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## **ABSTRACT**

### **A METHOD FOR ASSESSING TRANSPORTATION IMPACTS OF NEW LAND DEVELOPMENTS USING INTEGRATED LAND USE AND TRANSPORTATION NETWORK MODELING**

**by**  
**Branislav Dimitrijevic**

The transportation impact of new land developments on the local communities is reflected in an increase of trip-making activities, related increase in vehicular traffic, and expansion of transportation capacity necessary to serve the growing travel demand. To better analyze and understand these impacts, they can be classified in three categories: (1) new traffic flows generated directly by the users of a new development; (2) new traffic flows resulting from indirect developments, i.e., additional developments or growth in the local area related to or serving the needs of initial development; and (3) traffic flows induced by the new or improved transportation facilities, including flows associated with induced land developments. Proper assessment of the transportation impacts of new land development is critical in determining the required improvements in transportation infrastructure and other mitigating strategies, equitable allocation of costs associated with the transportation improvements and mitigating strategies, as well as the appropriate policies that serve the desired local and regional urban development goals. The assessment should, therefore, take into account all three components of transportation impact, i.e., direct, indirect, and induced.

The traffic impact assessment methodology developed in dissertation research integrates land use, travel demand, and transportation network modeling to quantify each component of the traffic impact on the highway network providing access to the new land development. The modeling procedure is accomplished in a iterative process over eight

modeling phases, and involves a feedback loop between travel demand and network model, and the corresponding land use model for a given geographic region. The methodology calculates incremental VMT associated with each component of the transportation impact, and thus can ascertain corresponding transportation costs if the cost of VMT is known. Using the appropriate formula, each cost component (direct, indirect, and induced) can be allocated to either the local community (to be paid from local taxes and development fees) or the regional traveling public (to be paid from regional transportation funds, such as proceeds from the gas tax). The methodology was demonstrated in a case study of a hypothetical land development in a local community and a corollary highway improvement in a medium sized metropolitan area. A sensitivity analysis was also conducted to evaluate response of the modeling procedure to changes in in key input parameters.

The results of the case study reveal that the immediate (short-term) induced traffic impacts are far more significant than the long term impacts, and they increase with the size of the highway capacity expansion. Besides being far less significant than short term impacts, the analysis showed the long-term induced impacts to be consistent regardless of the size of highway capacity expansion, measured as a percent of the overall change in VMT. The case study analysis demonstrated that the methodology can be a useful tool for quantifying direct, indirect, and induced traffic impacts of land development, as well as allocation of responsibilities for underlying transportation system improvements. The elasticities calculated as part of the sensitivity analysis can provide a guide in evaluating expected increase of VMT due to direct, indirect, short- and long-term induced impacts.

**A METHOD FOR ASSESSING TRANSPORTATION IMPACTS OF NEW LAND  
DEVELOPMENTS USING INTEGRATED LAND USE AND  
TRANSPORTATION NETWORK MODELING**

**by  
Branislav Dimitrijevic**

**A Dissertation  
Submitted to the Faculty of  
New Jersey Institute of Technology  
in Partial Fulfillment of the Requirements for the Degree of  
Doctor of Philosophy in Transportation**

**John A. Reif, Jr. Department of Civil and Environmental Engineering**

**August 2018**

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**APPROVAL PAGE**

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I dedicate my dissertation to my mom, Elisaveta and my wife, Vesna. They endured with support and faith in my academic endeavor, every step of the way. This dissertation is their success as much as it is mine.

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# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction of the Research Topic

Besides their social, demographic, and economic implications, new land developments also have a profound impact on the surrounding transportation system. Whether residential or commercial, new developments inevitably result in an increase of trip-making activity, as well as related vehicular traffic.

The primary transportation impact of a new land development is travel demand generated directly by users of the new development, and the corresponding traffic flows. This is defined as *direct* transportation impact of new land development. The new land development may also have a secondary, *indirect* effect on the host community and the nearby area traffic. This indirect effect is a consequence of additional development(s) or growth that take place within the community, related to the initial development. For example, a portion of those employed at the initial development would also reside in the same area. This may result in a development of additional residential units in the area. Both residential and non-residential components of the initial development will create demand for locally procured goods and services, which would support additional jobs in the local community. Altogether, the indirect developments create additional travel demand in the local community, which affects the traffic patterns and likely results in additional traffic volumes and vehicle-miles traveled that have to be accommodated by the local roadway infrastructure.

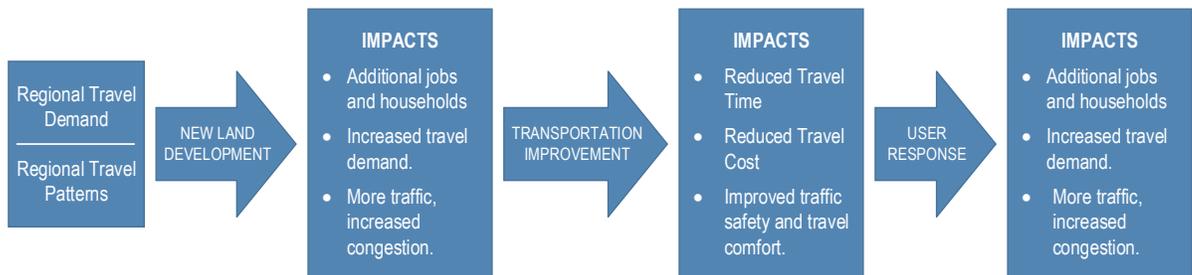
To provide adequate access to the new land development and accommodate additional traffic, resulting from both direct and indirect effect of the initial development, it is often necessary to improve or expand the transportation infrastructure near the new development. These improvements in roadway and other transportation infrastructure must be designed to preserve or improve the existing level of service of the area roadways, measured in terms of travel time and traffic-related travel delay. The improvements may include redesigned or expanded intersections and/or interchanges, new signalization and signage, widening of arterials, addition of acceleration and deceleration lanes, parking, transit stops, etc.

The share of the cost of roadway improvements to accommodate direct transportation effect of new development is generally recovered from the land developers through impact fees. The share of the cost of roadway improvements attributed to the indirect effect of new development is generally covered by the local community, but may be recovered over time through impact fees from the developers of indirect development(s).

The roadway improvements implemented in the area are generally designed to provide additional capacity to accommodate direct and indirect growth of traffic. In the immediate period these improvements improve the levels of service relative to the existing conditions. The improved level of service and expanded capacity attract new users to the improved roadway facility. These additional users are not attracted to either initial or indirect development in the area, but merely seek to take advantage of the improved highway facilities (or more generally, improved transportation infrastructure). The travel demand, and the resulting traffic, induced by the improvement of transportation system,

are respectively referred to in literature as *induced demand* and *induced traffic* (Lee et al., 1999).

The sequence of transportation impacts following the new land development is illustrated in Figure 1.1. The new development creates new jobs and brings new households to a community, which generates more demand for travel and more traffic in the local transportation network, possibly in the regional transportation network as well. The additional traffic contributes to increase of traffic congestion in the local and regional transportation network. Subsequently, to mitigate the traffic congestion, transportation network is improved or expanded to handle additional traffic. The improvement results in reduced travel times and costs, and may also improve safety and comfort of travel. Users (travelers) react to improved transportation conditions by using the improved or newly built transportation facility to complete their trips, or locate their activities, so as to take advantage of reduced travel time and cost, and improved safety. This in turn attracts more jobs and households to locations along the improved facility, and results in an increase of travel demand, more traffic, and more congestion in the community where the initial development took place.



**Figure 1.1** Sequence of transportation impacts following the new land development.

To properly assess the overall traffic impact of new land development and the associated improvements of highway (and other transportation) facilities, the induced travel demand and the corresponding traffic flows should be taken into account. An analysis that considers direct, indirect, and induced traffic impacts of new development will enable a more accurate assessment of:

- The ability of OR the need for transportation infrastructure improvements to provide required (or desired) roadway level of service.
- The traffic flows utilizing the improved transportation facilities.
- Equitable impact fees and other fiscal models to support maintenance and improvements of transportation infrastructure.

The nature and sources of induced demand and induced traffic flows are well researched and documented (Hansen, 1995), (Lee et al. 1999), (Cervero, 2002). The sources of induced traffic include rerouting of existing trips to the improved transportation facility, change of destination, time of travel, or mode of existing trips, new trips made by the current users of the facility that would not have been made without the transportation improvement, and trips generated by new land development induced by the transportation improvement. What is less clear is how best to estimate the magnitude of induced traffic, while differentiating between different sources of induced demand. This is especially the case with estimating the travel demand and traffic flows attributed to *induced developments*, i.e., land developments nearby the improved transportation infrastructure that are induced by the improved accessibility and attractiveness of the location due to the transportation improvement.

Ewing and Lichtenstein (2002) provide a review of analytical methods for estimation of induced traffic. The reviewed methods rely on empirically derived or

modeled relationships between changes in vehicle-miles traveled (VMT) and increase in transportation supply, where transportation supply may be expressed in terms of additional highway lane-miles or reduction in travel time. While the applied calculation methods vary among these models, they all seek to estimate trip-rates attributed to induced demand, or elasticity of travel demand with respect to change in transportation supply, without ascertaining changes in trip generation and trip distribution patterns resulting from the transportation improvements. The shortcoming of these methods is that they do not explicitly consider induced development and the resulting traffic demand. The analysis of traffic attributed to induced development would require the use of land use analysis (to quantify induced development) and transportation demand analysis (to quantify the impact of induced development on traffic flows). While a possible application of land use models for the purpose of estimating induced development has been considered and described, it has not been demonstrated, especially not in the form of methodology that supports determination of traffic impacts of induced development. The lack of such methodology identifies a need for research directed towards development of an analytical modeling framework and methodology that can ascertain the interaction between transportation and land use as it relates to induced development and the resulting induced travel demand.

## **1.2 Structure of the Dissertation**

The dissertation research is presented in seven chapters. The first chapter provides a brief introduction of the research problem, and structure of the dissertation. The second chapter defines the research problem and objectives of the dissertation, and outlines the research methodology for addressing the stated research problem. Chapter 3 provides a summary of

literature review accomplished as a background for dissertation research. Chapter 4 presents the proposed methodology for assessing direct, indirect, and induced transportation impacts using integrated transportation and land use modeling. The case study analysis and research results are summarized in Chapter 5. Chapter 6 summarizes research outcomes and contributions of the dissertation, including a discussion about contributions to and implications for transportation systems planning and analysis of induced development and associated traffic flows. Chapter 7 outlines future research direction. There are also two Appendices: Appendix A, providing a summary description of the travel demand modeling tool used in the case study model, and Appendix B, providing a brief description of the TELUM land use modeling system, also used in the case study model.

## CHAPTER 2

### RESEARCH PROBLEM AND APPROACH

#### 2.1 Research Problem Statement

The research questions that constitute the problem statement for this dissertation are the following:

- Can an integrated transportation and land use modeling approach be effectively applied to estimate direct, indirect, and induced traffic, including the traffic generated by induced development, which result from a localized land development and the concomitant improvement in transportation infrastructure?
- Can the results of this analysis be effectively used to assess an equitable distribution of fiscal impacts of new land developments onto the travelers onto the travelers, as they relate to improvements in transportation system necessary to serve the traffic demand following the new land development?

The presented research focuses on developing a method for assessing transportation impacts of new land developments that takes into account direct, indirect, and induced traffic associated with the new development and the related transportation improvements. The presented modeling methodology ascertains each of the three components of additional traffic and resulting impact on the level of service of local roadway system. In this context, a special attention is given to assessment of induced demand, and more specifically to the portion of this demand generated by induced developments.

#### 2.2 Research Objectives

The main goal of this dissertation was to develop an integrated transportation and land use modeling method for quantifying induced traffic demand. The method developed in

dissertation research was implemented and demonstrated using a case study. The purpose of the case study demonstration was to evaluate applicability and usability of the proposed integrated transportation and land use modeling approach, discuss implications of the use of this modeling approach, and potential extensions for assessing fiscal impacts of transportation infrastructure improvements and related policies related to land development. The more specific research objectives are the following:

1. Develop a methodology for calculating traffic impacts of new land developments, including induced traffic, using integrated travel demand and land use modeling.
2. Apply the methodology to evaluate the impacts of the combined travel demand effects (direct, indirect, and induced) on a highway network near the new land development.
3. Demonstrate the application of the proposed methodology using a case study.
4. Ascertain the traffic fiscal policy implication of the proposed methodology in terms of efficiency and equity.
5. Ascertain possible theoretical and practical contribution, implications, and extensions of the proposed methodology.

## **2.3 Research Approach**

The research approach was organized in five tasks, each focusing on a specific aspect of the research process. The tasks are described in the following five subsections.

### **2.3.1 Understand the Research Problem and Analysis Framework**

The primary objective of this task was to develop comprehensive understanding of the interaction between the land development, local and regional land use, and the corresponding impacts on the local and regional traffic patterns. The purpose of this task was also to review and become familiar with the modeling tools used in transportation

planning that can be applied to address the stated research problem. This helped identify what needs to be done to adapt or modify these tools to achieve the objectives and the overall goal of dissertation research.

### **2.3.2 Develop the Analysis Methodology**

This task focused on developing the modeling methodology for analyzing transportation impacts of new land developments, considering an integrated travel demand and land use modeling approach. The methodology identified the analytical procedure that should be followed, explained the inputs and outputs in each phase of the modeling process, and described the anticipated results of the analysis.

The capability of the proposed methodology to ascertain the changes in land use driven by the improvement in transportation system, and vice versa, was critical to assessment of induced development and the resulting induced traffic. The induced development, as defined in this research, occurs when new or improved transportation infrastructure improves accessibility of the nearby land, thus increasing its attractiveness for new developments. This is the effect that transportation infrastructure improvements have on land use. When the new land developments are introduced in the community, they generate additional traffic in the local and regional transportation network, affecting the underlying transportation level of service. This is the effect that changes in land use have on the transportation system. The proposed methodology was designed to quantify the interactions between the regional transportation system and land use in relation to new land development and the related transportation improvements.

### **2.3.3 Demonstrate the Methodology Using a Case Study**

The methodology developed in Task 2 was demonstrated using a case study. The case study analysis quantified the traffic impacts of a hypothetical land development in terms of vehicle miles traveled attributed to each component of additional traffic, including direct, indirect, and induced traffic. This was accomplished by making appropriate adjustments in the land use model, highway network model, trip generation and trip distribution modules of the travel demand model, and executing the traffic assignment to calculate the resulting traffic flows in the network. The adjustments in the land use model, network model, trip generation and trip distribution were made in an iterative protocol that reflects the progression of respective changes in the case study area following the initial land development.

### **2.3.4 Analyze and Discuss the Results**

Results from the modeling exercise conducted in Task 3 were reviewed and discussed in detail. The interlaced effects of changes in land use, changes in travel demand, and improvements in transportation system capacity were ascertained. The potential fiscal implications of the observed changes in traffic flows and effects on the local traffic in the vicinity of new development were also discussed.

The results of the case study analysis, as well as the proposed modeling methodology were further discussed in the context of various policy implications. More specifically, this pertains to policies that address assessment and distribution of costs related to transportation improvements required to mitigate the traffic impacts of the new land developments, including the induced traffic. They may include policies for assessing impact fees to be paid by the developers, as well as fiscal burden on the local community

and regional or State government associated with new land developments. These implications arise from the fiscal impacts that traffic imposes on the local and regional communities in terms of capital improvement, operations and maintenance of transportation infrastructure. Other implications were also discussed, such as usability and applicability of the proposed methodology and models. Possible extensions of the proposed methodology and related future research direction were also documented.

## CHAPTER 3

### RESEARCH BACKGROUND

#### 3.1 Assessing Transportation Impacts of New Land Developments

The effects of direct and indirect land development on transportation demand, and the resulting traffic flows, can be estimated using various traffic impact analysis models, usually as part of traffic impact studies. The traffic impact studies typically use travel demand models to assess the number of trips generated by the new development and the resulting traffic flows on the highway network. The results of the analysis are also used to identify appropriate improvements in the transportation system that would mitigate the impacts of additional traffic on mobility, safety, and the overall operation of the local and regional transportation network.

##### 3.1.1 Estimation of Traffic Impacts Using (Four-Step) Travel Demand Models

The traditional travel demand models consist of the following four components or steps:

1. *Trip Generation*, which estimates the number of trips produced by and attracted to each geographic analysis zone, based on the underlying type and intensity of land use and activities. The result of the trip generation are estimated total trips (flows) into and out of each analysis zone (trip productions and attractions).
2. *Trip Distribution*, which estimates flows between analysis zones, i.e., the linkage of the trip ends predicted by the trip generation model. The result of the trip distribution model are presented in a form of trip interchange matrix between pairs of analysis zones (i.e., trip origins and destinations, or O-D pairs). The trip distribution output matrix is also called ‘trip table’.
3. *Modal Split*, which estimates the percentages of travel flow that will use each of the available transportation modes between each O-D pair.
4. *Trip (Traffic) Assignment*, which assign the O-D flows for each mode on specific routes of travel through the respective modal networks. The output of the traffic assignment are vehicle volumes on each segment of the highway

network. Based on the result of the traffic assignment it is possible to calculate vehicle-miles traveled (VMT) on each highway segment or part of the highway network, as a measure of traffic intensity over a period of time, e.g., a day, month, or a year.

All inputs in the travel demand model must be appropriately stratified according to the model properties. For example, households may be stratified by income level and car ownership; population may be stratified by age and employment status; employment may be expressed in terms of number of jobs by industry type, etc. The direct and indirect developments are represented in a four-step model by adjusting inputs for the trip generation model, such as increase in number of residents, households, and employment in the geographic zones where new developments are located. The adjustments are based on the expected number and stratification of new residents, as well as type and size of commercial establishments that will be added as part of new direct and indirect developments. The adjusted number of households or residents, as well as employment (i.e., number of jobs) are then multiplied by the corresponding trip rates per household or resident, and per square foot of commercial space respectively, to obtain number of trips generated in the area after the addition of new developments. The trip rates are obtained from empirical data and surveys of previous similar developments, such as trip rates and trip generation formulas based on statistical regression analysis documented in Trip Generation Manual published by the Institute of Transportation Engineers (ITE, 2017).

The trip distribution, modal split, and trip assignment steps are then accomplished using a regional or sub-regional travel demand model for the area where the new development is located. The trip assignment is accomplished by assigning trips between origins and destination to various paths across the highway network so as to minimize

users' travel cost. The travel cost on each travel path is determined as a sum of travel costs on individual links contained in the path. The travel cost on each link is calculated using *performance functions*, which express the average travel cost of traveling on the link as a function of total traffic volume on the same link. The functional relationship assumes that the operating and geometric characteristics of the transportation facility represented by the link remain unchanged in the short run. The most commonly used performance function of this type is the Bureau of Public Roads (BPR) function (Morlok, 1978), also referred to as the BPR *congestion curve*. The BPR performance function has the following mathematical expression:

$$t_a = t_{0a} \left[ 1 + \alpha \times \left( \frac{x_a}{C_a} \right)^\beta \right] \quad (3.1)$$

where:

$t_a$  = average travel time on link a

$t_{0a}$  = free flow travel time on link a

$x_a$  = equilibrium vehicle flow on link a

$C_a$  = capacity of link a

$\alpha, \beta$  = calibrated parameters

The travel time calculated in Equation (3.1) can be converted to cost by multiplying with the users' average value of time (*VT*), and combined with other user costs on a link, including average out-of-pocket cost (*OP*), to form a *Generalized Cost* function. For highway users, out-of-pocket cost may include cost of highway tolls, vehicle operating

cost, and parking fees. An example of generalized cost function that applies a linear weighted combination of out-of-pocket and travel time cost is shown in Equation (3.2).

$$g_a(x_a) = OP_a + VT \times t_{0a} \left[ 1 + \alpha \left( \frac{x_a}{C_a} \right)^\beta \right] \quad (3.2)$$

where:

$g_a(x_a)$  = generalized cost of travel on link a with flow  $x_a$

$OP_a$  = out-of-pocket cost on link a

$VT$  = highway users' average value of time

The generalized cost derived from Equation (3.2) is calculated for each link and aggregated for each path considered in trip assignment. The assignment of trips to network paths can then be accomplished with one of the following three optimization objectives: (1) minimize travel costs of individual trips (also called *User Equilibrium* traffic assignment), or (2) minimize the total cost of all trips combined (*System Optimal* traffic assignment), or (3) minimize perceived travel costs of individual trips (*Stochastic Equilibrium* traffic assignment) (Papacostas & Prevedouros, 2000). User equilibrium and stochastic equilibrium principles can be considered to be more applicable for traffic impact analysis, as they reflect more realistically the general travel behavior. The mathematical formulation of the user equilibrium traffic assignment problem is shown in Equation (3.3) (objective function), Equation (3.4) (flow conservation constraints), Equation (3.5) (link-path definitional incidence relationships), and Equation (3.6) (non-negativity constraints) (Sheffi, 1985).

$$\min Z = \sum_a \int_0^{x_a} g_a(x_a) dx \quad (3.3)$$

Subject to:

$$\sum_k f_k^{rs} = q_{rs} : \forall r, s \quad (3.4)$$

$$x_a = \sum_r \sum_s \sum_k \delta_{a,k}^{rs} f_k^{rs} : \forall a \quad (3.5)$$

$$f_k^{rs} \geq 0 : \forall k, r, s \quad (3.6)$$

$$x_a \geq 0 : \forall a \in A$$

where:

$g_a(x_a)$  = generalized cost of travel on link a with flow  $x_a$

$k$  = network path

$x_a$  = equilibrium vehicle flow on link a

$f_k^{rs}$  = vehicle flow on path k connecting origin zone r and destination zone s

$q_{rs}$  = trip rate between origin zone r and destination zone s

$\delta_{a,k}^{rs}$  = binary parameter, equals 1 if link a is contained in path k connecting origin zone r and destination zone s, 0 otherwise

In the analysis of traffic impacts of new land developments, the new trips generated by direct and indirect developments will increase vehicle flows ( $x_a$ ) on certain links in the network, thus increasing average travel time for all other users utilizing the same links to

complete their trips. Increase in travel time implies travel delay experienced by the users, as compared to the travel time prior to addition of new land development. The travel delay, in turn, translates to a decreased level of service on impacted highway facilities. The travel time, travel cost and the corresponding level of service on said highway facilities can be restored to pre-development levels by increasing capacity of these facilities, represented as  $C_a$  in Equations (3.1) and (3.2). This capacity increase is accomplished through appropriate transportation improvements of the highway facilities impacted by the additional traffic resulting from the new land development.

