 23$ for MOVES operating mode bins)

ER_i = Modal average emission rate for VSP mode i

T_i^{VSP} = Trip time spent in the VSP mode i

E_{trip} = Total emission produced during the trip

For each operating mode, MOVES has an emission rate (in units of grams emitted per hour of operation) that is used to calculate the emissions emitted during driving. Besides, MOVES also has another type of bin, called a source bin, which is created based on vehicle-specific characteristics (source=vehicle). Eventually, once all the bins (of both types) are defined, MOVES assigns a unique emission rate to each combination of source bin and operating mode bin and the emission rates are aggregated for each vehicle type based on every bin that vehicle might possibly be present in. Vallamsundar and Lin (2011) present a more detailed description of the MOVES emission estimation methodology. Certain adjustment factors are also applied to the emission output before giving out the final results to account for additional factors like external temperature, in-vehicle air-conditioning, etc. The following relation represents the estimation methodology of MOVES during a vehicle process, essentially the discussion above,

$$E_{vtype}^{process} = \left[\sum ER_{bin}^{process} A_{bin}\right] \alpha^{process} \tag{4.3}$$

where,

$E_{vtype}^{process}$ = Total emissions from a vehicle type

$ER_{bin}^{process}$ = Emissions rate for the corresponding bin

A_{bin} = Vehicle activity in that bin

$\alpha^{process}$ = adjustment factor

The following Figure 4.1 illustrates the methodology followed in MOVES for emission inventory computation:

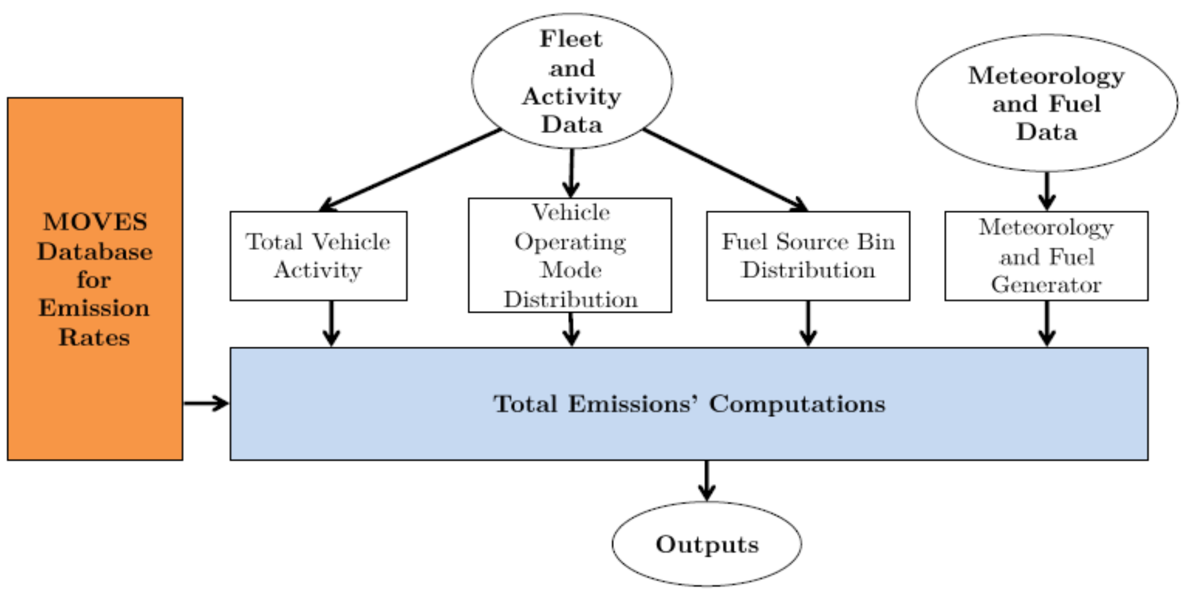

Figure 4.1: The MOVES approach to mobile source emissions estimation

Thus, there are multiple notable capabilities of MOVES, like a multi-modal binning approach for emissions estimation based on vehicle operating modes. These modes are defined by a number of dynamic factors such as speed, acceleration and road grade, as opposed to just average values of a static nature. Also, the multiple geographical scale capability of macro-, meso- and micro-scales, increased avenues to model alternative vehicle and fuel types and the finer spatial and temporal resolutions enable the effective integration with mesoscopic DTA models like VISTA. This enables development of effective pollutant estimation mechanisms.

4.5 Methodology and Application to Williamson County, Texas

The entire methodology is divided into a number of subsections, each describing one component of the process.

4.5.1 Study Area Description

The analysis is performed on Williamson County in the central part of Texas. Its fast growth rate is due in large part to its location immediately north of Austin coupled with Austin's rapid expansion northward, and the traffic conditions have shows a commensurate increase in tandem, making it an interesting location to apply emissions analysis on the traffic. The following figure shows the study area and the corresponding region network on which the DTA model is run.

