

A TRAVEL DEMAND MODEL FOR RURAL AREAS

by

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GLOSSARY

ADT = Average Daily Traffic

ALT = Alternate

AMOS = Activity-Mobility Simulator

AON = All Or Nothing

ARC = Atlanta Regional Council

BAU = Business As Usual

BPO = Bannock Planning Organization

BPR = Bureau of Public Roads

EMP = Employee

GIS = Geographic Information Systems

GLA = Gross Leasable Area

HBO = Home-Based Other

HBW = Home-Based Work

HH = Household

HU = Housing Unit

ITE = Institute of Transportation Engineers

LUTAQH = Land Use, Transportation, Air Quality and Health

MDT = Montana Department of Transportation

MF = Multi-Family HU (i.e. one apartment unit)

MNL = Multi-Nomial-Logit

MPO = Metropolitan Planning Organization

GLOSSARY-CONTINUED

MSA = Method of Successive Averages

NCHRP = National Cooperative Highway Research Program

NHB = Not Home-Based

NRET = Non-Retail Employment

O-D = Origin - Destination

PECAS = Production, Exchange and Consumption Allocation System

PUMS = Public Use Microdata Sample

RDC = Relational Database Consultants

RET = Retail EMP

RMSE = Root Mean Square Error

SACOG = Sacramento Area Council of Governments

SDDOT = South Dakota Department of Transportation

SF = Single-Family HU (Detached)

TDM = Transportation Demand Management

TGM = Trip Generation Manual

TH = Townhome HU (i.e. condo or Attached SF)

Veh = Vehicle

VMT = Vehicle Miles Traveled

WTI = Western Transportation Institute

ABSTRACT

Gallatin County has experienced dramatic population growth over the past decade. The Sonoran Institute has been developing land use planning tools to help address the issues arising from this high growth. One of the most serious impacts of high population growth is increased vehicle traffic, typically measured through vehicle miles traveled. The Sonoran Institute's land use planning tools were used to develop two future growth scenarios, one representing growth following current trends and the other representing a higher population density and higher employment/residential mix of development. The project task was to predict the total daily vehicle miles traveled for the two future scenarios using a travel demand model. The project goals were to develop a travel demand model that was simple to run, accurate, sensitive to changes in urban form, and could output daily vehicle miles traveled for future land development scenarios.

The project used a literature review to determine expected effects of changes in urban form on travel behavior, and the sensitivity of current travel modeling methods to changes in urban form. For simplicity, the travel modeling method known as the four-step process was selected for the project with modifications to add sensitivity to urban form. Current literature almost entirely states that the basic four-step model is not sensitive to urban form. One source did indicate that the four-step process might have some sensitivity to changes in urban form, but this sensitivity was not quantified. A basic four-step process model was run for a base year and the two future scenarios. The results indicated that the high density/high mix scenario reduced daily vehicle miles traveled by about 13%. This shows that the basic four-step model is sensitive to urban form. This sensitivity was analyzed through a series of idealized land development scenarios, and the sensitivity of the process to changes in urban form was quantified. The results were then incorporated into a now modified four-step model that produced a 16% reduction in daily vehicle miles traveled between the future scenarios while also providing better comparative accuracy between the two scenarios. This method met the initial objectives of the project.

CHAPTER 1

INTRODUCTION

Travel demand modeling techniques have advanced significantly over the last twenty years. However, as models become newer and more accurate, their development and running costs also increase rapidly. The state of Montana has seen major growth in several rural areas, especially in the Gallatin Valley. An accurate travel demand model would be extremely beneficial for planning future development patterns for this county. However, the cost of running an accurate model would be beyond the means of any of the towns in the county, none of which are even a Metropolitan Planning Organization (MPO) yet.

The Sonoran Institute is a research body focused on promoting sustainable development. They have recently been building a land use planning model for the Gallatin Valley using the Envision Tomorrow process. The model was used as a tool for community leaders and interest groups to compare different future growth scenarios for the region. The Sonoran Institute then built two future scenarios for the Gallatin Valley, one predicting growth to continue according to current trends (called the Business As Usual, or BAU scenario), and the other as more idealized smart growth option with higher densities and more land use mix (called the Alternate, or ALT scenario). The Sonoran Institute wanted to compare the travel effects of the two scenarios in terms of total vehicle miles traveled (VMT), a common variable in calculated community impacts, such as emissions. The Sonoran Institute requested that the Western Transportation Institute (WTI), a partner on the project, develop a travel demand model that could

produce VMT output from the Envision Tomorrow inputs. This thesis details the development and application of the travel demand model built for the Sonoran Institute.

While the main goal of the travel demand model was to produce daily VMT totals for two future scenarios, WTI had a secondary goal of making the model sensitive to changes in urban form. The most basic types of travel demand models to build and run (based on data and software requirements) were not expected to be sensitive to changes in urban form. Therefore, while the travel demand model developed in this project followed the basic process, certain portions of the process were modified to increase the model's sensitivity to urban form. However, during the actual modeling an inherent sensitivity to some types of urban form was found to already exist in the basic process. This led to entirely new and unexpected research project which attempted to quantify the sensitivity of the basic modeling process to changes in urban form. The findings of this portion of the project were combined with the modification to the model previously developed, and the resulting model was run for the Sonoran Institute's future scenarios.

This project focused on the urban form variables determined to have an arc elastic (see Equation 1-1) effect on two principle travel variables directly related to VMT, average trip rate and average trip length. An arc elastic relationship denotes a linear dependence between an independent variable (in this case, an urban form variable) and a dependent variable (in this case, either average trip length or rate).

$$e = \frac{\% \Delta X}{\% \Delta Y}$$

Equation 1-1

Where:

$e = \text{arc elasticity}$

$\% \Delta X = \% \text{ change in dependent variable } X \text{ relative to VMT}$

$\% \Delta Y = \% \text{ change in independent variable } Y \text{ relative to urban form}$

Another form of elasticity utilized in this project was point elasticity. Point elasticity takes the form of an exponential function, leading to a varying sensitivity as the magnitude of the independent variable increases. Equation 1-2 shows the general form of a point elasticity function. Point elasticity will be introduced again in Chapter 4.

$$X = \left(\frac{X_0}{Y_0^E} \right) \times Y^E$$

Equation 1-2

Where:

$X = \text{dependent variable}$

$Y = \text{independent variable}$

$E = \text{point elasticity}$

The two urban form variables ultimately investigated were density and land use mix (described in more detail in the ensuing chapters). The effects of the two urban form variables on the average trip length and average trip rate were determined from literature (discussed in Chapter 2). A basic four-step trip-based travel demand model (described in detail in Chapter 3) was then run for a base year and the two Sonoran Institute scenarios and some sensitivity between the previously mentioned VMT variables and the two urban form variables was observed. Several idealized tests were run in an attempt to quantify the elasticity relationship between the VMT and urban form variables (presented in

Chapter 4). The results from this portion of the project were then used to modify the basic four-step model through added elasticity, and the modified model was ultimately used to compare the total daily VMT for the two future scenarios provided by the Sonoran Institute (Chapter 5). The results from each chapter of the project are summarized in Table 1-1.

Table 1-1: Elasticities

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 6)	Modified Model Resulting Elasticity (Ch. 6)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04	None	None	-0.086	-0.173 (ALT) +0.065 (BAU)
	Land Use Mix	-0.06	None	None	None	None
Average Trip Length (per trip)	Density	-0.05	-0.021 (ALT) -0.236 (BAU)	-0.212 (ALT) -0.437 (BAU)	+0.162 (ALT) +0.388 (BAU)	+0.010 (ALT) -0.066 (BAU)
	Land Use Mix	-0.05		-0.022	-0.028 (ALT) -0.028 (BAU)	

The goals for the project are ultimately summarized in Equation 1-3. Note that the elasticity values for average trip length from Chapters 3 and 5 are the average elasticity for the two urban form variables. The elasticity for each variable could not be calculated independently from the travel modeling results.

$$B = C, D = A - C, E = A$$

Equation 1-3

Where:

A-E are the column numbers from Table 1-1

The final goal of the project was to make E equal to A.

The first step was to determine the effects of change in urban form on the travel behavior variables of average trip length and trip rate (results in column A of Table 1-1). Next, a basic four-step model was run for the Envision Tomorrow scenarios, and the results showed a definite sensitivity to the two urban form variables investigated (results in column B of Table 1-1). Several idealized scenarios were then run in an attempt to quantify the sensitivity of the four-step process to changes in urban form (results in column C of Table 1-1). The sensitivity of the model was found to vary depending on the magnitude of the change in urban form, not following the linear (arc elastic) travel behavior found in the research. The results did not exactly match the output from the from the Envision Tomorrow scenarios (column B does not quite equal column C). Based on the results from the idealized scenarios the four step model was modified for the Envision Tomorrow scenarios (results in column D of Table 1-1). The Envision Tomorrow scenarios were then run with the modified model (results in column E of Table 1-1). The final goal of the project was to make the modified model sensitivities match the literature sensitivity values. While this final goal was not completely achieved, the sensitivity of the modified model was more consistent between the two future scenarios than for the basic model. Also, the final results were on average closer to the literature models than the basic model's sensitivity.

The final result of the project was a travel demand model that was sensitive to change in two critical urban form variables, density and land use mix. The model also accounted for the inherent sensitivity of the modeling process. The modified model also greatly decreased the bias due to the sensitivity of the basic model to changes in the urban form variables of land use mix and density. This decrease in modeling bias can be

observed by comparing the difference in elasticity for the two future scenarios for the basic model (Chapter 3 results) to the difference in elasticity for the future scenarios for the modified model (Chapter 6 results). While the model was developed to run off the Sonoran Institutes Envision Tomorrow model outputs, it could easily be adjusted to run with other data inputs. The model could also be run fairly quickly and with minimal data requirements, keeping the total cost very low while still providing satisfactorily accurate results. This thesis follows the entire process, from researching the effects of urban form on travel, through the model development, and finally to the final modeling results. This background should help to provide understanding of the incentives and reasoning being the project.

CHAPTER 2

LITERATURE REVIEW

Introduction

Before any modeling took place a literature review was performed to provide the information necessary for developing and modifying a model that is sensitive to changes in urban form. The literature review covered four primary topics: Travel models, land use models, effects of urban form on travel behavior, and sensitivity of current travel models to changes in urban form. The research performed in these four areas provided the background for the modeling process developed in this project.

Travel Models

Travel demand models can vary greatly depending on the analysis area of the model. However, all travel demand models follow one of two fundamental travel development processes: trip-based modeling and activity based modeling. This section will give a quick overview of trip based modeling (the primary modeling method for all rural and many urban areas) and also a brief summary of activity based modeling (used for some larger and high-budget urban areas). This section also outlines a brief case study of a typical trip-based and activity based model. The modeling method ultimately used in this project was based off the trip-based four step model.

Trip-Based Modeling Process

The four-step process is the traditional trip-based method of travel demand forecasting. All trip-based methods are derived from the four-step process. The four steps are trip generation, trip distribution, mode choice, and traffic assignment. According to McNally (2000) the process was developed the 1950s, with the major breakthrough occurring in 1954. While the methods of application of the four-step process have changed over the past years, the process still provides the base method and theory for many travel demand forecasting models.

The first step of the four-step process is trip generation. First, the analysis region is divided into zones. These zones are selected based on street network, population centers, land-use types, or some other geographic or demographic factor. In this step productions and attractions are calculated within the each of the model analysis zones. The methods for calculating the productions and attractions vary between models. Some of these different methods will be discussed later. The purpose of the productions and attractions is to create trip start and end points. Trips are expected to form between productions and attractions. The data used to calculate productions and attractions varies depending on the design of the travel demand model. Examples of data types required for these calculations will be given later.

The second step of the four-step process is trip distribution. In this step the productions and attractions developed in the trip generation step are paired. The methods of pairing the productions and attractions again vary between models but generally use some type of assignment method involving the zone's relative attractiveness (i.e. more attractions than other areas) of other zones. Some type of impedance is used to

incorporate the cost (in travel time) of the trips. The results of trip distribution can be represented in matrices matching productions to attractions, thus forming a table of round trips between zones.

The third step of the four step process is mode choice. The goal of this step is to convert the production and attraction round trips into origins and destinations, thus moving from person round trips to one-way vehicle trips. Mode choice data is used to incorporate vehicle occupancy into the model. Future mode choice data can be projected by using base year percentages (i.e. the percent of all trips taken with transit will not change over time), by multinomial logit calculations, or other mode split prediction calculation methods.

The final step in the four-step process is trip assignment, also called route choice. The goal of this step is to establish the link flows between the analyses zones. These flows are calculated from the origin destination matrix, using the least costly (shortest travel time) routes for each trip. The link capacities can be considered in this step, which may lead to some updating for the time components of the equations used in the distribution step. Once the four steps of the process have been completed, including any iteration for travel times back through the distribution step, the model link flows can be compared to the existing traffic, and the model can then be calibrated. After the model is calibrated the projected growth of the demographic variables affecting the productions and attractions within each analyses zone can be input into the model, outputting projected link flows for the analysis region.

An example of a four-step model is the Rapid City Travel Demand Model was developed for the Rapid City, SD in 2004. The model divided the city into 210 traffic

analyses zones (TAZ's) and established 16 external stations based of the principle highways and arterials leading out of the city. The TAZ's were sized according to the county's census blocks (See Figure 2-1 for typical Rapid City census block TAZ layout). The Rapid City MPO was able to provide socioeconomic GIS data that broke the region down into the following ten categories: single family residential, multi-family residential, manufacturing, military, retail, drive-through retail, office / service, medical, school / public, and motel / hotel. The GIS data also contained solid household data for the region, and none-residential floor-space data, which was then used to calculate the employment for the base year (for this model, the year 2000).

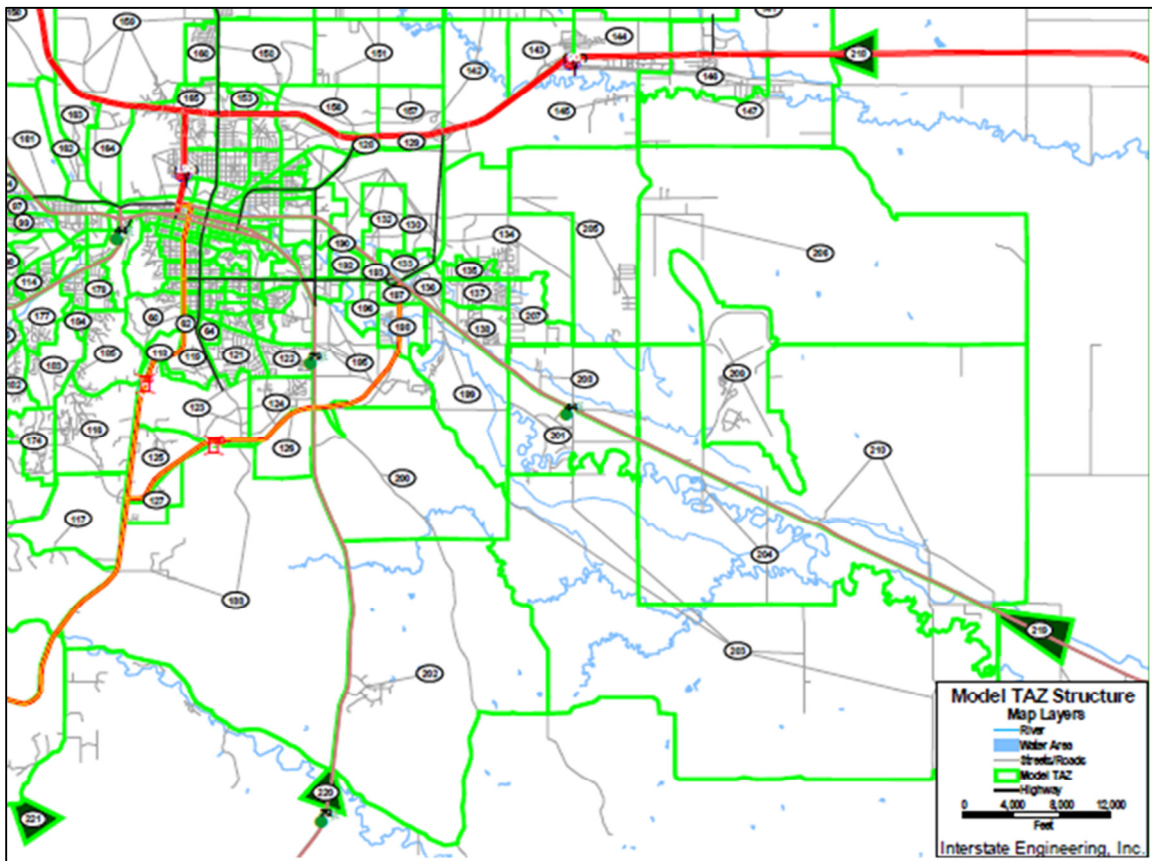


Figure 2-1: Rapid City TAZ Layout Sample (SDDOT 2004)

For the trip generation step, the Rapid City Model categorized trips into home-based work (HBW), home-based other (HBO), and not home-based (NHB). Trip productions and trip attractions were calculated separately. The trip productions were calculated according to the NCHRP 365 Report recommended trip rates and the trip productions model. This trip model is based on household incomes, household vehicles, and household size and numbers. The recommended trip rates were then adjusted using the current trip data available to the city. The trip attractions were calculated the same way, except that the attraction model was based off retail employment, service employment, households, and camping sites. Both the production and attraction models used different parameters for HBW, HBO, and NHB calculations. Twenty-two TAZ's were also determined to contain special generators, which were analyzed separately to determine their respective productions and attractions. Special generators are used when land uses such as ball parks, universities, etc...land uses with traffic that deviates significantly from the surrounding region. The productions and attractions from the external stations were calculated using the Fratar distribution technique described in NCHRP 365. The goal of the model designers was to have the productions and attraction with 15% of each other for each zone.

The Rapid City Model distributed trips using the gravity model. The gravity model uses an impedance function to factor in the cost (mainly travel time) of inter-zonal travel. The Rapid City Model used the gamma function to derive and calibrate the impedance for the gravity model. Once the impedance function was calibrated the productions and attractions were distributed between the TAZ's.

For the mode choice step the Rapid City Model utilized occupancy rates based off the NCHRP 365 national averages and some local knowledge within the model design team about Rapid City vehicle occupancy rates. These rates were then applied to the production and attraction matrices developed in the trip distribution step to convert person trips to vehicle trips, thus outputting the origin-destination (O-D) matrices.

The trip assignment step involved assigning the trips from the O-D matrices to routes. The shortest routes between the TAZ's had been calculated based on link speed, length, and capacity data integrated in the GIS software. The Rapid City Model utilized the user equilibrium method, essentially assuming that everyone would take the shortest possible route to their desired destination. The Bureau of Public Roads (BPR) equation was used to determine how many vehicles would take each route. When the results for the trip assignment were output as link volumes, the link congestion data was incorporated into the impedance functions of the trip distribution, and the distribution, mode choice, and trip assignment steps were run one more time. The final output from the model gave link flows for the primary as well as many of the local roads in the network. This data could then be used to determine locations within the network that would see experience congestion issues in the future.

Activity-Based Modeling Process

Activity based modeling takes a different approach than the traditional trip-based modeling process and philosophy. While the four-step process is based entirely on trips (with data usually collected from similar geographic regions), activity based modeling uses trip purposes (i.e. activities) to generate travel demand. Rather than creating zones

with productions and attractions to generate trips, an activity based model tracks the daily activity patterns of individuals. As activities occur at different locations within the zone of interest, trips are created by simulating activity schedules upon a population.

Essentially, activity-based modeling takes travel demand down to the micro simulation level. The data for the activity simulation is collected from activity diary surveys and is then applied to the population as a whole.

Activity based modeling focuses on households rather than on zones for trip generation and distribution. This can lead to some computational issues when household trips are distributed, since iterating to find the best routes by time, cost, and distance for every household can take super-computers days to compute. Most activity based models take small household samples and compute the distribution for the sample, then apply it to all the households in the analysis area.

The Sacramento Travel Demand Model is an example of an activity based travel demand model. The modeling process is summarized in Figure 2-2.