Following this approach, the estimated traffic flows and the level of service are compared between the baseline traffic model (i.e., before addition of the new developments) and the traffic model modified to reflect the new land developments. The comparisons are made for all network links in order to identify which ones are impacted by additional traffic, and how much. The difference in traffic flows between the baseline and modified traffic assignments, expressed in terms of vehicle volume and VMT, indicates the amount of additional traffic generated by direct and indirect developments that will be utilizing both local and regional highway facilities. The increase in traffic volume translates to a decrease in highway level of service on individual highway segments (links). The level of service is usually expressed in terms of travel time delay or volume/capacity ratio.

### **3.1.2 Determining the Need and Responsibility for Transportation Improvements**

The difference between the underlying traffic flows and the level of service before and after the addition of new land development, indicates the need for transportation improvements. The purpose of the improvements is to increase capacity of individual

highway facilities, or add new capacity to the network, so as to accommodate additional traffic generated by the new development, without deteriorating level of service.

The bigger this difference, the more substantial transportation improvements ought to be undertaken to mitigate the transportation impacts of the new land development and maintain the levels of service prior to the development. Besides mitigating impacts of the new development on highway traffic, the transportation improvements must also mitigate any negative impacts on pedestrian, bicycle, and public transit transportation. Transportation safety should be included in the analysis of transportation impacts, and be addressed as part of mitigation strategies.

The transportation improvements are recommended based on the results of the traffic impact analysis. If the impacts are such that only local traffic in the vicinity of the development is affected, it may be sufficient to improve signal timing, add traffic signals, or provide additional turning lanes at the intersections in relative proximity to the new development. Any increase in pedestrian and bicycle traffic may be addressed by installing additional pedestrian and bicycle facilities and traffic control devices in the vicinity of new development.

Larger developments may have more substantial impacts, affecting both local and regional traffic. When traffic generated as a result of new development is expected to affect major regional highways, the improvements must be implemented to mitigate those impacts. The resulting mitigation measures may include building a new interchange, expanding capacity of roadways by addition of new lanes and even building new highway facilities.

Financial responsibility for mitigation of traffic impacts attributed to direct and indirect developments is assigned to developers through impact fees. The impact fees are determined using various cost estimation methods, such as Fiscal Impact Analysis Models and Per Capita Transportation Cost Models (Burchell et al., 2009). The cost of improvements includes capital, operating, and maintenance costs, and is based on the type and scope (size) of the underlying transportation improvements.

### **3.1.3 Evaluation of the Effects of Mitigating Transportation Improvements**

Transportation models that are used for evaluation of traffic impacts of new land developments can also be used to evaluate effect of transportation improvements designed to mitigate those traffic impacts. This is accomplished by modifying the highway network representation to reflect the proposed improvements and the associated increase in highway capacity. The modified highway network is then used as an input in travel demand modeling process. The improvements of the existing facilities are usually reflected in the traffic assignment model as increase in link capacity (value of  $C_a$  in Equation (3.2)), while new facilities are represented by new links in the network, each providing additional capacity that can be utilized to accommodate traffic flows as an alternative to existing facilities, and alleviate the traffic on the more congested links with poor level of service.

The results of the travel demand modeling procedure provide the estimated traffic flows and the level of service on of the highway facilities, considering the transportation improvements and increase in travel demand resulting from the new land development. It is expected that the results of the travel demand modeling analysis would confirm that the proposed improvements would accomplish the goal of preserving or improving the level of service of the highway facilities impacted by the new development. If that is not the

case, additional analysis would be required to identify and evaluate additional and other transportation system improvements that would adequately address the need to mitigate the traffic impacts of new developments.

It should be noted that the traffic flows calculated in the travel demand modeling process include the flows generated by the direct and indirect land development, but may also include induced travel. Therefore, the resulting level of service on some highway facilities may be worse than it was prior to the land development and prior to the implementation of the proposed transportation improvements. This can happen even though the proposed transportation improvements and the corresponding increase in transportation capacity would be sufficient to accommodate additional traffic attributed to direct and indirect impact of new development, while at minimum maintaining the level of service. However, addition of transportation capacity may cause a redistribution of the existing traffic, both locally and regionally, and even generate new trips and additional regional traffic. This induced demand and induced traffic may be significant, to a point where transportation improvements designed to mitigate direct and indirect impacts of new development may not be sufficient to maintain the level of service prior to new land development. One such example is the Long Island Expressway in New York, which became congested virtually the same day it opened to traffic, even though it was planned as a high-speed thoroughfare connecting Long Island suburbs with the New York City (Caro, 1974).

Certainly, the burden of accommodating induced traffic in the local and regional network cannot be transferred to developers. It is therefore important to properly analyze and quantify induced traffic, which can then be used to identify incremental transportation

improvements to mitigate the traffic impacts of induced traffic, or developing other appropriate travel demand management measures. Consequently, better understanding and assessment of induced traffic can be used to justify investments in transportation improvements that should be made on a regional level, rather than burdening local communities with substantial costs associated with these improvements.

### **3.2 Induced Traffic, Induced Demand, and Induced Development**

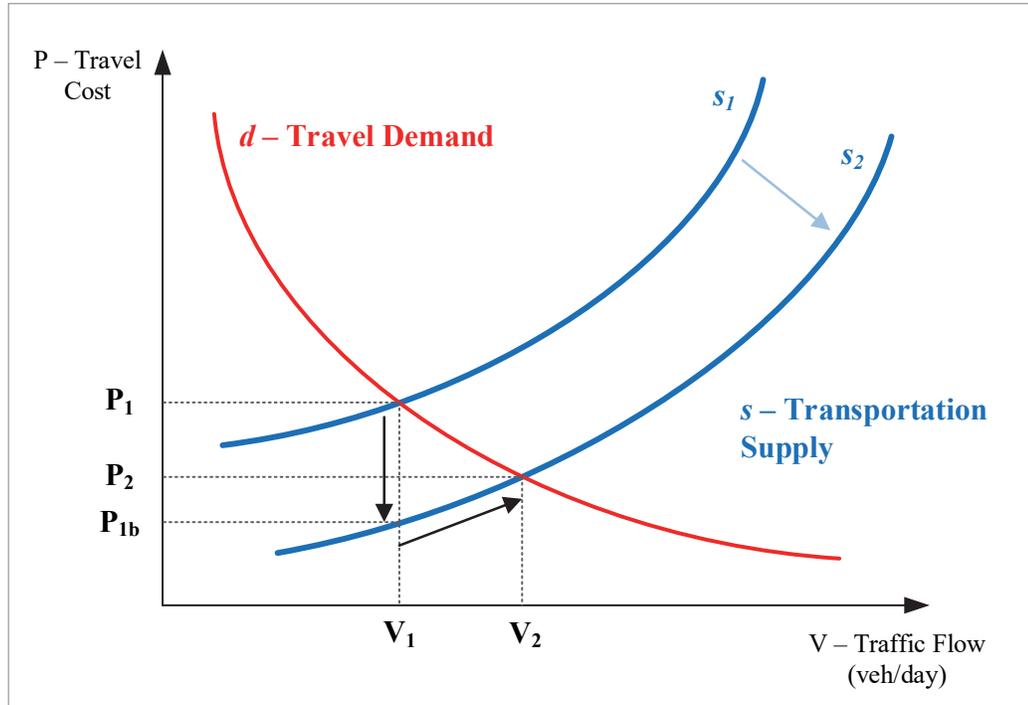
Before discussing the concepts of induced traffic, induced demand, and induced development, it is worth noting that these terms are used in literature somewhat interchangeably. While they are related, these terms describe distinct phenomena. It is therefore useful to define each of these terms as follows:

- *Induced Traffic* is defined by DeCorla Souza (2000) as “any increase in daily vehicle miles of travel in the long-term at the region-wide level resulting from expansion of highway capacity”. Induced traffic is also referred to in literature as *induced travel* and *generated traffic*, describing additional vehicle travel generated as a result of increase in road capacity (Litman, 2001)
- *Induced Demand* is defined as additional trips stimulated by or created directly as a result of a transportation improvement. Accomplishment of these additional trips creates additional travel, which is manifested in a highway network as additional VMT. Induced demand can occur as a result of any transportation improvement, not only highway improvements.
- *Induced Development* is new land development, residential or non-residential, that occurs as a direct consequence of an expansion of transportation capacity, and would not have occurred otherwise (without the said transportation improvement) (Ewing and Lichtenstein, 2002). Induced development is one (but not the only) source of new (induced) travel demand, which in turn results in additional (induced traffic).

Concepts of induced demand and induced traffic can be explained using economic theory of transportation supply and demand. Figure 3.1 illustrates the short-term change in

travel demand in response to increase in transportation supply for a highway network or corridor. Let us assume that the demand curve  $d$  represents demand for travel, while the curve  $s_1$  represents the existing capacity of a highway network or corridor (transportation supply). The equilibrium between demand for travel and transportation supply is established at traffic flow  $V_1$  and the average cost of travel of  $P_1$ . Expansion of transportation network capacity, through improvements of the existing facilities or construction of new facilities, increases transportation supply – represented by shift of supply curve from  $s_1$  to  $s_2$  (Figure 3.1). As a result, the travel time and the cost of travel in the highway network decrease from  $P_1$  to  $P_{1b}$ . However, soon after, more traffic is attracted to the new or improved facility, seeking to take advantage of reduced travel costs. This increase in demand leads to increase in traffic volume in the highway network, which causes increase in travel time and travel cost. Consequently, a new equilibrium between travel demand and transportation supply is reached at traffic flow  $V_2$  and cost of travel  $P_2$ .

The resulting travel time and cost of travel are higher than they would have been had the demand remain at the initial level. The increase in demand caused by the transportation improvement represents the induced demand, and the resulting increase in traffic,  $V_2-V_1$ , represents induced traffic.



**Figure 3.1** Short-term effect of induced traffic resulting from the change in travel demand in response to the change in transportation supply.

Source: Adapted from Ewing and Lichtenstein, 2002.

The induced traffic illustrated in Figure 3.1 occurs in a **short term** upon implementation of the transportation infrastructure improvement (e.g., intersection or corridor signal improvements, road widening, building a new road, adding a new highway ramp, etc.). Some of the possible sources of induced traffic are (Lee et al., 1999):

- Diverted traffic, result of re-routing of the existing area traffic from other facilities to the new, expanded or improved, transportation facility. Re-routed trips considered here seek only to improve their travel time or reduce travel cost, while their origins and destinations do not change.
- Temporal shift of trips – traffic that previously used the facility at a different (less congested) time.
- Trips shifted from other modes. For example, improved highway facility that provides faster travel, may attract users of non-highway modes.
- Changed destination resulting from the improvement of the facility.

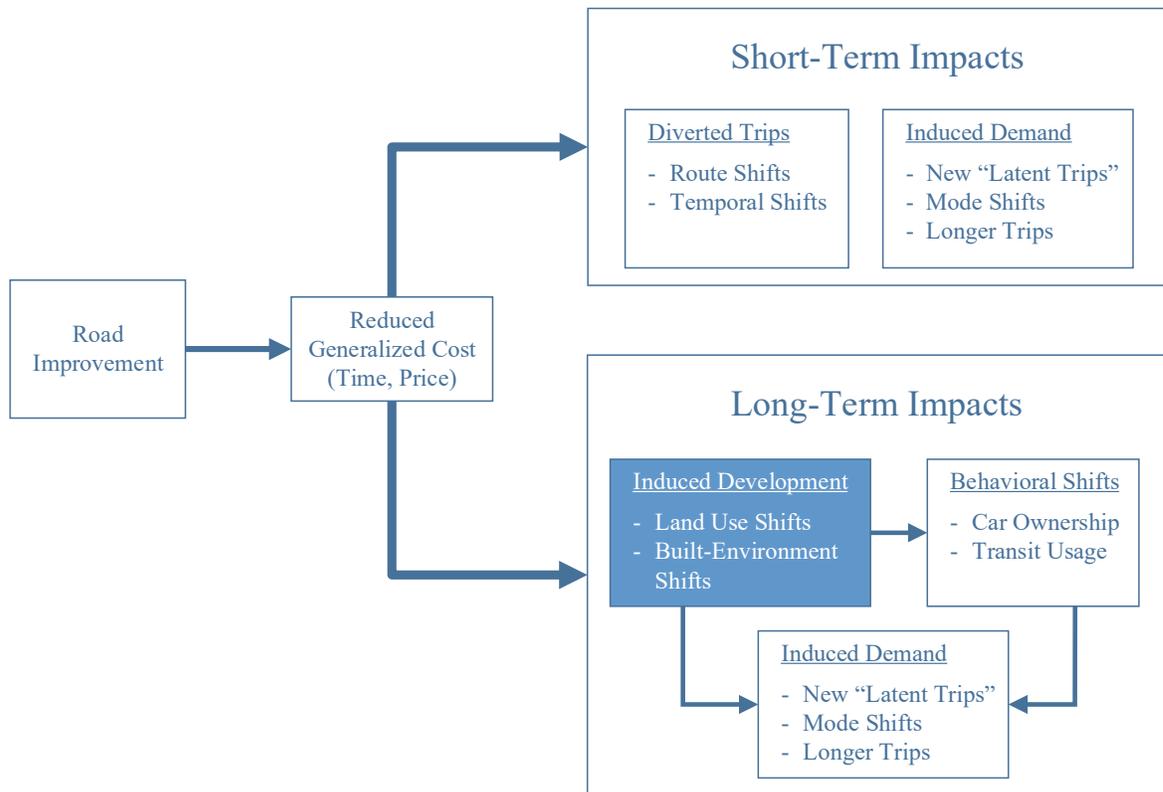
- Additional travel (additional trips and changed itineraries) by the current users of the facility. These trips are also referred to as “latent trips” – trips that were desired but not realized before the improvement, due to travel time or cost.

This portion of induced traffic can be estimated using a regional travel demand model, described in Section 3.1.3 of this chapter, as a difference between the traffic flows before and after the introduction of capacity expansion in transportation network. One could also quantify induced traffic by different sources. This can be accomplished by analyzing trip-tables and assignment of trips on network links affected by induced traffic.

Besides the short term impact, there is also a long-term impact of transportation improvement on induced traffic. Both short-term and long-term impacts are summarized in Figure 3.2. Some of the possible sources of induced demand in long term include:

- Shifts in land use, including residential or non-residential developments whose location, size, and character are influenced directly by the new or improved transportation facility. These are defined as *induced developments*.
- Shifts in travel behavior, reflected as changes in car ownership, trip making frequencies, and use of different modes of travel.

The long-term change in demand is illustrated in Figure 3.3. The changes in exogenous factors of travel demand, such as land use and trip-making characteristics, cause a short-term demand curve to shift. Because the transportation improvements resulted in reduced cost of travel (previously explained by the shift of supply curve from  $s_1$  to  $s_2$ ), the long term changes in the exogenous factors will cause general increase in demand for travel. This change in demand is illustrated in Figure 3.3 as an outward shift of demand curve, from  $d_1$  to  $d_2$ .



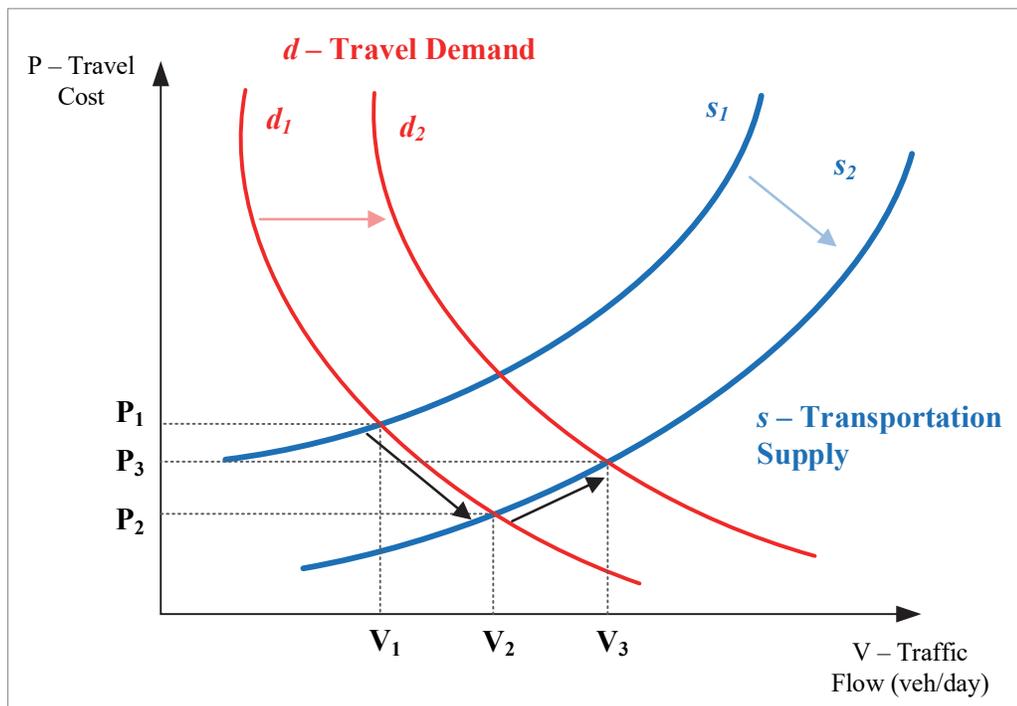
**Figure 3.2** Short-term and long-term induced effects of road improvement.

Source: Adapted from Cervero (2002).

This long-term change in demand, induced by the transportation improvement, results in an increase in traffic. This increase will reach an equilibrium over time at travel cost  $P_3$ . The change in traffic flow from  $V_2$  to  $V_3$  represents the long-term effect of transportation improvement on induced traffic. The resulting, average long-term cost of travel ( $P_3$ ), may or may not be lower than the initial cost of travel ( $P_1$ ), but it is certainly higher than the cost of travel in short-term ( $P_2$ ).

Estimation of the long-term effect of transportation improvements on induced traffic is more complex than is the case with short-term effects. The long-term changes in demand are influenced by changes in regional land use, which are in turn caused by the improvements in transportation infrastructure. The newly improved transportation facility

increases the accessibility of the nearby area, making it more attractive for location of additional commercial and residential developments. The interactions between new geographic allocation of jobs and residences, as well as changes in transportation network (in terms of improved level of service or expanded roadway capacity), will cause changes in travel demand and trip-making characteristics, thus changing the regional travel patterns.



**Figure 3.3** Long-term effect of induced traffic resulting from the change in travel demand in response to the change in transportation supply.

Therefore, the changes in land use, specifically induced development, must be taken into account in the analysis of induced demand and the resulting traffic. This can be accomplished by analyzing changes in land use using land use models, which would provide inputs for the travel demand and traffic analysis.

### 3.3 Integrated Transportation and Land Use Planning and Modeling

Demand for travel is derived from demand for spatially distributed human activities. Transportation system provides a conduit for overcoming the “friction of space” between spatially separated activities. For example, daily travel between one’s residence and the workplace, or residence and school; shopping trips made between residences and stores; trips made to recreational, cultural, and vacation facilities to satisfy one’s need for recreation, cultural activities, and relaxation; or, transport of goods between locations of production and locations of consumption. Some of these activities occur daily, at given times, while others occur less frequently and have more flexible schedules. Therefore, the spatial distribution and configuration of human activities, which comprises a *land use pattern* of an area, along with temporal schedule of activities, has a critical influence on travel decisions.