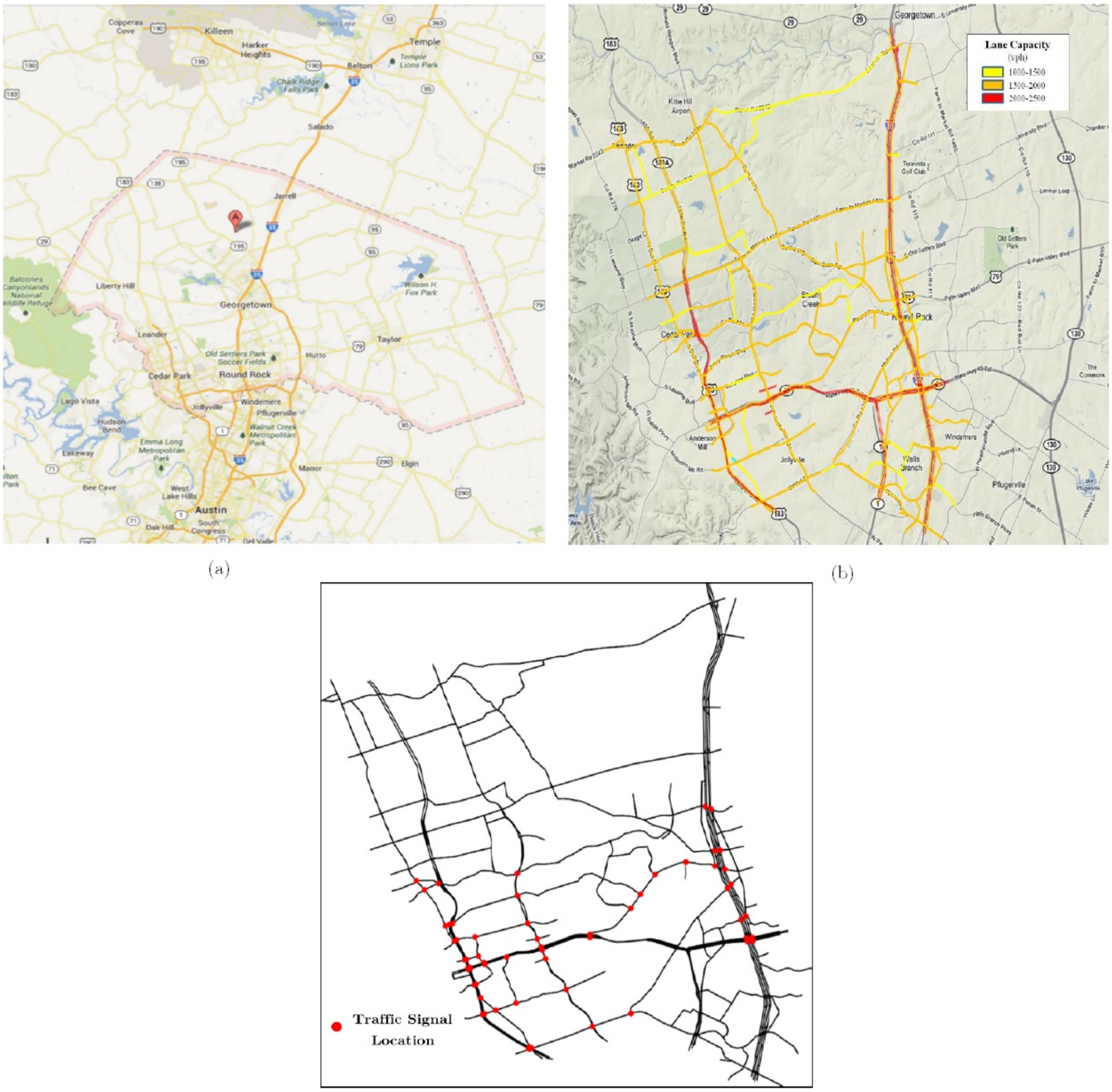

Figure 4.2: Study area description–Williamson County, central Texas
(a) geographical region, (b) network representation and (c) locations of traffic signals in the network

Figure 4.2(a) shows the regional bounds of the Williamson County, as represented by Google Maps. Figure 4.2(b) shows the network used to run the DTA model on, and is superimposed on the local map of the region to best illustrate the study area.

As seen from it, the Interstate Highway-35 (IH-35), a major and congestion-prone freeway in the state of Texas passes through most part of the county, represented on the right-most cluster of links in the network in Figure 4.2(b). Recent years have seen escalated traffic congestion and hence air pollution. This work can form an important part of pollution mitigation strategies in addition to quantification of emissions. The base network for Williamson County has 1620 links, 961 nodes and 113 traffic analysis zones (TAZs) and 66 signals. The signal component and corresponding locations were included in the network representation in a separate Figure 4.2(c), as it becomes crucial to include them in emissions related analyses as vehicles at signalized locations, at red lights and ones facing congestion have major proportions in the total emissions estimates and have a much higher rate of vehicle activity and thus, emissions. Two other major road segments included in the model are the US Highway 183-A forming the left edges of the network and the toll road SH-45 on the southern periphery.

4.5.2 Dynamic Traffic Assignment and County Level Emissions Modeling

Integration Framework

The emissions methodology in MOVES at the county-level requires many region-specific and traffic-state-specific data inputs obtained from multiple sources. For each type of data input, a brief description of what is represents, its source and implications on the emissions outcome is given in the respective section. At places where traffic-related data or DTA-specific data is to be input, its conversion from the VISTA-specific format to the MOVES-specific format is described as well. All the data and the model specifications are input in MOVES in a separate file called the Run Specification (RunSpec) and one RunSpec is created for every new scenario that is to be modeled. The input files are managed by the County Data Manager (CDM), which is a part of the larger RunSpec and the tables stored in an input database. Following is a brief description of the major input requirements for the integrated approach.

1. *Road Type Distribution*

   This component incorporates data related to the VMT by the type of the road for the domain to be modeled, Williamson County in our case, and data is entered as a distribution of VMT across road types. Only the road types selected in the RunSpec are included in the distribution. VISTA-recognizable link types were converted to the MOVES-recognizable road types, and this data were extracted from the DTA model output VMT.

2. *Source Type Population*

   Source type population includes the number and types of vehicles in the geographical area to be modeled. Vehicles are the 'sources' of emissions, hence the name source type population. This is a regional level input and since our modeling premise is the county level, vehicle registration data from regional planning authorities was used.

3. *Vehicle Type VMT Population*

   This input component involves the yearly VMT and the monthly, type of day and even hourly VMT fractions. County specific values for the present study area are added. MOVES requires that yearly VMT be imported irrespective of the time duration being modeled. Data is supplied for each HPMS (Highway Performance Monitoring System) defined vehicle type (e.g., passenger cars, combination trucks, etc.) as indicated in the source-use types selected in the RunSpec. The VMT obtained from the DTA model is extrapolated to the HPMS Year format required by MOVES and the breaking down of this VMT into monthly, daily and hourly factors is carried out by using the VMT factor converters provided by EPA.

4. *Source Age Distribution*

   This input contains the distribution of the vehicle fleet by age for each calender year and vehicle (source) type. In the data file, the age is represented by a fractional number called 'ageID' which must sum to 1 for every vehicle type and year. Local Williamson County data is used for this input, again based on the vehicle registration history.

5. *Average Speed Distribution*

   This is an important component from the standpoint of inclusion of dynamic factors in the process. It includes the input for average speed data specific to vehicle type, road type and the time of the day and the type of the day (weekday or weekend). Variations on vehicle speeds over the time of day can be incorporated here. MOVES defines sixteen 'speed bins', each corresponding to a range of average driving speeds on a link. We enter the fraction of driving time in each speed bin (called *avgSpeedFraction*) for each hour/day type, vehicle type, road type and average speed, where the fractions sum to one for each set. This time based distribution of vehicle speeds makes it most closely related to DTA capabilities. The relevant data points from the link attributes table are extracted and they are put in a new MOVES-compatible tab input format.