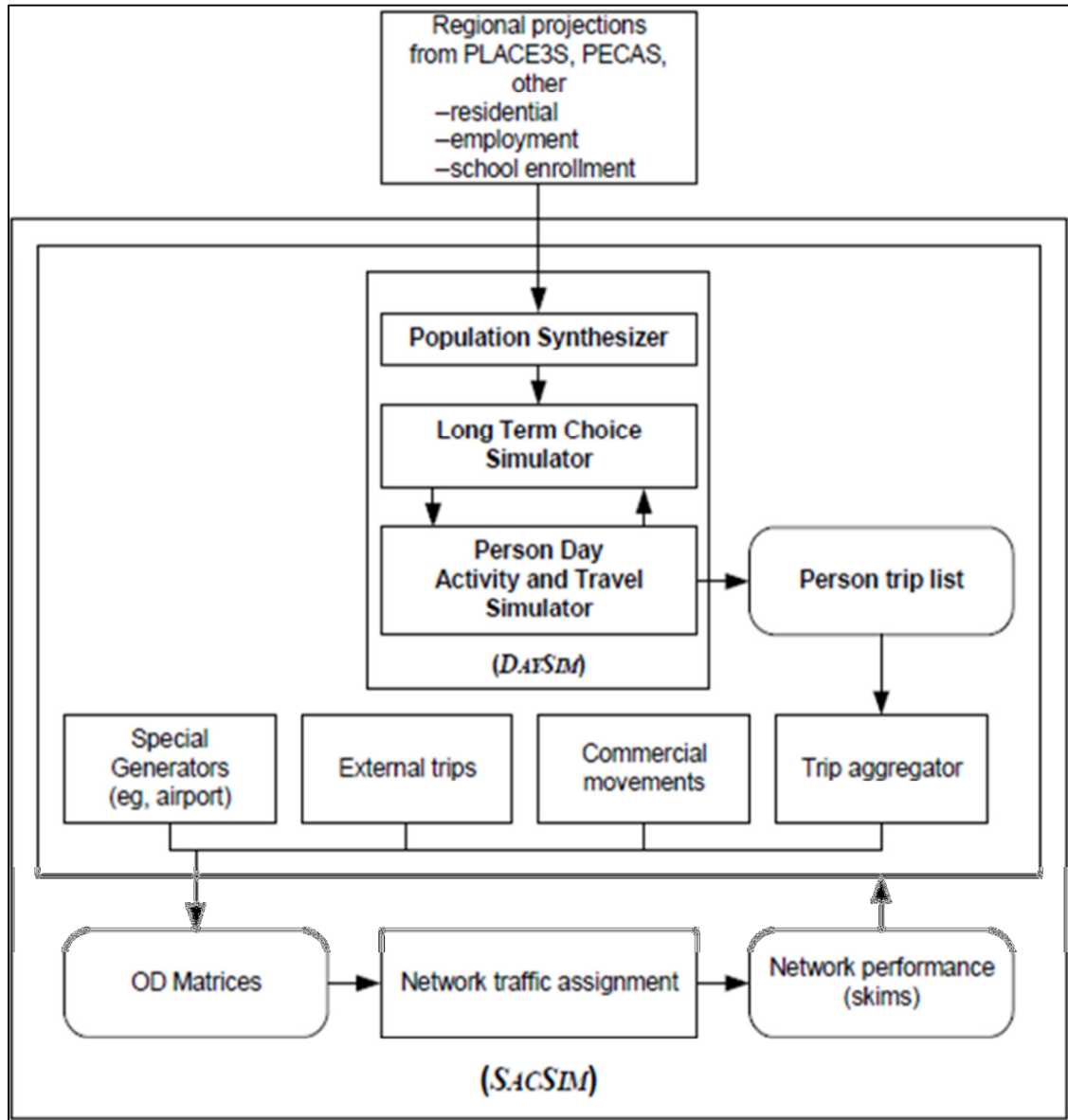


Figure 2-2: SACOG Travel Forecasting Model System (Bowman & Bradley 2006)

According to Bowman and Bradley (2006) the model takes regional demographic predictions for residential, employment, school data and land use predictions from models such as PECAS (discussed further in the land-use models section). The forecast data is not developed within the model, but is derived separately. This data is then put into a population synthesizer, which creates a synthetic population from the regions U.S.

Census Public Use Microdata Sample (PUMS) and allocates it to different land parcels. Then the population's long term choices for work location, school location, and auto ownership are simulated. After the long-term employment, education, and vehicle choices have been made for the entire population the activities and travels completed in a typical day are simulated for each person. This step utilizes a person day activity and travel simulator called DaySim.

According to Bowman and Bradley (2006), the DaySim model uses four levels of choices: longer term person and household choices, single day-long activity pattern choices, tour-level choices, and trip-level choices. These choices are used to create households, which are then defined by five levels of variables:

- household: income, family status, residence location
- person: gender, age, employment and student status, hours worked per week, work location, school location
- person day: time availability for 48 half hour time periods
- tour: priority, purpose, origin, destination, main travel mode
- trip: half-tour; sequence in half-tour; location, arrival time and departure time at trip origin and destination; trip mode.

The levels of variables were used to simulate household trips by day, subject to constraints of time, space, and time of day. The tour level contains seven categories of trip purpose: work, school, escort, shop, personal business, meal, and social/recreation. These seven categories add more detail to the model than the traditional home-based work, home-based other, and not home-based trip categories.

After the daily activity and travel patterns have been simulated for the population a person trip list is output by the simulation. The trips list is then used to build aggregated trip matrices for the analysis region. Trips from special generators (such as airports), commercial movements, and external areas (trips entering and leaving the region) are calculated and combined with the aggregated daily trips. These trips are then used to form the origin-destination (O-D) matrices, similar to the O-D matrices developed in the mode choice step of the four step process.

Once the O-D matrices have been developed, the trips are loaded onto the network. According to Bowman and Bradley (2006), the Sacramento Model did not have an equilibrium theory for distributing trips, as trip based models do. Rather, the model used the convex combination Method of Successive Averages (MSA). A convex combinations method is used to help the trip matrix solutions to converge during the trip assignment step of the four-step process. A convex combination takes the weighted average of the previous best solution from the iteration trip flow iterations and a new alternative flow set corresponding to the current iteration step. In a trip based model, the iterations are performed for trips between analyses zones. The Sacramento Model being on households rather than on origin-destination pairs could not do this. Instead, the iterations were performed for the trips made by a small sample of the households within the synthetic population, and then applied across the whole.

Once the trips made by the synthetic population have been distributed over the network, the network performance is simulated. The flows created from the distributed household trips show which areas of the network may be over capacity. This data is then fed back into the trip distribution equations as additional impedance values, and the

household trip distribution are re-calculated. This process is repeated until none of the network is over capacity. The Sacramento Model is an example of an activity based model. Activity based model generally have similar or greater levels of complexity. Although theoretically modeling an individual's activity chains may be more accurate than a trip based process, the complexity of the combinations of choices makes many activity models unwieldy and difficult to implement.

Land Use Models

Land-use models are used mainly by cities and counties to predict different types of land development growth. The models help city planners to determine zoning requirements and to predict which types of land use should be expected within the city or county regions. This data can then be used by developers to decide on the best locations for housing developments, retail centers, or industrial complexes. Land-use models typically use recent population and employment growth trends to predict what types of land use will be required to support the expected growth.

Travel demand models rely heavily on land-use model data, especially for trip generation calculations. Activity-based travel demand models are especially reliant on solid land use prediction data, as the locations of future households are crucial for calculating trip lengths, trip times, and link flows. Some land-use models are even run within travel demand models, providing an additional feedback step in the model after the link flows have been calculated. This means that land use may change depending on nearby link flows, thus adding another step in the trip distribution and trip assignment feedback loop.

Land-use models can be very different, and each is tailored specifically to the region that it was designed for. However, several models may have similar basic methods. This section discusses two common types of land use models, cellular automata and input/output models, plus the Envision Tomorrow model used by the Sonoran Institute in conjunction with this project. Numerous other methods of land use modeling exist but are beyond the focus of this project.

Cellular Automata Models

According to Hedge et al. (unknown) cellular automata was developed in the 1940's to provide the framework for investigating complex, extended systems. The cellular automaton system is a grid of cells each containing a finite amount of states. Each cell is updated through discrete time steps, with the state of the cell being determined from the states of the cells surrounding it. In a cellular automaton land-use model, the grid cells of the system are land parcels, and the states of each cell are different stages and categories of development. However, the cells within a land use model usually contain more than one state, with states relating to demographic conditions, population density, and land value. Thus, if several cells near an updating cell have high population density, the population density for the updating cell will increase, if stages such as land value and land use (i.e. primarily residential) do not constrain it. Each cellular model has specific transition rules involving how many neighboring cells must be at the same stage to change a cell. Also, the actual terrain of the cell is a major factor in determining whether development is possible.

Input/output Models

Input/output models are less independent than cellular automata models.

Input/output models rely on an activity model to indicate where growth is required.

Similar to the cellular automata models, input/output models are broken down into zones, but not necessarily a regular grid. Rather, the model zones are generally matched up with the current land-use specific areas of the region being researched, or set to match the zones used to generate activities.

The Production, Exchange and Consumption Allocation System (PECAS) Model is an example of an input/output model. According to Hunt and Abraham (2003) this model is used to determine the activity schedules for a population. These schedules are then used by an activity based travel demand model to develop predicted trips for a region. The PECAS model uses a space allocation and activity module to simulate land-use and population growth. During each time step, the space allocation module uses the input/output method to classify a certain amount of space within each zone into one of the following categories: each separate category of existing floor-space and developed land, serviced vacant land, un-serviced vacant land, and derelict land. The time steps between the activity module and the space allocation module are meant to model the time required for developers to react to the land use needs of the zone. A logit model is used to determine what percentage of the zone should be assigned each category of space during the space allocation time step. The variables within the logit function are related to the land and rent prices of the zone relative to the nearby zones. The logit function may also contain a constant to account for the restrictiveness of local or regional zoning laws.

The PECAS model is calibrated by taking known land-use and development data for base year, and running the model to another known year. According to Hunt and Abraham (2003) the current data and the model data are then compared, and the model coefficients can be calibrated based on these results. The PECAS model has been used extensively to provide growth data for travel demand models. Other input/output models have many similar characteristics. However, the PECAS model is designed more to be a transportation planning tool than an exclusive land-use prediction model.

Envision Tomorrow Model

The Envision Tomorrow model uses a GIS based database to assign development types to an area at the parcel level. The parcels are used as the model zones. The spatial scale of the typical zones is shown in Figure 2-3.

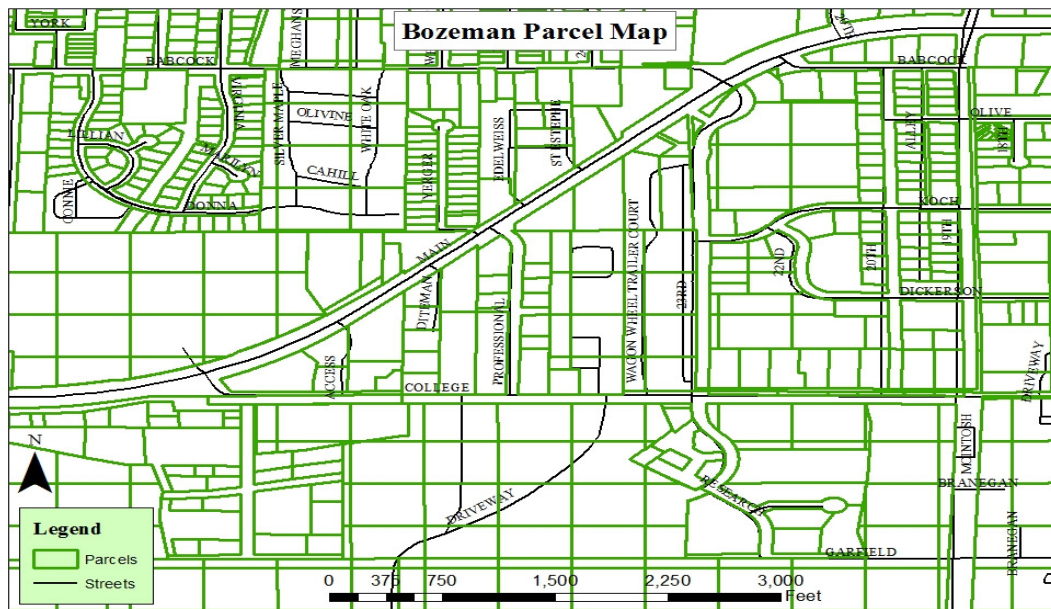


Figure 2-3: Typical Parcel Layout

The Envision Tomorrow model does not account for existing development but is used as a planning tool for determining hypothetical development scenarios for a rural region. The model uses 18 different land development types, each of which contains a certain amount of employment square footage (by different employment types), parking, housing square footage (by three different housing unit types), and open space. The development types and some of their characteristics are summarized in Table 2-1.

Table 2-1: Envision Tomorrow Development Types

Development Type Name	Quick Summary Statistics							
	Housing Units / Gross Acre	Jobs / Gross Acre	Land Use Composition (%)					
			Single Family	Townhome	Multi-family	Retail	Office	Industrial
Urban Core	159.95	869.16	-	-	34%	7%	59%	-
City Center	319.9	71.09	-	-	90%	10%	-	-
Town Center	100.71	35.54	-	-	85%	15%	-	-
Village Center	41.47	35.54	-	-	70%	30%	-	-
Mixed-Use Corridor	26.27	35.02	-	-	60%	40%	-	-
Main Street	648.56	-	-	-	100%	0.00%	-	-
City Neighborhood	14.01	-	-	100%	-	-	-	-
Town Neighborhood	12.51	-	-	100%	-	-	-	-
Village Neighborhood	8.11	-	100%	-	-	-	-	-
Suburban Residential	5.84	-	100%	-	-	-	-	-
Rural Residential	2.92	-	100%	-	-	-	-	-
Office Park	-	250.16	-	-	-	-	100.0%	-
Regional Retail	-	17.51	-	-	-	100%	-	-
Strip Commercial	-	29.19	-	-	-	100%	-	-
Flex Park	-	7.3	-	-	-	-	-	100%
Industrial Park	-	7.3	-	-	-	-	-	100%
Educational	-	125.08	-	-	-	-	100%	-
Open Space	-	-	-	-	-	-	-	-

The primary growth variables input into the Envision Tomorrow program are housing units and employment. The program is used as a tool for community leaders and interest groups to create hypothetical future growth scenarios. The different development types are basically painted into the zones until the future housing unit and employment goals are met. The model outputs the housing units for each zone by three types: Single family, multi-family, and townhome units. The model outputs the employment for each zone by four types: Retail, services, office, and industrial employees. These were the outputs provided by the Envision Tomorrow program that could be used to develop a travel demand model.

There are a number of land use models in use, all with similar outputs predicting the location of homes and employment. Envision Tomorrow is one model, but the travel demand model used in this project could be applied to any land use model.

Effects of Changes in Urban Form on Travel Behavior

Travel behavior patterns are critical to predicting future travel demands. Generally, base year travel behavior patterns are determined from surveys and then applied to a travel demand model to determine future travel estimations. However, studies show that travel behavior is somewhat dependent on urban form. If an analysis area's urban form is predicted to change, with new commercial, retail, or residential development expected in the future, travel behavior could change, with residents making more or less average trips depending on the type of development. Also, average trip lengths and the mode split could be affected. Therefore, the effects of urban form on

travel behavior must be understood to increase the accuracy travel demand prediction models.

Demographic Travel Behavior Characteristics

Travel behavior varies over a population by demographics. Household travel behavior can vary based on household size, income, and age. While these variables are normally incorporated into a travel demand model when their impact is determined to be significant, they can also be dependent on land use. For example, if a large apartment complex is built next to a high income residential neighborhood, the cheap housing provided by the complex will attract a different population group to the area. The new population group will have different travel behavior patterns based on their lower incomes. They may even be less likely to own an automobile than their high income counterparts. Therefore, some investigation into how demographics may affect travel behavior patterns is warranted. This section will discuss some methods for obtaining travel behavior information and will list some qualitative examples of demographic travel behavior characteristics.

Measurement Techniques: Travel behavior patterns are often determined from trip based surveys or travel diaries in which the surveyed person records all of their trips over a specified period of time. The trips are recorded by type (work, shopping, recreation, etc...) and by length and/or time. The survey also asks for some general demographic data (i.e. household vehicles, household sizes, etc...) to match up trip data for demographically different people.

Activity based surveys are similar to trip-based surveys, but focus on activities instead of trips. Activity times and locations are recorded in journals, and the trips made by each household are extrapolated from the journals. Bose and Sharpe (2005) attempted to compare the utility of activity-based trip surveys to trip-based surveys, but their findings were inconclusive, mainly showing that each survey type had certain strengths pertaining to its general purpose.

General Characteristics Example: Anzhelika Antipova (2010) investigated some general travel behavior characteristics by demographics in part of her doctorate thesis for Louisiana State University. Her study focused on the Baton Rouge metropolitan area. The data for her study was obtained from the Baton Rouge Personal Transportation Survey (BRPTS) database, collected by the Research Triangle Institute. The final travel data set used for the study provided detailed travel day data of 1,104 working individuals. Some of the main findings of her study are listed as follows:

- Female workers commute less than male workers
- Workers with less than a high school diploma had shorter commuting trips (i.e., almost 6 minutes less and 4 miles shorter) than workers with some degrees
- Workers with no children in their households tend to commute less
- Workers who did not usually drive (i.e. used different mode such as transit, walking, etc...) commuted more
- Part-time workers commuted less than their full-time worker counterparts, and also tend to live closer to their jobs

Antipova (2010) also investigated some trip chaining impacts of demographics. She found that non-workers were 66% more likely to trip chain than workers, and women were 44% more likely to trip chain than men.

These are just a few of the ways population demographics might affect travel behavior. However, the numerous ties of demographics to travel behavior are not the concern of this study, so these examples are given merely to show that urban form is not the only variable in travel behavior decisions. As discussed earlier, the output from the Envision Tomorrow program does not provide sufficient data to implement much demographic sensitivity into the travel demand model.

Urban Form Measurement Techniques

Land use can often be used to describe urban form. However, land use is a difficult characteristic to measure quantitatively. It is easy to describe a specific land use (i.e. single family unit residential, commercial, etc...) but very difficult to measure land use types comparatively. Also, an analysis area may not be homogeneous by land use. Urban areas do not typically contain neat, geographically separated blocks of exclusive land uses. Most areas contain some variation, with perhaps some-single unit and multi-unit residential mixed with some retail. This section will discuss some of the methods used to measure and compare areas by land use, including neighborhood characteristics, density, land mix, street network, and accessibility.

Urban form can be quantified by ranking resident perceptions. Cao et al. (2007) developed a structural equations model to relate the effects of neighborhood characteristics on travel behavior. The neighborhood characteristic variables used for the

structural equations model were collected through a survey of residents in four suburban regions in northern California. The survey participants were asked to rank their value for various neighborhood characteristics on a scale of one to four, one being “not important” and four being “extremely important.” Cao et al. (2007) used significance testing to narrow the survey responses data to the following six factors: accessibility, physical activity options, safety, socializing, attractiveness, and outdoor spaciousness. These factors were then used to develop the structural equations model, which could then be used to determine how changes in urban form would affect travel behavior.

Kevin Krizek (2003) used another method to put quantitative values to urban form. His study focused on operationalizing neighborhood accessibility as a tool for research and modeling. Neighborhood accessibility could be loosely defined as the ease with which a neighborhood’s residents can access common amenities (such as groceries or gas). Krizek (2003) used three dimensions to define neighborhood accessibility: density, land use mix, and street network design.

According to Krizek (2003) density is the most common measure of urban form in current practice. He also states that density is best measured as population over total land area (as opposed to developed land or non-paved land area). Holtzclaw (1994) related the amount of travel (VMT) to density (measured as households per residential acre) and a variable called the transit accessibility index (related to transit seats available per hour within a certain distance). However, according to Krizek (2003) density is only one of the dimensions of the effects of urban form on travel behavior.

Krizek (2003) defines land use mix as the synergy created when banks, restaurants, shops, offices, housing, and other uses locate close to one another, allowing

for decreased travel distances between origins and destinations. A greater land use mix could be expected to decrease typical trip times. Krizek (2003) operationalized land use mix by three different methods: inspection, employment, and entropy/index of dissimilarity. The inspection method involves selecting some binary variables that represent different indications of land use mix and applying these variables to surveyed households. These binary variables are generally related to whether or not there is some specific form of retail or shopping area within a fixed distance of the surveyed household. The employment method takes employment data and derives a land use mix estimate based on type number of retail employees near a household, or within the traffic analysis zone (TAZ), depending on the planning method in use. The entropy/index of dissimilarity method is meant to measure the diversity of land uses within a block or zone. The entropy method derives an index value based on the amount of different land uses present within a zone. However, the entropy method does not specify what land uses are present, so a diverse industrial area may have the same entropy index as diverse residential/retail zone. Also, proportions do not make a difference if they are reversed, so a zone with very high commercial and low residential land use will have the same entropy index as a zone with low commercial and high residential land use. The dissimilarity index method assigns a land use to each hectare within the analysis area, according the spatial distribution of land uses within the block. The dissimilarity index is derived from the number of nearby hectare blocks with a different land use.

According to Krizek (2003), several studies have shown that the traditional grid street network design is more efficient and trip friendly due to less required stop intersections and more connectivity due to the dense network. Krizek (2003) also stated

that street patterns are not the measures of street network design that effect neighborhood accessibility. He broke the street network design dimension down into four categories: street patterns, pedestrian amenities, experiential elements, and composite indices. Street patterns can be measured by the number of four-way intersection per unit area, indicating the presence of a grid-like network. This measure could also be termed as “intersection density”. Pedestrian amenities can generally be estimated either a ratio of total sidewalk length to road frontage length. Experiential elements can be estimated based on lighting spacing, block distances, terrain, and the percentage right-of-way not taken by travel lanes. Composite indices take into account more pedestrian and bicycle friendly characteristics such as ease of street crossings and sidewalk continuity. The data required to develop composite indices can be difficult to obtain, making this category of street network design assessment usually impracticable.

Krizek (2003) used the three previously defined dimensions of neighborhood accessibility to develop neighborhood accessibility index by block for the metropolitan Puget Sound Region in Washington State. He used the three dimensions as continuous variables which could be reduced by factor analysis to a single factor. This factor could then be interpreted as a single measure of neighborhood accessibility.

Frank et al (2008) developed another method for measuring urban form variables. The method was focused on the effects of urban form on the travel behavior of a household. The method used a “network buffer,” as shown in Figure 2-4. The network buffer was created by all the area within a 1.0 km walk of the housing unit under analysis. The 1.0 km walk was a network distance (versus “as a crow flies” distance) from the housing unit, meaning that the distance was measured along the most efficient

(by distance) street route leading away from the house. Therefore, the network buffer would always be contained within a 1.0 km radius as a crow flies away from the housing unit. The total area of the network buffer would also always be less than 3.14 km^2 , and varied depending on the network density around the housing unit.