The travel decisions are also influenced by transportation supply, including availability of alternative travel modes and routes, as well as travel times and travel costs associated with each alternative. The trips between different origins and destinations will be more likely to occur, or occur more frequently, if they take less time or are less costly to complete. Trip making is also influenced by trip purpose (e.g., work-related vs. non-work trips). The distribution of trips between different origins and destinations in a geographic area, their temporal schedule (daily, weekly, or seasonal), and the resulting traffic flows in the underlying transportation network comprise a *travel pattern* or *traffic pattern* of the area.

However, there is also an influence of travel patterns on land use. Individuals may look for an alternative location of their activities if the travel to current locations becomes

too costly or requires consistently longer travel time. For example, one can change the residence to a location that provides shorter travel time to the workplace, or look for a job closer to the residence. One can also consider other (non-work-related) activities and their location, and relocate the residence or workplace to provide better accessibility to the locations of these activities. Transportation improvements also influence land use. New or improved transportation facility that provide faster and less costly travel to specific locations will make these locations more attractive due to improved accessibility. This in turn may influence the land use pattern by attracting residencies and businesses to locate in the vicinity of the improved transportation facility, or locations that benefit from travel time and cost savings brought about by the transportation improvement.

It is important to recognize that these interactions between land use and transportation patterns in a region, and the underlying changes do not occur instantaneously. For example, changes in land use in response to a newly built transportation facility may be realized over several years. Increasing levels of traffic congestion may impact the land use patterns over several years, and transportation improvements are often accomplished in phases, depending on available resources and funding. By the same token, the gradual changes in land use patterns gradually influence the traffic patterns.

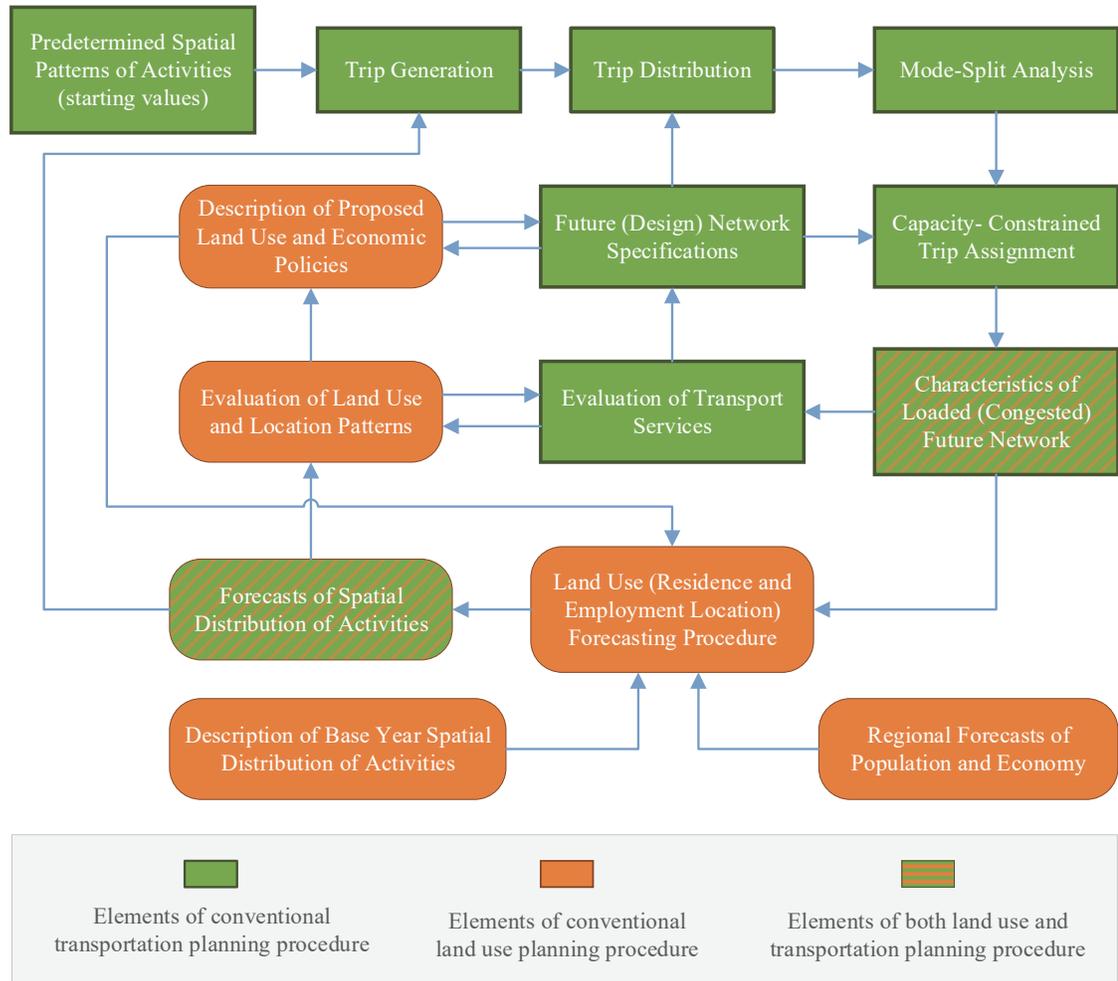
In regional (urban) planning, the inter-relationship and interaction between land use patterns and travel patterns is recognized and understood (Putman, 1983), (Papacostas & Prevedouros, 2000). As part of regional transportation and land use planning process, the responsible planning agencies are tasked with analyzing current and forecasting future transportation and land use patterns. This analysis is accomplished using transportation and

land use planning models, respectively. Transportation models, such as travel demand models described in Section 3.1.1, take as an input forecasted regional land use patterns, consisting of spatial distribution of residences and employment, along with the corresponding demographic and socio-economic characteristics. Similarly, land use planning models take into account regional traffic patterns.

Despite of the inter-dependency of inputs and outputs between the land use and transportation forecasting, many transportation and land use planning models are operated independently of each other. This means that the travel demand forecasting is informed by the initial forecast or regional land use considered to be fixed over the planning horizon; similarly, the land use forecasting is informed by the initial forecast of traffic pattern, also considered to be fixed over the planning horizon. In long-range planning, the planning horizon may be 20-25 years. The shortcoming of this approach is the missing feedback between the land use and transportation models that would reflect gradual changes in regional land use and transportation patterns.

An integrated transportation and land use planning method, which provides iterative feedback between the two planning processes, addresses the shortcomings of independent planning and modeling of travel and land use patterns. Putman (1983) conceptualized this method as shown in a block diagram in Figure 3.4. The traditional steps in a transportation planning process are shown in squared green boxes, while the steps in land use planning process are shown in rounded orange boxes. The connections between the two processes provide for the “feedback loop”. The output from the transportation planning procedure, labeled as “characteristics of loaded (congested) future network”, is used as an input for land use forecast; the feedback loop is completed by providing

“forecasts of spatial distribution of activities” (i.e., forecasted land use), produced by the land use forecasting procedure, as the input for the trip generation phase of the transportation planning procedure. Additional connections between the two planning procedures are possible and desirable, as shown by arrows in Figure 3.4.

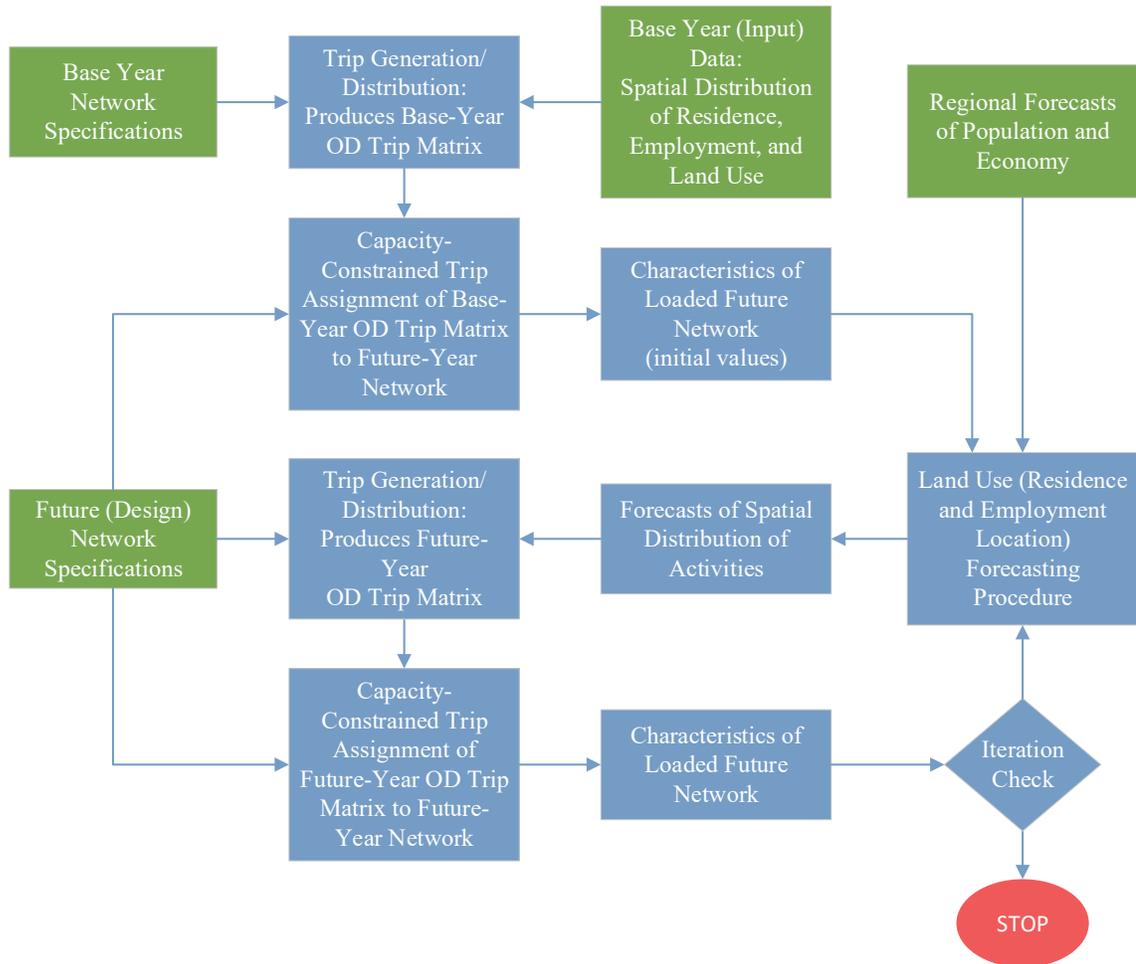


**Figure 3.4** Conceptual diagram of an integrated transportation and land use planning process.

Source: Adapted from Putman (1983)

The integrated transportation and land use planning method can be translated in a modeling process. Putman (1983) described and conceptualized an integrated

transportation and land use modeling package, illustrated in a block diagram shown in Figure 3.5.



**Figure 3.5** Conceptual diagram of an integrated transportation and land use model.

Source: Adapted from Putman (1983)

As shown in the block diagram, the inputs into the integrated model consist of base year transportation network specifications, future network specifications (including planned transportation improvements), base year spatial distribution of residences, employment, and land use, and regional forecasts of population and economy. The inputs are used to generate the initial (base year) OD trip matrix, and then execute the capacity-

constrained trip assignment to obtain an initial forecast of future traffic patterns, i.e., initial characteristics of loaded future network. These characteristics of loaded future network assume no change in spatial distribution of activities (land use patterns) in the future year. The next step, land use forecast, takes the initial characteristics of loaded future network and the regional forecast of population and economy to generate the forecasted spatial distribution of activities. The forecasted spatial distribution of activities, along with the future network specifications, is then used to generate modified (more realistic) future year OD trip matrix, which takes into consideration both the forecasted future land use patterns and the future transportation network specifications. The capacity-constrained trip assignment is used to assign the trips from the modified OD trip matrix to the network, and produce the modified (updated) characteristics of the loaded future transportation network. The updated characteristics of the loaded future network are then compared with the previously generated network characteristics: if there is no significant difference between the two, an equilibrium has been reached and procedure stops; if there are significant differences, the modified network characteristics are loaded in the land use forecasting procedure for a new iteration of land use and transportation forecast is executed.

This integrated modeling procedure explicitly includes the feedback between the land use and transportation modeling procedures. In planning studies that extend over a longer time horizon, e.g., 20-25 years, this procedure would be repeated for several forecasting period within the planning horizon, usually in 5-year increments. The forecast of transportation and land use patterns for each 5-year increment would use the integrated model outputs from the previous 5-year increment as inputs for the base year forecast.

### 3.4 Operational Land Use Allocation Models

Several authors and studies have reviewed available operational land use modeling packages (or modeling tools) that can be integrated with the transportation models in a fashion similar to the procedure described by Putman (1983). Most of reviews discussed land use modeling tools based on the underlying analytical models and methodologies, data requirements, and applicability for different types of analysis (Ewing & Lichtenstein, 2002), (Lemp et al., 2008), (Papacostas & Prevedouros, 2000), (Sivakumar, 2007), (Zhou & Kockelman, 2009). The following classification of land use allocation models, based on the underlying modeling methodology, has been adopted in this review:

- Aggregate Spatial Interaction Models;
- Input-Output and Random-Utility Spatial Equilibrium Models;
- Discrete Response Simulation Models;
- Activity- or Agent-Based Simulation Models; and
- Cellular Automata Models.

*Aggregate Spatial Interaction Models* are largely based on the modeling approach introduced in Lowry's gravity-based model. The models in this group allocate activities, reflected in population (residences or households) and employment, to geographic zones based on the attractiveness or potential of each zone in a study area. Most widely used model in this group is DRAM/EMPAL (Putman, 1983), (Putman (1991). Spatial allocation of households (DRAM model) and employment (EMPAL model) is accomplished using gravity-based allocation methodology, where attractiveness of each zone is determined based on zone-to-zone impedances, along with disaggregate (stratified) regional projections of population and employment. The impedances are obtained from the regional

travel demand models as output skim-tables (average zone-to-zone travel time or generalized cost). The model parameters are calibrated using historical household and employment allocation statistics. DRAM/EMPAL was later updated and released under the name METROPILUS, which allowed additional forecast controls to better reflect regional land use policies, and was integrated with a Geographic Information System (GIS) platform. DRAM/EMPAL and METROPILUS were implemented in a number of regional planning agencies nationwide and were integrated with travel demand models as part of regional urban planning programs. DRAM/EMPAL models are also used in the FHWA-sponsored land use modeling tool called TELUM. TELUM has a user-friendly interface, does not require excessive data inputs, and is relatively easy to implement. It was primarily developed for small- and medium-size urban areas has been implemented by several Metropolitan Planning Organizations (MPO) and in regional planning studies.

*Input-Output and Utility-Maximization Spatial Equilibrium Models* utilize macroeconomic input-output models and multinomial logit models to determine demand for space by different land uses in each zone of the study area. The spatial allocation of activities (or land uses) to zones is determined using random utility models, and connects spatially distributed production and consumption, which creates demand for travel. Representative examples of models in this group are TRANUS (Johnston & De la Barra, 2000), MEPLAN (Abraham & Hunt, 1999), METROSIM (U.S. Environmental Protection Agency, 2000), and PECAS (Hunt & Abraham, 2003). Both TRANUS and MEPLAN consist of integrated land use model and transportation model, which makes the interaction or integration with an existing travel demand model for an area challenging from operational aspect. METROSIM employs econometric and random utility model for spatial

allocation of households and employment similar to TRANUS and MEPLAN, but it also adds urban economic bid-rent (real estate) model. It consists of seven sub-models, providing analyses of a region's basic industry, non-basic industry, residential and commercial real estate, vacant land, households, commuting and non-commuting travel, and traffic assignment within a single structure. The model was implemented to study land use and transportation patterns, and their interactions, in Chicago, IL and New York City metropolitan areas. PECAS is a hybrid of input-output and microsimulation models for spatial allocation of activities. It employs econometric and random utility (multinomial logit) theoretical model very similar to previous models in this group, and it also contains microsimulation sub-model for household allocation, and a disaggregate land development sub-model. Generally, implementation of economic input-output and random-utility maximization models is more suitable for larger areas, given that the underlying modeling framework is rooted in macroeconomic theory and trading between industry sectors within a region. However, the developers of these models have demonstrated their applications at the smaller scale, such as census block and even parcel-level. The challenge for implementation of these models, especially with more granular resolution of the study area, is data, both in terms of availability and accuracy required to reflect the economic and market interactions that drive location decisions for individuals and businesses.

*Discrete Response Simulation Models* use discrete simulation to determine location choices by households (residences), businesses (jobs or employment), land developers, and public entities, as well as their market interactions. The models are highly disaggregate, dynamic, and generally apply multinomial logit models to determine utilities of special allocation choices. The travel demand model considers trip tours, rather than individual

trips. An example of modeling tools in this group is UrbanSim (Lemp et al., 2008). UrbanSim is open-source software package, it is well documented and can be modified by users as needed. It can also be integrated with external travel demand model through a input-output feedback loop. The main challenge of UrbanSim and similar models in terms of implementation are data requirements. Disaggregate structure of the models requires very detailed data on each locational unit, including land use mix, density, property values and rents, access to employment, population, retail marketplace, and transportation facilities, as well as development and redevelopment costs. This data is usually hard to obtain at the level of accuracy, reliability, and granularity required for these models to accurately forecast land use patterns at high resolution.

*Activity- or Agent-Based Simulation Models* simulating activities of individual actors in a market, including the schedules of these activities and the associated travel behavior. One example of agent-based simulation model is Integrated Land Use, Transportation, Environment (ILUTE) modeling system (Miller & Salvini, 2001). ILUTE implements a fully m microsimulation-based framework for modeling urban systems, including land use patterns, travel patterns, and the relationships between the two, as well as their environmental impacts. Population and their activities are represented by individual persons, households (as the group of people occupying the same dwelling unit), and decision making units (defined as individuals within households who make decisions about household's status, including decisions about its location, type of dwelling, and travel behavior). Economic activities are modeled by simulating behavior of firms, individual firm establishments (each occupying specific location), and jobs contained within each establishment. Market interactions in both residential and economic sectors of the urban

system are modeled using economic input-output models, much like in previously described land use systems MEPLAN and TRANUS, but at a much more disaggregate level. Furthermore, activity locations are not modeled only with respect to geographic zones, but also consider buildings within zones. Economic simulator also includes determination of exchange of goods between economic actors and the resulting traffic flows. Finally, the trips are generated for individual agents based on the sequence of their daily activities and corresponding schedules, rather than disaggregating them into individual trips or trip tours. While it attempts to represent activity system of individuals and firms as realistic as possible, ILUTE and other similar models are extremely data intensive. The reliability of model results, considering the availability and quality of input data, is still being evaluated; thus, practical applicability of these tools is limited.

Another example of microsimulation-based models are those that employ *cellular automata (CA)* modeling concept. The CA models consider a system that consists of a grid of cells, where each cell has a finite number of possible states. In land use modeling applications the specification of cellular states may be defined by land use, socio-economic, and spatial interaction parameters. The cellular state can change based on the current status of the cell and the dynamic status of the neighboring cells, according to so called *transition rules*. The transition rules may be deterministic or stochastic. One weaknesses of the CA models is that transportation network is not explicitly defined and traffic flows are not modeled. However, the CA models could be linked to travel demand models through an input-output feedback loop, where travel impedances would be reflected in updates of state transition rules. Another weaknesses of the present CA models is that they do not have a strong foundation in social and economic theory and statistics (Lemp et

al., 2008). The Slope, Land use, Exclusion, Urban extent, Transportation and Hillshade (SLEUTH) is an example of CA model developed to analyze regional land use. Like most CA models to date, SLEUTH has been applied to simulate regional urban growth and urban change, but more recent research aims to develop CA protocols for multi-agent simulation and competition for space that consider travel patterns from an activity-based transportation model (Arentze & Timmermans, 2003).

Ewing and Lichtenstein (2002) provide a review of different operational land use models that can be used to estimate induced development. They specifically reviewed applicability of DRAM/EMPAL, TRANUS, MEPLAN, and UrbanSim models. Their review found that the biggest concerns and challenges when it comes to implementing these modeling tools for assessing induced demand, include the following:

- Availability and quality of required data;
- Requirement for experienced and technically knowledgeable planners who can be devoted to land use analysis for various purposes, or consultants and associated costs;
- Flexibility of the models and their ability to provide information that can be useful for analyzing and formulating planning policies; and
- Quality and accuracy of projections and analysis produced by these models.