6. *Fuel*

   This component is divided into two types of data, fuel supply and fuel formulation, which are to be used together. The fuel formulation importer allows the user to select an existing fuel in the MOVES database and change its properties, or create a new fuel formulation with different fuel properties and for this study, default Williamson County data available in MOVES were used. The fuel supply importer allows the user to assign existing fuels to counties, months, years, and also the associated market share for each fuel. The market share for a given fuel type (gasoline, diesel, etc.) must sum to one for each county, fuel year (i.e., calendar year), and month. For the fuel supply component, since area-specific data is required, Williamson County data was acquired and input in the model.

7. *Alternative Vehicle and Fuel Type Technologies*

   The fuel type and technologies importer is a new feature in MOVES 2010b and allows the user to specify the distribution of fuel types in the model. Specifically, this importer allows the user to supply the fleet distribution fraction by fuel type, source type, model year, and engine technology. A value of one designating the conventional internal combustion for engine technology is generally supplied, and for this study, the same was used without changing the defaults.

8. *Meteorology*

   Local temperature and humidity conditions for the months, days, hours for which the emissions are modeled are important data. This component allows us to include that data for the conditions specified in the RunSpec. While the MOVES model contains thirty-year average temperature and humidity data for each county, month, and hour, data specific to Williamson County for the required analysis period is entered.

Figure 4.3 illustrates the integration framework–

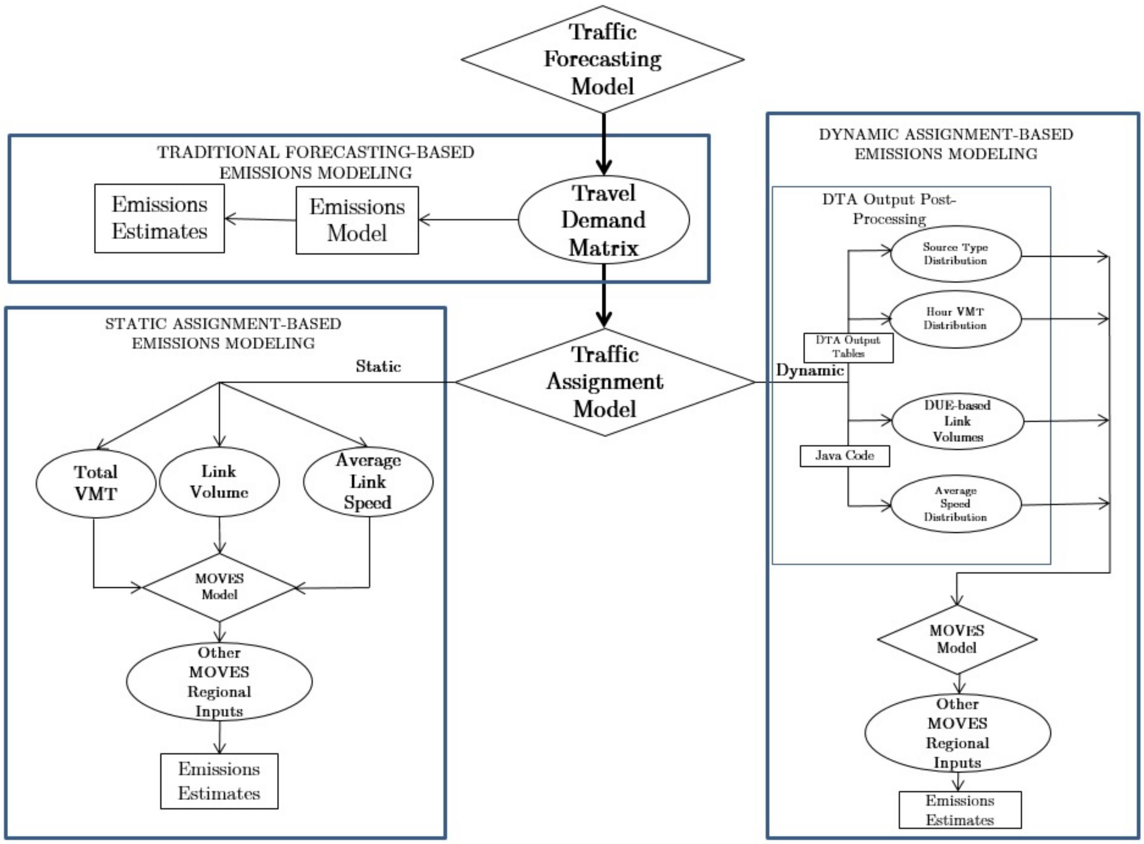

Figure 4.3: Integration framework flowchart

4.5.3 Emissions Modeling for Williamson County, TX

The DTA model for Williamson County is developed using CAMPO's 2008 base year data for AM peak period. Demand was loaded onto the network in 15-minute assignment intervals and the model is simulated for five hours (7 AM–12 PM). The emissions estimates for the AM peak period for the summer month of July 2008 are modeled. This DTA model and its outcomes were validated based on field data provided by URS Corporation. The traffic-specific MOVES input files are generated pertaining to this period. The remaining county-specific data was acquired from CAMPO. SIP-relevant criteria air pollutants (CAP), criteria air pollutant precursors, greenhouse gas (GHG) emissions, particulate matter and total energy consumption of the vehicles are estimated. Carbon dioxide (CO2) is included as the GHG. CAPs include carbon monoxide (CO) and oxides of nitrogen (NOx). The highly reactive sulfur dioxide (SO2) is also included in the CAPs. Among the particulate matter, the coarser PM-10 is included. Total energy consumption estimates are also generated to provide additional pointers for planning agencies. The emissions 'inventory' output type is used in the MOVES model to provide regional estimates as inventory generation is requisite in SIPs.