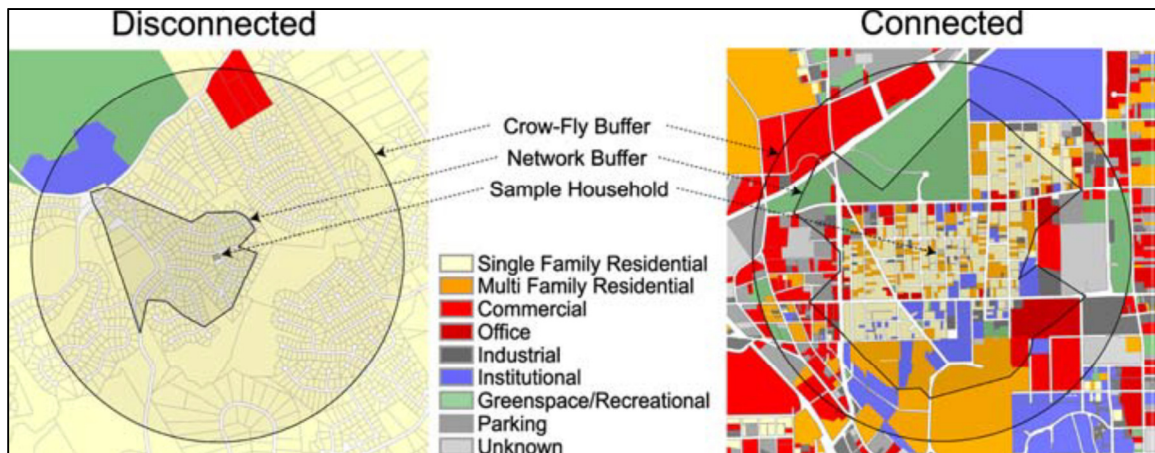


Figure 2-4: Network Buffer (Frank et al. 2008)

The method developed by Frank et al (2008) was too detailed for the model developed in this project. However, the urban form variables used in the project model were measured using a very rough approximation of the 1.0 km network distance from the center of each zone.

While density has been commonly viewed as the easiest and most usable method for analyzing urban form, Krizek (2003) shows that there are more factors such as those discussed above that should and can be included in urban form analysis. The effects of these factors on travel behavior will be discussed in the following sections.

Urban Form and Number of Work Trips

While work trip length and mode choice may be affected by urban form, the number of work trips made by residents is not typically affected. Most employed residents commute to and from work once a day, regardless of what type of neighborhood they live in, the local street network layout, and the population density of their residential area. Antipova (2010) did find some interesting effects of urban form on trip chaining during work trips.

The only other situation where work trip numbers may be effected by urban form are when employees live so close to their employment center's that they can return home for their lunch break, thus doubling their number of daily commuting trips. However, this situation is usually only a widespread occurrence when employees can easily walk or bike to work, and these effects of urban form discussed further in a later section. The other effects of urban form on work trips will be incorporated into the travel length discussion.

Urban Form and Number of Non-Work Trips

According to Litman (2011) 85.2% of all trips, and 81.9% of all vehicle miles traveled (VMT) in the United states are non-work trips. Litman (2011) also states that 19.6% of all trips are shopping trips. Urban form may be expected to have a greater impact on the amount of non-work trips made by residents, from the travel behavioral analysis perspective. The amount of shopping trips made by a household could likely depend on accessibility to retail centers. Urban form could also indicate the likelihood of

trip chaining for a resident, as more shopping options could lead to more stops on a typical shopping trip.

Susan Handy (1996) investigated the link between urban form and non-work travel behavior. Her research was centered on four different neighborhoods in the San Francisco Bay Area. Two were “traditional” (typical older grid network designs) and the other two were “modern” (recent development cul-de-sac) neighborhoods. The residents of all four neighborhoods were within roughly the same demographic brackets, to prevent the effects of demographics on travel behavior from impacting the study.

According to Handy (1996), the traditional neighborhoods both contained more convenience stores than the modern neighborhoods, due to the number of “corner stores” remaining in the area. Corner stores are no longer included in most residential development designs. Also, one of the traditional areas was cut by a major arterial which might have impacted the travel behavior of the residents.

As discussed previously, Antipova (2010) found urban form can impact travel behavior, particularly trip chaining. Since a non-work activity is accomplished during a work trip, trip chaining essentially eliminates non-work trips. She found that employed women were more likely to trip chain if they lived in a medium or high density residential area, while non-employed persons are less likely to trip chain in these urban form situations. She also found that non-employed women living in a rural or agricultural area is 2.3 times more likely to trip chain (obviously on non-work trips) than a non-employed women living in an urban area. She also found that employed women living in high density areas were more likely to trip chain than employed women living in lower

density areas. Antipova (2010) stated that, in general, the trip chaining behavior of men is not affected by urban form.

Urban Form and All Trips

DKS Associates (2007) performed a comprehensive analysis of the current literature and studies regarding the effects of different urban form variables on trip rates and trip lengths. Their analysis also included data from a study performed in the San Diego area. Their measurements of the effects of urban form on trip rate and trip length were based on changes in urban form variables, measured as arc elasticity. Their project and research found that a 10 percent increase in land use mix (calculated as shown in Equation 2-1) led to a 0.6% decrease in average trip rate. Additionally, a 10 percent increase in density (calculated as shown in Equation 2-2) also led to a 0.4% decrease in average trip rate. It should be noted that these density and land use mix variables were used in Section 2-4-6 to calculate average trip length elasticity values. The elasticities are given in their equation form in Equation 2-3 and Equation 2-4.

$$Density = \frac{Population + Employment}{Area}$$

Equation 2-1

$$Land\ Use\ Mix = 1 - \frac{|b \times Population - Employment|}{b \times Population + Employment}$$

Equation 2-2

Where $b = \frac{Total\ Regional\ Employment}{Total\ Regional\ Population}$

$$e = \frac{-0.6 \% \text{ change in trip rate}}{10\% \text{ change in land use mix}} = -0.06$$

Equation 2-3

$$e = \frac{-0.4 \% \text{ change in trip rate}}{10\% \text{ change in density}} = -0.04$$

Equation 2-4

Urban form should be expected to play an important role in non-work trip choice. As discussed in this section, the number of trips made by a household can vary simply based on where the house is located relative to shopping attractions. Therefore, the amount of non-work (especially shopping) trips taken by a household cannot be assumed to be dependent simply on a local or regional growth rate. Trip generation rates should account for the urban form of an analysis area to incorporate the effects discussed in this section into a travel demand prediction model.

Urban Form and Mode Choice

Mode choice may also be affected by urban form. Recent planning efforts have focused on developing more walkable and transit friendly neighborhoods. The goal of the designers is to promote alternatives to the traditional single car trip.

Cervero et al. (2010) discussed the effects of infill on mode split in commuter travel. Their study was focused around two recent infill projects in California that involved converting employment centers to mixed use neighborhoods. The neighborhoods were designed to be especially transit and pedestrian/bicycle friendly. Although Cervero et al. (2010) did not have enough data to show how an infill neighborhood's residents' mode split compared to other types of neighborhoods, they did

find that residents who had lived in the neighborhood before the infill were very reluctant to change their mode choice patterns.

Handy (1996) found that higher accessibility increases the number of walking trips made by residents. Accessibility was defined the distance from a residence to destinations of possible shopping trips. According to Handy (1996), traditional neighborhoods had higher accessibility, based on their downtown areas and street network grid like layouts. However, one of the traditional neighborhoods studied was cut by a major arterial. The arterial blocked many of the residents from easy walking access to the downtown area, thus breaking the continuity of the neighborhood and reducing the total number of walking trips. Therefore, Handy (1996) found that arterials through a neighborhood can reduce the number of walking trips made by the residents by creating a barrier to pedestrian movements. It should be noted here that Handy (1996) focused her study on shopping trips.

Litman (2011) found that as employment density increases, the commuter mode split increases as well. He hypothesized that when more worker have the same employment destination (which occurs with increased employment density), rideshare opportunities and transit access increase as well. He also found that the presence of a central business district (CBD) promoted a greater percentage of non-single passenger car commuting trips.

Litman (2011) also investigated the effects of intersection density and neighborhood connectivity on mode split. He found that residents of neighborhoods with high intersection densities were more likely to make walking trips than residents of neighborhoods with low intersection densities. He also found that residents of more

connected neighborhoods (greater sidewalk connectivity) were more than twice as likely to walk to local shopping areas as residents of neighborhoods with poor connectivity. However, these results should be interpreted with care, as many neighborhoods with high connectivity usually have a more traditional layout, with more local stores available at a short distance to residents.

According to the Litman (2011), biking and walking trips are affected by the following conditions:

- Bike racks and changing facilities.
- Ease of road crossing (road width, traffic speeds and volumes, presence and quality of crosswalks) and protection (separation between traffic and non-motorized travelers).
- Network connectivity (how well sidewalks and paths are connected and the overall extent of the pedestrian and cycling network).
- Security (how safe people feel while walking).
- Environmental quality (exposure to noise, air pollution, dust, sun and rain).
- Topography (inclines).
- Land use density and accessibility (distance between common destinations, such as shops, schools and parks).
- Attractiveness (quality of urban design).

Neighborhoods that utilize these conditions favorably should be expected to generate a higher pedestrian and bicycling mode split.

Transit access can also affect mode split. Ewing and Cervero (2010) found that the nearer residents live to a transit stop, the higher the likelihood that they will select transit as their transportation mode for a trip. Litman (2011) found that employees living near a transit station were five times more likely to use transit to commute than average workers on a given day (based on a California study). These findings are expected, as the practicality of using transit increases greatly when reaching the station does not involve another vehicle trip.

The LUTAQH (Land Use, Transportation, Air Quality and Health) research project sponsored by the Puget Sound Regional Council used elasticity to determine the effects of urban form on home-based other (HBO) trips (Frank et al. 2005). Their findings are summarized as follows:

- A 10 percent increase in auto-fuel and parking costs is associated with a reduction in drive alone by 0.6 percent, an increase in carpooling of 0.4 percent, an increase in transit use by 1.5 percent, an increase in bicycling by 1.4 percent, and an increase in walking 0.6 percent.
- Increasing auto travel time by 10 percent was associated with an increase in transit ridership by 2.3 percent, an increase in bicycling by 2.8 percent, and an increase in walking by 0.7 percent. Conversely, reductions in auto travel time would be expected to be associated with lower levels of transit, bicycling, and walking for non-work travel.

- Increasing a tour's destination retail floor area ratio and level of land use mix by 10 percent was associated with increased levels of transit demand by 3.4 percent and 3 percent respectively.
- Increasing home and destination intersection densities by 10 percent were associated with a 2.4 percent and 2.3 percent respective increase in transit demand.
- Increasing street network connectivity at the home location by 10 percent was associated with a 2.8 percent increase in walking, and increasing street network connectivity by 10 percent at the destination was associated with an additional 2.7 percent increase in walking for non-work tours.
- Increasing land use mix at the home location by 10 percent was associated with an increase for non-work travel of 0.6 percent for walking and 1.5 percent for bicycling.

This section shows that urban form has numerous effects on mode split. These effects may be minimal for areas with a very high proportion of trips made by single occupant passenger vehicles. For example, if a region has a mode split of 5 percent transit and 95 percent auto, a 10 percent increase in transit travel will change the mode split to 5.5 percent transit and 94.5 percent auto, reducing auto trips by 0.5 percent. However, new neighborhood designs promoting transit and pedestrian travel are being implemented. The urban form characteristics of these neighborhoods could have a significant effect on residential mode splits. Therefore, urban form should be accounted for in future mode split calculations in travel demand prediction models. But if a travel

demand model's primary focus in auto trips, changes in mode split due to changes in urban form could be incorporated through reduced trip rates.

Urban Form and Trip Length

Trip length can also be dependent on urban form. The length of non-work trips could be more affected by urban form, as employment locations are generally based on a range of choices available to a resident. However, work trip length may be affected by infill development around employment centers, as employees will take advantage of nearby housing to reduce commuting costs. Shopping trip length is expected to be highly dependent on shopping center availability and accessibility, as residents may be expected to take advantage of the closets available shopping centers.

Vehicle miles traveled (VMT) per person can be calculated by multiplying average trip length by average trip rate. Manville and Shoup (2005) state that as density increases, commuter VMT decreases at a rate of 0.58% per 1.0% increase in density. This study is included in this section because its characteristics are more consistent with the studies involving average trip length. However, their findings were based on a rather sweeping analysis of the 20 largest urban regions in the United States, using only population density and VMT as variables. Therefore, their correlation between population density and VMT does not take into account the distribution or accessibility options of the populations analyzed, and therefore should not be assumed to represent the effect of urban form on travel behavior for all areas.

Litman (2011) found that regional accessibility effects trip length. He defines regional accessibility as the relative location of an individual site to the regional urban

center (either a central city or central business district), and the number of jobs and public services available within a given travel time (Litman 2011). He found that areas with lower regional accessibility would generate trips of greater length.

Crane and Chapman (2003) found that the spread of employment locations into suburban areas decreased average commuter trip lengths. Their study showed that commuter trip lengths decreased at a rate of 1.5% per 5% increase in employment growth in suburban areas. However, Litman (2011) states that the trip length saved by suburbanizing employment is lost to non-work trips, which will increase in length with the spread of employment locations.

Land use mix can also affect trip length. Krizek (2003) found that households in highly accessible areas (high land use mix) made shorter average errand trips than households in less accessible (more exclusive land use) area. Ewing and Cervero (2010) also found that trip lengths decreased with increased land use mix. Litman (2011) hypothesized that both commutes and shopping trips can be reduced in length by land use mix, as residents will be more likely to shop and work near their home.

The study performed by DKS Associates (2007) found a linear elastic relationship between trip length and both density and land use mix. The study found that a 10% increase in land use mix (Equation 2-2) led to a 0.5% decrease in average trip length. Additionally, a 10% increase in density (Equation 2-1) led to a 0.5 % decrease in average trip length. Of the average trip length reductions researched for this project, these elasticity values were the most easily incorporated into the project model and were therefore selected as the target average trip length elasticity values for the model. The elasticities are given in their equation form in Equation 2-5 and Equation 2-6.

$$e = \frac{-0.5 \% \text{ change in trip length}}{10\% \text{ change in land use mix}} = -0.05$$

Equation 2-5

$$e = \frac{-0.5 \% \text{ change in trip length}}{10\% \text{ change in density}} = -0.05$$

Equation 2-6

Urban Form Effects Summary

This chapter has discussed some of the main effects of urban form on travel behavior. While by no means the only factor in a person's travel decisions, urban form is still an important factor in determining a travel behavior. As shown in this chapter, urban form does have a significant impact on travel behavior. And unlike population demographics, the effects of urban form on travel cannot be easily determined from a survey. Therefore, the methods for measuring urban form discussed in this chapter are critical to estimate its effect on travel.

For this project, the DKS Associates (2007) elasticity values were selected for use in the model. These elasticity values were chosen because they were associated with travel behavior variables that could most easily be modified within the modeling process that would be used for the project. Also, the elasticity values appeared to be conservative compared to other studies. The selected elasticity variables are shown in Table 2-2.

Table 2-2: Elasticities

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 5.11)	Modified Model Resulting Elasticity (Ch. 5.12)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04				
	Land Use Mix	-0.06				
Average Trip Length (per trip)	Density	-0.05				
	Land Use Mix	-0.05				

Sensitivity of Current Travel Models to Changes in Urban Form

All travel demand models incorporate urban form data in some way. However, changes in trip behavior caused by changes in urban form may not always be captured through a travel demand model. In rural areas especially, urban form changes can entirely alter the travel behavior within each traffic analysis zone. Therefore, this section investigates the sensitivity of travel demand models to changes in urban form, both in a general sense and for some specific models.

How Changes in Urban Form Could Effect Model Inputs

As discussed in the previous sections, changes in urban form affect different parts of travel behavior. Urban form may affect the amount of trips made by a resident, and at the same time affect the person's average trip lengths (as discussed in previous sections). The inputs to travel demand models may be sensitive to changes in urban form. This section will discuss some of the urban form variables that may affect travel demand

model inputs, thus increasing the sensitivity of the model to changes in urban form. The two main urban form variables investigated in this section are density and land use mix, as the effects of these two variables were the most consistent and best quantified through the previous research.

Density: Population density appears to decrease non-work trip lengths. Most four-step process travel demand models use some sort of travel time distribution (either based on national averages or local data) to distribute trips between traffic analysis zones, such as the gamma function. The shape of a distribution modeled by a gamma function is controlled by the function coefficients. Most models do not change the coefficients for predicted year. However, a tighter travel time distribution (i.e. a lower average travel time) could be modeled by a gamma function by changing the coefficients.

Activity-based models use synthetic populations, where the residents make travel decisions based on a series of demographic household characteristics, calibrated with and validated against an activity diary survey. Each simulated household member makes their activity choices based on their assigned characteristics. Population density may be one of the factors impacting the activity choices of a simulated household member, if some correlation was found between activity choice and density in the survey. When the activity-based model is run on a future urban form scenario, the effects of increased (or possibly decreased) population density on activity (and consequently travel) choices would be captured.

Land Use Mix: Based on the research presented in the previous section, areas with higher land use mixes have lower vehicle miles traveled, higher mode splits, and shorter

travel times. The effect of land use mix on travel behavior might be considered similar to density, but possibly more dramatic. For example, placing a large retail center in the center of a primarily residential development will undoubtedly decrease the number of shopping trips leaving the zone. Building an employment center in a previously sparsely populated zone will not only encourage development within the zone, but also drastically change the travel behavioral patterns of the zone residents. New residents are very likely to be employed at the new center, leading to short work trips.

Land use mix is not a typical input into a travel demand model, at least directly. Most advanced models use a separate land use prediction model to provide the inputs to the travel demand model. The land use model is run for the future year, then the outputs from the land use model are used as inputs to the travel demand model for the future year. Sometimes this process is performed in time step feedback procedure, as changes to a network that are made based on traffic changes could serve as inputs to the land use prediction model. Land use mix could be an output from a land use prediction model, either as some dissimilarity index value, or some a value based on land use type percentages in each land use block. Land use mix plays an important role in determining where building may occur in the future. However, most travel demand models do not employ land use mix as a variable in trip (or activity) generation.

Other Factors

As discussed in the previous section, some other factors, mainly involving neighborhood layouts and street network are expected to affect travel behavior. Also, added access to a public transit facility is expected to increase the transit mode split.

Neighborhoods with a more traditional layout (grid network), more sidewalks, and better pedestrian and bicycle facilities are expected to increase the use of alternate modes of transportation (i.e. transit, bicycle, or pedestrian).

Transit access might input into a four-step process model by simply increasing the transit mode split for the future year for zones where a certain percentage of households are within 0.5 or 0.25 miles of a transit stop. However, a thorough knowledge of the prediction year transit system layout would be required to make this adjustment to the model. An activity-based model might include access to transit stops as factor in determining what mode of travel a member of the simulated population uses to reach an activity location. The Multi-Nomial-Logit (MNL) method could be used to determine the probability of a person using transit (or any other travel mode), with the utility of the transit mode increasing with accessibility to transit stops.

Values could be assigned to zones based on the amount of bicycle facilities. The values could be used with the MNL method to determine the utilities of the pedestrian and bicycle modes. Changes in mode split could be input in during the mode choice step of the four-step process for traditional models, or as increased probability of pedestrian/bicycling mode use for the simulated populations of an activity-based model.

Current Models Sensitivity Investigation

To better show how current models incorporate urban form characteristics that effect travel behavior, several different travel demand models were investigated. While the use of activity-based models at an operational level is rare, an investigation of the

sensitivity of some of these models to changes in urban form was included in this section. This section will investigate both the activity and trip based models.

Bannock Planning Model: According to BPO (2007), the Bannock Planning Organization (BPO) created a travel demand model for an area encompassing Pocatello and Chubbuck, Idaho, in 1997. This is a small urban area with a population of about 77,000. It has been updated several times with the the latest update to the model was performed in 2006. The purpose of the most recent model update was to update the demographic data for the projection year of 2035, modify the TAZ structure, and continue the development of the peak hour model. The BPO Travel Demand Model used the four-step process, using the TransCad software as the primary modeling tool.

The 2006 update of the BPO travel demand model had 323 TAZs. Smaller zones are more accurate and are also beneficial for urban form analysis, if the data is available at a TAZ level. Changes in urban form are more extreme when the block areas analyzed are smaller. Figure 2-5 shows the TAZ layout for the Bannock Planning model, indicating the amount of housing and employment aggregation used to run the model.