One modeling tool that was not reviewed by Ewing and Lichtenstein, but seems to have optimal properties for the purpose of analyzing induced development as a consequence of transportation improvements TELUM. TELUM (Transportation, Economic and Land Use Model) was developed at the New Jersey Institute of Technology as part of the Transportation Economic and Land Use System (TELUS) grant funded by the Federal Highway Administration. As noted by Ewing and Lichtenstein (2002), most of

the land use models require dedicated, well-trained staff, relatively large amount of data to be collected as input for the analysis, and often painful and time-consuming process of integration with the travel demand models. TELUM was specifically developed for use by small- to medium-sized MPOs with the objective to overcome the common obstacles to successful integration of land use models in the transportation planning process. The model has a simplified, user friendly interface that guides the user through the modeling process, and requires data inputs that are readily available for majority of urban areas in the United States from the U.S. Census Bureau datasets, such as American Community Survey (ACS) and Public Use Microdata (PUMS).

The core of the TELUM model are employment and household location forecast models. Equation formulations for these two components of TELUM are provided here, while the more detailed information about TELUM is provided Appendix B.

*TELUM Employment Location Model Formulation (TELUM-Emp)* based on the EMPAL equation (Putman, 1983), (Putman 1991), with two distinct features:

- a) A multivariate, multi-parametric attractiveness function is used, and
- b) A separate, weighted, lagged variable included outside the spatial interaction formulation.

The model is applied to 4-8 employment sectors with individually estimated parameters. The equation structure is the following:

$$E_{k,j,t} = \lambda_k \sum_i P_{i,t-1} A_{k,i,t-1} W_{k,j,t-1} c_{i,j,t}^{\alpha_k} \exp(\beta_k c_{i,j,t}) + (1 - \lambda_k) E_{k,j,t-1} \quad (3.7)$$

where:

$$W_{k,j,t-1} = (E_{k,j,t-1})^{\gamma_k} L_j^{\delta_k} \quad (3.8)$$

$$A_{k,i,t-1} = \left[ \sum_m (E_{k,m,t-1})^{\gamma_k} L_m^{\delta_k} c_{i,m,t}^{\alpha_k} \exp(\beta_k c_{i,m,t}) \right]^{-1} \quad (3.9)$$

and

$E_{k,j,t}$  = employment (place-of-work) of type  $k$  in zone  $j$  at time  $t$ ;

$L_j$  = total land area of zone  $j$ ;

$c_{i,j,t}$  = travel impedance (travel time or cost) between zones  $i$  and  $j$  at time  $t$ ;

$P_{i,t-1}$  = total number of households in zone  $i$  at time  $t-1$ ;

$\lambda_k, \alpha_k, \beta_k, \gamma_k, \delta_k$  = empirically derived parameters.

TELUM Residential Location Model Formulation (TELUM-Res) is an aggregate form of a multinomial logit model of location choice, and is based on DRAM model formulation (Putman, 1983), (Putman 1991). When translated into computational form, this yields a modified version of a singly-constrained spatial interaction model with a multivariate, multi-parametric attractiveness function. The multivariate zonal attractiveness term enables the inclusion of knowledgeable professionals' input to the model structure in a consistent and replicable fashion. The model is applied to 3-8 household categories whose parameters are individually estimated. The model is described in more detail in Putman (1983, 1991). For reference, TELUM-Res equation structure is defined as follows:

$$N_{h,i,t} = \eta_h \sum_j Q_{h,j,t} B_{h,j,t} W_{h,i,t} c_{i,j,t}^{\alpha_h} \exp(\beta_h c_{i,j,t}) + (1 - \eta_h) N_{i,t-1}^{(T)} \quad (3.10)$$

where:

$$Q_{h,j,t} = \sum_k a_{k,h} E_{k,j,t} \quad (3.11)$$

$$B_{h,j,t} = \left[ \sum_m W_{h,m,t} c_{m,j,t}^{\alpha_h} \exp(\beta_h c_{m,j,t}) \right]^{-1} \quad (3.12)$$

$$W_{h,i,t} = (Lv_{i,t-1})^{q_h} (x_{i,t-1})^{r_h} (Lr_{i,t-1})^{s_h} \prod_n \left( 1 + \frac{N_{n,i,t-1}}{N_{i,t-1}^{(T)}} \right)^{\delta_n} \quad (3.13)$$

and

$E_{k,j,t}$  = employment (place-of-work) of type  $k$  in zone  $j$  at time  $t$ ;

$N_{h,i,t}$  = number of households of type  $h$  residing in zone  $i$  at time  $t$ ;

$N_{i,t-1}^{(T)}$  = total number of households residing in zone  $i$  at time  $t-1$ ;

$Lv_{i,t-1}$  = vacant developable land in zone  $i$  at time  $t-1$ ;

$x_{i,t-1}$  = 1 plus the percentage of developable land already developed in zone  $i$  at time  $t-1$ ;

$Lr_{i,t-1}$  = residential land in zone  $i$  at time  $t-1$ ;

$a_{k,h}$  = regional coefficient of type  $h$  households per type  $k$  employee;

$c_{i,j,t}$  = travel impedance (travel time or cost) between zones  $i$  and  $j$  at time  $t$ ;

$\eta_h, \alpha_h, \beta_h, q_h, r_h, s_h, \delta_n$  = empirically derived parameters.

In the original formulation of the DRAM model, all variables had the same time subscript. In late 1990's, as the necessary data became more available on the census block or transportation zone level, several new formulations were examined in an attempt to

include a lag term and thus increase forecast reliability of the model. This resulted in the current, updated form of TELUM-RES equation formulation.

## CHAPTER 4

### PROPOSED MODELING METHODOLOGY

#### 4.1 Basic Approach

To estimate direct, indirect, and induced traffic resulting from a land development and the associated transportation infrastructure improvement, while capturing the interactions between land use and transportation system, the following modeling approach is proposed:

1. Given the nature of the proposed land development, estimate the changes in trip tables to and from the development and the related regional zones.
2. Collect data on highway network capacity and travel times on network links. Record the new infrastructure improvements in the regional highway network.
3. Maintain a travel demand forecasting model that yields trip rates, trip interchanges, travel paths, resulting travel times and VMT. The model is capable of finding the least time travel assignment and estimating the re-distributed travel patterns.
4. Maintain a calibrated land use model that allocates and re-allocates residences and employment to zones based on zonal attractiveness and accessibility (as described in the inter-zonal trip tables). Given the regional growth in population, employment, current and proposed land use and available land, run the land use models to estimate zonal allocations.

In the first step of this process, the new trip attractions and productions are estimated based on the new residential and/or nonresidential development in the analyzed area. The new development includes both direct and indirect development. Direct is the initial residential and/or nonresidential development in the area of study. For example, this could be a condominium complex, or an office building, or a combination of residential and commercial developments. Indirect is a result of the direct development, as it provides additional residences for people who will be working in the new office building or

commercial establishment, as well as new businesses to serve subsequent residential and nonresidential-engendered expenditures (e.g., convenience stores, restaurants, various professional services, etc.).

In the second step, the regional highway network in the travel demand model is updated with highway improvements related to the new development. These changes would likely impact both local and regional travel patterns as the improvements usually provide more capacity, reducing the congestion and improving mobility. Therefore, more users will be attracted to the improved highways after the improvements are implemented.

In the third step the travel demand model is used to estimate the new travel patterns, i.e., vehicle volumes and vehicle-miles traveled (VMT) on the highway network adjacent to the new development. The results can be compared to traffic volume and VMT before the highway improvement, and the induced travel due to re-routing can be calculated as the difference between the two.

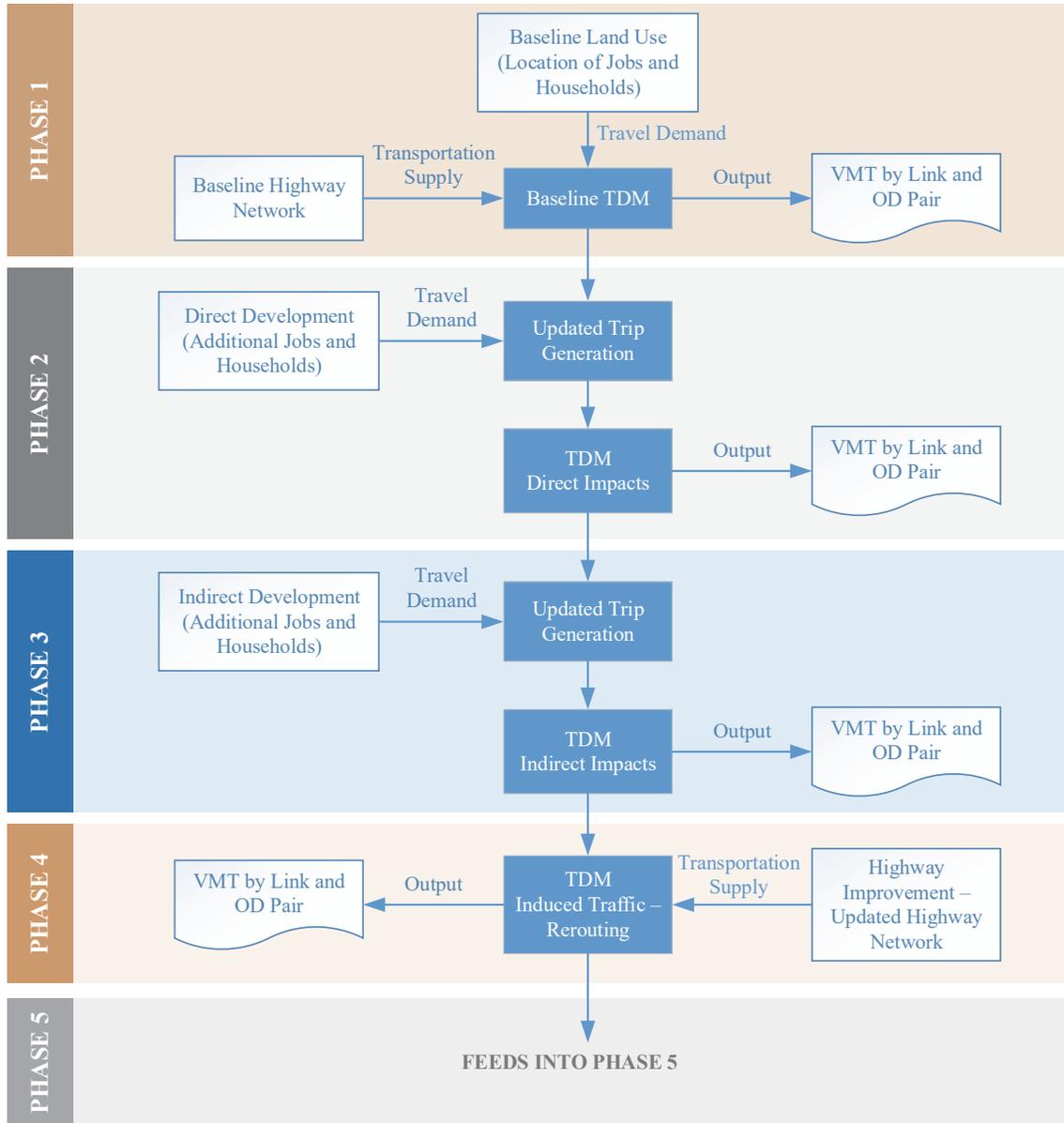
In the fourth step a land use model is employed and implemented, based on the travel impedances obtained from the travel demand model executed in the third step. The underlying land use is equivalent to that immediately after completion of the analyzed residential and/or nonresidential development. The land use model will determine the changes in location of residences and jobs in the region as a result of changed travel times (impedances) between regions' zones due to the implemented highway improvements. The new pattern of household and job locations (land use) is then fed back into the travel demand model, which can now be used to estimate the traffic flows on the regional highway network with the new land use. Comparison of these results with the outputs obtained from the travel demand model in the third step will reveal the induced travel due to changes in

land use resulting from the initial (direct and indirect) development and related highway improvements.

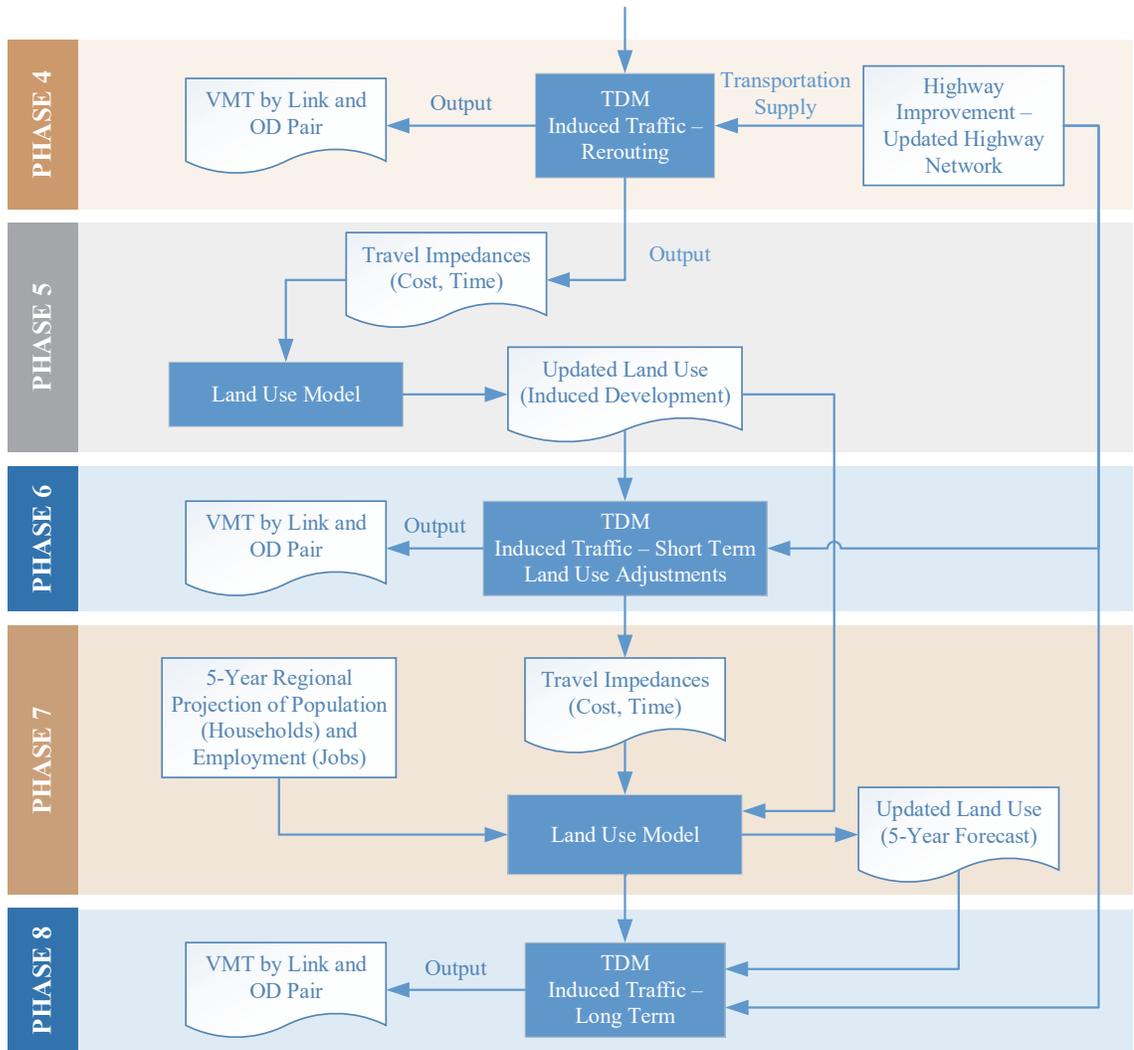
Changes in the transportation system and land use (i.e., location of residences and jobs) are mutually dependent; therefore, procedures explained in steps three and four can be repeated in an iterative fashion to obtain incremental projections of land use and travel patterns (e.g., in five-year increments) following the real estate development and related highway improvement.

## **4.2 Modeling Methodology**

The proposed modeling methodology utilizes a travel demand model to estimate the impact of direct and indirect development, as well as the component of the induced traffic attributed to rerouted trips. A combination of travel demand and land use models is then used to estimate induced changes in land use and associated traffic effects. A series of model runs of both travel-demand and the land use models need to be executed to capture all three components of change in travel demand and the resulting modeled traffic flows, as they relate to highway improvements. The proposed methodology is broken into iterative phases, as shown in Figure 4.1 (showing phases 1 through 4) and Figure 4.2 (showing phases 5 through 8).



**Figure 4.1** Proposed integrated transportation network and land use modeling system for analyzing direct, indirect, and induced impacts of land development, showing modeling phases 1 through 4.



**Figure 4.2** Proposed integrated transportation network and land use modeling system for analyzing direct, indirect, and induced impacts of land development showing modeling phases 5 through 8.

The phases of the proposed modeling methodology are defined as follows:

### 1. PHASE 1: Baseline

- Run the baseline travel demand model (before any development).
- Capture the vehicle-miles traveled (VMT) by origin-destination (O-D) pair on principal arterials in the vicinity of zones representing the area of the intended development.

## **2. PHASE 2: Direct Development Impacts**

- Add the direct residential and commercial development in the studied zones. The new development is expressed in terms of additional population and dwelling units (households), as well as additional jobs.
- Update the trip generation data in the travel demand model (trip attractions and productions will change as a result of the direct development).
- Rerun the travel demand model and capture the VMT by O-D on selected highway links serving the studied area (zones).

## **3. PHASE 3: Indirect Development Impacts**

- Add the indirect residential and commercial development in the studied zones. The indirect development is expressed in terms of additional population and dwelling units (households), as well as additional jobs.
- Update the trip generation data in the travel demand model (trip attractions and productions will change as a result of the indirect development).
- Rerun the travel demand model and capture the VMT by O-D on selected highway links serving the studied area (zones).

## **4. PHASE 4: Highway Improvement**

- Improve the highway facilities that serve the studied area (i.e., new developments). The improvements are expressed in terms of increase in highway capacity.
- Rerun the travel demand model and capture the VMT by O-D on selected highway links serving the studied area (zones). This model run will capture immediate impact of the highway improvement on rerouting of existing trips.

## **5. PHASE 5: Reallocation of Jobs and Households**

- Based on the regional and zonal demographic, socio-economic and land use data, and travel patterns obtained from the travel demand model executed in PHASE 4, develop a land use model for the region. The purpose of the land use model in this phase is to provide the forecasts of household and employment locations immediately following the direct and indirect developments and highway improvements.

- The land use model should consider (as inputs) zone-to-zone travel impedances produced by the travel demand model in PHASE 4. It should also produce (as outputs) the number of jobs and households in each zone.
- In the land use model the employment and household minima are set for the analyzed zones at the levels established in PHASE 4, and regional population and employment growth is disregarded (i.e., it is assumed there is no population and employment growth on the regional level). This scenario would reveal a shift in location of existing households and jobs as a result of new developments and highway improvements, which should reflect the reallocation of activities in the development zones due to improved travel impedances. These conditions are relevant only in the short time period following the improvements (0-5 years).
- Capture the data on future locations of jobs and households by zone in the region.

## **6. PHASE 6: Induced Development and Travel Impacts**

- Update the demographic and employment data in the trip generation module of the regional travel demand model, based on outputs from the land use model in PHASE 5 (trip attractions and productions will change as a result of the induced development).
- Rerun the travel demand model and capture the VMT by O-D on selected highway links.

## **7. PHASE 7: Regional Change in Land Use (5-year projection)**

- Update the impedances (zone-to-zone travel times) in the land use model based on the outputs from the travel demand model obtained in PHASE 6. These impedances are assumed to impact location decisions (for both jobs and residences) in the region five years after the analyzed developments and highway improvements.
- In the land use model the regional population and employment growth is set according to regional projections, while keeping the employment and household minima for the zones located within the analyzed community. This scenario provides conditions for analysis of the regional changes in location of jobs and households considering projected population and economic growth for a period of 5 years following the land development and the corresponding infrastructure improvements.

## **8. PHASE 8: Long-Term Induced Development and Travel Impacts**

- Update the demographic and employment data in the trip generation module of the regional travel demand model, based on outputs from the land use model in PHASE 7 (trip attractions and productions will change as a result of the induced development).
- Rerun the travel demand model and capture the VMT by O-D on selected highway links.