For demonstration and evaluation purposes, a comparison of the above mentioned estimates with the MOVES national level default data contained in its database is conducted. Often planning agencies tend to resort to the default data contained within MOVES for the county level inventory generation. However, the national default database contained in MOVES does not get updated regularly and this approach can overlook many characteristics of the region that can change a lot over time. From the traffic standpoint, it also does not enable the inclusion of traffic dynamics that a DTA-based modeling approach enables. Thus, such a comparison also offers an avenue for the performance assessment of the MOVES default county database. Taking into account these arguments, it has been advised in the MOVES documentation that the default database values are not be used in SIP analyses, this step incorporate this step just to evaluate the data and have another positive reinforcement and motivation for using local region-specific and sophisticated traffic-related data for SIP analysis for use by MPOs. The comparison results are shown in the Figures 4.4 to 4.9 below. The horizontal axis represents the MOVES modeling period, which is the AM peak in this study. Hour 1 in the plot represents the first modeling hour 7 AM-8 AM, going until hour 5, which is 11 AM-12 PM. The vertical axis represents the quantities of emissions of the respective pollutants obtained from the model run over that period. A diverse set of pollutants was selected as explained above. The two curves in each plot represent the outcomes from the DTA-integrated model run and the more general model that was run using the MOVES national default database.