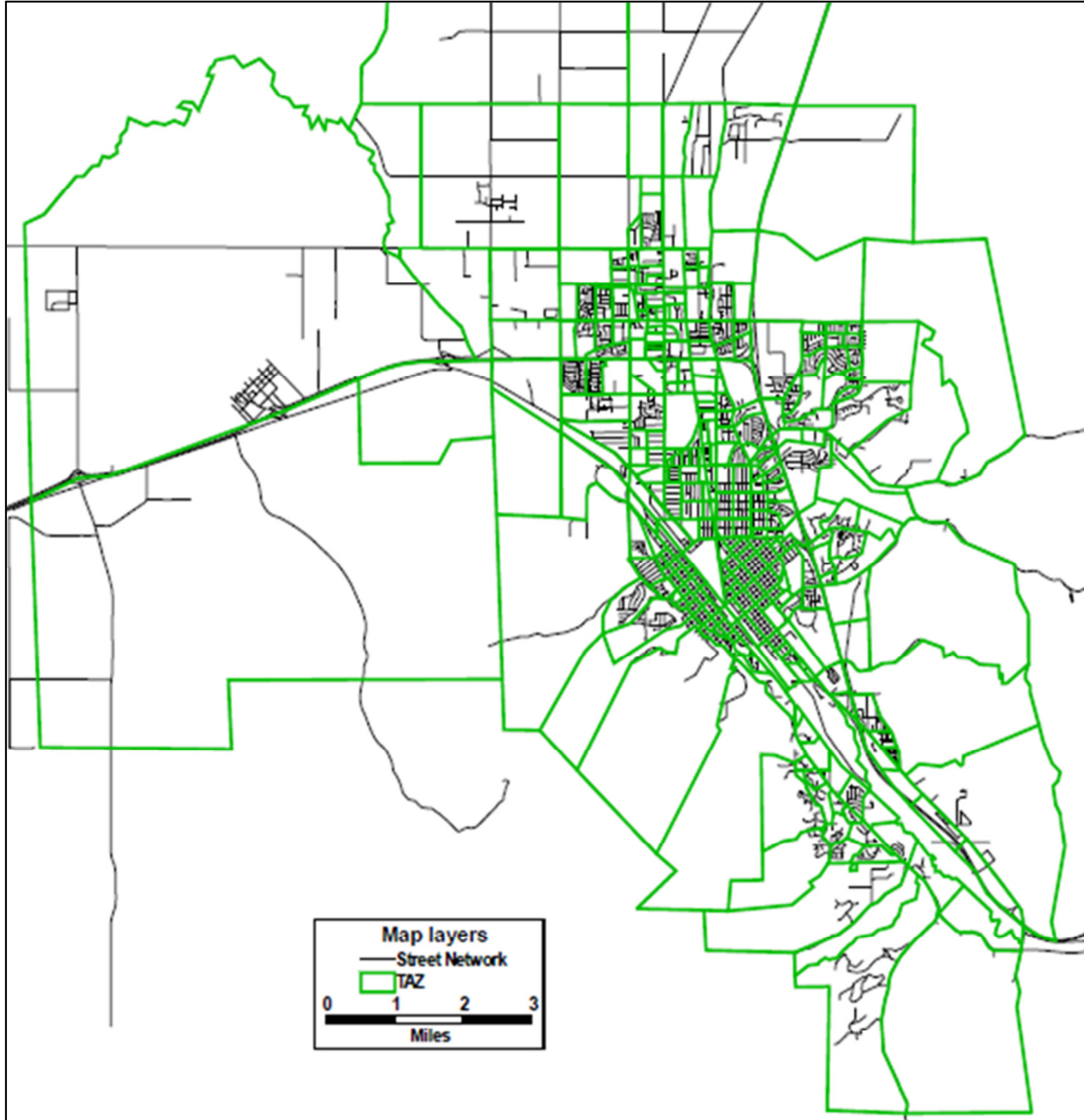


Figure 2-5: Bannock Model TAZs (BPO 2007)

The trip generation inputs for the BPO travel demand model were dwelling units and employment data (retail and non-retail). The model used a quick response method for estimating trip attractions while the trip production rates for each TAZ were calculated from a yearly survey. The estimated attractions and surveyed production rates were combined with the demographic and employment data to create the trip generation

models for each TAZ. All trips were assigned to one of three categories, home-based-work (HBW), home-based-other (HBO), and non-home-based (NHB). The proportions of each trip category were calculated based on national averages. The trip production models were all dependent on the number of dwelling units in each TAZ, while the trip attractions were based on retail employment, non-retail employment, and dwelling units within each TAZ (BPO 2007).

The BPO Planning model contained 15 external stations (representing interstates, arterials, etc. that lead out of the analysis area). The external to internal, external to external, and internal to external trips were estimated according to the NCHRP 365 procedure, which is based off national averages (BPO 2007).

For the trip distribution step, the gamma function was used to generate friction factor between TAZs. The friction factors were dependent on trip length, rather than travel time. The coefficients of the gamma function were calibrated to closely match the results of a travel survey conducted in the 1990's. The resulting function provided an average trip length of close to 5 miles. The travel time distribution was derived from the trip length distribution and resulted in an average travel time of 8 minutes (BPO 2007).

The Bannock model distributes trips using the doubly constrained gravity model, discussed further in Chapter 3. Some research has indicated that the doubly constrained gravity model is sensitive to land use mix and density. "Density and diversity provide opportunities to satisfy travel needs with shorter vehicle trips and non-motorized travel. Trip distribution models naturally place more trips between neighboring zone pairs with productions in one and attractions in the other, and intrazonal trips into mixed zones.

Conversely, in models as in the real world, persons in rural and homogenous areas must travel far to reach activities, and use auto modes for lack of alternatives (Gibb 2005).”

The mode choice step was not sensitive to urban form, as the mode choice splits were not modified due to any local or regional urban form variables. The route assignment step used in the BPO travel demand model was not of interest to this analysis, as route choice is not expected to be sensitive to changes in urban form. The BPO model highlights the issues of many current operational travel demand models. The trip generation rates were only a function of dwelling units and employment, thus failing to capture any possible changes in individual driver characteristics due to changes in density. The travel length distribution was somewhat dependent on urban form (through density and land use mix). However, this sensitivity was not quantified or validated against the actual sensitivity of trip length to these urban form variables. Therefore, future changes in travel behavior caused by different urban form planning schemes would not be captured accurately by the model, restricting the models usefulness for future growth development planning.

Atlanta Travel Demand Forecasting Model: According to the Atlanta Regional Commission (ARC), the Atlanta Travel Demand Model is a trip based model last updated in 2008. The modeled area consists of 20 counties including the entire Atlanta metropolitan area. The main data used for the model were travel surveys obtained from nearly 8000 households within the region, collected between April of 2001 and April of 2002. Additional calibration data was collected from nearly 5000 different daily traffic counts throughout the analysis region (ARC 2008).

The model uses six different trip categories, home based work, home based shopping, home based grade school, home based university, home based other, and non-home based. The large amount of trip production data available through the household survey (nearly 100,000 trips were recorded in the survey) allowed for the use of the six trip categories. The model used a logit function to determine the probability of a person making a certain number of trips in a day. The socio-economic categories used to determine the utility of each motorized trip amount for a person are the following (ARC 2008):

- HH size (1, 2, 3, 4+)
- HH income group (under \$20K, \$20 – 50K, \$50 – 100K, over \$100K)
- Number of workers (0, 1, 2, 3+)
- Number of children (0, 1, 2, 3+)
- Number of autos (0, 1, 2, 3+)

Note that none of the variables employed by the decision making logit function were related to urban form. During the model calibration, attempts were made to link some of the travel behavior to density, based on the theory that higher density areas would have lower trips, due possibly to more ridesharing (ARC 2008). However, as discussed in the previous chapter, density is actually expected to increase trip rates, which the model calibration results actually showed. Regardless, density was left out of the trip production models. Therefore, changes in urban form (such as density, or increased land use mix) were not captured by the model. However, as the city of Atlanta is not a high growth area, and the land uses of the region are not likely to vary greatly, the model's lack of

sensitivity to urban form is compensated by the dependence of the model on the regional travel surveys.

The model did take into account some accessibility characteristics, mainly to model transit trips. The model used an accessibility measure for each zone to determine the likelihood of a person using an alternate mode (walking or transit). The accessibility measure took into account the activity of the surrounding zones (measured as some combination of population and employment) and the impedance between the zone of interest and the surrounding zones (measured as either as transit travel time, walk to local travel time, highway distance, or highway travel time) (ARC 2008).

The trip distribution method used by the Atlanta Travel Demand Model used friction factors based off the travel time data collected from the analysis region (ARC 2008). The travel time distribution was not dependent on any urban form variables.

The Atlanta Travel Demand model is not sensitive to changes in urban form for motorized trips directly. However, the transit accessibility aspect of the model would be extremely useful for other transportation demand models trying to assess the impacts of new transit systems on travel. Also, the non-motorized portion of the model is highly dependent on urban form, with higher densities increasing the non-motorized portion of trips generated in each zone. This aspect could be very useful for regions expecting serious urban form changes, as increased mode split due to density or accessibility changes would be critical to evaluating future travel behavior. The dependence of the model on trip surveys for motorized trips may be sufficient for a highly urban model, but for areas where travel behavior is expected to change over time, the extensive calibration of the model against travel surveys may make the model inaccurate.

AMOS Activity-Based Model: According to the Relational Database Consultants (RDC) Inc., the Activity-Mobility Simulator (AMOS) is a model that predicts the responses of residents to Transportation Demand Management (TDM) measures. The AMOS model was an attempt to develop and implement an activity-based analysis tool for metropolitan planning. However, the study performed with the AMOS model was of an experimental nature. The model contains five modules: The Baseline Activity –Travel Analyzer (BATA), the TDM Response Option Generator, the Activity/Travel Pattern Modifier, the Evaluation and Search Termination module, and the Statistics Accumulator. The evaluation and Search Termination module and the Statistics Accumulator are not discussed in this analysis, as their contributions to the model are all based off travel patterns already determined by the first three modules (RDC 1995). Therefore, sensitivity to urban form changes in the model would be within the first three modules.

The AMOS model requires the following data: A traffic analysis zone (TAZ) system, a TAZ-to-TAZ network travel time by mode and distance, land-use inventory by TAZ, existing mode choice and trip distribution models, and standard trip diary data of household members with basic trip information such as origin, destination, trip purpose, departure and arrival times, and mode. If the AMOS model is implemented for TDM evaluation, the types and characteristics of the TDM strategies considered and the potential responses of individuals to those measures are also required (RDC Inc. 1995).

The AMOS model takes survey data from a population sample into a Baseline Activity-Travel Analyzer (BATA). The BATA uses the trip survey data against the network to create activity-travel patterns for each person analyzed. The demographics of

each person surveyed are also recorded, allowing the patterns to be applied to a much larger population. These patterns are used by the remaining components of the AMOS model (RDC 1995).

The TDM strategies are input into the TDM Response Option Generator, which creates the basic “response” of each individual. Demographic and socio-economic attributes for each individual are also input into the TDM Response Generator, as well as the modified activity-travel pattern from the BATA. Stated-preference and revealed-preference data is also input into the module. Stated-preference data comes from surveys, where individuals are asked how their activity-travel behavior might change due to some TDM strategy. Revealed-preference data is derived by measuring the effects of similar TDM strategies on activity-travel patterns (RDC Inc. 1995). Revealed-preference data can be difficult to obtain, especially if the TDM measures under consideration are relatively new and innovative.

The Activity-Travel Pattern Modifier provides alternatives to the baseline activity-travel pattern of an individual based on the responses created by TDM Response Option Generator. However, due to complex nature of activity-travel behavior, the following assumptions are made in the AMOS model (RDC Inc. 1995):

- Activity and task allocation among household members is not considered. Only the activity-travel pattern of one individual in a household is analyzed, independent of activity-travel behavior exhibited by other household members.

- Out-of-home activity durations for various purposes are kept a constant before and after the introduction of the TDM measures. However, in-home activity duration and travel times may vary.
- The frequency with which various out-of-home activities are pursued is also kept a constant before and after the introduction of the TDM measures. However, trip frequencies may vary as trip chaining may be modified.
- The activity-trip re-sequencing algorithms do not consider multi-day activity-trip engagement. Only one-day activity-travel itineraries are adjusted, independent of activity-travel itineraries on any other day.
- The algorithms deal only with activity-travel pattern modifications for commuters.

The assumptions show that non-work trips are not analyzed by the AMOS model. As the previous chapter shows, non-work trip travel behavior has the most sensitivity to urban form. Therefore, the AMOS model would not capture the main effects of changes in urban form. However, the model could potentially be used to measure the effects of urban form changes on travel behavior. The TDM responses could be based on stated-preference data for urban form changes such as bicycle or pedestrian facility improvements, or for revealed-preference data based on density or land use mix changes. The current AMOS model could also be used to determine the changes in trip chaining behavior (discussed in the previous chapter) on commute trips.

The assumptions of the AMOS model also restrict the frequency of out-of-home activities, effectively fixing trip rates. As some urban form changes are expected to

change trip rates, the assumption made by the AMOS model prevents some of the travel behavioral changes caused by urban form changes from being modeled correctly.

Overall, the AMOS model could become a useful tool for analyzing different change in urban form possibilities based on reported preferences. However, the model would have to be modified from its current functionality to provide this type of sensitivity. The current assumptions behind the model create too many simplifications for trip types to be effected by changes in urban form.

Sacramento Activity-Based Travel Demand Model: According to Bowman et al. (2006), the Sacramento Activity-Based Travel Demand Model was created from the regional travel forecasting simulation system called SacSim. The program initially treated regional land use forecasts as exogenous. However, the SacSim system expects to imbed Sacramento's new land use prediction model, PECAS, in the future.

The Sacramento model uses an activity-based procedure to model travel demand. Regional land use projections (from some land use model), residential, employment, and school enrollment data are input into a population synthesizer. The resulting synthetic population is then input into a long term choice simulator. The long term choice output is used by the person day activity and travel pattern simulator (known as DaySim) to output a person trip list for the synthetic population. The trip list is input into a trip aggregator, which is combined with external trips, special generator trips, and commercial movement trips to create O-D matrices. The trips from the O-D matrices are then used for network traffic assignment, which is then used to determine the network performance. The

network performance data are then re-input into the model, and the simulations continue until an equilibrium situation is reached (Bowman et al. 2006).

The effects of urban form could be incorporated into the Sacramento Activity-Based Travel Demand Model during the person day activity and travel pattern simulation. The DaySim system uses the household data (including residence location), person data (including work and/or school location), tour, and trip data to determine the activity travel patterns for each person within the synthetic population. Therefore, the DaySim system currently does not incorporate urban form into travel pattern simulation.

The effects of changes in urban form on the on travel behavior could potentially be captured by the Sacramento Model. If activity-travel behavior of the synthetic population could be partially linked to the urban form characteristics of the persons surveyed to provide calibration for the synthetic population, the future year synthetic population could carry over their linked urban form activity-travel behavioral patterns. As the residential location of every person surveyed was recorded, the urban form characteristics of the zone of each resident could easily be determined to provide the links between urban form and travel behavior. However, the overall accuracy of the Sacramento model might be affected, especially depending on how well the activity-travel surveys were distributed throughout different types of urban form. Also, the cost of a simulation model similar to the Sacramento model might be too great for a rural area with an interest in the effects of high change in urban form.

Urban Form in Current Models Summary

More four-step process models do not incorporate urban form. The AMOS model contained some useful tools for determining the effects of changes in urban form on travel behavior. However, the AMOS model was also too specific to provide a comprehensive travel demand model for a rural area where needed data may be unavailable. All the models discussed could be made sensitive to urban form changes, but the model is still in the development stage, and cost issues may preclude its use for rural cities.

This chapter shows the lack of sensitivity of current four-step process travel demand models to changes in urban form. However, as shown by the Atlanta model, a four-step model can be made sensitive to changes in urban form but requires significant data collecting efforts. Unfortunately, regions that might expect the most drastic changes in urban form are rural areas. Rural areas generally cannot afford to collect the data required to run an effective activity based model. Therefore, a method for incorporating accurate urban form sensitivity without greatly increasing the cost and data requirements for a travel demand model would be extremely useful for rural development planning.

Literature Review Summary

The purpose of this literature review was to investigate the sensitivity of travel behavior to changes in urban form, and then to compare this researched sensitivity to the actual sensitivity of current travel demand models. The research indicates that travel behavior is sensitive to changes in urban form. The sensitivities vary depending on the sensitivity variables used. The elastic sensitivities selected were based on urban form

variables with low data requirements. The investigation into the sensitivity of current model indicated some possible inherent sensitivity, but nothing quantifiable. In general, existing models do not incorporate changes in urban form. However, as will be discovered in the next chapter, there is some inherent sensitivity to changes in urban form within the basic four-step process. The next chapter will focus on the development of a basic four-step model, which will then be analyzed for inherent sensitivity to changes in urban form.

CHAPTER 3

THE BASIC FOUR-STEP PROCESS

Introduction

The four step process is still the most commonly used method of travel demand modeling, particularly for rural areas. This is probably due to the lower data requirements of a typical four-step model. The four-step process was discussed briefly in the literature review chapter. This chapter will focus on the application of the basic four-step process to the Bozeman. The model was initially expected to have no sensitivity whatsoever to changes in urban form. Surprisingly, the results described in this chapter did indicate sensitivity to urban form within the basic four-step process. This inherent sensitivity of the basic four-step model is quantified in Chapter 4. This basic model will be modified as discussed in Chapter 5 to better match the actual sensitivity of travel behavior found in the literature review.

Overview

The general process for any travel demand process is to build a model for at least one base year. Real travel data for the base year is then used to validate and calibrate the model. Once the base year travel can be accurately represented, the model can then be used to predict future travel. As discussed in chapter 1, the four-steps of the four-step process are trip generation, trip distribution, mode choice/time of day, and traffic

assignment. Figure 3-1 shows the typical flow of a four-step model. The figure includes the data inputs and outputs for each step of the process.

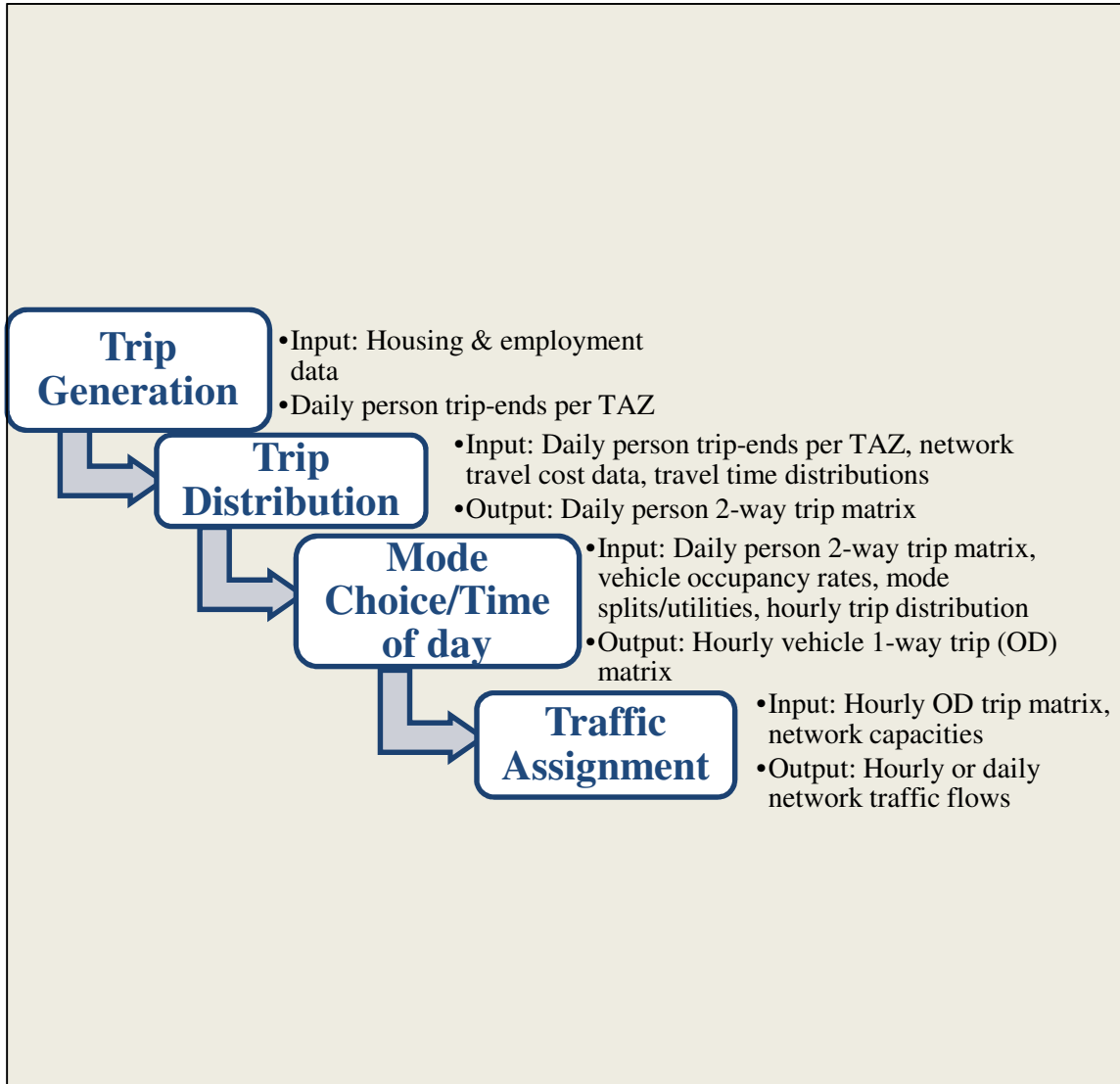


Figure 3-1: The Four-Step Process

Some four-step models also contain feedback loops for model calibration. Figure 3-2 shows the general process with a calibration feedback loop. Note that the model may be run several times until the desired accuracy is reached. Note also that the calibration feedback may sometime go into the mode choice/time of day step, either as updated

mode splits or new vehicle occupancy rates. More typically, the trip rates in trip generation are factored up or down to match total travel.