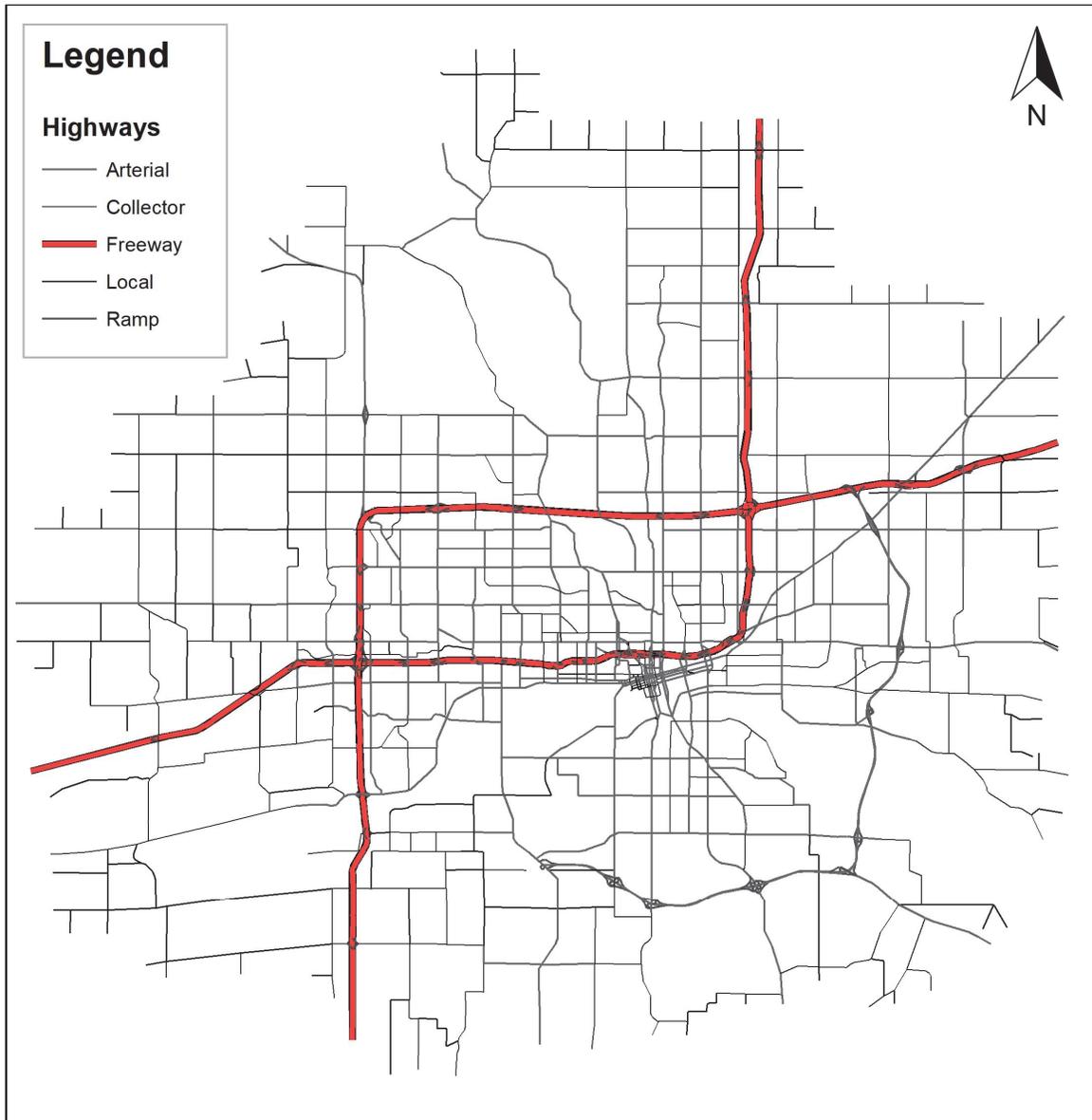
The applicable land use modeling tool must take into account and be capable to accept as an input the estimated zone-to-zone impedances or travel times. This is one of the basic outputs of the regional travel demand models. As an output, the land use modeling tool should be able to produce the forecasted location of jobs and households (or residences) for each traffic analysis zone (TAZ) defined in the travel demand model.

**CHAPTER 5**  
**DEMONSTRATION OF THE MODELING METHODOLOGY**  
**USING A CASE STUDY**

The proposed modeling methodology is demonstrated using a case study of hypothetical residential and commercial development in an urban community. The study area selected for this case study is located in the region of a medium-sized metropolitan urban area in the United States. For the purpose of implementation and demonstration of the proposed methodology, the travel-demand forecasting model for this region was obtained from the local transportation planning agency. Based on the socioeconomic and land use data for the case study region, as well as the trip impedances produced by the travel demand model, a land use model was developed for the same region using the TELUM land use modeling software.

**5.1 About the Case Study Area**

The case study location is in a metropolitan region with a population of about 395,000 residents, 157,000 households, and an employment base of approximately 248,000 jobs. The total land area of this region is about 320,000 acres (500 sq. miles). The regional highway network is dominated by three interstate highways and three U.S. highways serving as the main thoroughfares for the regional traffic. The representation of the regional highway network in the regional travel demand model is shown in Figure 5.1.



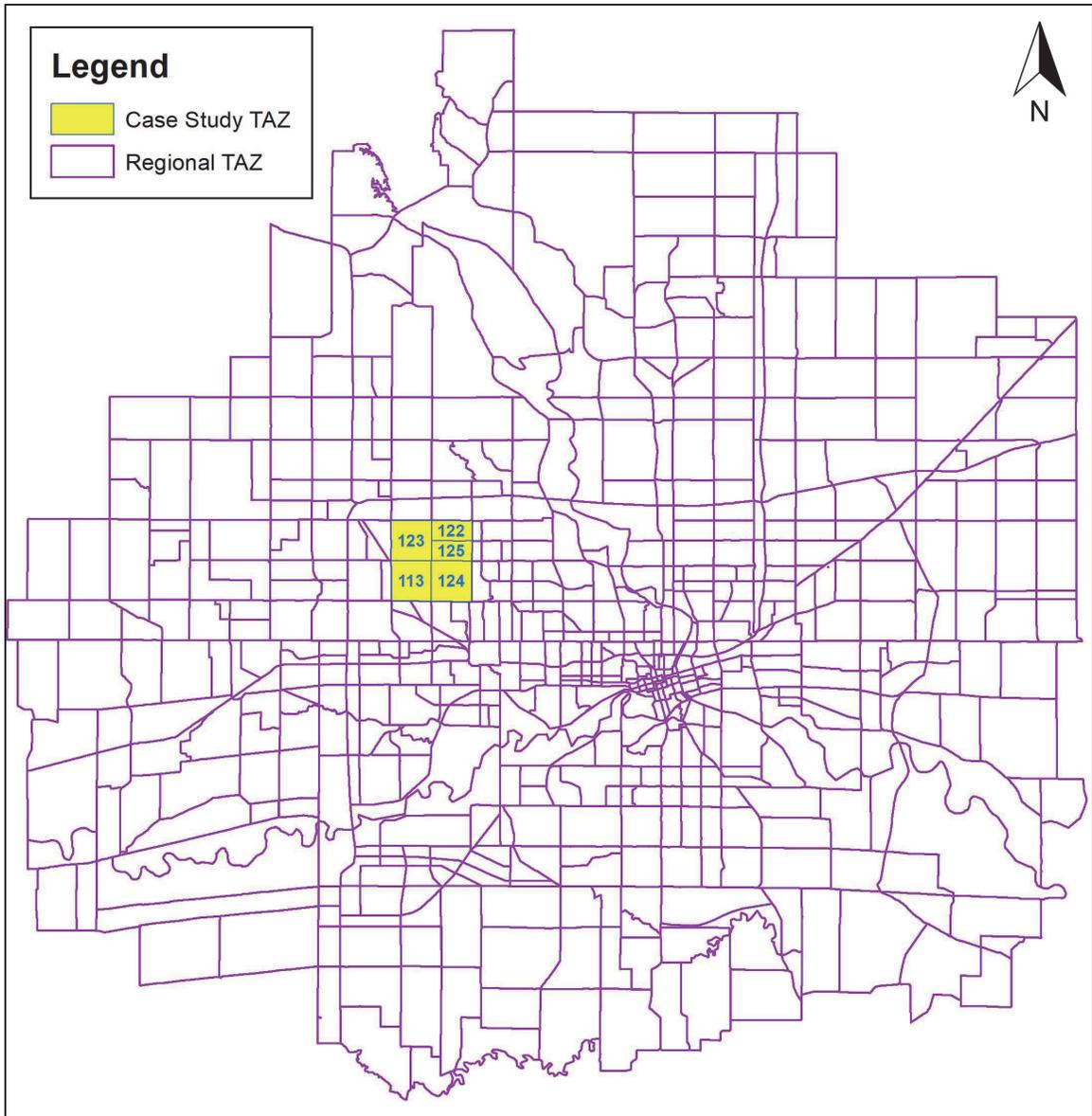
**Figure 5.1** Representation of the highway network of the study region.

For the purposes of travel demand and land use modeling, the entire region is divided into 641 traffic analysis zones (TAZs). The TAZ structure is based on the US Census Blocks. For this case study analysis, a detailed socio-economic, demographic, land use, and transportation planning dataset was assembled for the case study region on a TAZ-

level. For consistency and efficiency of the analysis, the same TAZ structure was established in both travel demand model and TELUM land use allocation model.

The land development to be studied is located in a community encompassing five (5) TAZs, namely TAZ #113, #122, #123, #124, and #125. This five-TAZ community (“community”) has a resident population of 15,702, out of which 10,670 are employed. There are 6,383 households and 4,883 jobs in this community. The total land area encompassing these five TAZs is 2,573.44 acres. Of the total area, 1,005.53 acres are for residential and 493.20 acres are for commercial land use. The street and highway network occupies 448.65 acres, and 295.15 acres are available for development. The location of the community on a map of regional TAZ is shown in Figure 5.2.

The community is served by several collector streets and minor arterials, as well two principal arterials. The two principal arterials run north-south and east-west and intersect in the middle of the community. The two principal arterials connect to two freeways in the vicinity of the community. The length of each arterial through the community is approximately three miles. These are four-lane arterials with signalized intersections, and bidirectional capacity of approximately 32,500 vehicles per day (vpd), or 16,250 vpd in each direction.



**Figure 5.2** Map of TAZ defined in the case study region with highlighted five-TAZ area of the development community.

## 5.2 Case Study Land Development and Highway Improvements

Before proceeding with the description of the hypothetical land development in the case study area, it is important to note that these residential and nonresidential developments, as well as the highway improvements described in this case study, do not represent actual (existing or planned) projects. Rather, they should be regarded as realistic exercises whose

purpose is to showcase a modeling approach for estimating the traffic implications of new land development.

### **5.2.1 Direct New Development**

Land development analyzed in the case study is located in the vicinity of the intersection and along the two principal arterials in the community. The new development includes:

- Residential development – two- and three-bedroom townhouses with 1,085 dwelling units (households) and 2,670 new residents (among them 1,800 employed residents); and
- Commercial development – three office buildings with 830 on-site jobs (all in Services sector).

Overall, the new development increases the population, number of households, and jobs in the five-TAZ area by about 17%. The community's population after this direct development will grow to 18,372, and number of households to 7,468. The employment will grow to 5,713 jobs.

### **5.2.2 Indirect New Development**

As a result of the new development, additional jobs in the retail sector will be created in the same community. In addition, new employee households (supported by jobs in direct development) will locate in the additional new housing in the community. The additional (indirect) development will add:

- 192 dwelling units (households),
- 470 new residents (among them 180 employed residents), and
- 148 jobs (all in Retail sector).

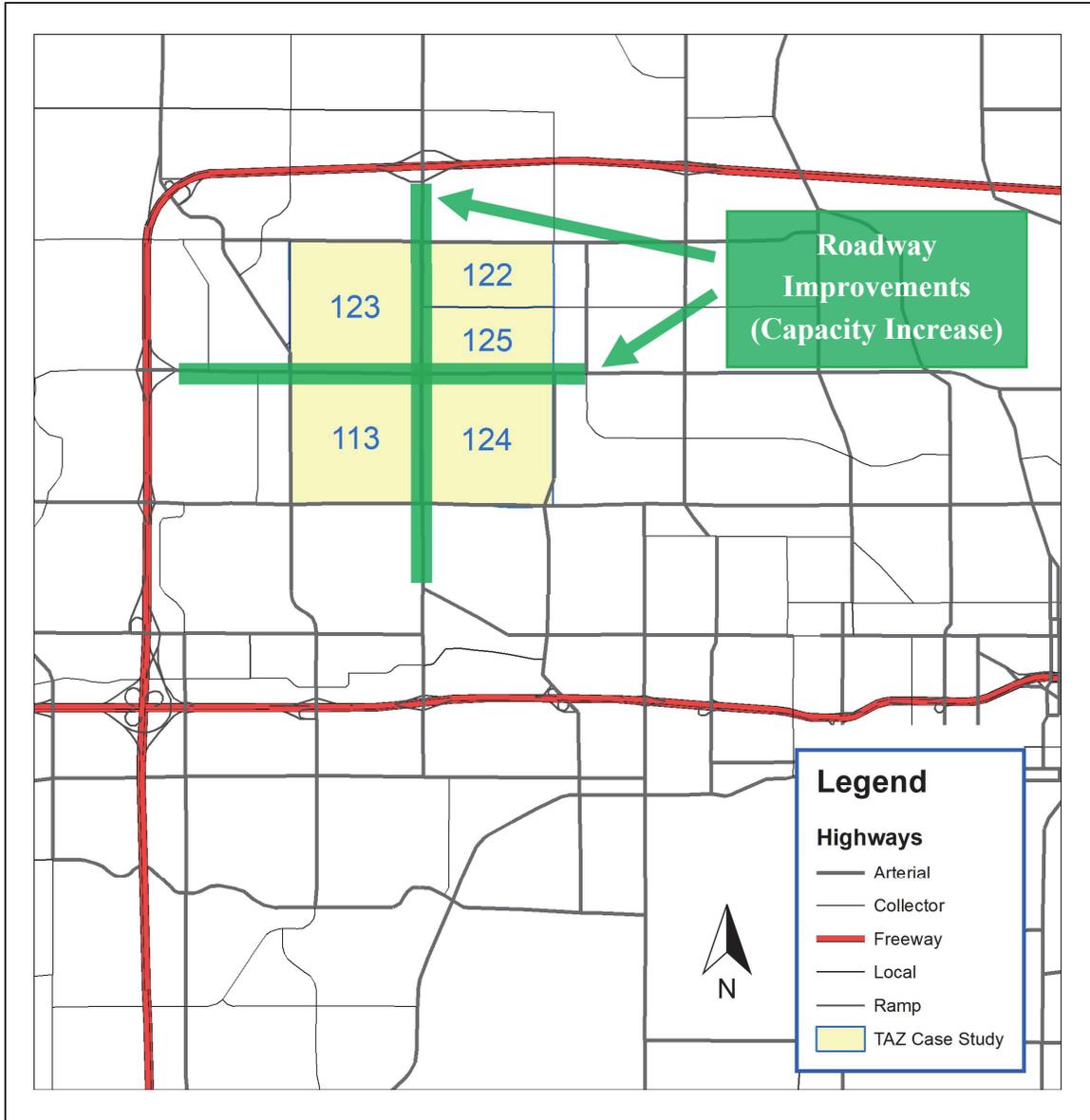
These additional residential and commercial developments are referred to as indirect new development, as they come as a result of initial direct development. They will add another 3% increase in resident population, number of households, and jobs as compared to the existing conditions.

### **5.2.3 Total New Development**

After both direct and indirect development, the community will have 18,842 residents occupying 7,660 households. There will also be 5,861 jobs in the community. Together, direct and indirect development constitute about 20% increase in population, households, and jobs in the five-TAZ community.

### **5.2.4 Highway Improvements**

To support the new development's transportation needs, the two principal arterials adjacent to the developments are upgraded. These 4-lane arterials with signalized intersections are upgraded to include intersection signalization improvements, construction of left-turn lanes, and lane widening at several locations. The improvements are implemented the sections of the two principal arterials that provide immediate access to the community, as well as access to ramps for the two freeways north and west of the community. These improvements would increase the capacity of the two principal arterials by 20% to about 19,500 vpd in each direction. The sections of the two principal arterials to be upgraded are shown on the map in Figure 5.3.



**Figure 5.3** Map of the roadway network in the vicinity of the five-TAZ case study area. The roadways that are upgraded to accommodate the development-related traffic are highlighted.

### 5.2.5 Induced Development

The highway capacity improvement will likely increase the attractiveness of the community as a location for new jobs and households. The capacity increase will attract more regional traffic to the improved principal arterials as well. Some of those traveling

through the community on their way between home and work may decide to relocate their households and jobs near or even within the analyzed community. These are considered to be induced effects of the new land development and related transportation system improvements.

Direct and indirect developments, as well as induced relocation of jobs and residencies and rerouting of trips, will put a burden on the local highway network. In order to estimate the transportation infrastructure costs associated with each component of the demand (direct, indirect, and induced), it is necessary to identify the corresponding amount of travel, usually expressed in terms of vehicle-miles traveled (VMT).

### 5.3 Case Study Results

#### 5.3.1 Summary of the Case Study Model Inputs and Outputs

The results of the integrated land use and transportation modeling procedure for this case study are summarized in Tables 5.1, 5.2, and 5.3. The output data is summarized by modeling phase as follows:

- *Baseline*: Reflects the highway network and zonal trip tables before any new development.
- *Direct*: Direct development in the community produced new trips. Highway network (capacity) remained unchanged.
- *Direct + Indirect*: Indirect development was added in the community. Together with the direct development, it generated additional travel demand in the local community. Highway network (capacity) remained unchanged.
- *Direct + Indirect + Hwy upgrade*: Travel demand remained the same as in the previous modeling phase. The highway capacity on two principal arterials serving the community increased by 20%.

- *Induced land use shift – short-term*: There is a relocation of population and employment and thus of the travel demand (relocation of zonal trip productions and attractions) as a result of providing additional capacity on two principal arterials traversing the community. No growth in the regional population and employment was assumed in this phase. The re-allocations of jobs and households to different TAZ are calculated using the TELUM land use model.
- *Induced land use shift – long-term (5-yr. regional growth)*: This phase accounts for 12% growth in regional population and 8.5% growth in employment compared to the baseline. That includes the increase in population and jobs created by the direct and indirect development. TELUM is used to forecast allocation of new (additional) households and jobs in the region, including the five-TAZ community. This allocation creates new future travel demand (new zonal trip productions and attractions).

The Table 5.1 reports the annual VMT attributed to local traffic, as well as the total annual VMT (including both local and through traffic) on two arterials for each *phase* of the modeling process. The *local traffic* consists of trips with either trip end (origin and/or destination) in one of the five zones comprising the analyzed community. Conversely, *through traffic* consists of trips that have neither trip-end within the analyzed community. The table also provides the average V/C (volume over capacity ratio) along the two principal arterials within the community as the measure of traffic congestion. The V/C ratios indicate that the local arterials were already operating at capacity and were congested before the new development was introduced. This is indicated by the baseline V/C ratio of 1.01. The local traffic accounted for 28% of total baseline VMT on the two principal arterials serving the five-TAZ community in which the new development was located.

**Table 5.1** Annual VMT for Different Modeling Phases in the Case Study

Phase	Modeling Phase	Total VMT	Local VMT	Local VMT % of Total	Average V/C
1	Baseline	71,212,230	20,018,067	28%	1.01
2	Direct Development	72,876,265	23,498,533	32%	1.04
3	Direct and Indirect Development	73,108,040	24,140,962	33%	1.06
4	Direct and Indirect Development with Highway Improvement	81,087,670	25,482,606	31%	0.98
5, 6	Induced land use shift – short-term	81,178,190	25,494,796	31%	0.98
7, 8	Induced land use shift – long-term (5-yr. regional growth)	89,027,880	27,690,463	31%	1.07
	<i>* Baseline 5-yr. growth (5-yr. regional growth without highway improvements)</i>	<i>79,949,600</i>	<i>26,453,270</i>	<i>31%</i>	<i>1.14</i>

For comparison purposes and later calculation of the net effect of long-term induced travel on VMT, the traffic data in Table 5.1 also includes the projected VMT considering 5-yr. regional demographic growth and growth in number of jobs, but without any changes in the underlying highway network. This data is shown in the bottom row of Table 5.1 and it is labeled with an asterisk as opposed to association with any of the modeling phases. The incremental changes in population, households and employment in the community between different modeling phases are shown in Table 5.2, while Table 5.3 provides an overview of incremental increases in VMT between different modeling phases.

**Table 5.2** Change in Population, Households, and Employment in the Case Study Community

Phase	Added Population	Added Households	Added Jobs
Direct Development	2,670	1,085	830
Indirect Development	470	192	148
Short-term reallocation of jobs and households	76	32	16
Long-term reallocation of jobs and households	2,016	570	641
Total	5,232	1,879	1,635

\* Direct and Indirect change in population/households and jobs is known and is an external input, while induced changes (immediate and 5 years following the development) are calculated using TELUM.