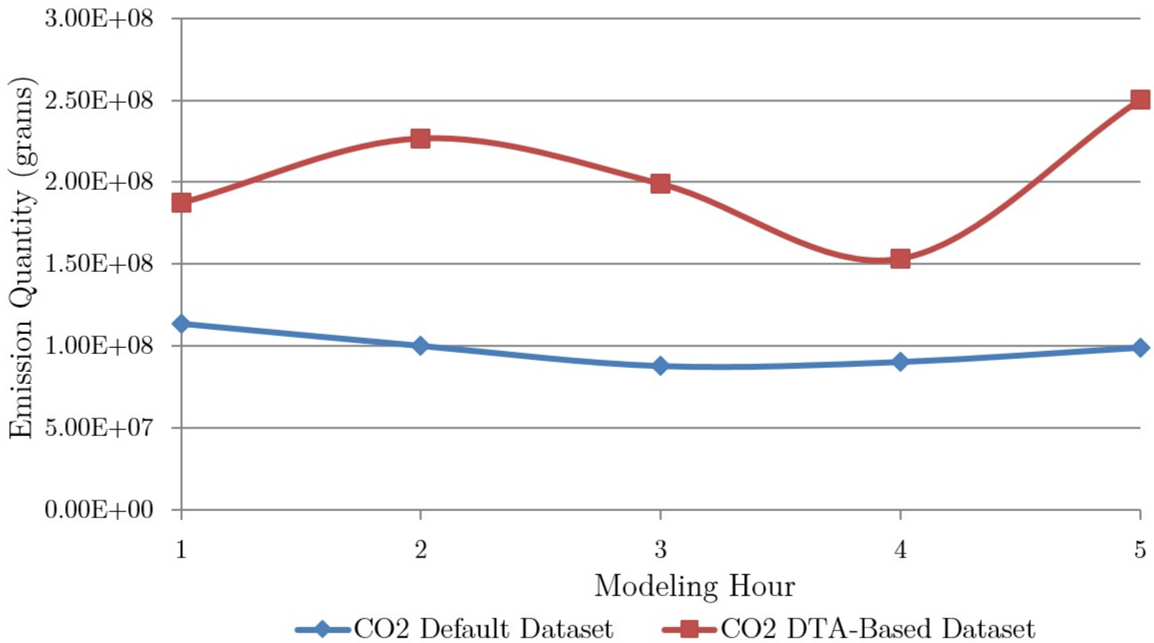

Figure 4.4: Carbon dioxide (CO_2) emissions inventory comparison

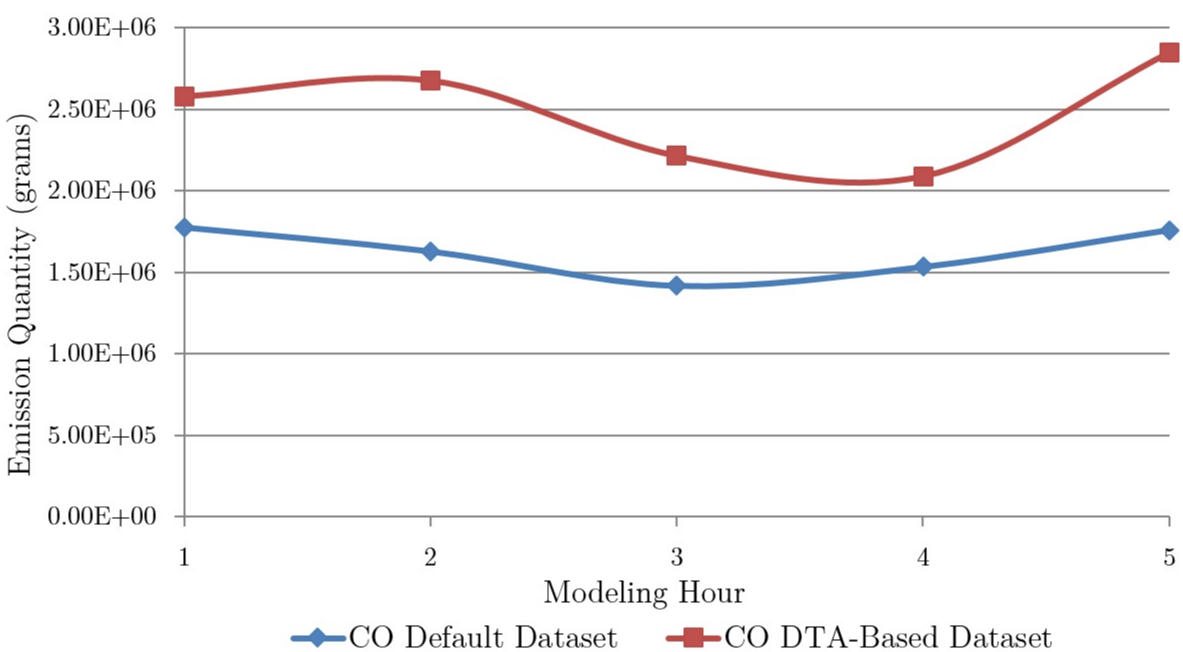

Figure 4.5: Carbon monoxide (CO) emissions inventory comparison

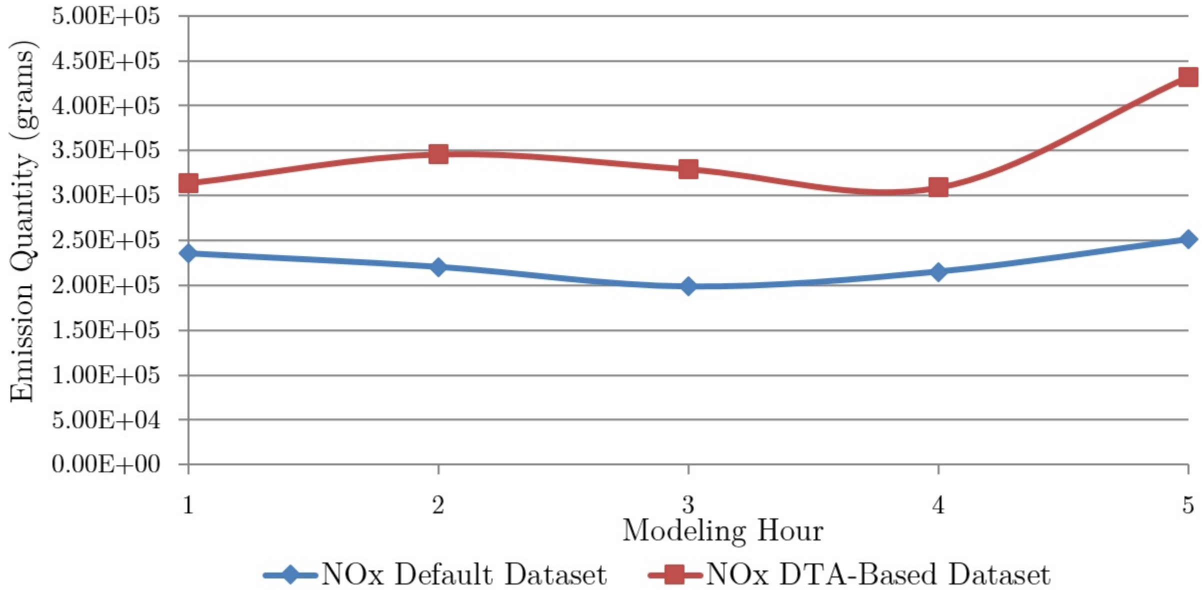

Figure 4.6: Nitrogen oxides (NOx) emissions inventory comparison

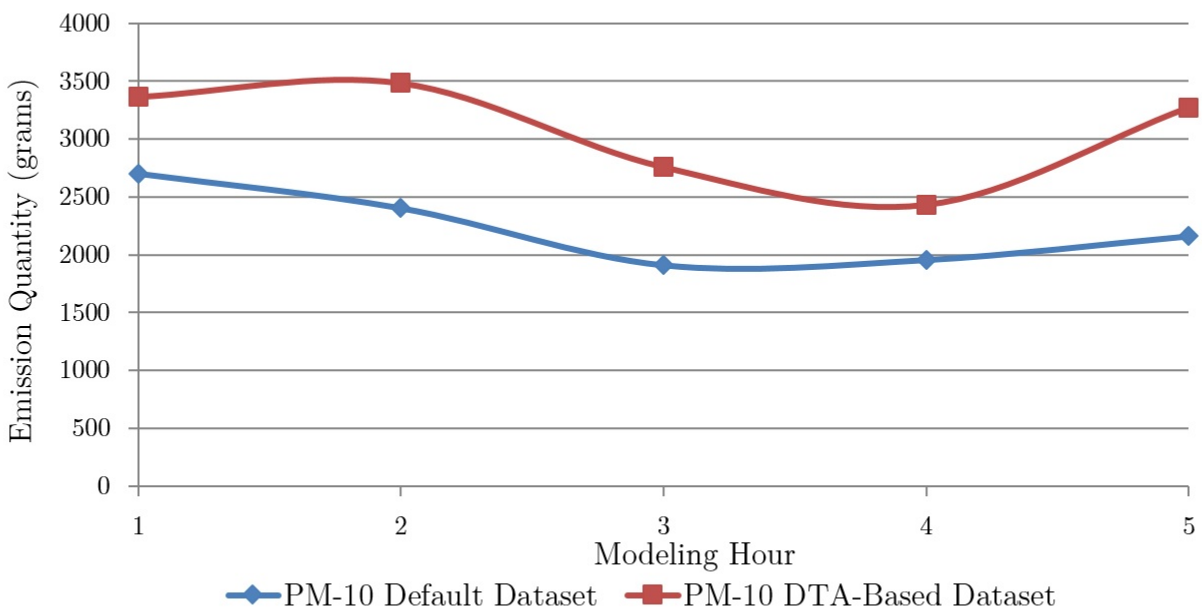

Figure 4.7: Coarse particulate matter (PM-10) emissions inventory comparison

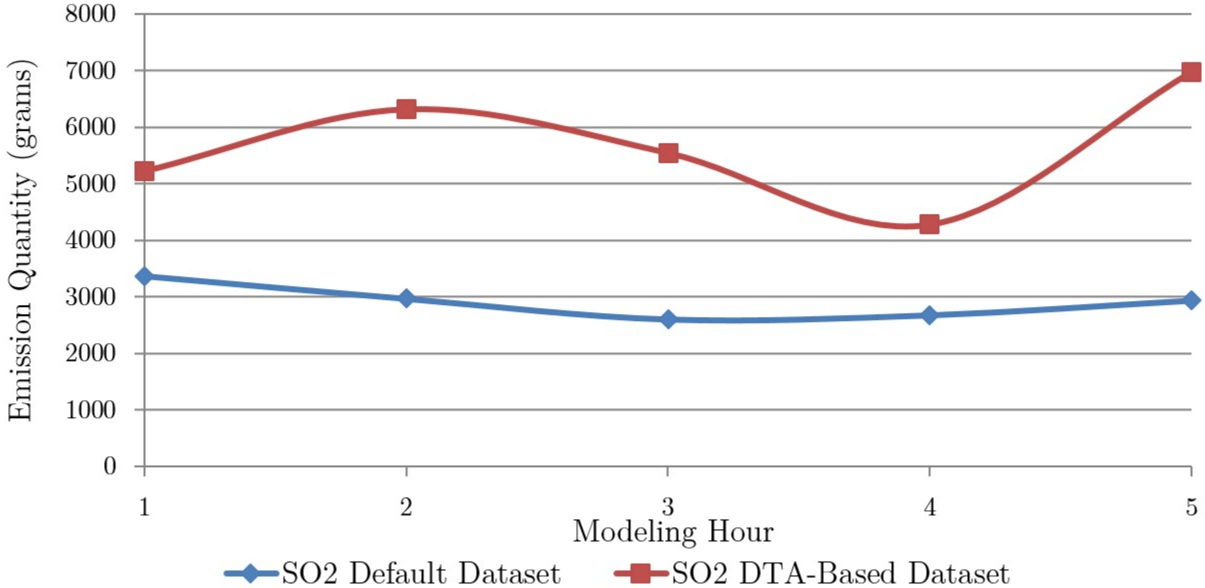

Figure 4.8: Sulfur dioxide (SO2) emissions inventory comparison

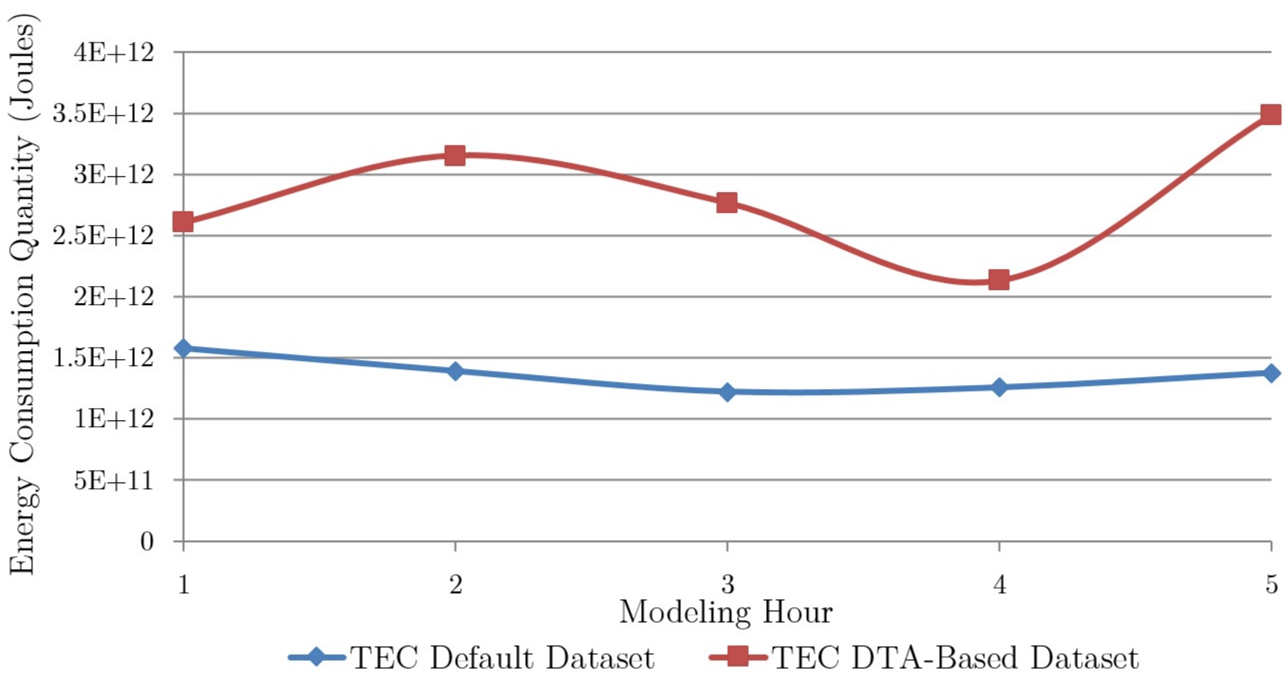

Figure 4.9: Total energy consumption (TEC) inventory comparison

4.5.4 Observations and Analysis

It can be seen that there are substantial differences in the estimates provided by the MOVES default database and this study-specific database that was created via the county data manager using locally collected and DTA-modeling based inputs. This analysis is for a specific time frame, location and other conditions, it can be seen that the modeling approaches lead to much different scenarios based on the region-specific data. The DTA-specific dataset yields slightly higher estimates on a consistent basis for all pollutant categories. However, the trend of emissions shows similar patterns on the temporal scale during the modeling period in this study. The magnitude of differences in the estimates obtained, however, is different for the different approaches.

Starting with the GHG category, CO2 demonstrates the largest differences both in terms of magnitude and trends. While the DTA-based inventory is higher in terms of magnitude, a lot of variation is observed across the range of modeling hours included. The inventory obtained from the default dataset is relatively more stable across the modeling period, only showing a steady growth. The changing trends in the magnitude of the CO2 estimates are a reflection of the changing dynamics of the system traffic over the AM peak period, which the DTA-based modeling approach is able to capture. Among the CAPs considered in this study, CO and NOx show nearly similar observations, especially in variation. In terms of magnitude, the differences are less than the ones observed for the CO2 GHG. The other CAP, SO2, however is more fluctuating, and shows higher differences among the two approaches, the relative differences almost comparable to the GHG scenario. It is interesting to note the similarities in the CO2 and SO2 outcomes. Particulate matter (coarse, PM-10) shows trends different from the other pollutants, in the sense that the variations in the emissions outcomes from the two approaches are lesser. Also, similar trends are observed across the modeling hours. Finally, the total energy consumption (TEC) upon observation yields trends much similar to GHGs. Figure 4.10 highlights the differences in the emissions inventories obtained using the two approaches for the pollutants considered in the study, and illustrates most of the points discussed as regards comparison of the emissions outcomes.