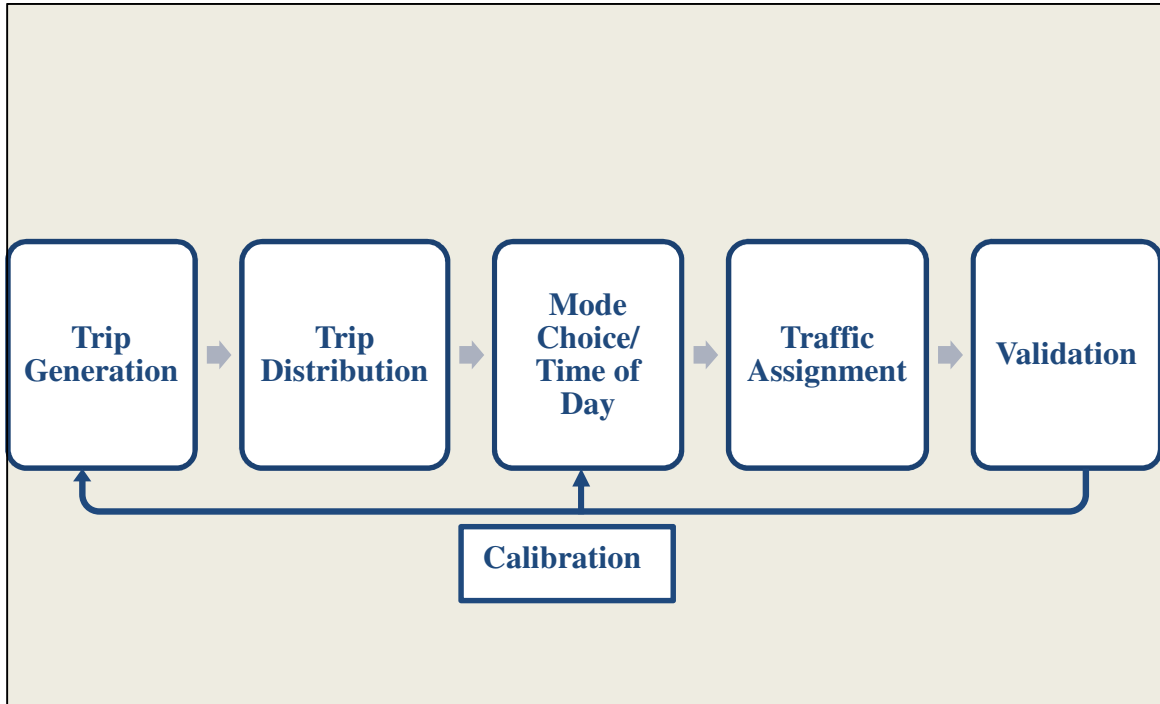


Figure 3-2: Four-Step Process Calibration Feedback Loop

The basic model initially developed for the Sonoran Institute was built for the area shown in Figure 3-3. The model was developed using a combination of the Montana Department of Transportation methods and the NCHRP 365 methods. The process is outlined by each step in the following sections.

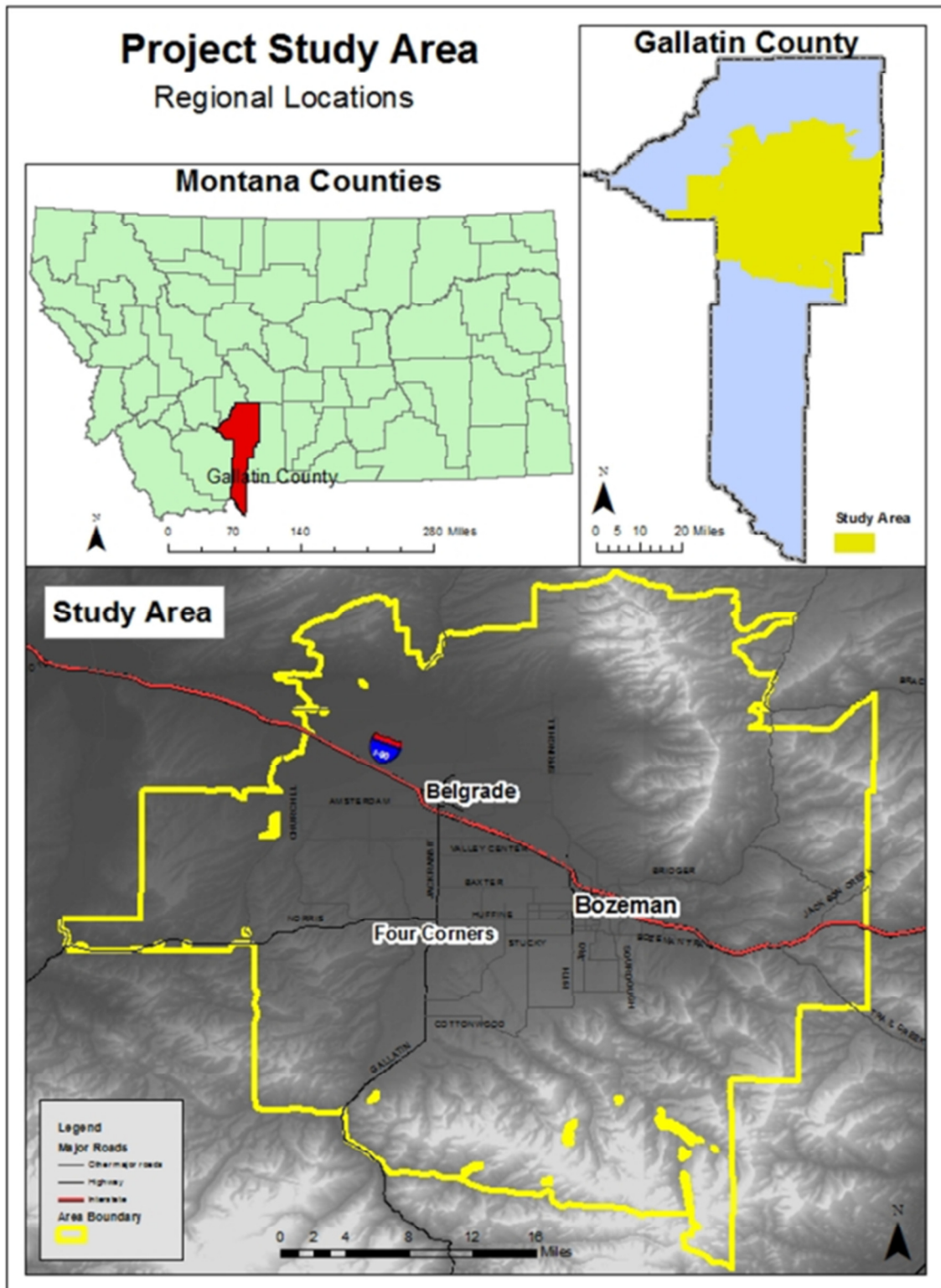


Figure 3-3: Project Study Area

Trip Generation

The first step of the four-step process is trip generation. First, the analysis region is divided into traffic analysis zones (TAZ). These zones are selected based on street network, population centers, land-use types, or some other geographic or demographic factor. The zones may be as large as census tracts, or as small as census blocks, or even parcels. Figure 3-4 shows some examples of possible TAZ sizes. In the trip generation step, daily productions and attractions (two-way person trip-ends) are calculated for each TAZ.

The methods for calculating the productions and attractions vary between models. Many models use travel surveys to determine the relationships between various household demographics and trip rates. Others used published national trip rates when survey data is unavailable. All trip production rates are dependent mainly on a base unit of either housing units or population. Regression equations can be used to match travel survey data to other variables, such as household income and vehicle ownership. These variables are aggregated for each TAZ, and are then used to calculate the total person trips produced in each TAZ.

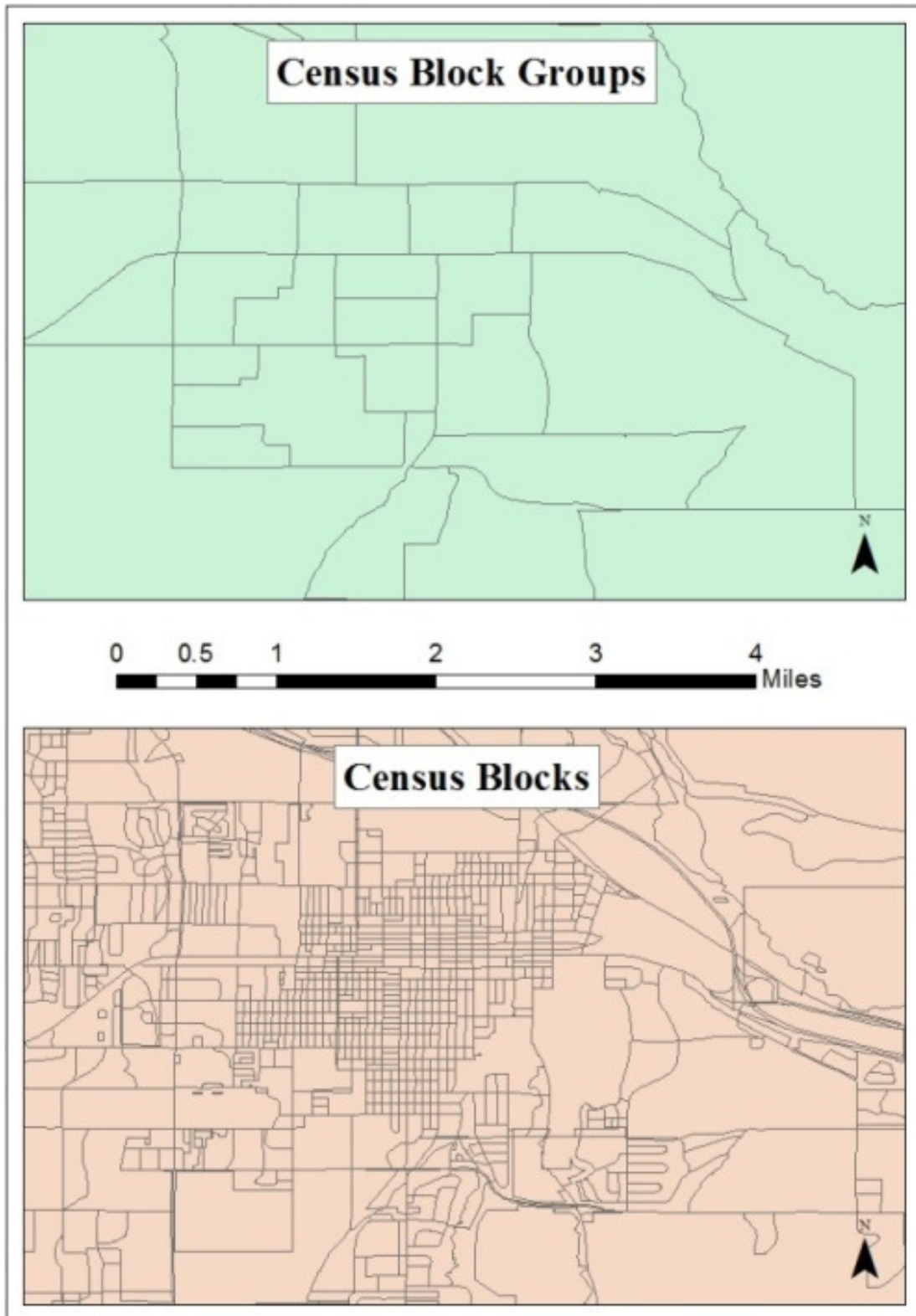


Figure 3-4: Typical TAZ Units

Attraction rates are generally less accurate than production rates. The basic

variables for attractions are generally retail and non-retail employment. However, different types of variables attract wide varieties of trip rates. Again, data availability usually determines which types of employment might be used for trip attraction rates. As much employment data is sensitive information, this data is generally fairly aggregated. The inaccuracy of trip attraction data is partially combated when the total trips for a region are balanced. For a four-step model to function, the total production and attractions for the entire region must be equal. As trip productions are dependent on housing data that is usually far more accurate than employment data, the trip attractions for all of the TAZs are scaled for the entire region to equal the productions.

Not all TAZs use the same trip generation equations. Some zones have a very unique land use, such as stadiums, universities, or airports. When published trip rates or local data is available for these TAZs (called “special generators”), the trip ends for the zones are calculated separately. Also, major highways and roads bring traffic into the analysis region. NCHRP 365 contains specific methods for incorporating these so-called “external stations” into a model. The implementation of special generators and external stations into a model varies widely depending on the goals of the model and the region being analyzed. The basic model described in this chapter did not use any special generators.

The basic model based all trip productions off housing units and attractions of housing units, retail employment, and non-retail employment. No income or car ownership data (the two most common housing cross variables used by MDT) was available for the future scenarios provided by the Sonoran Institute. The retail and non-retail employment data for the base year was provided by Alan Vander Wey of MDT.

The TAZs used for the model were based off the TAZ files provided by Alan Vander Wey. The Sonoran data was aggregated into these TAZs for the future scenario analysis.

Figure 3-5 shows the TAZ map of the model.

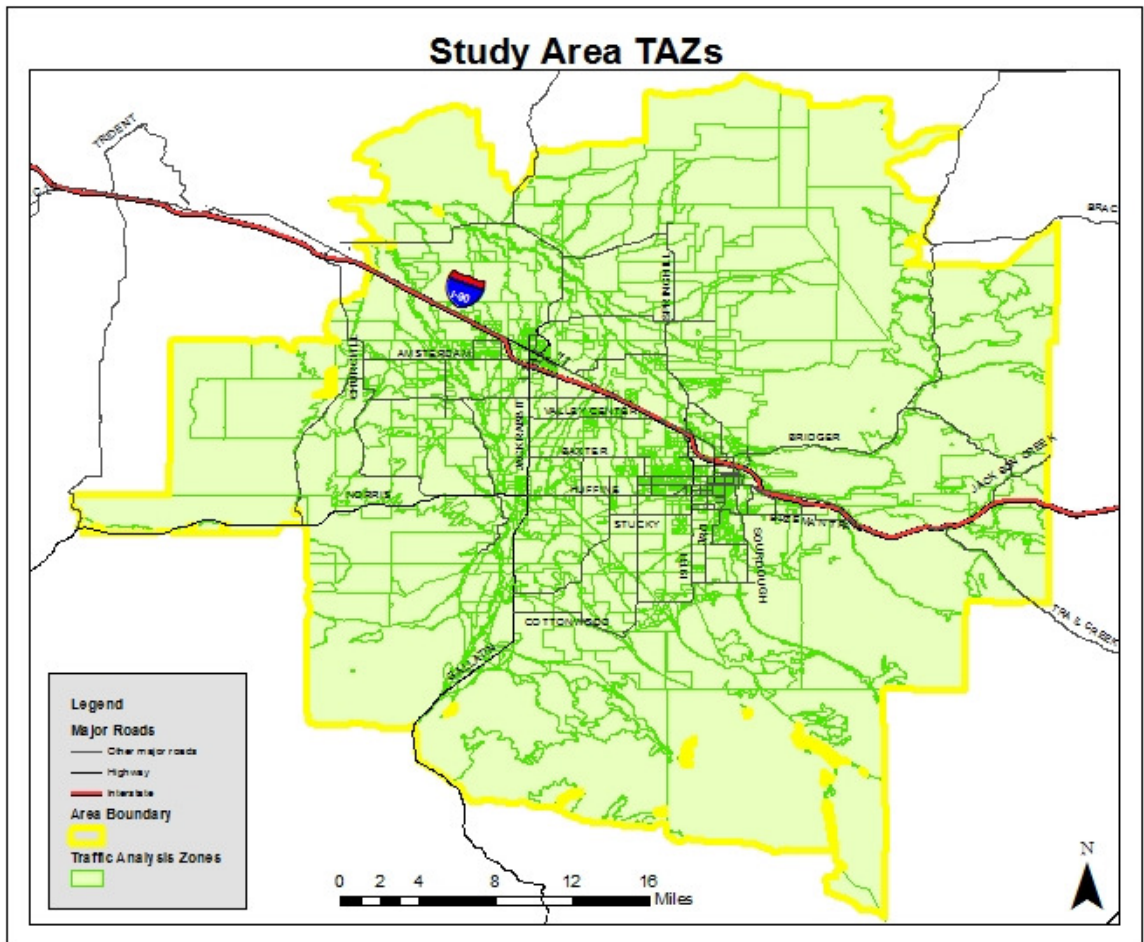


Figure 3-5: Project TAZ Layout

More detail as to the development and aggregation of the TAZs will be given in Chapter 5. The trips generated in the model were divided into three types, home-based work (HBW), home-based other (HBO), and not-home based (NHB). Table 3-1 shows the trip rate functions used for the model.

Table 3-1: Trip Rate Equations

Trip Type (as two-way person trips)	Trip Rate Equation
Home-Based Work Productions	$0.57^1 \times 0.16 \times 14.1 \times (\text{Housing Units})$
Home-Based Work Attractions	$0.57 \times 1.7 \times (\text{Total Employment})$
Home-Based Other Productions	$0.57 \times 0.61 \times 14.1 \times (\text{Housing Units})$
Home-Based Other Attractions	$0.57 \times [10 \times (\text{Retail Employment}) + 0.5 \times (\text{Non} - \text{Retail Employment}) + 1.0 \times (\text{Housing Units})]$
Non-Home Based Productions	$0.57 \times 0.16 \times 14.1 \times (\text{Housing Units})$
None-Home Based Attractions	$0.57 \times [2 \times (\text{Retail Employment}) + 2.5 \times (\text{Non} - \text{Retail Employment}) + 0.5 \times (\text{Housing Units})]$

The basic model did contain external stations, but no special generators. The Montana State University zones were treated like any of the other zones, and the final results for the model did not show any serious accuracy issues on the streets around and in the university. The external stations were converted to person trips by the equations shown in Table 3-2. These equations are based off the external station method used by Alan Vander Wey.

Table 3-2: External Station Trip Rates

Trip Type (as two-way person trips)	External Station Trip Rate Equation
Home-Based Work Productions & Attractions	$0.25 \times 0.16 \times 1.4 \times (\text{Average Annual Daily Traffic})$
Home-Based Other Productions & Attractions	$0.25 \times 0.61 \times 1.9 \times (\text{Average Annual Daily Traffic})$
Non-Home Based Productions & Attractions	$0.25 \times 0.23 \times 1.6 \times (\text{Average Annual Daily Traffic})$

¹ This coefficient calibrates the trip rate equations and is discussed further in Section 3-7

The locations of the external stations are shown in Figure 3-6. It should be noted that I-90 was the only major road that remained continuous through the study area. The NCHRP 365 has a method for calculating the percent through trips for each road type. This method was used to calculate the percent through trips for I-90 in the base and future scenarios. These through trips were then subtracted from the I-90 traffic and added back in later.

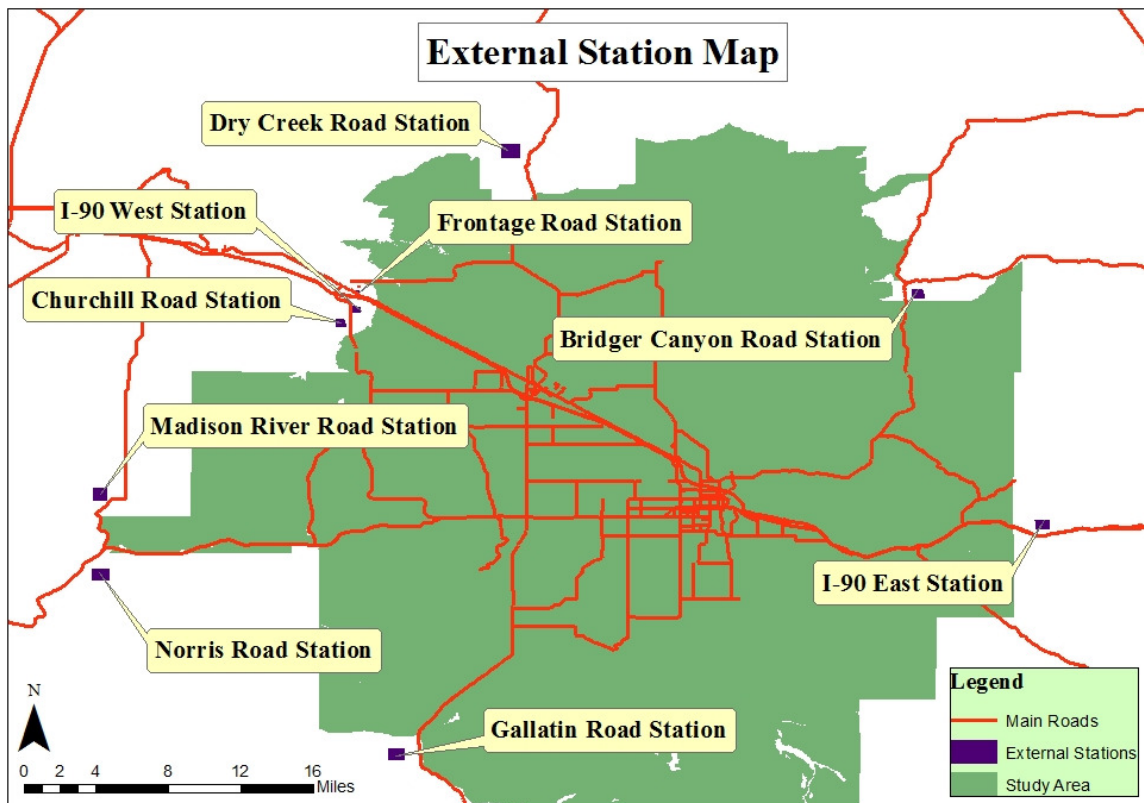


Figure 3-6: External Stations Map

The trip generation step does contain several inherent limitations. Most trip rates are static, not varying based on anything other than changes to the housing characteristics with each TAZ. The effects of changes in urban form discussed in Chapter 2 are often

ignored. Also, aggregating household characteristics for each zone may mask some of the variety within each zone, again blunting the sensitivity of the model to local accessibility. The trips are not generated as part of a logical chain. Rather, each trip is generated based on the average of some characteristic for the TAZ. This leads to issues with trip chaining which will be discussed in the next section. The basic model had absolutely no sensitivity to urban form in trip generation, as all the trips were based off simple housing units, leading to identical trip rates per housing unit for all future urban form scenarios.