### 5.3.2 Ascertaining Transportation Impacts of Direct and Indirect Development

As shown in Table 5.3, the addition of new development with 2,670 residents, 1,085 households and 830 jobs had a direct impact on local traffic and added 3.48 million local VMT per year, a 4.9% increase in the total VMT over the baseline. At the same time, however, VMT attributed to through traffic decreased by 1.81 million. This means that a fair portion of through-trips was displaced as the local trips ‘consumed’ a larger portion of the available highway capacity on local roads. Indeed, the local traffic, including the traffic generated by the direct development, accounted for 32% of the total VMT, up from the baseline of 28%. Overall, the net impact of direct development on VMT is increase of 1.66 million over the baseline. Because the highway improvements have not been made, the travel conditions deteriorated as more VMT were added, increasing the average V/C ratio to 1.04.

**Table 5.3** Change in VMT Between the Modeling Phases

Modeling Phases	TOTAL TRAFFIC			THROUGH TRAFFIC (VMT)			LOCAL TRAFFIC (VMT)			
	Annual VMT	Incremental Change	Average VOC	Annual VMT	Incremental Change	Cumulative Change	Annual VMT	Incremental Change	Cumulative Change	% of Total VMT
Baseline	71,212,230	-	1.01	51,194,163	-	-	20,018,067	-	-	28%
Direct Development	72,876,265	1,664,035	1.04	49,377,732	-1,816,431	-1,816,431	23,498,533	3,480,466	3,480,466	32%
Direct and Indirect Development	73,108,040	231,775	1.06	48,967,078	-410,654	-2,227,085	24,140,962	642,429	4,122,895	33%
Direct and Indirect Development with Highway Improvement	81,087,670	7,979,630	0.98	55,605,064	6,637,986	4,410,901	25,482,606	1,341,644	5,464,539	31%
Short Term Land Use Re-allocation	81,178,190	90,520	0.98	55,683,394	78,330	4,489,231	25,494,796	12,190	5,476,729	31%
Regional Growth (5 yr.) with Highway Improvement	89,027,880	7,849,690	1.07	61,337,417	5,654,023	10,143,254	27,690,463	2,195,667	7,672,396	31%
Regional Growth (5 yr.) Without highway improvement (*)	79,949,600	6,841,560	1.14	53,496,330	4,529,252	2,302,167	26,453,270	2,312,308	6,435,203	33%

(\*) Incremental and cumulative changes in traffic in this modeling phase are calculated relative to phases preceding the introduction of highway improvements (capacity increase) in the highway network.

Addition of the indirect development in the community, including 192 new households with 470 residents, and 148 additional jobs, still without any highway improvements, generates another 642,429 VMT annually attributed to local trips. This increase is offset by additional decrease in through-trips (reduction of 410,654 VMT annually), making the net effect of indirect development equal to addition of 231,775 VMT annually to the traffic on the two principal arterials adjacent to the development area of five TAZ. This incremental increase of VMT also resulted in a slightly increased congestion level, reflected in the V/C ratio increase to 1.06.

### **5.3.3 Ascertaining Transportation Impacts Induced by the Highway Improvement**

After introducing both direct and indirect development in the analyzed community, the transportation model network was updated by increasing the capacity of the two principal arterials in the vicinity of new land development to 39,000 vpd, a 20% increase over the baseline capacity. The traffic assignment was then executed to obtain updated traffic volumes in the regional network. As the capacity of the arterials traversing the case study area increased, travel conditions improved (i.e., travel times decreased) and more traffic was attracted to the newly upgraded roads. Some of this traffic is attributed to local trips that used alternative routes in and out of the community, but have switched to the arterials after the capacity expansion. In addition, many through-trips (that did not have either origin or destination within the community) switched to the improved arterials as well, thus taking advantage of faster travel with less congestion.

The model recorded a net increase of approximately 7.98 million VMT immediately following the introduction of highway capacity increase in the model network. This is almost 11% increase compared to the VMT before the highway improvements were

added. Of this increase, about 1.34 million VMT (or 17%) is attributed to local traffic, and the remaining 6.64 million VMT to the through traffic. The average V/C ratio dropped to 0.98, indicating less congested traffic conditions. The fact that the local traffic increased after the highway improvements without any additional developments indicates that a portion of the trips that would have used the adjacent arterials before the improvements, avoided these roads due to congestion. After the improvement was implemented these trips switched onto the arterials.

At this point in the analysis it is possible to calculate the direct, indirect, and the first two components of the induced traffic. Using the data provided in Table 5.3 one can conclude that the direct traffic impact is equal to the additional local traffic generated as a result of introducing the direct development: in this case this amounts to 3,480,466 VMT per year. It can also be noted that the pressure of the local traffic “chased out” some of the through traffic, reducing it by 1,816,431 VMT per year. The indirect traffic impact can be estimated as the additional (incremental) traffic recorded after the indirect development is added to the network. This impact is 642,429 VMT per year. As was the case with direct impact, the additional local traffic caused a portion of the through traffic to reroute away from the two arterials, reducing the total through traffic on these roads by an additional 410,654 VMT per year.

The component of the induced traffic attributed to local trips attracted to the improved roadways, is estimated as a difference in local VMT before and after the introduction of highway improvements. This traffic accounts for 1,341,644 VMT annually. The second component of the induced traffic includes the through-trips that were re-routed to the arterials traversing the community after the roadway improvements were

implemented. This impact is reflected in the incremental increase of VMT attributed to through-trips after the introduction of the highway capacity expansion in the model network. As shown in Table 5.3 this increase is equal to 6,637,986 VMT annually. However, given that a portion of the through-trips would have been rerouted away from these roadways had there been no capacity expansion, the net impact of the highway improvement on induced through-trips is reduced by the corresponding VMT ‘lost’ due to the direct and indirect traffic impacts. Therefore, the net induced impact on through-trips is reflected in additional 4,410,901 VMT annually. It is revealing that the component of the induced traffic via through-trips immediately following the roadway improvement contributed to the overall traffic increase as much as the sum of all additional trips associated with the direct and indirect development, and local induced trips.

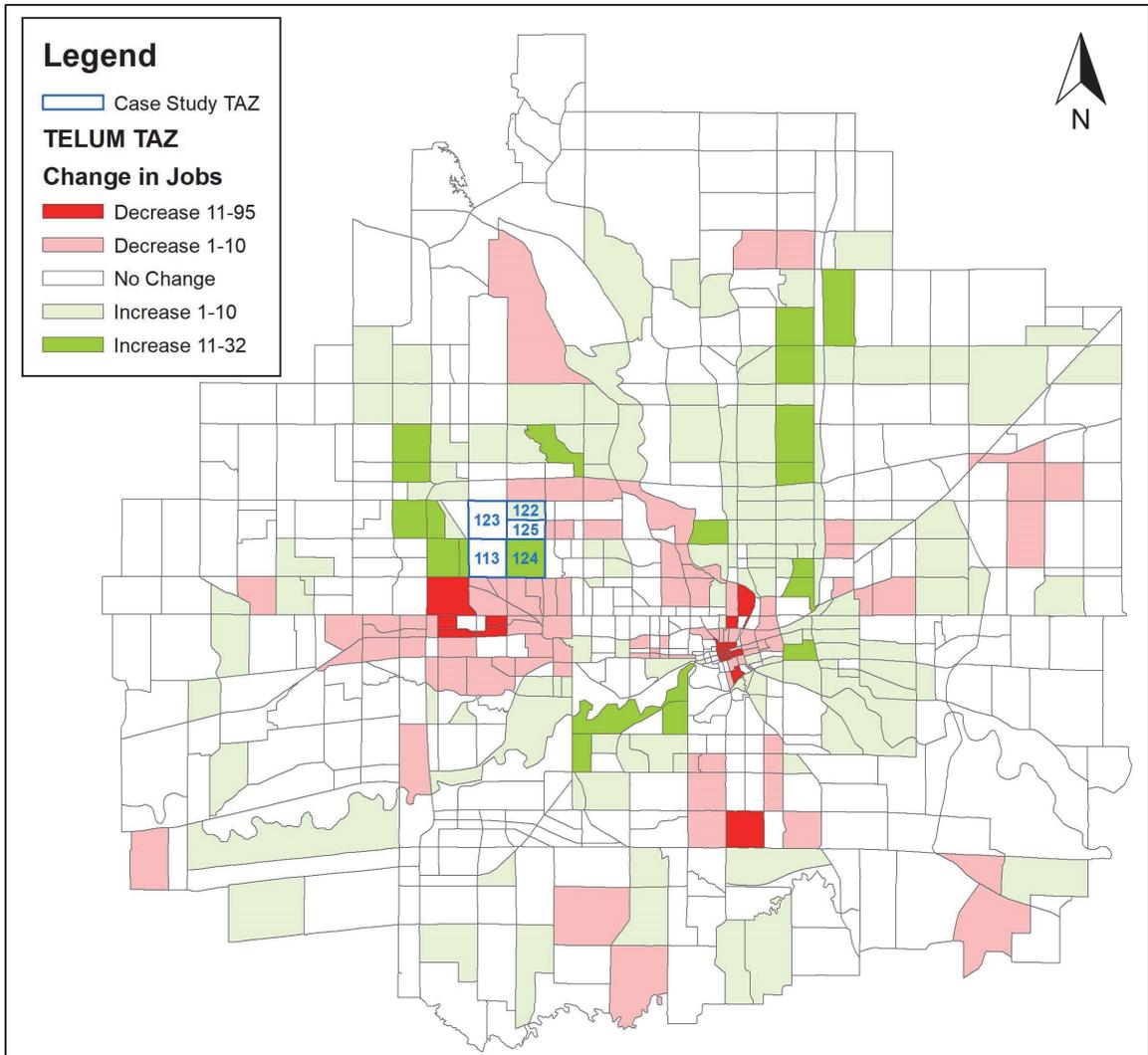
#### **5.3.4 Ascertaining Impact of Land Use Changes on Induced Demand**

The analysis so far did not consider the relocation of jobs and households (i.e., change of land use and activity locations) as the result of the community development, increase in local highway capacity, and long-term regional growth of population and employment. The TELUM land use model was used to estimate regional re-allocation of jobs and households, including reallocation in the case study area.

The baseline TELUM model reflects the location of jobs and households, land use, and travel patterns after the direct and indirect developments have taken place and the highway improvements have been completed. The travel patterns are reflected in inter-zonal travel time impedances imported from the travel demand forecasting model. Two scenarios (modeling phases) were introduced for the land use forecast: *Induced land use shift – short-term* and *Induced land use shift – long-term*.

In the modeling phase *Induced land use shift – short-term* there were no changes in the total regional population, number of households, and employment. However, their location was allowed to change from one zone to another. The TELUM model estimated the 5-zone community would attract additional 33 households with 76 residents, and additional 16 jobs. Moderate re-allocation of jobs and households elsewhere in the region is also projected, as shown on the maps in Figure 5.4 and Figure 5.5. The maps show relative zonal changes in number of jobs and households immediately following the highway improvement.

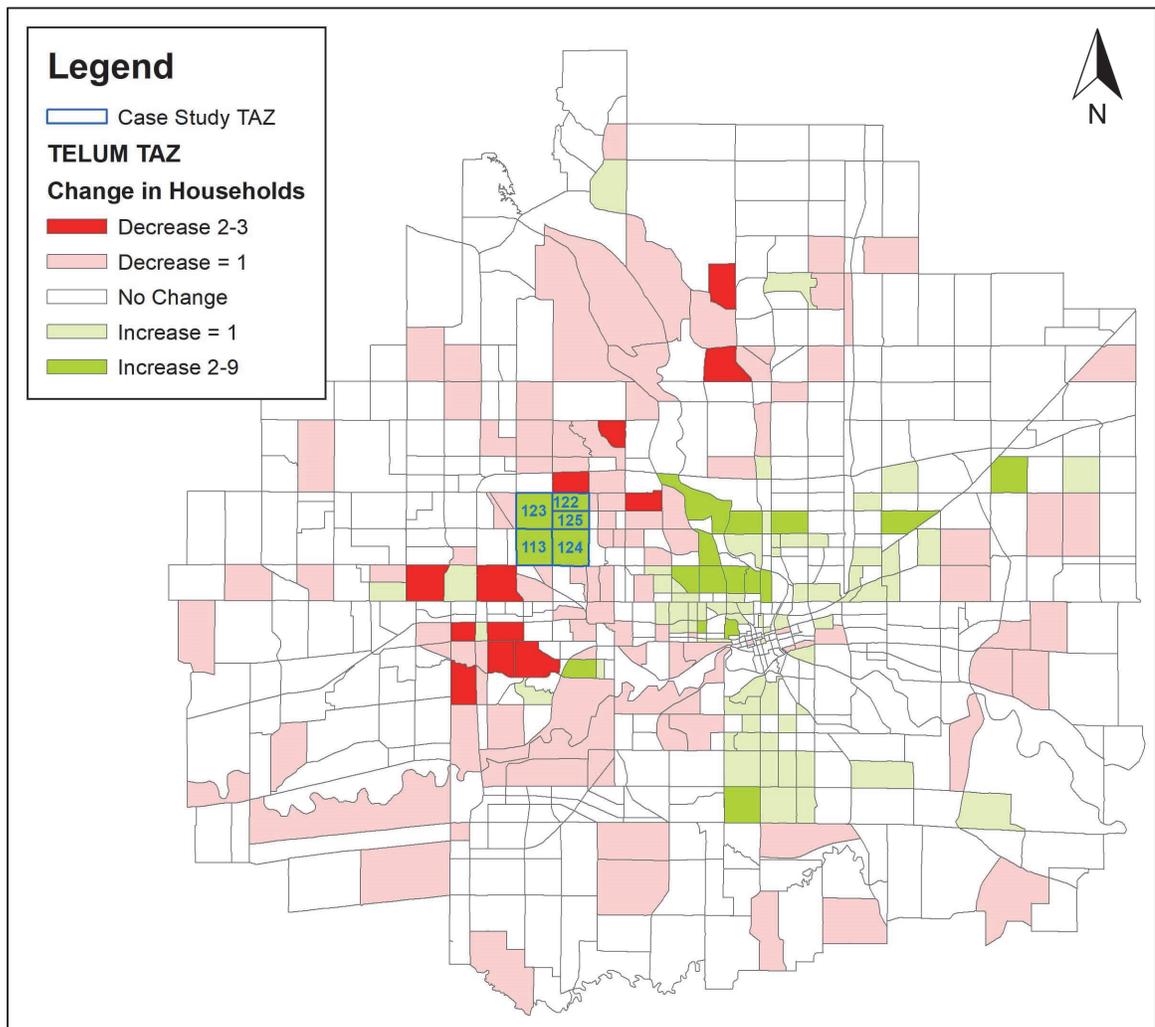
The map in Figure 5.4 shows that within the five-TAZ development community only TAZ #124 and TAZ #122 attracted additional jobs, with majority of them locating in TAZ#124. The map also shows reallocation of jobs within the region as a response to changes in accessibility and attractiveness of the respective TAZ resulting from the highway improvement. It should be noted that most significant decrease in jobs is projected in the area immediately south-west to the five-TAZ community. It can be assumed that these jobs are relocated to the induced development within the five-TAZ development area to take advantage of its improved accessibility. The projected re-allocation of jobs throughout the rest of the region does occur, but it is less significant than the changes in the vicinity of improved highways.



**Figure 5.4** Induced zonal change in employment following the land use shift (no growth in regional employment or population is assumed).

As shown in Figure 5.5 the projected regional re-allocation of households in response to the highway improvements is far less significant than re-allocation of jobs. While the changes are projected in the majority of TAZ throughout the region, they are very small (plus/minus 1 household in most of the zones). These kinds of changes are not considered meaningful when it comes to the underlying impact on travel demand. However, one can observe that a bit higher increase in the number of households is

projected in the five-TAZ community, as well as in TAZ zones to the east and along the improved arterial that runs through the five-TAZ community in the east-west direction. More pronounced decrease in the number of households is again projected in TAZ zones south-west to the five-TAZ community. The explanation for this shift is the same as one given in the previous discussion of the projected re-allocation of jobs.



**Figure 5.5** Induced zonal change in number of households following the land use shift (no growth in regional employment or population is assumed).

Consequently, both regional and local trip attractions and productions changed based on the TELUM outputs, which translated in changes of the regional travel demand. The changes in travel demand further translated into changes of trip distribution and assigned traffic flows on the regional highway network, including the two principal arterials adjacent to the five-TAZ community. The changes in traffic flows on the local arterials are reflected in the results of the travel demand and traffic flow forecast summarized in Table 5.3 for this modeling phase. The total increase in traffic on two analyzed roadways was 90,520 VMT annually, while the VMT pertaining to local traffic alone increased by 12,190. This means that most of the additional VMT resulting from induced land use changes was generated by trips that did not start or end within the five-TAZ community (78,330 VMT annually, or 87% of the total incremental increase in VMT). Nevertheless, the overall impact of short-term induced land use shifts on the traffic on two arterials in this case study is almost negligible: the increase of 90,520 VMT annually is equivalent to 0.1% of the VMT projected before considering the short-term land use shifts.

In modeling phase *Induced land use shift – long-term*, the same inter-zonal travel times were entered into TELUM model as in the short-term analysis. However, the total regional projection of population was increased by 12% and number of regional jobs by 8.5% to reflect the projected regional growth over the next 5 years. The TELUM model forecasted that 570 more households with 2,016 residents would locate in the five-TAZ community, as well as additional 641 jobs. This increase is on top of the increase in resident population, households, and jobs added by the direct and indirect development, and short-term land use shift. The total Regional growth was also distributed among all other TAZ

in the region. The new allocations of jobs and households by TAZ were extracted from TELUM model and used to update the trip generation in the regional travel demand model and calculate new regional travel demand pattern.

The travel demand model was then executed and projected traffic flows on critical arterial links were recorded and summarized in Table 5.3. As expected, due to increase in both local and regional demand the overall traffic on the two arterials increased. The increase is reflected in additional 7,849,690 VMT annually. This is almost a 10% increase over the previous modeling phase, and about 11% of the baseline VMT on same roadways. The portion of this traffic attributed to local trips is 2,195,667 VMT annually (28% of the net VMT increase in this modeling phase). The remaining increase (about 72%) is attributed to through-trips.

The increase in traffic contributed to the increased level of traffic congestion, as reflected in the V/C ratio of 1.07. It should be noted that this is very close to the V/C ratio estimated after adding direct and indirect development without any improvements on the adjacent roadways (V/C ratio was 1.06).

### **5.3.5 Summary of the Case Study Model Results**

As discussed in the analysis thus far, after the capacity improvements had been made on the arterials, the local and through traffic were re-routed, the existing residential and business entities had re-located in response to the roadway improvement, and the regional growth over the next 5 years added more households and jobs causing an increase in the overall travel demand in the region, as well as the local community. At the end of the modeling procedure the analyzed sections of the two arterials carry 61,337,417 VMT of through traffic and 27,690,463 VMT of local traffic. The change from the baseline is

reflected in an overall increase of 17,815,650 VMT annually (25% increase), of which 10,143,254 VMT is attributed to through-trips and 7,672,396 VMT is attributed to local trips. These outputs are also summarized in Table 5.4.

**Table 5.4** Cumulative Increase of VMT on Two Analyzed Arterial Sections Relative to the Baseline

Traffic Flow Components	Increase of VMT	% Share
Through Traffic	10,143,254	57%
Local Traffic	7,672,396	43%
TOTAL	17,815,650	100%

The overall increase in VMT can be further broken down by modeling phase to ascertain direct, indirect, and induced traffic impacts. This breakdown is summarized in Table 5.5 (based on the detailed results provided in Table 5.3). It can be calculated that 11% of the incremental increase in the overall traffic is attributed to the initial (direct and indirect) new development (1,895,810 VMT). It should be noted that this increase is a combination of added local trips and reduction in through traffic. Additional 45% of the increase (8,070,150 VMT annually) is related to the short-term induced traffic, including re-routing of existing local and regional trips (7,979,630 VMT annually) and short-term re-allocation of jobs and households in the region (90,520 VMT annually), both in response to the improved travel times resulting from the highway capacity expansion and related improved accessibility of the area adjacent to the improved roadways.

**Table 5.5** Breakdown of the Overall Increase of VMT among Different Traffic Impact Components

Traffic Impacts	Increase of VMT	Relative Share (%)	Percent of the Baseline VMT
Direct and Indirect	1,895,810	11%	3%
Induced - Short Term	8,070,150	45%	11%
Induced - Long Term	1,008,130	6%	1%
Regional Growth	6,841,560	38%	10%
<b>TOTAL</b>	<b>17,815,650</b>	<b>100%</b>	

The remaining 44% of the overall incremental traffic increase is associated with the projected (exogenous) 5-yr. regional growth (12% growth of the regional population and 8.5% growth of the regional employment) and the highway network that only reflects improvement on the two arterials adjacent to the five-TAZ development area. This increase consists of two components:

1. Baseline increase of traffic that would have happen due to regional growth without any highway improvement; and
2. Increase in traffic due to re-allocation of jobs and households in response to the highway improvements (induced demand).