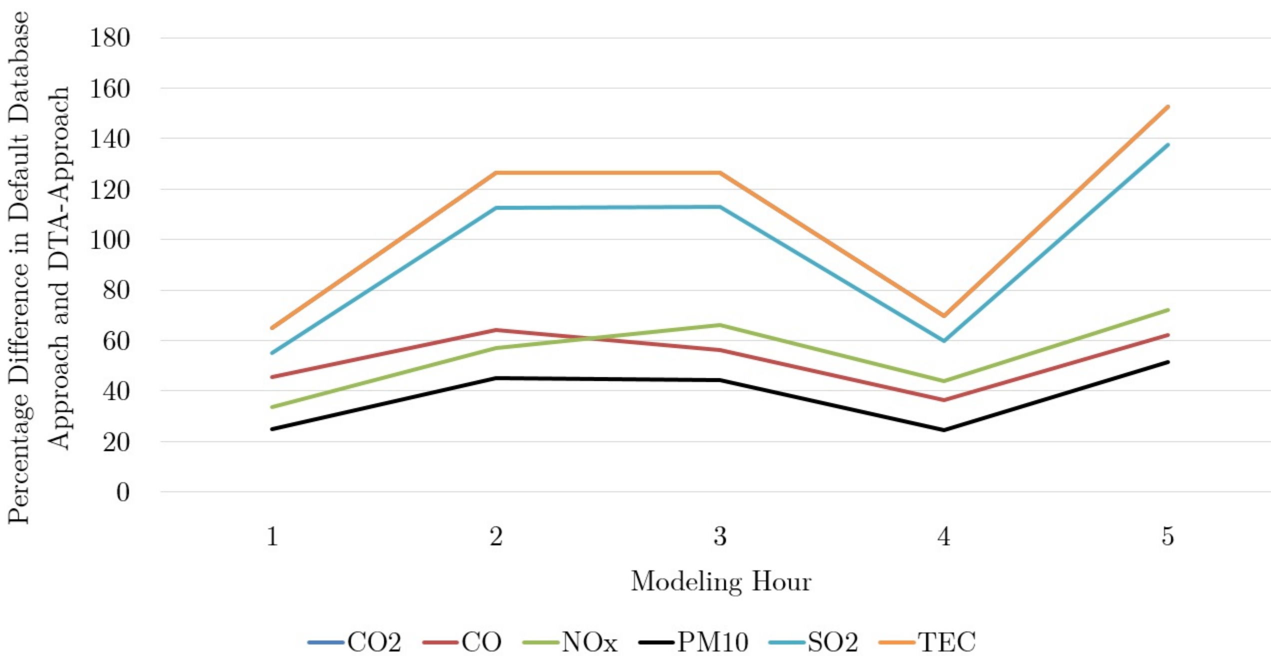

Figure 4.10: Temporal trends in emissions inventories using the two approaches for different pollutants

The next section will analyze the findings and draw some policy insights out of them, and conclude this part of the study.

4.6 Discussion and Conclusions

From the findings of the study described and illustrated above, significant differences in emissions trends were observed for GHGs, CAPs and PMs (noted here in decreasing order). This can mainly be attributed to the fact that there are differences in the input databases for the two modeling approaches, the national defaults approach essentially representing an older and 'static' nature of the data for a host of input parameters while the DTA-based approach accounting for most of the inherent dynamic features arising in these kind of modeling exercises and considering the nature of the traffic emissions modeling problem. These differences can once again be attributed to the characteristics associated with each of these approaches discussed in Sections 4.1 through 4.2. The study and the outcomes also bring to light significant divergences and estimation variations in emissions that can arise when simpler approaches such as modeling the county by simply using default parameters and input specifications are taken. It provides further reinforcement to using study-specific data, specifications and approaches to the emissions modeling exercise. Speed distributions and VMT, important inputs to the county-level emissions modeling can be predicted with better accuracy using advanced traffic modeling approaches such as the one used in this study. This approach also integrates the inherent dynamics associated with traffic dynamics, especially during peak periods of the day and accounts for the factors associated with congestion such as queue spillbacks. These have been major factors affecting emissions from the traffic sector, as has been established in numerous other studies discussed in Section 4.3. The current modeling excursion and application provides outcomes of a similar nature, but what is crucial is the context in which it has been carried out and the implications for practice. The methodology and approaches are aimed at MPOs and state agencies to prepare emission inventories for their SIPs and conformity documentation and analyses. Not accounting for these essential features as discussed above opens a wide range of possibilities for emissions estimation errors to creep in. Incomprehensive emissions inventories can lead to imperfect SIP documentation, and thus erroneous policy decisions for regional air-quality conformity and NAAQS attainment. Emissions inventories are one of the most important considerations in these decisions. From a qualitative standpoint, these inconsistencies in characterizing and accurately quantifying emission estimates, and ill-informed environmental policies and regulations based on them can have significant health impacts and implications for the environment as a whole.

To summarize, in this study, a framework was developed to integrate a mesoscopic DTA model with the EPAs regulatory emission model, MOVES. The framework enables the MPOs to perform CAA-mandated regulatory conformity analyses and SIPs using improved emission modeling that takes into account traffic dynamics. The DTA model used strikes a balance between computation time (mesoscopic simulation), geographical scale capabilities (multiple counties to regional scale), and traffic fidelity (modeling each vehicles spatio-temporal path in the network). Possible extensions to this framework include a 'custom-domain' analysis in MOVES which can model multiple counties in a metropolitan area simultaneously. Some recent modeling approaches in these aspects appear in Clifford and Cooper (2012) and Shah and Nezamuddin (2014). An exploration of different scales of modeling within MOVES can be an interesting extension as well. However, the county-level scale of analysis is required for SIP documentation and conformity demonstrations by MPOs and DOTs.

Chapter 5

Conclusions

This chapter summarizes the major objectives of the study, approaches, methodologies developed, major findings from applications, their larger implications and finally research contributions and future research avenues.

5.1 Research and Modeling Goals Achieved

The main goals and the research philosophy of the present study are questions of transportation planning and urban development by means of simulation-based dynamic traffic assignment. DTA-based models and approaches are relatively recent, with newer models and computational advancements are being introduced. Traffic congestion location, vehicle queuing, queue spill-backs, peak period saturation of links in the network and departure time component of users (drivers) are some essentially dynamic and critical features of traffic and regular transportation systems that traditional static traffic assignment and demand forecasting frameworks cannot account for. Hence the DTA-based approach for this study. These factors, as discussed in earlier chapters, are critical in the context of the specific planning questions raised in this study, hence their incorporation becomes imperative. The mesoscopic scale of DTA used in this study is able to strike a balance between usability and fine-level detail, and hence is applicable large sized study areas which are typically counties or metropolitan statistical areas (MSAs); these areas are commonly under the purview of planning organizations.