Trip Distribution

The second step of the four-step process is trip distribution. In this step the productions and attractions developed in the trip generation step are paired. The methods of pairing the productions and attractions again vary between models but generally use some type of assignment method involving the relative attractiveness (i.e. more attractions than other areas) of a TAZ compared to other zones. Some type of impedance is used to incorporate the cost (in travel time) of travel between two TAZs. The results of trip distribution are represented in matrices matching productions to attractions, thus forming a table of daily person two-way trips between zones (also called a PA matrix).

The most common method used for trip distribution is the Doubly-Constrained Gravity method. This method distributes productions and attractions between zones while maximizing the entropy, or randomness, of the locations where productions and attractions are matched. The method constrains the TAZs to their original number of production and attractions. Also, the method fits the distributed trips to a certain cost distribution. The cost distribution is generally based off the minimum free-flow travel

time between zones. Zones within a short free flow time of the TAZ whose trips are being distributed will have more attractiveness than zones that are farther away, depending on the cost distribution used. The relative cost of travel between two zones is assigned a friction factor (or cost factor) based on free flow travel time between the zones. More detail will be given in the next chapter on how the trip distribution step functions.

The basic model used the doubly constrained gravity model to distribute the two-way person trips throughout the TAZ map. A free-flow travel time matrix was created, giving the shortest path (by time) between each zone and all the other zones in the map. The costs for travel between zones were assigned by using the friction factors developed for the NCHRP 365. These friction factors represented the average national travel time distribution (by frequency) for each of the three trip types modeled. Figure 5 shows the plots of the friction factors used for the model. The trip distribution step for the basic model resulted in three (one for each trip type) two-way person trip matrices for the study area.

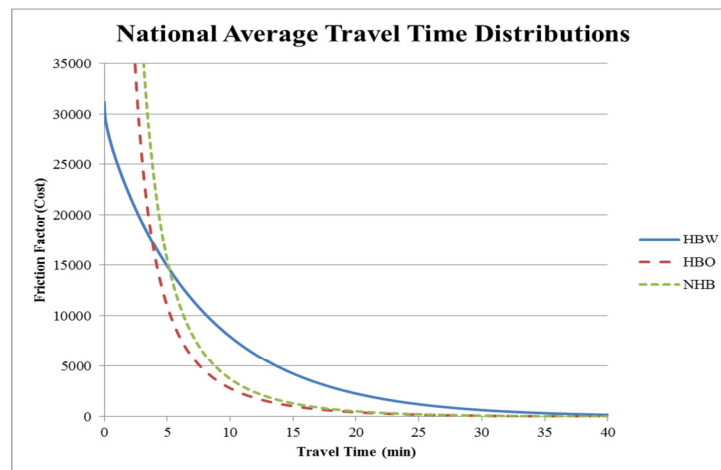


Figure 3-7: NCHRP 365 Friction Factors

Trip distribution does contain several inherent limitations as well. Trips are distributed based on free flow travel times. As congestion increases, the free flow travel times will increase, leading to different possible trip distribution patterns. This limitation can be combated by updating the free-flow travel time matrix for the network after assigning traffic and recalculating travel times. However, this feedback loop will only work if the productions and attractions can be calculated for every hour of the day, as congestion costs will be greatest during the peak hours. For a peak hour analysis only, this feedback may be feasible. The model also focused on daily travel, this feedback loop could require more data than is available. The distributed trips also do not account for trip chaining. All trips are two-way, having the same starting and ending location. However, in the real world many trips have intermediate stops, stops that cannot be modeled using trip distribution. Also, trip distribution is “not sensitive to changes in urban form.” This statement is not entirely accurate, and will be discussed further in Chapter 4.

Mode Choice/Time of Day

The third step of the four step process is mode choice/time of day. The goal of this step is to convert the production and attraction round trips into an origins and destinations, thus moving from daily person trips to hourly vehicle trips. Mode choice data is used to incorporate vehicle occupancy into the model. Future mode choice data can be projected by using base year percentages (i.e. the percent of all trips taken with transit will not change over time), by multinomial logit calculations, or other mode split prediction calculation methods.

The mode choice portion of the four-step model has been evolving rapidly in response to increased transit modeling demands. This project does not address alternative travel modes, focusing instead on personal vehicle travel. The reasons for leaving alternate modes out of the model will be discussed in the case study chapter.

Average vehicle occupancy rates may be used to convert the person-trips to vehicle trips. Multinomial logit models may also be used to predict the future utility of different forms of transportation, predicting how many people per TAZ will switch to a different mode of travel. Some models also use cost elasticity equations to determine how the mode split will vary in the future. The alternate mode trips are placed in separate matrices for traffic assignment if they are walking or pedestrian trips. Transit trips are included with vehicle trips for traffic assignment. Table 3-3 lists some of the typical vehicle occupancy rates recommended in NCHRP 365.

Table 3-3: NCHRP 365 Average Vehicle Occupancy Rates

Trip Type	Vehicle Occupancy (persons/vehicle)
Home-Based Work	1.12
Home-Based Other	1.62
Non-Home Based	1.43

Once the person trips have been assigned to a mode, the trips are then distributed over a 24 hour period, generally in one-hour segments. Some typical time of day distributions are shown in Figure 3-8. Note how widely travel varies throughout the day.

The distribution indicates the importance of having at least hourly trips when including congestion effects.

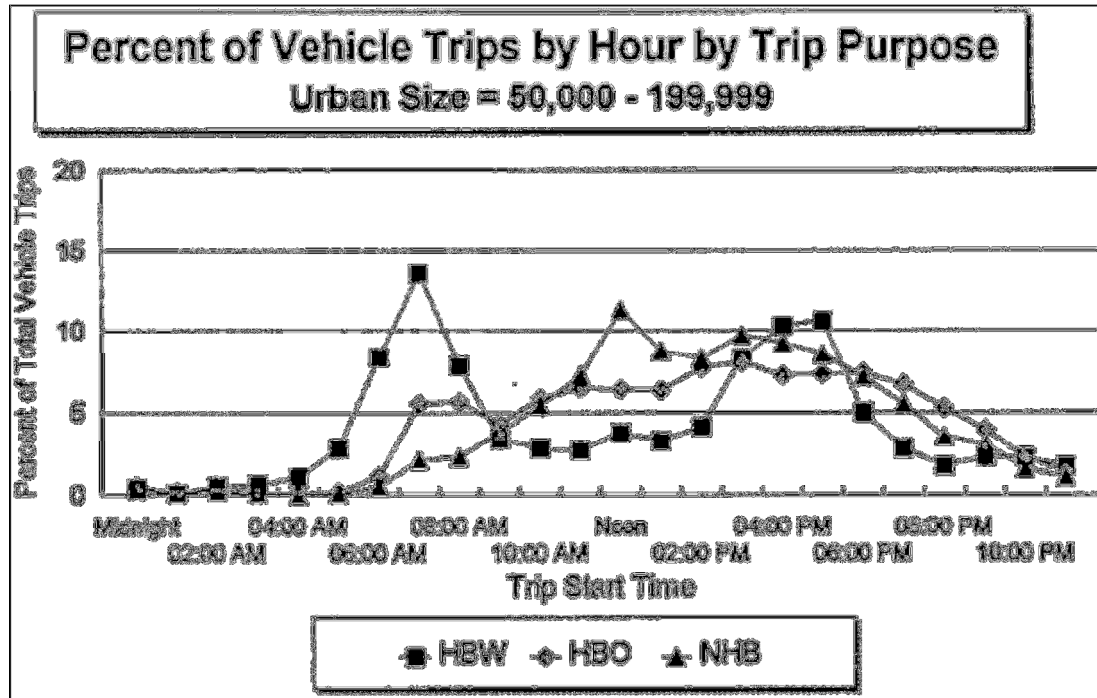


Figure 3-8: NCHRP 365 Hourly Trip Distribution (NCHRP 1998)

The basic model converted the person trips to vehicle trips using the average vehicle occupancy values shown in Table 3-4. These occupancy values are used by MDT and are expected to represent typical Montana vehicle occupancies.

Table 3-4: Montana Vehicle Occupancies

Trip Type	Vehicle Occupancy (persons/vehicle)
Home-Based Work	1.4
Home-Based Other	1.9
Non-Home Based	1.6

The trips were not broken down by time of day, as the main goal of the model was not to represent individual link flows, but rather to compare total travel in the form of total daily vehicle miles traveled (VMT). The results were three one-way vehicle trip matrices (one for each trip type), which were then combined to form a single vehicle trip matrix. The through trips for I-90 were added to this final matrix (called an Origin-Destination, or OD matrix). Before calibration the model generated 547137 vehicle trips (including 9594 I-90 through trips).

Traffic Assignment

The final step in the four-step process is trip assignment, sometimes called route choice. The goal of this step is to establish the link flows. These flows are calculated from the origin-destination (O-D) matrices developed in the mode choice/time of day step. There are several methods for assigning these vehicle trips to the network. The two most common methods are User Equilibrium and All or Nothing (AON).

User equilibrium assumes that as congestion delay rises, drivers will seek alternative routes until all vehicles traveling between two zones will take the shortest route available, and all of the shortest route available between the two zones will have equal travel times. This method uses some function that increases travel time as a link volume approaches or exceeds the capacity for a given road. The most common function used is the Bureau of Public Roads (BPR) Function, given in Equation 3-1. Trips are first assigned to the shortest routes between zones based on the free flow travel times. Once the trips are assigned, the travel times are recalculated with the BPR function using the assigned traffic volume and the road capacity. If the route is no longer the shortest

available, the shortest route now available receives a portion of the travel. This process continues iteratively until user equilibrium is achieved.

$$t_{f,i} = t_{0,i} \times \left[1 + \alpha \times \left(\frac{v_i}{c_i} \right)^\beta \right]$$

Equation 3-1

Where:

t_f = the actual speed on link i

$t_{0,i}$ = the free flow speed on link i

v_i = the traffic volume on link i

c_i = the capacity of link i

α and β are coefficients, generally 0.15 and 4.0 respectively but varying between different highway classification types

All or Nothing (AON) traffic assignment is much simpler. Congestion is not taken into account, with all trips simply taking the shortest route available based on free-flow travel times. AON analysis is not recommended for peak hour analysis (which is used to identify locations for network improvements). However, AON is very useful for models concerned with total VMT, as the changes in VMT due to congestion are often quite small. Also, AON is very good for any VMT comparison analysis. AON assignment models can be difficult to validate at times due to the lack of traffic shift caused by congestion. Cut lines (discussed in the next section) may be used to combat this validation issue.

The basic model used AON assignment as the main focus of the model was not to exactly represent link flows, but only to produce the total daily VMT for the area. The

trips were assigned using the free flow travel times for all the links in the network. The resulting link flows for the finalized base year model are shown in Figure 3-9.

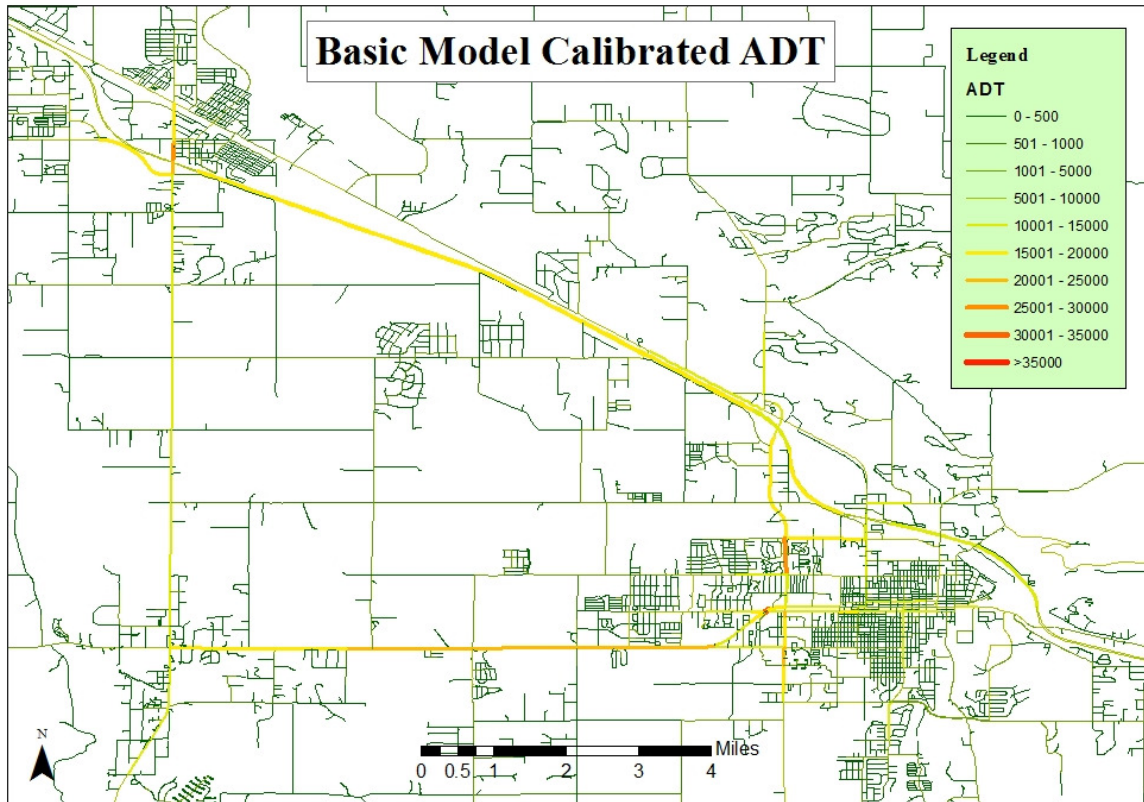


Figure 3-9: Basic Model Base Year ADT

Validation and Calibration

Any travel demand model should use some type of validation and calibration. The most common validation data is average daily traffic (ADT) volume. This data is generally available from the city, county or state department of transportation. ADT data can also be collected fairly easily either with road tubes or manual counts. While ADT is never available for every street segment, counts are usually maintained along higher

volume principal roads. The ADT data can then be compared to the base year network flows output by the travel demand model.

Some typical validation measures are ADT ratios, VMT ratios, root mean square error, cut lines, and screed lines. ADT ratios simply select all links containing real ADT data, and divide the model ADT by the real ADT. If the average of these ratios is near 1.0 and the standard deviation is not too high, the model is performing well. VMT ratios work the same way, using model VMT over real VMT. However, averaged VMT ratios can easily be biased by long high volume links. Root mean square error accounts for both the variation and average of the ADT ratios (see Equation 3-2). Cut lines are used when several adjacent major roads have available traffic counts. A cut line is used to compare the total model ADT to the total actual ADT for all the segments cut. Screed lines perform a similar function, except that they are cut across the entire study region.

$$\%RMSE = 100\% \times \left[\frac{\sqrt{\frac{\sum_{i=1}^n (ADT_{m,i} - ADT_{a,i})^2}{n}}}{\frac{\sum_{i=1}^n ADT_{a,i}}{n}} \right]$$

Equation 3-2

Where:

$ADT_{m,i}$ = The modeled Average Daily Traffic on link i

$ADT_{a,i}$ = The actual Average Daily Traffic on link i

n = the number of links with measured actual average daily traffic

Additional validation can be performed after each step of the four-step process, providing data is available. Some travel surveys provide enough data to determine the total production and attractions for at least some of the TAZs in a study region. This data

can be used to validate and calibrate the trip generation rates. Trip distribution can be validated by comparing the travel time distribution to an actual local travel time distribution. The total trips in the O-D matrix can be validated against local estimates for total daily and/or peak hour travel. And the final validation comes after the trips are assigned, matching model ADT to actual ADT.

Four-step models have numerous calibration lever arms. The specific calibrations made are generally up to the engineering judgment of the travel modeler. A common calibration method is to adjust the trip rates to increase or decrease total trips, either for the entire region or for some certain TAZs. The travel time distribution used during the trip distribution step can also be modified to help calibrate the model. Vehicle occupancies and the time of day distribution can be changed as another calibration technique. Other methods may also be used, but they are beyond the scope of this project.

The basic model was validated through the RMSE and the average ratio of measured to predicted ADT for the base year. The trip rates were multiplied by the average measured ADT over the average predicted ADT to adjust the trip productions. This calibration factor is shown in the trip rate equations listed in the trip generation section. The entire four-step model was then re-run using the new trip rates, and the final results (shown in Table 3-5) were determined to be satisfactory, as the %RMSE was less than 50% and the average predicted ADT was within 5% of the measured ADT.

Table 3-5: Base Year Calibration Results

	Initial Base Year Model	Calibrated Base Year Model
Total Trips	547,137	320,017
Total VMT	3,369,186	2,169,999
%RMSE	111.3%	49.0%
Modeled to Actual ADT Ratio	1.7515	1.0254

Application of Basic Model

After the basic model was calibrated, two future scenarios representing different urban forms were run based off the Envision Tomorrow land use model output provided by the Sonoran Institute. The Business As Usual scenario predicted growth in the Gallatin Valley to continue following current trends, while the Alternate scenario predicted more high land use mix and high density future development. More detail into the specific characteristics of the two future scenarios is given in the presentation of the final modified model described in Chapter 5. For this chapter, the only information required is that the populations for the two scenarios were equal (same number of housing units). The future scenarios were run using the same process as the base year model. The ADT for the external stations was calculated by multiplying the base year ADT by the ratio of the future year population to the base year population. The link flows for the two future scenarios are shown in Figure 3-10.

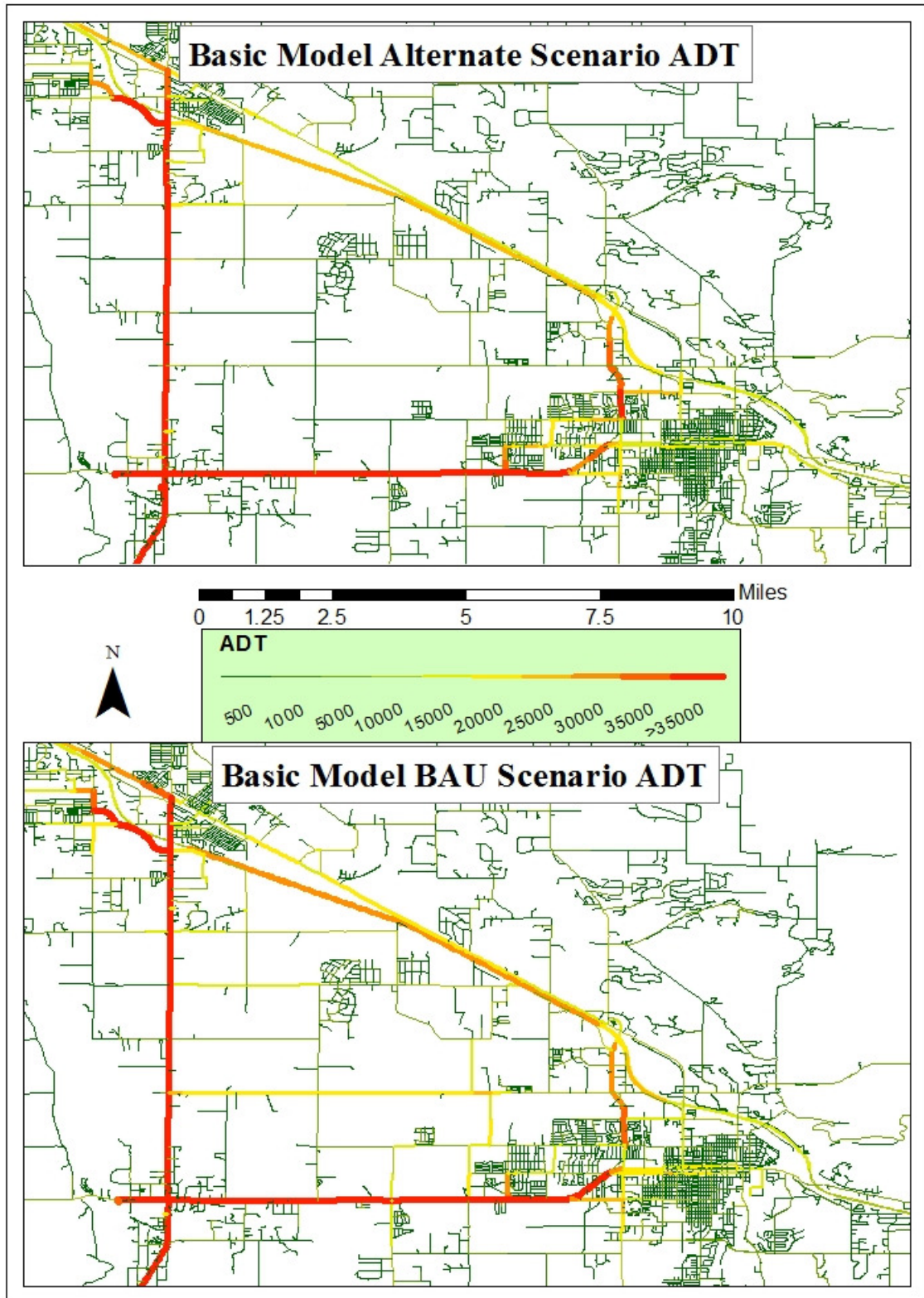


Figure 3-10: Basic Model Future Scenario ADT

The final results for the basic model application are summarized in Table 3-6.

These values were used to calculate the elasticity of the average trip lengths produced by the model to the urban form variables of density and land mix. The effect of density and land use mix could not be calculated separately from the results, so the average effect of the two variables was calculated instead.