The net impact of the long-term induced demand is calculated as a difference between the VMT reflecting the projected five-year traffic with and without the roadway improvement. Based on the data provided in Table 5.3 this can be calculated as follows:

Projected 5-yr. increase in annual VMT:

With roadway improvement = 7,849,690

Without roadway improvement = 6,841,560

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Difference (net long-term induced impact) = 1,008,130

The summary presented in Table 5.5 reveals that the most significant overall traffic impact on the improved roadways is that of the short-term induced demand, both as a share of the overall increase of VMT and as a percentage of baseline VMT. The long-term induced demand has comparably lower impact, measured in terms of incremental increase of VMT.

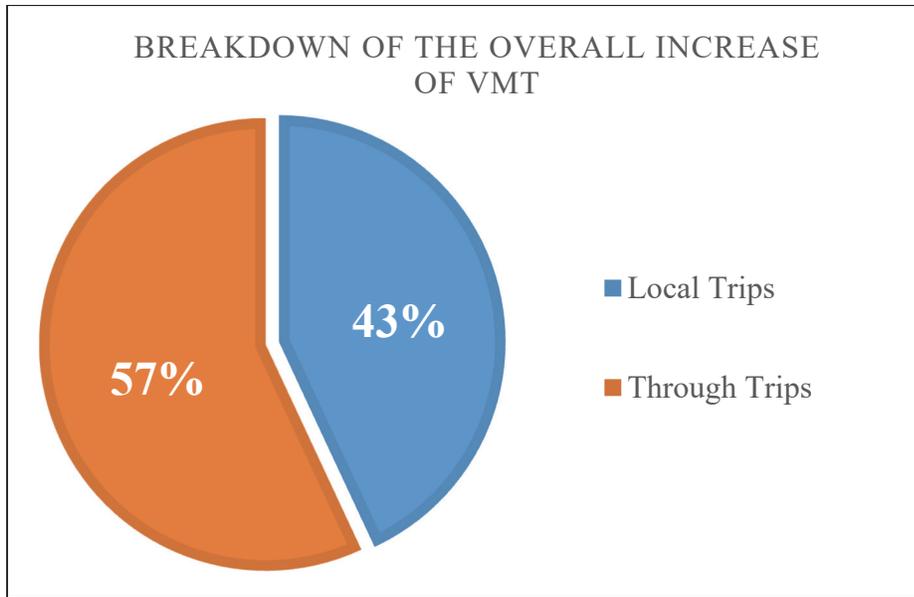
The increase in traffic attributed to local trips can be broken down in similar fashion as was done with the overall traffic. The breakdown is summarized in Table 5.6 and it is quite different from the breakdown shown for the overall traffic. The largest share of the traffic increase attributed to local trips is associated with direct and indirect development (direct and indirect impact). Short-term induced impact accounts for about 18% of the VMT increase, including the combined impacts of re-routing of existing trips (1,341,644) and short-term re-allocation of jobs and households in the region in response to changes in accessibility resulting from the highway improvements (additional 12,190 VMT annually attributed to the local trips). Most interestingly, the long-term induced impact is negative! This means that the highway improvement did not result in increased traffic due to a long-term induced development in the five-TAZ community, at least not beyond the increase in population and jobs driven by the regional growth. This can be explained by the fact that much of the improved accessibility of the development community had already been ‘consumed’ by the initial developments (direct and indirect) and short-term induced shifts in traffic patterns and regional land use.

**Table 5.6** Breakdown of the Increase of VMT Attributed to Local Trips Among Different Traffic Impact Components

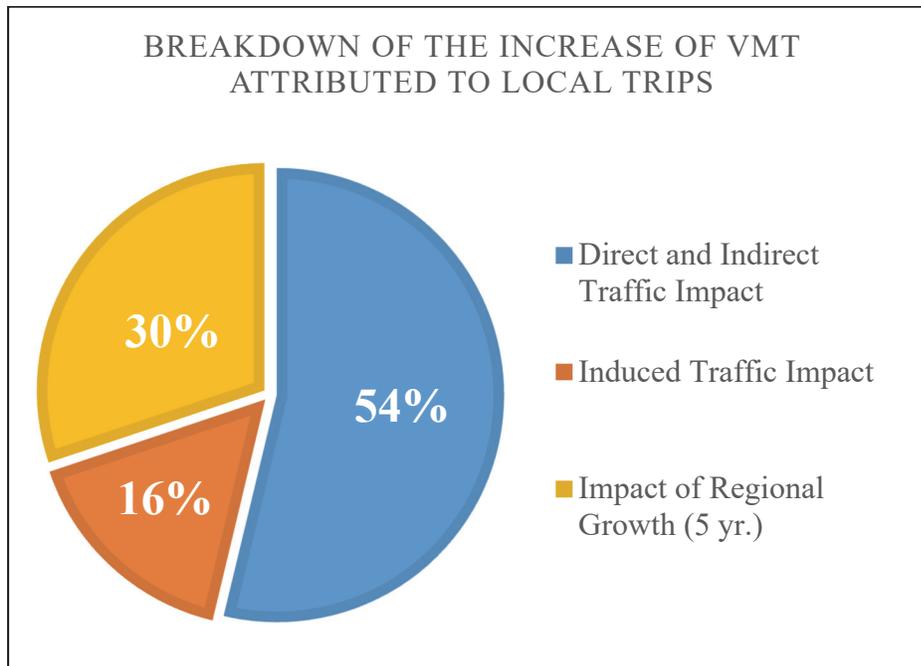
Traffic Impacts	Increase of VMT	Relative Share (%)
Direct and Indirect	4,122,895	54%
Induced - Short Term	1,353,834	18%
Induced - Long Term	-116,641	-2%
Regional Growth	2,312,308	30%
TOTAL	7,672,396	100%

#### **5.4 Implications on Allocation of the Costs of Highway Capacity Improvements**

The changes in VMT quantified in each modeling phase can be used as a proxy to allocate the cost of improvements of the arterials to users, or rather categories of users who are the primary beneficiaries of the capacity improvements. In doing so, one may consider incremental VMT attributed to local trips and through-trips following the new land development and related traffic improvements. Based on the analysis of results presented in Section 5.3 and summarized in Table 5.4, about 57% of the overall cost of transportation improvements considered in the case study should be allocated to regional traffic, i.e., regional jurisdiction. The remaining 43% of the cost of transportation improvements should be allocated to the local community. This includes capital costs, as well as operations and maintenance costs. The “regional share” of the cost of transportation improvements could be covered using funds from the regional or statewide transportation improvement program, which is funded from the gasoline tax proceeds paid by system users.



**Figure 5.6** Responsibility for highway improvement costs based on the breakdown of the increase in VMT between local trips and through trips.



**Figure 5.7** Breakdown of increase in VMT attributed to local trips among different impact categories.

Note: Induced traffic impact includes both short-term and long-term induced impact.

The “local share” of the overall costs should be covered by the local community and could be broken down and paid for as follows:

- Cost allocation for direct and indirect impacts – about 54% of the local share, should be recovered from developers of direct and indirect developments through impact fees. This share is equivalent to the increase of VMT attributed to local trips related to direct and indirect land development.
- Cost allocation for induced impacts should be about 16% of the total local share. The cost recovery for this portion of the local share initially may be from local taxes. This cost may be offset in the future by the revenue from impact fees assessed to developers of induced developments, as well as ‘value capture’ revenues – i.e., increase in local tax revenues resulting from the increase in value of land and real estate due to improved accessibility and attractiveness of the community.
- Cost allocation equivalent to the share of local traffic generated due to five-year regional growth is about 30%. The cost for this portion of the local share should be covered from local taxes. This costs may later be recovered from developers of new housing and commercial development through impact fees.

## **5.5 Sensitivity Analysis**

The sensitivity analysis was conducted to assess the ability of the proposed modeling methodology to respond to changes in the exogenous factors used as the key input parameters. There are two key input parameters describing the underlying changes in travel demand and transportations supply:

1. Size of new land development, in terms of increase in population, number of households and jobs; and
2. Increase in highway capacity on roads adjacent to the development.

For the purpose of the sensitivity analysis, the proposed modeling methodology was applied to the same case study area and regional highway network considering several modeling scenarios. In each modeling scenario, either the size of the new development or

the underlying increase in highway capacity on local roads were modified, and outputs were recorded and summarized similar to those presented for the case study scenario.

In the first set of scenarios, the size of new development was varied by increasing the existing population, number of households, and number of jobs in the five TAZ where the hypothetical development was located. The variation of the development size in various scenarios was 10%, 20%, 30%, 40%, and 50% of the existing (baseline) population, households, and jobs located in the five-TAZ area. The size of the new development was treated as representation of the increase in local travel demand. In all scenarios with variable size of new development, the highway improvement (capacity increase) on select local highway links was unchanged and was equivalent to the capacity increase set in the case study example – which was 20% increase in capacity over the existing condition.

In the second set of scenarios, the increase in roadway capacity on local roads that provide access to the new land development was varied as a percent increase over the existing capacity. The roadway capacity was defined in the model network for each highway link in terms of vehicles per day for each direction of travel. In each modeling scenario in this set the roadway capacities (vehicles per day) on select network links were increased by 10%, 20%, 30%, 40%, and 50% respectively. In all scenarios in this set the size of the new development in the five case study TAZ was unchanged and was equivalent to the development size set in the case study example, which was 20% increase in population, number of households, and jobs over the existing (baseline) conditions.

Overall, the sensitivity analysis included comparison of results from scenarios defined by the size of new development and local capacity increase as shown in Table 5.7

and Table 5.8. It should be noted that scenario #2 is the same in the two sets, and was already analyzed as the case study scenario.

**Table 5.7** Sensitivity Analysis Scenarios with Fixed Highway Capacity Increase of 20%

Scenario No.	% Change in Travel Demand
1	10 %
2	20 %
3	30 %
4	40 %
5	50 %

**Table 5.8** Sensitivity Analysis Scenarios with Fixed Increase in Demand of 20%

Scenario No.	% Change in Highway Capacity
1	10 %
2	20 %
3	30 %
4	40 %
5	50 %

The response of the modeling methodology to underlying changes of the two input parameters was identify by recording the indicators previously defined and discussed in the analysis of the case study results. They include the following:

1. Breakdown of the total increase of VMT on select local roads among direct and indirect impacts, short-term induced impacts, and long-term induced impacts, as a percent of baseline VMT;
2. Breakdown of the total increase of VMT on select local roads among direct and indirect impacts, short-term induced impacts, and long-term induced impacts (absolute increase);

3. Breakdown of the total increase of VMT on select local roads among local and through traffic; and
4. Breakdown of the increase of VMT on select local roads pertaining only to local traffic among direct and indirect impacts, short-term induced impacts, and long-term induced impacts

The calculated values of these indicators for each scenario are presented in Table 5.9 (scenarios with fixed increase in local demand) and Table 5.10 (scenarios with fixed increase in highway capacity). Based on the results of the analysis, elasticities were calculated for each indicator relative to the variation of increase in highway capacity of select local roads in each scenario (see Table 5.9) and the variation of increase in local travel demand in each scenario (see Table 5.10). Since both the increase in local demand and increase in roadway capacity were expressed in relative terms, and so were the indicators (as percentages of the total increase in VMT on select local roads), the elasticities were calculated as slopes of the regression lines, as defined in the following equation:

$$E = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (5.1)$$

where:

$E$  = elasticity;

$n$  = number of scenarios (observations) with fixed local travel demand or fixed highway capacity (in this experiment  $n = 5$  in both cases);

$x_i$  = value of the indicator in  $i$ -th modeling scenario;

$\bar{x}$  = mean value of the indicator in the given set of five scenarios;

$y_i$  = value of the explanatory variable (variable input parameter) in i-th modeling scenario;

$\bar{y}$  = mean value of the explanatory variable (variable input parameter) in the given set of five modeling scenarios.

The results of the sensitivity analysis reveal that the change in VMT indicators is consistent with the assumptions about the relationship between highway demand, highway capacity, and the resulting traffic flows. The results show that the direct and indirect traffic impacts stay virtually unchanged when local demand is fixed, and gradually increase with the increase in local demand when the roadway capacity is fixed.

More interesting are the results of the sensitivity analysis pertaining to induced impacts, both short-term and long-term. Looking at the analysis of varying highway capacity with fixed local demand (Table 5.9), the results show consistent increase in induced impacts as a share of the overall increase in VMT on the local network. It should be noted that the share of short-term induced impacts is larger than that of the long-term impacts. This means that traffic rerouting, change of activity patterns, and immediate relocation of jobs and households have more significant impact on local traffic than long-term induced changes in demand. In fact, the model outputs suggest there would be no impacts of long term induced demand on local trips, as reflected in the elasticity of -0.0062. The negative value of elasticity even suggests that the traffic conditions after the direct, indirect, and short-term induced impacts would make the local area less attractive for any induced development and additional demand of local trips.

**Table 5.9** Results of the Sensitivity Analysis with Fixed Increase in Local Demand (20% Relative Increase)

Explanatory → Variable	Relative increase of highway capacity on select local roads in the respective scenario				
↓ Output Indicator ↓	10%	20%	30%	40%	50%

Breakdown of increase of VMT as a percent of baseline VMT						Elasticity
Direct and Indirect	3%	3%	3%	3%	3%	0.0000
Induced – Short Term	5%	11%	16%	19%	21%	0.3969
Induced – Long Term	3%	1%	3%	6%	7%	0.1278

Breakdown of the overall increase of VMT						Elasticity
Direct and Indirect	13%	11%	9%	7%	7%	-0.1654
Induced – Short Term	25%	45%	51%	51%	52%	0.6041
Induced – Long Term	15%	6%	9%	16%	18%	0.1582

Breakdown of increase of VMT among local and through traffic						Elasticity
Local Traffic	50%	43%	37%	34%	31%	-0.4785
Through Traffic	50%	57%	63%	66%	69%	0.4785

Breakdown of increase of VMT pertaining to local traffic						Elasticity
Direct and Indirect	57%	54%	50%	47%	46%	-0.2878
Induced – Short Term	11%	18%	23%	28%	29%	0.4555
Induced – Long Term	0%	-2%	-1%	-1%	0%	-0.0062

**Table 5.10** Results of Sensitivity Analysis with Fixed Increase in Local Highway Capacity (20% Relative Increase)

Explanatory → Variable	Relative increase in population, households and jobs (direct + indirect) in each respective scenario				
↓ Output Indicator ↓	10%	20%	30%	40%	50%

Breakdown of increase of VMT as a percent of baseline VMT						Elasticity
Direct and Indirect	2%	3%	5%	6%	8%	0.1623
Induced – Short Term	10%	11%	11%	11%	10%	0.0073
Induced – Long Term	3%	1%	2%	2%	2%	-0.0085

Breakdown of the overall increase of VMT						Elasticity
Direct and Indirect	6%	11%	18%	23%	27%	0.5460
Induced – Short Term	41%	45%	40%	39%	37%	-0.1392
Induced – Long Term	12%	6%	8%	9%	7%	-0.0700

Breakdown of increase of VMT among local and through traffic						Elasticity
Local Traffic	32%	43%	54%	62%	70%	0.9382
Through Traffic	68%	57%	46%	38%	30%	-0.9382

Breakdown of increase of VMT pertaining to local traffic						Elasticity
Direct and Indirect	40%	54%	62%	67%	74%	0.8143
Induced – Short Term	19%	18%	16%	15%	10%	-0.2045
Induced – Long Term	1%	-2%	0%	1%	3%	0.0730

With fixed demand, it is also evident that most of the increase in VMT on local roads can be attributed to through traffic, and this share increases consistently with increase in roadway capacity. This can be explained by the limit in the amount of activity that can be accomplished in the local community, which stops to grow at some point even with

further increase in highway capacity. Therefore, any additional increase in highway capacity will attract and serve through traffic, rather than traffic generated by the local activities.

Looking at the analysis of varying demand with fixed highway capacity (Table 5.10), there is virtually no change in the share of induced traffic impact as a percent of the baseline VMT (indicated by very low elasticities, of 0.0073 for the short-term and -0.0085 for the long-term induced impact). Any increase in traffic due to induced demand can be attributed to the fixed increase of highway capacity on local roads of 20%, which was maintained throughout the five scenarios presented in Table 5.10. The induced impact slightly decreases as a share of the overall increase of VMT (as reflected in elasticities of -0.1392 and -0.0700 for the short-term and long-term induced impacts respectively). Similar trend can be observed in the share of induced impact on local traffic VMT, although it is slightly more pronounced for the short-term induced impact as reflected in elasticity of -0.2045. The long-term induced impact on local trips in all evaluated scenarios is insignificant (between -2% and 3%) and inelastic (elasticity of -0.0730). This can be explained by the fact that the major portion of the additional highway capacity on local roads will be 'consumed' by the direct and indirect demand, as well as immediate rerouting of traffic and shift in local activity patterns, rather than long-term induced demand.

In conclusion, the outcomes of the sensitivity analysis can be summarized as follows:

1. The results of the analysis and calculated elasticities confirm the responsiveness of the proposed modeling methodology to changes of the two key underlying input parameters – travel demand and highway capacity.

2. The response of the model is consistent with the travel demand and traffic forecasting premises and assumptions.
3. The analysis shows consistency across all scenarios in terms of greater impact of short-term induced traffic as compared to long-term induced traffic. This is especially visible when it comes to local trips, where long-term induced traffic is insignificant.
4. The elasticities calculated as part of the sensitivity analysis can be used to estimate the expected changes of VMT for demand increase and capacity increase scenarios that were not included in this analysis.

## CHAPTER 6

### RESEARCH OUTCOMES AND CONTRIBUTIONS

#### 6.1 Summary of the Dissertation Research Outcomes

The presented methodology for calculating transportation impacts of new residential and commercial development applies integrated regional travel demand and land use modeling. The methodology calculates incremental VMT associated with each component of the transportation impact (direct, indirect, and induced) and thus can ascertain corresponding transportation costs if the cost of VMT is known. Using the appropriate formula, each cost component (direct, indirect, and induced) can be allocated to either the local community (to be paid from local taxes and development fees) or the general traveling public (to be paid from gas tax, for example).

Induced travel demand includes both rerouting of the existing trips, as well as additional trip-making due to induced development and new trips taking advantage of improved mobility and land accessibility resulting from transportation improvement(s). The key advantage of the method presented here is the capability of integrated land use and travel demand modeling to ascertain regional aspect of changes in attractiveness of the studied communities, and the corresponding changes in land use, travel demand, and traffic flows. In other words, impacts of the land development and improved transportation infrastructure in a local community is analyzed relative to regional land use and travel patterns. In the presented case study example, the transportation improvement significantly improved the traffic conditions on local arterials relative to the highly congested neighboring area. In fact, the V/C ratio on the local network was reduced by almost 10%

following the improvements, and remained slightly lower than the baseline even with the short-term induced demand. This resulted in an increase of accessibility and attractiveness of the studied community, which in turn caused a higher number of induced jobs and households to relocate so as to take advantage of the newly improved highway facilities.

The results of the case study also reveal that the immediate (short-term) induced traffic impacts are far more significant than the long term impacts, and they increase with the size of the highway capacity expansion. Besides being far less significant than short term impacts, the sensitivity analysis showed that the long-term induced impacts are consistent regardless of the size of highway capacity expansion, measured as a percent of the overall change in VMT.

Finally, the dissertation research demonstrated implementation of the proposed methodology that can be applied in any transportation planning study or traffic impact study to quantify direct, indirect, and induced traffic impacts, as well as allocation of responsibilities for underlying transportation system improvements.

## **6.2 Contributions to Transportation Planning**

The analysis methodology developed and presented in this dissertation is critical in understanding the totality of impacts of transportation improvements on the overall performance of the transportation system. The presented methodology provides means for disaggregation of anticipated (forecasted) transportation impacts of new developments among direct, indirect, and induced effects, and quantifies induced demand, including demand generated by induced development, as well as the resulting (induced) traffic flows. The implication of this analysis for the host community is the ability to develop appropriate

development and fiscal policies related to land development and transportation infrastructure improvements. This also serves the purpose of identifying transportation impacts on the regional transportation system and land use, which can inform regional transportation planning and urban development policies.

The presented method also provides a tool for determining equitable distribution of fiscal burden for transportation system improvements. This is accomplished by quantifying proportions of local and regional traffic utilizing improved transportation facilities, including induced traffic. This is important aspect of determining needs, responsibilities, and sources of funding for transportation capital improvements, as well as operations and maintenance. The presented model can help determine the fair share of transportation cost allocations to local jurisdictions, as well as regional jurisdictions. This in turn can help the local communities determine appropriate levels of traffic impact fees for new developments, and can inform and stimulate local and regional smart growth development strategies and policies. Similar to the concept of value capture in transit planning practice, a local community may benefit from the improved transportation facility through increased accessibility and attractiveness, which would translate to higher land and real estate values, and increase in tax base and tax returns. This would be the case as long as the traffic capacity on roadways that providing access to the community can accommodate traffic growth without increasing the congestion to levels that diminish the initial mobility and accessibility gains.