Two main planning questions were extracted by analyzing the trends and rationales of both federal and regional level policy developments and directions in the past few decades. These are also in sync with the directives of regional MPOs and state DOTs for implementing effective, efficient and environmentally sustainable transportation planning in their regulation areas. These are integral aspects in overall sustainable planning and development of regions. These questions primarily included investigating development patterns of urban/suburban streets and their effects, and developing frameworks for quantification of environmental effects of transportation to inform compliance with federal air-quality conformity regulations. These two questions, though seemingly unrelated, have actually emerged over time in a synchronous manner and are quite interdependent, with traffic and congestion dynamics being a common factor. DTA-based modeling paradigms were utilized to develop frameworks to address these planning questions independently and consequently gleaning potential interrelations. In the earlier parts of the thesis, it was inferred that the diverse emergent street patterns lead to different levels of inter-connectivity and arterial accessibility at the local level which has significant impacts on traffic dynamics of the system; in the subsequent parts, progressing into the environmental aspects of transportation planning, it was inferred that traffic dynamics have significant impacts on regional emissions inventories for a variety of pollutant categories. From the review of past research literature, such a correlation and linkage of two commonly encountered but yet largely unexplored research questions with transportation and traffic engineering research has not been developed in the past. Further analytic and empirical support for the 'complete streets' arguments have been presented. In addition to drawing these important policy insights and qualitative arguments, the thesis and the study therein also make contributions to transportation modeling.

Policy insights for the individual questions were also unearthed through the outcomes of applying the modeling frameworks to test areas, which are large regional transportation systems in themselves. These insights are mainly having an understanding of system traffic and congestion impacts of potential future street designs, and considering traffic dynamics in emissions modeling for transportation conformity decisions directives. From a modeling perspective, the thesis developed modeling paradigms for two contemporary issues germane to the metropolitan planning process. It was able to replicate different levels of local street connectivity, in line with the real-life suburban developments in the past few decades. It also enabled quantification of emissions and environmental impacts from the traffic sector in a more inclusive manner. These paradigms can potentially aid numerous urban transportation planning and sustainable development studies, and can be an integral part of many higher-level frameworks in regional planning where these questions commonly arise. The impacts of development patterns and the built-environment on the region's transportation system and traffic dynamics are important considerations that need to be made before making decisions on future designing and construction of streets. On the operations and environmental side, accurately characterizing and quantifying emissions inventories by merging inherent traffic dynamics in the process is critical in making future planning and environmental policy decisions. The linkage that thus goes from urban development patterns into traffic dynamics and further into regional emissions impacts of transportation is characterized through this study in a novel and quantitative manner.

From the policy standpoint, instruments to weigh the effects of accessibility-mobility against the environmental, economic and system impacts can potentially be utilitarian. Congestion has been known to impose economic costs by adding to time consumption and slowing down passage of goods and services. Traditional transportation planning approaches may be more concerned with just improving mobility and standalone aspects such as infrastructure improvements. The thesis forays into some larger domains and provides integrated frameworks encompassing wider aspects of economic and environmental sustainability with quantitative support; it simultaneously accounts for the critical dynamic features of traffic flow common to urban transportation systems.

5.2 Summary of Research Findings

DTA based modeling frameworks are developed to investigate contemporary planning questions relating to street connectivity and emissions-related impacts. The connectivity study quantifies the effects of varying degrees of connectivity have on system-wide automobile traffic; centroid-connector modifications were employed for creating such scenarios. It emerges that as the levels of connectivity and accessibility are closely intertwined with traffic dynamics and congestion, and as the levels of connectivity go down, system-wide traffic and congestion metrics are more. Specifically, travel time (both at the system level and the individual vehicle level), path length (at the origin-destination level and vehicle level), VMT and volume-over-capacity ratios of links are used as performance metrics for system-wide traffic state and congestion. For the environmental impacts question, a DTA-based integrated framework is developed to model the emissions from the transportation sector by integrating EPA's regulatory MOVES model with a DTA-simulator VISTA.

Since the policy motivation behind this part of the study is to design frameworks to potentially aid MPOs and agencies in conformity analyses and SIPs, a county-level study area is chosen for demonstration since that is a typical area of operation for these organizations, and besides there are EPA guidelines on conducting conformity and SIP analyses at the county scale. Also, instead of a simple demonstration of the framework by generating emissions inventories for the region, they are compared to the inventories generated using a MOVES national default database oriented approach, which is typical of many planning agencies and practice. This is mainly to demonstrate the utility of the study in the current state-of-practice and also to explore the implications of incorporating high-resolution traffic data and dynamics into the emissions modeling process. Variations both in terms of magnitude of differences and direction, whether it is higher or lower and also time-based trends observed over the modeling period and location - which was the morning (AM) peak period for Williamson County, Texas are gleaned. Not accounting for traffic features can lead to an under-estimation of emissions inventories, while the time-based trends of the intensities of these emissions showed similarities using both the approaches. Four different categories of metrics were considered including common criteria air pollutants, greenhouse gases, coarse particulate matter and total energy consumption; different trends and variations in inventories were observed across them. The findings reassert that in emissions modeling and SIP preparation and conformity studies, region-specific data be used and the dependence on MOVES national default databases and inbuilt modules be reduced as much as possible.

5.3 Future Research Avenues

Many prospective future directions emerge from the research for both planning questions raised in the study, and from various dimensions including modeling approaches, dynamic traffic assignment, policy development and planning decisions. Some prospective areas were discussed in detail at the end of Chapter 3. For the connectivity studies, extending the framework to include multi-modal analyses, specifically bicycling and pedestrian modes, and quantifying the impacts of street connectivity patterns on them have good promise. Another modeling extension to have a more exhaustive framework for impacts of local street connectivity can be incorporating the effects of time spent in traversing local streets, essentially by assigning a 'connector travel time' based on the current modeling approach. Also, innovative modeling and simulation approaches to represent levels of local street connectivity can be interesting.

There are a number of further research directions for emissions modeling, some of which were introduced at the end of Chapter 4. One direction is to develop a multi-scale modeling approach that more effectively makes use of the finer-resolution (per second) data from the DTA model to conduct project-specific emissions studies. While these would be crucial model evaluations and modeling exercises, it would not aid planning organizations in SIP documentation and conformity assurances since emission inventories generated from aggregated county-level analyses are the ones prescribed for those purposes. However, it would tap most into the capabilities of DTA in capturing high-fidelity and high-resolution traffic states. Also, observing the effects of spatial aggregations on emissions through creation of customized areas or counties would be interesting areas for further explorations. Additionally, modeling the dispersion of the emissions obtained from the integrated-framework using dispersion plume modeling tools such as AERMOD can be logical extensions. Additional environmental justice analyses examining the different impacts of emissions on socio-economically different pockets of population would also be able to address equity concerns associated with rapid transportation developments on the infrastructure side. Equity has emerged as an important component of planning, and is one of the "three E's" of sustainable development besides environment and economy.

The current work and the thesis lay a firm groundwork on which many of these above mentioned further research paradigms and policy arguments can be built.

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