Table 3-6: Basic Model Results

	Base Year	BAU Scenario	Alternate Scenario
Total Trips	320,017	543,001	548,061
Total VMT	2,169,999	4,263,495	3,666,503
Total Housing Units	32,344	54,346	54,889
Trips/Housing Unit	9.89	9.99	9.99
Average Trip Length (miles)	6.781	7.852	6.690
Average Density ² (population + employment/mi ²)	5057	3276	9608
Average Land Use Mix ³	0.670	0.457	0.496

Conclusion

The basic four-step model was developed, calibrated, and then applied to two potential future scenarios each with nearly the same population, but different urban form. The total VMT for the two scenarios was expected to be the same. Table 3-7 provides the

² Weighted by zonal population

³ Calculated by Equation 2-2 and weighted by zonal population

calculated elasticity values for the basic four-step model applied to the Envision Tomorrow scenarios. Note that the elasticity of the BAU scenario to the two urban form variables was far higher than it was for the alternate scenario. These results indicated that at least one of the two urban form variables probably did not have a linearly elastic effect on the average trip length.

Table 3-7: Elasticities

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 6)	Modified Model Resulting Elasticity (Ch. 6)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04	None			
	Land Use Mix	-0.06	None			
Average Trip Length (per trip)	Density	-0.05	-0.021 (ALT) -0.236 (BAU)			
	Land Use Mix	-0.05				

These results indicated a definite sensitivity within the four-step modeling process to changes in land use mix and or density. However, the results varied between the two future scenarios, indicating a non-linear sensitivity. The next chapter details this project's attempt to quantify the inherent sensitivity of the four-step process.

CHAPTER 4

SENSITIVITY OF THE FOUR-STEP PROCESS TO CHANGES IN URBAN FORM

Introduction

As discussed in Chapter 1, travel behavior is sensitive to changes in urban form. However, the four-step model is not designed to include this sensitivity. But the preliminary results from the project indicated that the four-step model did include some sensitivity to changes in urban form. The inherent sensitivity of the modeling process was identified to be coming from two steps, trip generation and trip distribution. This chapter will investigate the sensitivity of the four step model contained within these two steps.

Trip Generation Sensitivity

The most basic four step modeling process (as described in Chapter 3) has no sensitivity to changes in urban form in the trip generation step. The household trip rates were only dependent on the number of housing units within each zone. However, the modified model discussed further in Chapter 5 utilized a different set of trip rates that did result in a sensitivity calculated here. The data provided by the Sonoran Institute for the project broke down the housing unit data into three types: Single-family (SF), Multi-family (MF), and Townhome (TH) housing units. These three housing types typically produce the average trip rates shown in Table 4-1.

Table 4-1: ITE Housing Unit Trip Generation Rates (ITE 2003)

Housing unit type	Daily one-way vehicle trips per housing unit
Single-family unit	9.57
Multi-family unit	6.72
Townhome unit	5.86

The ITE trip rates indicate that neighborhoods with more multi-family and townhome housing units will produce fewer trips per unit than a neighborhood consisting primarily of single-family units.

The Sonoran Institute's land use model consisted of 18 different development types. These development types are summarized in Table 4-2.

Table 4-2: Sonoran Land Use Model Development Types

	Housing Units / Gross Acre	Jobs / Gross Acre	Land Use Composition (%)		
			Single Family	Townhome	Multi-family
Urban Core	159.95	869.16	-	-	34%
City Center	319.90	71.09	-	-	90%
Town Center	100.71	35.54	-	-	85%
Village Center	41.47	35.54	-	-	70%
Mixed-Use Corridor	26.27	35.02	-	-	60%
Main Street	648.56	-	-	-	100%
City Neighborhood	14.01	-	-	100%	-
Town Neighborhood	12.51	-	-	100%	-
Village Neighborhood	8.11	-	100%	-	-
Suburban Residential	5.84	-	100%	-	-
Rural Residential	2.92	-	100%	-	-
Office Park	-	250.16	-	-	-
Regional Retail	-	17.51	-	-	-
Strip Commercial	-	29.19	-	-	-
Flex Park	-	7.30	-	-	-
Industrial Park	-	7.30	-	-	-
Educational	-	125.08	-	-	-
Open Space	-	-	-	-	-

In order to estimate the elasticity of trip rates to density (measured as employment plus population per area) the 18 different land development types were mixed together to form typical square mile developments. The data from Table 4-1 and Table 4-2 was combined to calculate the average trip rate and density for each typical development. Note that the density calculations assumed the average housing unit occupancy to be 2.5 persons, regardless of the housing unit type. The densities and trip rates were plotted against each other and regression analysis was run to determine the arc elastic relationship between the two variables. Figure 4-1 shows the trip rates plotted versus the density for 22 different development type combinations.

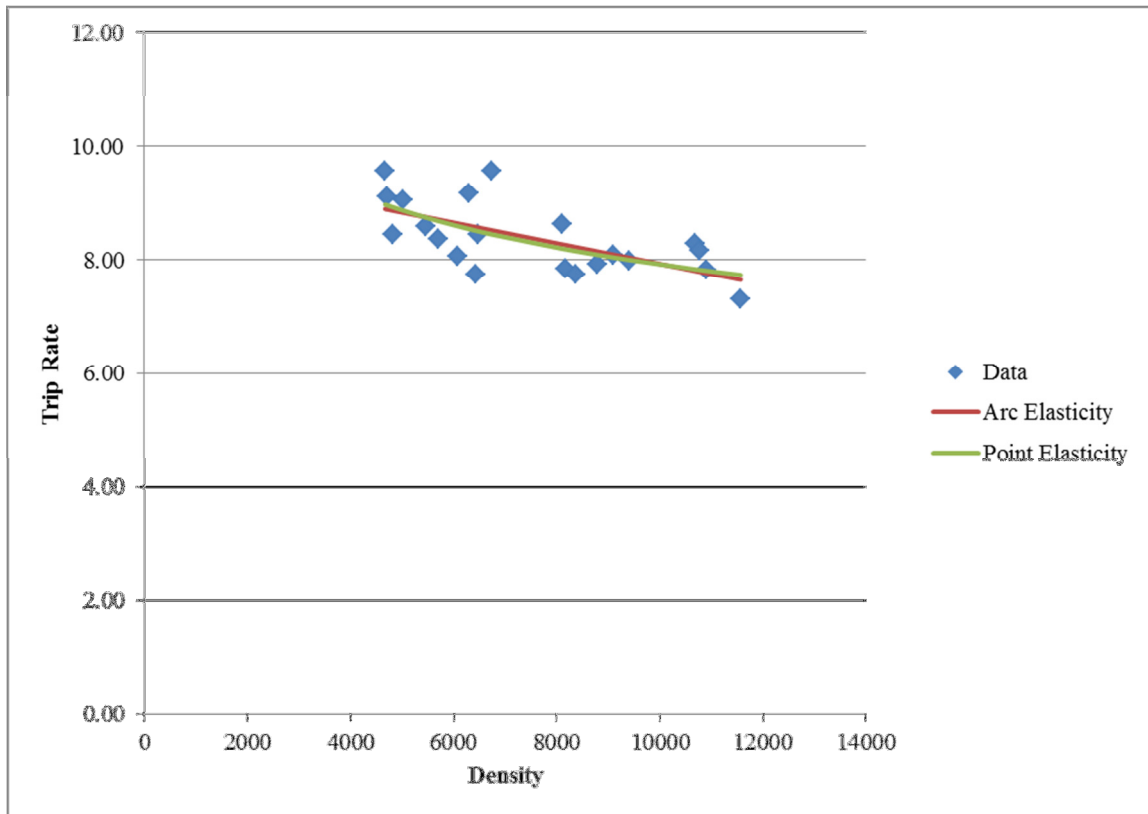


Figure 4-1: Trip Rate Sensitivity to Density

Although the point elasticity has a slightly better regression fit to the data, arc elasticity was ultimately selected to represent the relationship. Arc elasticity relates better to the literature descriptions of the sensitivity of trip rate to changes in density. Neither the arc nor the point elasticity provided a good fit to the data. Therefore, the arc elasticity was selected. Table 4-3 summarizes the elastic relationship between the density and trip rate variables.

Table 4-3: Trip Rate Elasticity to Density

Type	Elasticity	R squared
Arc Elasticity	-0.086	0.426
Point Elasticity	-0.162	0.446

As shown in the results, the regression fits were not very accurate. However, they did represent the general trend between increased density and decreased trip rate. The arc elasticity was chosen as the modified elasticity of the model to density. No elastic correlation could relate the land use mix to the trip rates based on the same development mix data. Table 4-4 shows the updated elasticity table.

Table 4-4: Elasticities

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 6)	Modified Model Resulting Elasticity (Ch. 6)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04	None	None	-0.086	
	Land Use Mix	-0.06	None	None	None	
Average Trip Length (per trip)	Density	-0.05	-0.021 (ALT) -0.236 (BAU)			
	Land Use Mix	-0.05				

Trip Distribution Sensitivity

The second portion of the investigation into the inherent sensitivity of the basic four-step model analyzed the trip distribution step of the process. This section begins with a more detailed description of the trip distribution step, giving some background as to the calculations behind the step. Then the effects of the two urban form variables (density and land use mix) were analyzed independently through a series of idealized urban/rural development scenarios. The results from the idealized scenarios were then used to develop elastic sensitivities for some general city types. The final products were some elasticity values and equations representing the inherent sensitivity of trip distribution to changes in the density and land use mix.

Friction Factors

As discussed in Chapter 3, trip distribution uses friction factors to determine the relative attractiveness of travel between TAZs. These friction factors are usually modeled

after some sort of travel time distribution. When no local data is available, the national average travel time distribution is typically used. For this project, no local travel time distribution data was available. Therefore, the national distribution was used. Figure 4-2 shows the national travel cost (cost defined as a relative friction factor) distribution by travel time for three different trip types, home-based work (HBW), home-based other (HBO), and non-home based (NHB).

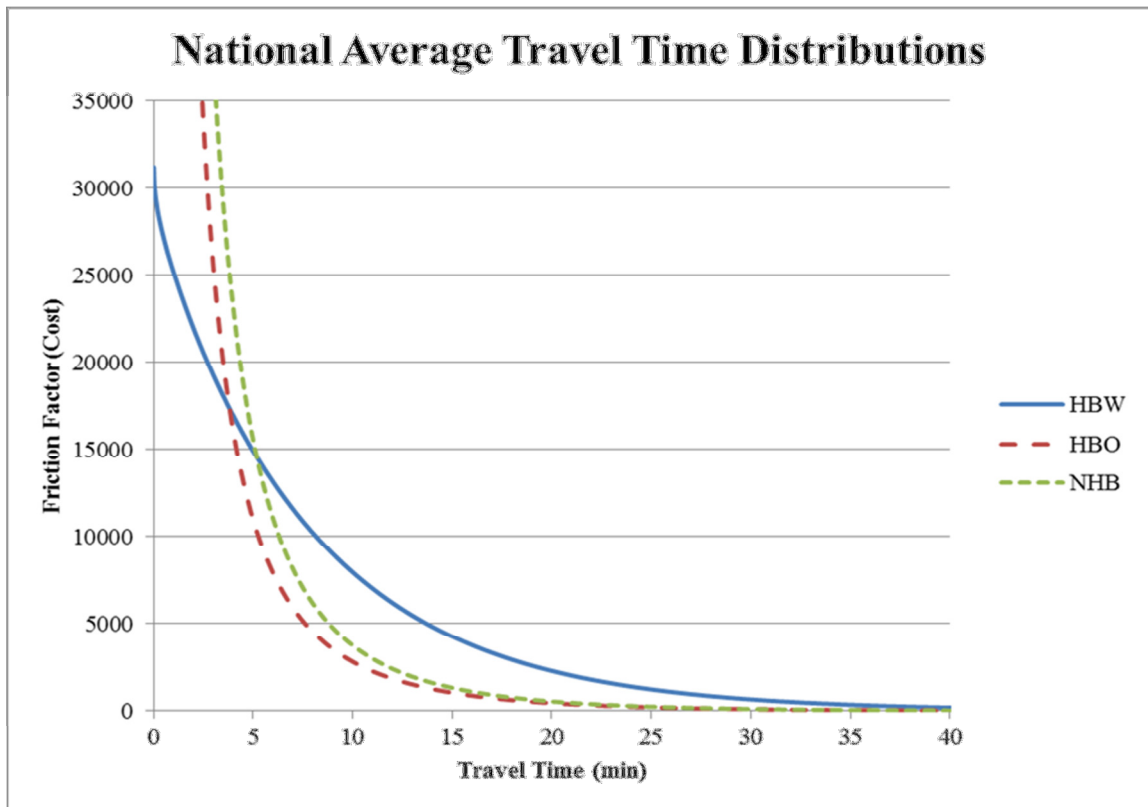


Figure 4-2: NCHRP 365 Friction Factors

If the friction factors are normalized into the form of a probability density function (area under the curve = 1.0), the distribution is expected to match the travel time distribution of the two-way person trips output by the trip distribution step. However,

preliminary model results indicated that high-mix, high density development provided a more natural fit to the distribution and lower (or at least nearer to expected) travel times, while low-mix, low density development led to a poorer fit and higher average travel times. The following sections attempt to quantify the sensitivity of the friction factor distribution to changes in urban form in terms equivalent to the urban form measures identified in Chapter 1.

Empirical Scenario Layout

To better understand the effects of variation in specific urban form variables, an idealized analysis region layout was developed. The goal of the layout was to eliminate all factors that might affect the trip distribution step with the exception of the urban form variables under investigation. The two urban form variables selected for investigation were land use mix and total density. These variables were selected because of their quantifiable relationships to average trip length. Other researched urban form variables could not be quantified in the model, or did not have a clear relationship to average trip length.

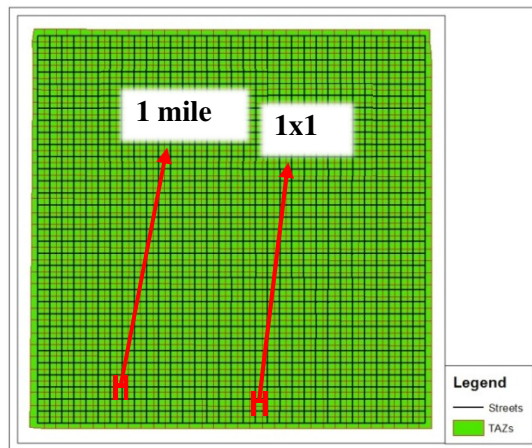


Figure 4-3: Empirical Scenario Layout

The empirical scenario layout (shown in Figure 4-3) was designed as a square grid of 1089 (33 by 33) TAZs. Each TAZ was a square, with an area of one square miles. A grid road network was used to connect all the TAZs together. The road network also consisted of one mile by one mile blocks. Each TAZ contained an intersection. All street segments were given a speed of 30 mph (two minutes travel time for every one mile segment). Centroid connectors were used to connect each TAZ to its' intersection. The centroid connectors were all assigned a travel time of 0.1 minutes. Therefore, the shortest possible trip from one TAZ to another was 2.2 minutes (one segment length plus two centroid connectors). This general model layout was used for all the empirical tests performed on the trip distribution step.

The consistent segment lengths, speeds, and travel times helped to simplify the analysis area. The size of the TAZs made density calculations easy. The size of the TAZs was also roughly equivalent to the area of influence where urban form variables are known to impact travel behavior (see Chapter 1). The large number of TAZs used for the empirical analysis helped to minimize biases due to an overly-aggregated analysis area.

Elasticity Equations

The first step in developing the empirical scenarios was to put the elasticity equations for land use mix and total density in terms easily modeled on the idealized layout. The equations for density and land mix developed by DKS Associates are given in Equation 4-1 and Equation 4-2. These variables were in terms of population and employment.

$$Density = \frac{Population + Employment}{Area}$$

Equation 4-1

$$Land\ Use\ Mix = 1 - \frac{|b \times Population - Employment|}{b \times Population + Employment}$$

Equation 4-2

Where $b = \frac{Total\ Regional\ Employment}{Total\ Regional\ Population}$

To simplify the model, population was assumed to be equivalent to productions and employment was assumed to be equivalent to attractions. For a travel demand model to function, the productions and attractions must be equal. Therefore, for the modified land use mix variable the b ratio factor is equal to 1.0. Equation 4-3 and Equation 4-4 show the modified density and land use mix equations.

$$D_i = \frac{P_i + E_i}{1\ mile^2}$$

Equation 4-3

$$LM_i = 1 - \frac{|1.0 \times P_i - E_i|}{1.0 \times P_i + E_i}$$

Equation 4-4

Where P_i and E_i are the population and employment for TAZ_i , the $1\ mile^2$ is area of TAZ_i , D_i is the total density of TAZ_i , and LM_i is the land use mix of TAZ_i .

The DKS associates variables were developed to be applied as arc elasticity with respect to VMT per trip, or average trip length. The form of the DKS associates elasticity equations is shown in Equation 4-5 and Equation 4-6.

$$\text{Density: } e = \frac{\% \Delta D}{\% \Delta V} = \frac{\frac{D - D_b}{D_b}}{\frac{V - V_b}{V_b}} \rightarrow V = V_b \times \left[e \times \left(\frac{D - D_b}{D_b} \right) + 1 \right] \rightarrow$$

$$\rightarrow V = e \times \frac{V_b}{D_b} \times D + (1 - e) \times V_b$$

Equation 4-5

$$\text{Land Use Mix: } e = \frac{\% \Delta LM}{\% \Delta V} = \frac{\frac{LM - LM_b}{LM_b}}{\frac{V - V_b}{V_b}} \rightarrow V$$

$$= V_b \times \left[e \times \left(\frac{LM - LM_b}{LM_b} \right) + 1 \right] \rightarrow$$

$$\rightarrow V = e \times \frac{V_b}{LM_b} \times LM + (1 - e) \times V_b$$

Equation 4-6

Where:

 D = Density V = VMT D_b = Base year density V_b = Base year VMT e = Arc elasticity LM = land use mix LM_b = Base year land use mix.

The DKS Associates elasticity equations were modified for the empirical model as shown in Equation 4-7 and Equation 4-8. Travel time was substituted for VMT (or average trip length per household). This was a fair substitute given the characteristics of the grid layout, as all of the travel speeds were equal, making trip length and trip time

directly proportional. Equation 4-9 shows the relationship between VMT and travel time for the model.

$$\text{Density: } t_i = e \times \frac{t_{bi}}{D_{bi}} \times D_i + (1 - e) \times t_{bi} \quad \text{Equation 4-7}$$

$$\text{Land Use Mix: } t_i = e \times \frac{t_{bi}}{LM_{bi}} \times LM_i + (1 - e) \times t_{bi} \quad \text{Equation 4-8}$$

$$t_i = \frac{VMT_i}{\text{total trips}_i} \times \frac{1}{\text{Average Link Speed (30 mph)}} \quad \text{Equation 4-9}$$

Where:

t_i = Model year average travel time for TAZ_i

e = Arc elasticity

t_{bi} = Average base year travel time for TAZ_i

D_i = Model year density for TAZ_i

LM_i = Model year land use mix for TAZ_i

D_{bi} = Base year density for TAZ_i

LM_{bi} = Base year land use mix for TAZ_i

VMT_i = Total VMT produced by TAZ_i.

To determine the inherent sensitivity of the trip distribution step to changes in urban form, two elasticity sensitivities would be calculated, arc elasticity and point elasticity. Arc elasticity is the sensitivity predicted by the DKS method and the derivation and equations are shown in Equation 4-5 and Equation 4-6. Point elasticity assumes that the elasticity is not totally dependent on a base value, but also on the magnitude of the % change of the independent variable, in the case of this study land use mix and density.

Equation 4-10, Equation 4-11 and Equation 4-12 summarize the derivation and final form of a point elasticity equation in terms of average travel time and density.

E = Point Elasticity

t = avg. travel time (min)

t₀ = base year travel time (min)

D = Density (as previously defined)

D₀ = Base Year Density

Equation Development:

$$\begin{aligned} E = \frac{dt}{dD} \times \frac{D}{t} &\rightarrow \frac{dt}{t} = \frac{E}{D} \times dD \rightarrow \int \frac{1}{t} dt = \int \frac{E}{D} dD \rightarrow \ln(t) = E \times \ln(D) + C \\ &= E \times \ln(D) + \ln(C) \rightarrow t = D^E \times C \end{aligned}$$

Equation 4-10

Solving for C in terms of t₀ and D₀:

$$t_0 = D_0^E \times C \rightarrow C = \left(\frac{t_0}{D_0^E} \right)$$

Equation 4-11

Final Equation:

$$t = \left(\frac{t_0}{D_0^E} \right) \times D^E$$

Equation 4-12

Effects of Land Use Mix

The effects of variation in land mix on trip distribution were analyzed in three different sets of scenarios. Each set of scenarios represented a general type of urban form. For each scenario modeled, the average travel time according to the NCHRP 365 national

average travel time distribution for work trips was calculated, along with the maximum and minimum possible modeled travel times. Theoretically, all scenarios modeled using the NCRHP 365 national average travel time distribution should have had the same average travel times. The minimum average travel time was modeled by using an average travel time distribution with an average of one minute. As one minute is less than half of the lowest possible travel time given the layout (2.2 minutes), this distribution essentially forced all trips to match up to the nearest possible TAZ. The maximum average travel time was calculated by assigning equal cost to every route, essentially removing the effect of travel time. This forced all trips to be distributed randomly between all TAZs in the layout. It should be noted that this is not the actual maximum average travel time, but is the highest possible maximum average travel time that can be modeled by the doubly constrained gravity model.