### 6.3 Contributions to Analysis of Induced Demand

The proposed modeling method can assist in quantifying and studying induced development and induced traffic, including the following aspects of the analysis:

- Geographic scale of induced effects. The presented method can be applied to same travel demand and land use models at different scales (e.g., local sub-area, corridor, or regional network) in order to analyze induced impacts of transportation improvements, and causality between the scale of analysis and forecasted outcomes.
- Influence of exogenous factors on induced demand. The presented methodology can further clarify the analysis of induced demand by distinguishing between the impact of transportation improvement and the influence of exogenous factors on induced demand. Exogenous variables, such as regional growth in population and employment, regional socio-economic trends, car ownership, price of gasoline and fuel efficiency standards, land and real estate value, and other similar factors, have a significant influence on demand for travel. In the proposed methodology they can be appropriately reflected and differentiated from the influence of incremental land development and transportation improvements by comparing baseline and improvement scenarios.
- Magnitude of induced effect relative to the scope of transportation improvement. It is understood that large expansions of transportation capacity have more significant influence on travel demand, and implicitly on induced demand. However, depending on the type of improvement, the land use context, and the current performance characteristics of transportation system, the magnitude of induced effects may vary among different localities for transportation projects of similar scope. Given that it employs integrated travel demand and land use modeling, the proposed method provides flexibility of evaluating a number of development scenarios, considering different levels of capacity expansion, and capturing the corresponding effect on induced development and induced demand. This analysis can also consider different planning time horizons (e.g., 5-, 10-, 20-years after the improvement), and predict anticipated induced effects over time.

## **CHAPTER 7**

### **FUTURE RESEARCH**

The envisioned future research that will build upon the research presented in this dissertation will focus on the following two directions of inquiry:

1. Application of the presented modeling methodology to further study induced travel demand.
2. Evaluate usability of presented methodology in studying different transportation system improvement and funding scenarios.

The first line of inquiry will focus on developing and testing similar models for regions and local communities with the variation of underlying factors determining travel demand and supply, such as:

- Different disposition of land use and urban development,
- Different levels of existing traffic congestion,
- Ability to expand highway network,
- Multimodal character of the regional and local transportation system, and
- Different regional socio-economic and demographic trends.

The research should try to reflect these differences in setting up the parameters for travel demand and land use modeling. The modeling experiments designed in such a way would have a greater potential for determining the impacts of these exogenous parameters on both activity and travel patterns, and how induced demand and induced travel can be better assessed and ‘guided’ when planning transportation system improvements.

The second line of inquiry is based on a premise that the usability of the presented modeling methodology can be extended to evaluation of different transportation system improvement and funding scenarios considering factors such as:

- Expansion of smart travel technologies for regional routing optimization, which may yield System Optimal traffic assignment more appropriate than User Equilibrium;
- Travel demand shifts in urban areas to transit and non-motorized modes;
- Reduced revenue from gasoline fees due to expansion of more fuel-efficient and electric vehicles and introduction of mileage-fees to address the s looming funding gap.

The modeling methodology and findings developed in the course of dissertation research provide a useful tool to evaluate such scenarios and their impacts on different components of travel demand and resulting traffic. This includes impacts on traffic flows attributed to local versus through trips in a local community, mode shifts resulting from various fiscal incentives or disincentives, and relocation of jobs and households in response to transportation and fiscal policies. One of the factors that will be studied are trip-making characteristics of the users in a region, and changes in transportation cost functions that would reflect advent of autonomous and shared mobility. Car ownership may also not be as critical factor in trip generation modeling in the future, or at least not the only one, given that younger generations of travelers seem to embrace with greater enthusiasm shared transportation options, as well as social aspect of transportation, especially in urban areas. The extensions and expansions of the models developed in this dissertation to take these factors into consideration and evaluate their impacts on traffic patterns will be pursued as part of future research.

**APPENDIX A**

**TRAVEL DEMAND FORECASTING MODEL PARAMETERS USED IN THE**

**CASE STUDY**

The travel demand forecasting model used in the case study was a traditional four-step highway-only model. (The mode split step was not considered as all the demand was realized using the highway mode). The model was implemented in TransCAD modeling software. The TransCAD flow diagram for the case study travel demand forecasting model is shown in Figure A.1.

In the case study presented in this dissertation, underlying direct, indirect, and induced demographic and socio-economic changes were coded in the spreadsheet model that was set-up to calculate balanced trip productions and attractions. The trip generation step considered three types of households by size (with 1, 2, and 3 or more residents per household) and car ownerships (with 1, 2, and 3 or more cars per household). For each combination of household size and car ownership, trip production rates are shown in Table A.1. The trip attraction rates are shown in Table A.2. In addition, trips tied to special generators such as airport, hospitals, shopping malls, and recreation centers were also considered, as well as internal-external trips.

The trip productions and attractions are balanced to satisfy the requirements of the balanced trip assignment model. The balancing was done by adjusting the non-home-based trip attractions and productions, excluding special generators. The adjustments were made using linear scaling on productions. The resulting balanced trip productions and attractions were input into the travel demand model in Step 7 shown in Figure A.1. The changes in

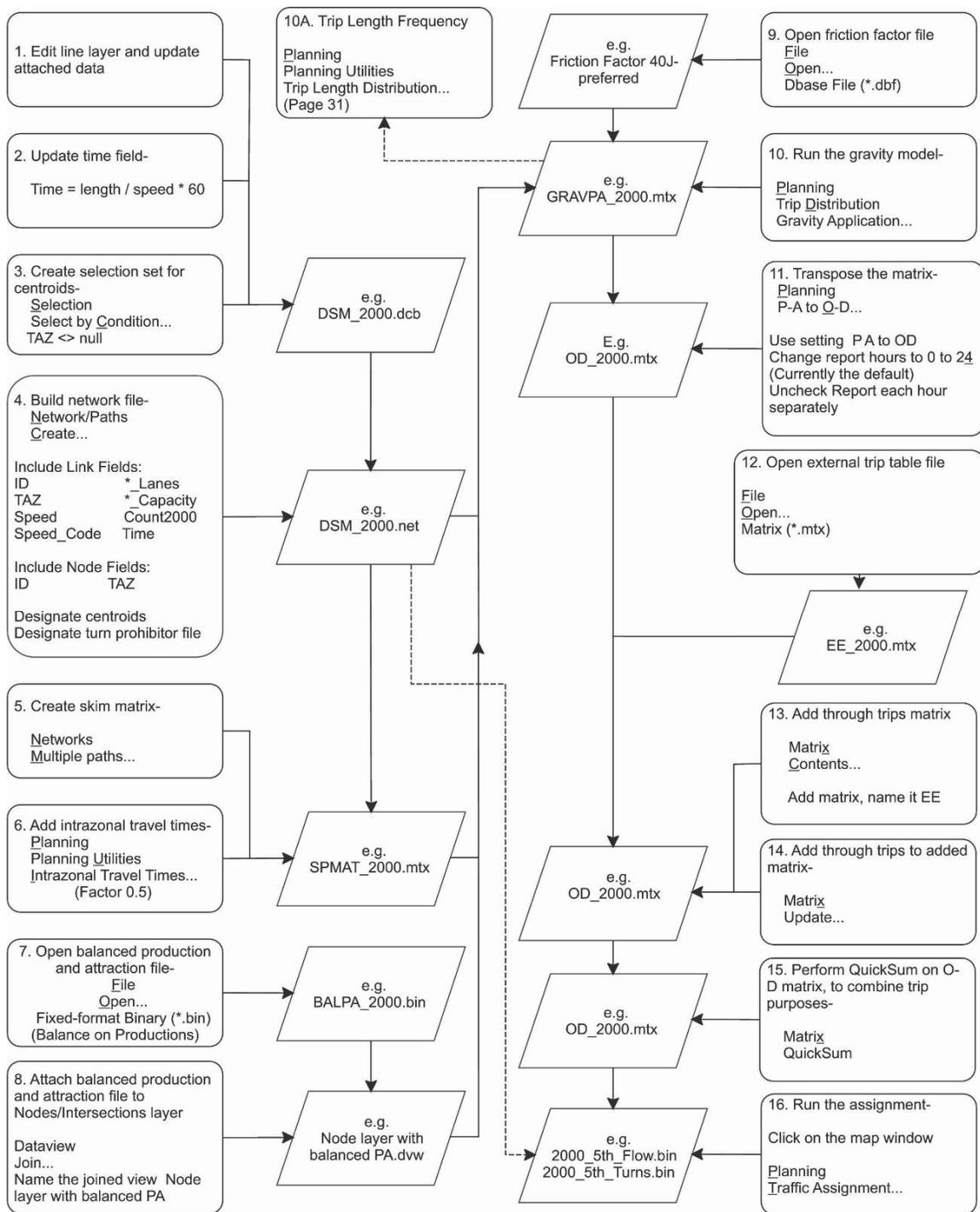
the link capacity reflecting road improvements were coded in the network file and input into the modeling process in Step 1 (see Figure A.1).

**Table A.1** Trip Production Rates by Household Size and Car Ownership

Trip Purpose	Household Size	Autos Owned		
		1	2	3+
Home-based Work	1	0.64	0.78	0.46
	2	0.74	1.53	1.90
	3+	1.10	1.93	2.29
Home-based Other	1	1.97	2.49	1.84
	2	2.85	3.07	3.12
	3+	4.51	4.40	5.54
Non-home-based	1	1.57	1.81	0.54
	2	1.83	2.14	1.83
	3+	5.96	2.47	3.01

**Table A.2** Trip Attraction Rates by Trip Purpose

Trip Purpose	Variable	Rate
Home-Based Work	Total Employment	0.830
Home-Based Other	Retail Employment	2.330
	Other Employment	1.630
	School Enrollment	0.800
Commercial Vehicles	Dwelling Units	0.357
	Retail Employment	0.263
	Other Employment	0.034
Internal-External	Dwelling Units	0.060
	Total Employment	0.259



**Figure A.1** TransCAD file flow diagram for the travel demand forecasting model used in the case study.

Source: Des Moines Area Metropolitan Planning Organization.

## **APPENDIX B**

### **REVIEW OF TELUM LAND USE MODELING SOFTWARE**

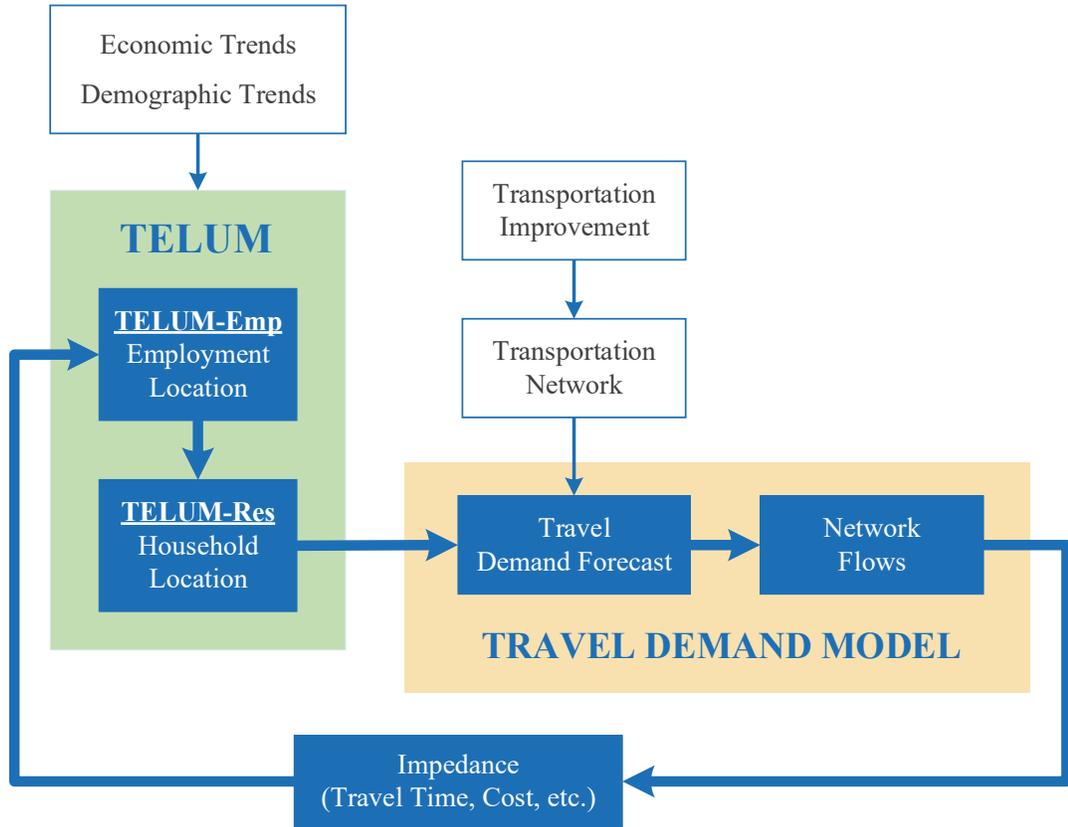
TELUM is an integrated interactive software package for evaluation of land use impacts of regional transportation improvement projects. It was developed by the New Jersey Institute of Technology as part of the Transportation Economic and Land Use System (TELUS) grant funded by the Federal Highway Administration. TELUS is an information-management and decision-support system designed to assist Metropolitan Planning Organizations and State Departments of Transportation in preparing their annual Transportation Improvement Programs. TELUM is a “land use component” of TELUS. Most recent version of TELUM is 5.0 released in January 2006.

TELUM evolved from, and is largely based on, its precursor METROPILUS (NJIT, 2005). Although it was developed as part of the larger research endeavor it became a self-contained, novice-friendly land use modeling system designed to project the location of new residential and nonresidential development based upon analysis of (1) prior and existing residential and nonresidential development, (2) the location of transportation improvement(s), and (3) overall congestion in the system. TELUM forecasts the location and amount of household and employment growth for up to 30 years. This information is used to estimate regional travel demands in travel-demand-forecasting models. From METROPILUS, TELUM inherited the main spatial allocation models: the Disaggregated Residential Allocation Model (DRAM) and the Employment Allocation Model (EMPAL). Both DRAM and EMPAL employ sophisticated mathematical models to quantify the interactions between the regional employment and population location patterns and the

underlying transportation network. DRAM and EMPAL models are integrated into TELUM as TELUM-Res and TELUM-Emp.

It is important to understand that TELUM-Res and TELUM-Emp constitute only a portion of a complete regional transportation, location, and land use model system. In addition to TELUM, such a system would include transportation analysis model(s) including the steps of trip generation, trip distribution, mode split, and trip assignment. The planning agencies making use of TELUM are expected to have their own transportation analysis tools that can be integrated with TELUM. The outputs of TELUM then become the inputs to the agency's own travel demand forecasting models and modeling software systems (e.g., EMME2, MINUTP, TRANPLAN, VISUM, TRANSCAD, Cube, etc.). The network travel times and/or costs produced as output from these packages are used as inputs for subsequent land use allocation forecasting in TELUM. The iterative loop of integrating land use and travel demand models is illustrated in Figure B.1.

TELUM-Emp, as a spatial allocation model, employs a multivariate, multi-parametric attractiveness function to determine attractiveness of each analyzed area (referred to as a “zone” in the model). TELUM-Res is an aggregate form of a multi-nominal logit model of location choice. When translated into computational form, this yields a modified version of a singly-constrained spatial interaction model. The analytical models implemented in TELUM are described in more detail in TELUM Manual (NJIT, 2005), as well as in (Putman, 1983) and (Putman, 1991).



**Figure B.1** Schematic description of the feedback loop between TELUM and travel demand model. The feedback loop is represented by the thick arrow-lines.

Besides TELUM-Emp and TELUM-Res, TELUM includes a calibration procedure that calibrates each of these two location prediction models based on user-defined and supplied historical information about the regional employment and household locations.

TELUM forecasting is done in time increments of five (5) years. The location of employment and households is forecasted for each zone within the analysis region. Each forecasting iteration begins with the execution of TELUM-Emp. To forecast the location of employment by zone, TELUM-Emp uses the data from the previous time increment (previous 5-year period forecast or current data for the first increment), including

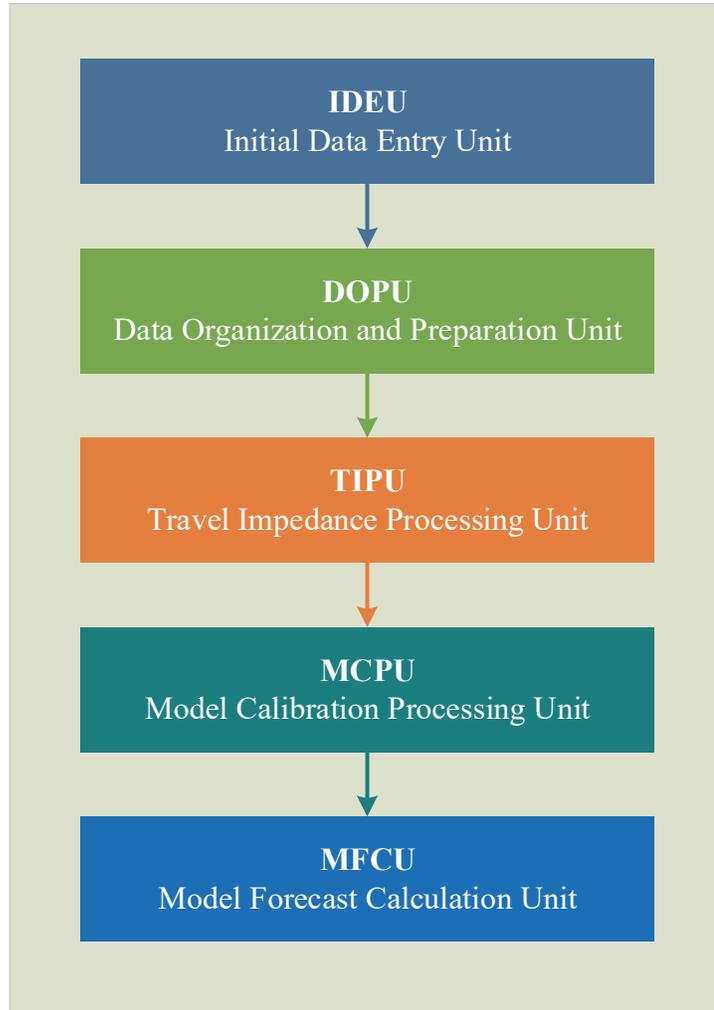
employment and population by type and zone, land area by type and zone, and travel cost (or time) between all zone pairs.

Following the employment location forecasts produced by TELUM-Emp, TELUM-Res produces a set of residence location forecasts. Residencies are represented by households. To forecast the location of residencies (households) by zone, TELUM-Res uses land-use information from the previous time increment, forecasted zone-to-zone travel cost (or time), and employment location information previously calculated by the TELUM-Emp.

The residence and employment location forecasts produced by TELUM may then be used (sometimes after a further step of spatial disaggregation) as input to travel models that generate and distribute trips, split trips by mode, and then assign vehicle trips to the transportation network(s), and calculate congestion (NJIT, 2005). The loop of integrating land use and travel demand models is then closed by using outputs from the travel model to calculate zone-to-zone travel times and costs (or their aggregate, often referred to as travel impedance), which are used as input for the next increment forecasts in TELUM (see Figure B.1).

As stated earlier, TELUM in conjunction with the travels demand models is used primarily for regional planning. In the current development stage TELUM is designed primarily for small- to medium-sized MPOs or SDOT, where number of aggregated analysis zones does not exceed 800. In addition, corridor level analysis would have to be put in the wider regional (or sub-regional) context when forecasting land use using TELUM, since it is designed as a regional planning tool and deals with geographic areas rather than network structures.

TELUM is distributed as an integrated software package that consists of several modules, each one executed through a user-friendly, Windows-based interface. The interface allows users an easy navigation through all phases of the forecasting process depicted in Figure B.2. It also has a GIS component that allows users to view, print, and perform geographic analysis of zonal land use, demographic, and employment data, including both inputs entered by user, and forecasts generated by the model. The *Help* tools provide answers to commonly asked questions and tips regarding various problems or difficulties that users most often encounter as they prepare the model inputs and interpret the model outputs. It also requires less data inputs necessary for the analysis as compared to METROPILUS, relying mostly on data available from the U.S. Census Bureau and commonly collected by State and regional planning agencies as part of their regional planning activities. The software is available free of charge from NJIT and can be downloaded from <http://www.telus-national.org/telum/downloads.htm>.



**Figure B.2** TELUM process flowchart.

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