For all of the modeled scenarios, trips were distributed between the TAZs using the free flow travel times. No congestion costs were used. For each model run, each person was assumed to make one round trip to work per day. Therefore, the total population and total employment were made equal for every scenario. Each set of scenarios consisted of a base year scenario and several alternative future scenarios. To better represent real life alternative modeling all of the future scenarios were given equal total populations (and employment).

Land Use Mix - Stratified City: The first set of land use mix scenarios investigated was based on a stratified city layout. The layout was separated into two equal halves (see Figure 4-4). The suburbs half of the city contained more population

than employment while the Central Business District (CBD) half of the city contained more employment than population. Note that the center TAZ had an even (perfect) mix for all of the scenarios run. This was done to make an equal number of TAZs in the suburbs and in the CBD, a necessary adjustment to keep the density equal throughout the layout (the total number of TAZs was an odd number, 1089). A base year and twenty future scenarios were run on the layout. Each scenario had equal density (per the DKS Associates 2007 definition) but varied land use mix. Table 4-5 summarizes the characteristics for each scenario.

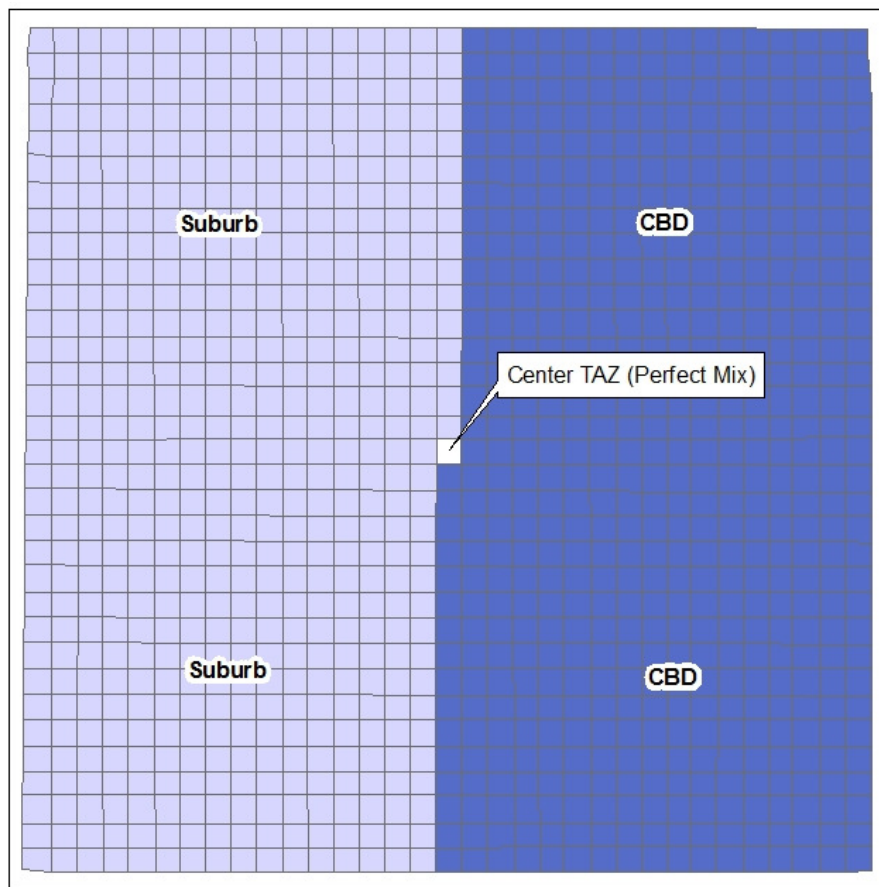


Figure 4-4: Stratified City Land Use Mix Layout

Table 4-5: Stratified City Land Use Mix Scenario Characteristics

Scenario	Suburb Side			CBD Side		
	Population/ TAZ	Employment/ TAZ	%LM ⁴	Population/ TAZ	Employment/ TAZ	%LM ¹
Base	975	25	5%	25	975	5%
1	1000	1000	100%	1000	1000	100%
2	1050	950	95%	950	1050	95%
3	1100	900	90%	900	1100	90%
4	1150	850	85%	850	1150	85%
5	1200	800	80%	800	1200	80%
6	1250	750	75%	750	1250	75%
7	1300	700	70%	700	1300	70%
8	1350	650	65%	650	1350	65%
9	1400	600	60%	600	1400	60%
10	1450	550	55%	550	1450	55%
11	1500	500	50%	500	1500	50%
12	1550	450	45%	450	1550	45%
13	1600	400	40%	400	1600	40%
14	1650	350	35%	350	1650	35%
15	1700	300	30%	300	1700	30%
16	1750	250	25%	250	1750	25%
17	1800	200	20%	200	1800	20%
18	1850	150	15%	150	1850	15%
19	1900	100	10%	100	1900	10%
20	1950	50	5%	50	1950	5%

The shifting land use mix of the CBD and suburbs represented an increasingly diverse urban form. Initially, the city was divided between the employment (CBD) region and the population (suburb) region. However, the shifting land use mix led to a more even mix throughout the city, finally resulting in a city with equal employment and population in each zone. The results from the stratified city land mix scenarios are given in Table 4-6. As shown in Figure 4-5, the average travel time decreased for all the trips produced in the suburbs as the land use mix in the suburbs increased. This indicated that

⁴ %LM calculated per Equation 4-5 as a percent

trips from the suburbs grew shorter (both in time and distance) as the employment in the suburbs increased.

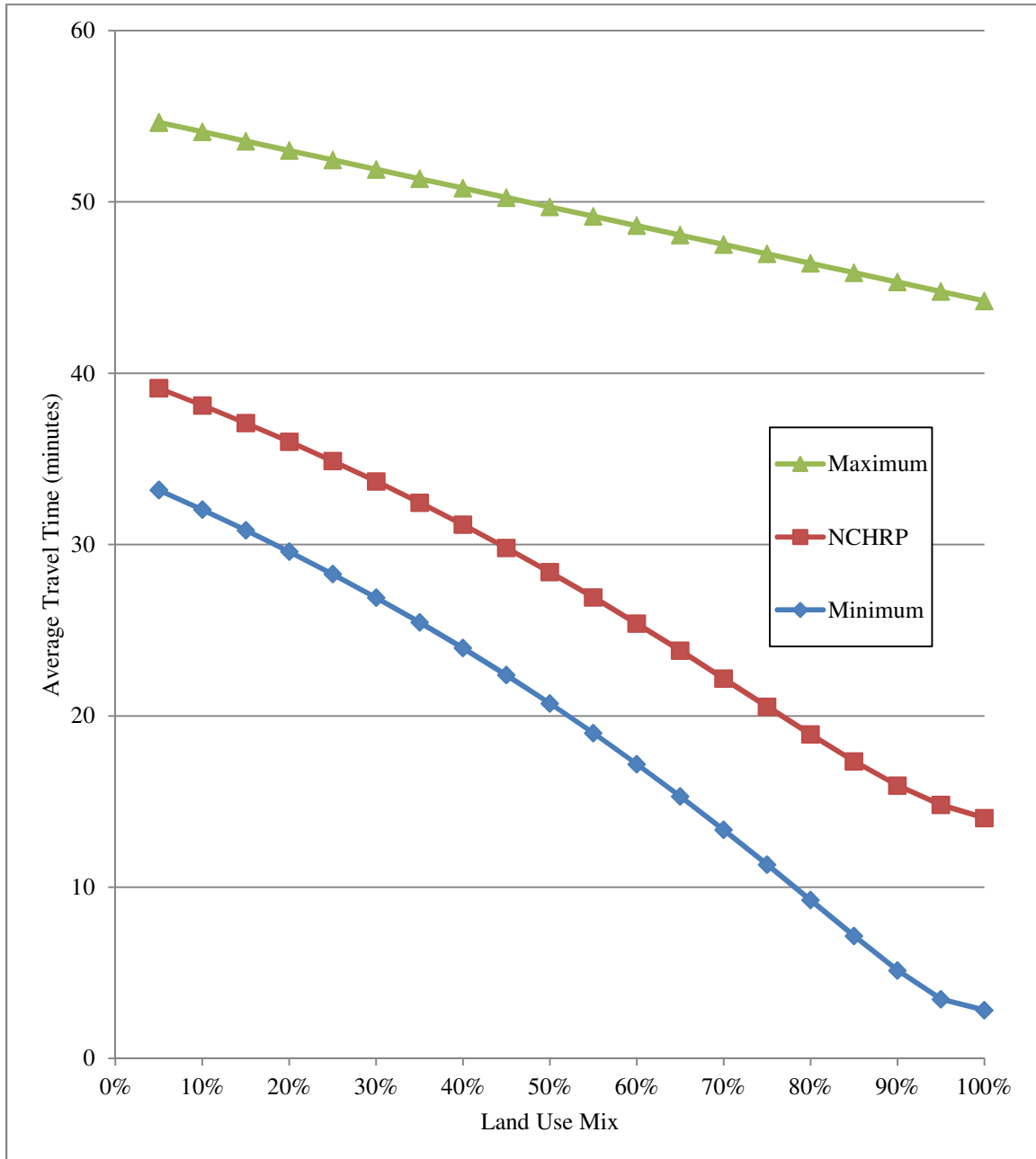


Figure 4-5: Stratified City - Suburb Results

As shown in Figure 4-6, the average travel time did not vary greatly as the population in the CBD zones increased. This indicated that as long as the employment within a zone was greater than the population, a resident's average travel time would remain constant.

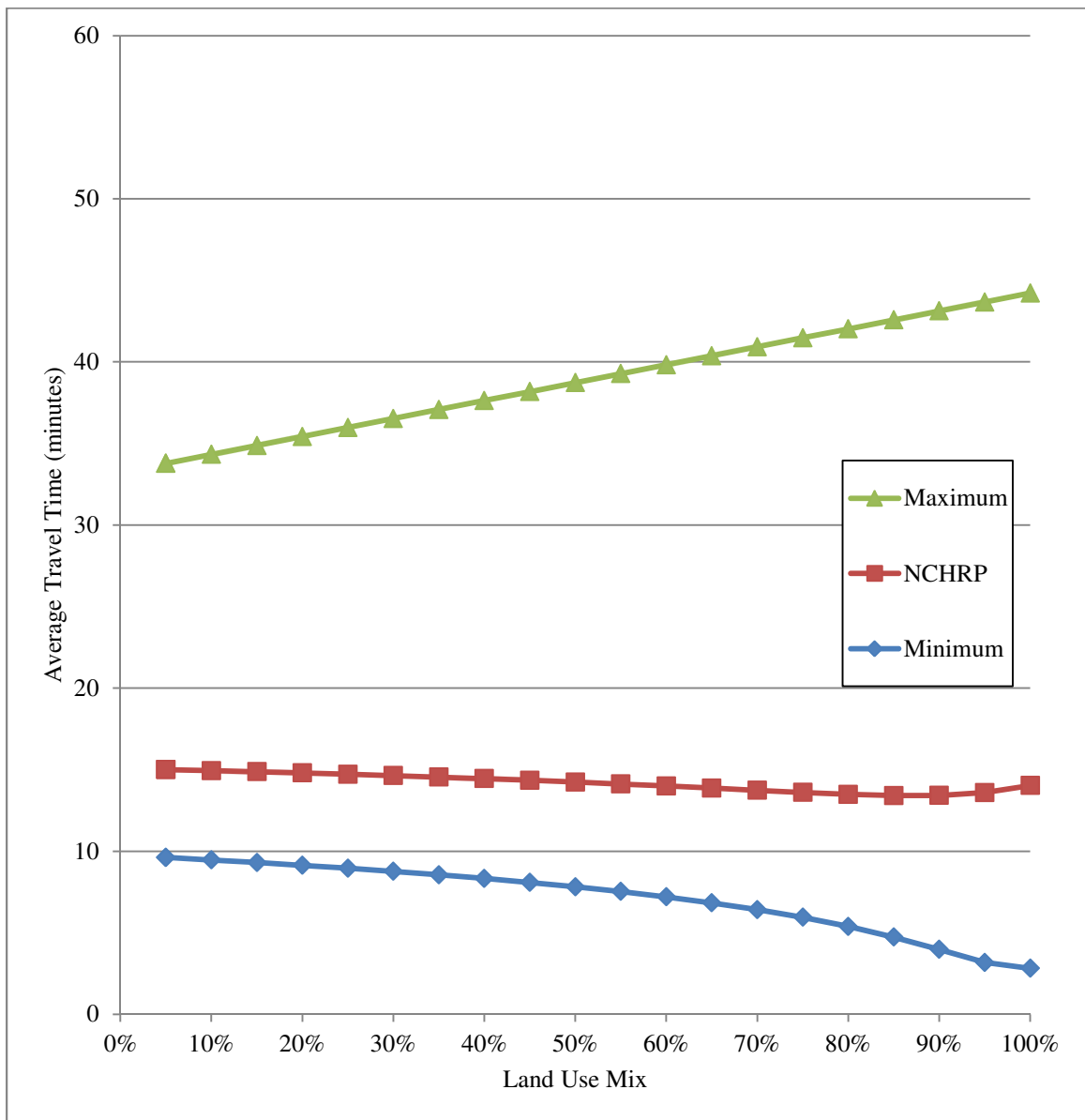


Figure 4-6: Stratified City - CBD Results

Table 4-6: Stratified City Land Use Mix Scenario Results

Scenario	Suburbs Average Travel Time (min)			CBD Average Travel Time (min)		
	Minimum	NCHRP	Maximum	Minimum	NCHRP	Maximum
Base	33.18	39.12	54.64	9.62	15.01	33.77
1	2.82	14.04	44.22	2.82	14.03	44.22
2	3.46	14.80	44.77	3.18	13.59	43.67
3	5.14	15.94	45.32	3.98	13.42	43.12
4	7.16	17.35	45.87	4.74	13.41	42.57
5	9.25	18.92	46.42	5.39	13.49	42.02
6	11.32	20.54	46.96	5.95	13.60	41.47
7	13.35	22.18	47.51	6.42	13.73	40.92
8	15.30	23.81	48.06	6.84	13.87	40.37
9	17.19	25.39	48.61	7.20	14.00	39.82
10	19.00	26.92	49.16	7.53	14.12	39.27
11	20.73	28.39	49.71	7.82	14.24	38.72
12	22.38	29.81	50.25	8.09	14.35	38.17
13	23.96	31.16	50.80	8.33	14.45	37.62
14	25.46	32.45	51.35	8.55	14.54	37.07
15	26.90	33.69	51.90	8.76	14.63	36.52
16	28.27	34.88	52.45	8.95	14.72	35.97
17	29.59	36.01	53.00	9.13	14.80	35.42
18	30.84	37.09	53.54	9.30	14.87	34.87
19	32.04	38.13	54.09	9.46	14.94	34.32
20	33.18	39.12	54.64	9.62	15.01	33.77

To determine the elasticity of the land use mix with respect to density, a linear (for arc elasticity) and logarithmic (for point elasticity) regression was run to determine the best fit to the data. The calculations and equations used for the regressions are given in Appendix A. The elasticity regression equations are plotted with model data in Figure 4-7 and Figure 4-8. The resulting arc elasticity and point elasticity for the stratified city layout are given in Table 4-7, along with the goodness of fit statistics for the functions.

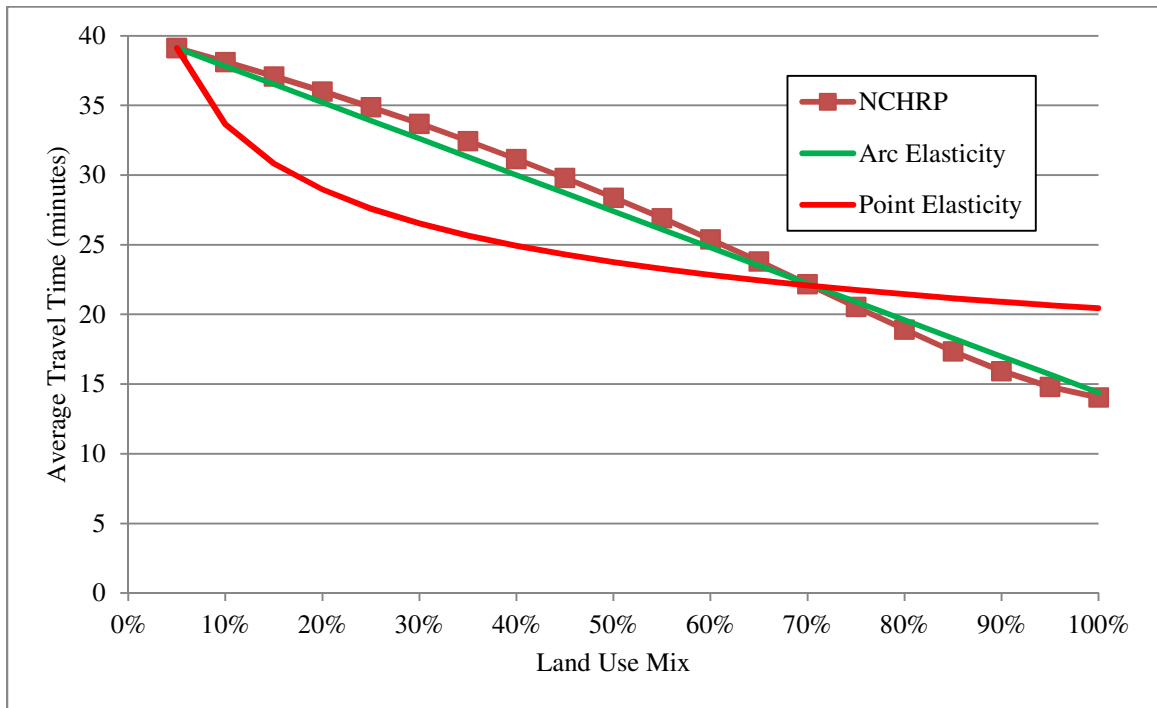


Figure 4-7: Stratified City – Suburb Elasticity

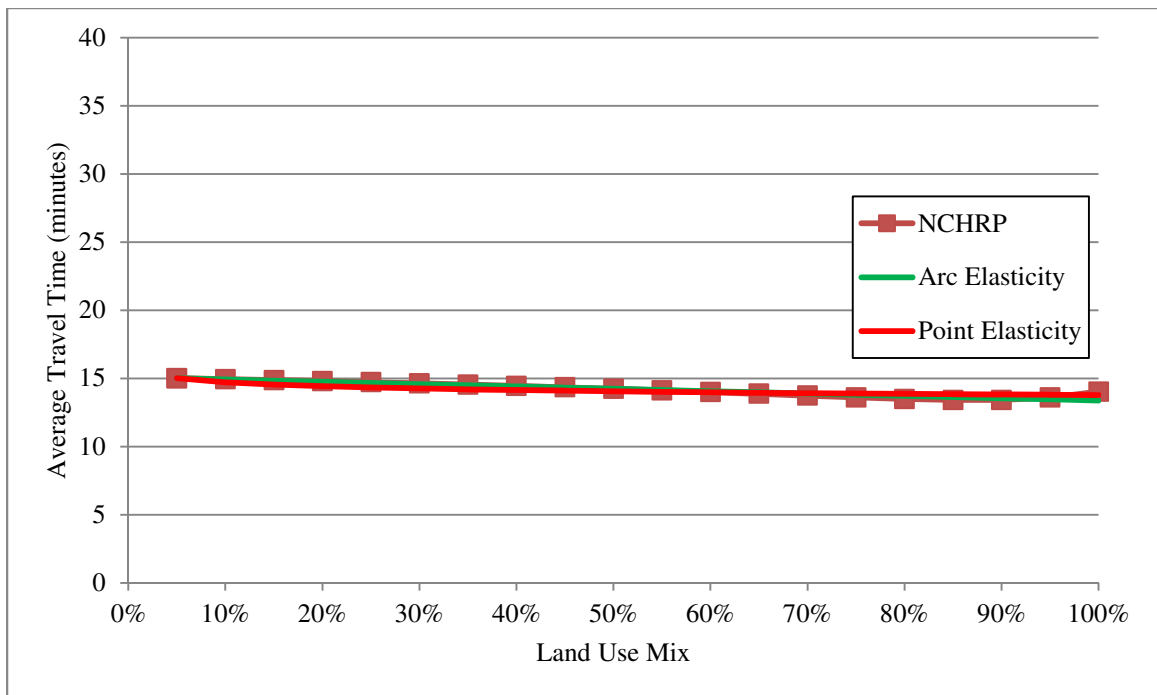


Figure 4-8: Stratified City - CBD Elasticity

Table 4-7: Stratified City Land Use Mix Scenario Statistics

	Suburbs		CBD	
	Point Elasticity	Arc Elasticity	Point Elasticity	Arc Elasticity
Base Year Travel Time (min)	39.121	39.121	15.005	15.005
Elasticity	-0.217	-0.033	-0.029	-0.006
R ²	0.643	0.991	0.733	0.893
t - stat	4.311	44.151	5.653	12.628

As shown in Figure 4-8 and Table 4-7, the CBD TAZs showed almost no sensitivity to changes in land use mix. This result was expected, as the CBD TAZs contained more employment than population. As the elasticity adjustment eventually used in this project would only be applied to the housing (population) side of the trips, TAZs with more employment than population would simply be assigned a land mix ratio of 1.0 (or 100%). More discussion on this is included in the case study chapter.

Land Use Mix – Mono-Centric City: The second set of land use mix scenarios investigated was based on a mono-centric city layout. The layout was separated into a block of CBD TAZs in the center surrounded by an equal number of suburb TAZs (see Figure 4-9). The suburbs half of the city contained more population than employment while the CBD half of the city contained more employment than population, identical to the previous scenario. Note that the center TAZ had no population or employment. This was done for the reasons discussed in the previous section. A base year and nineteen future scenarios were run on the layout. Each scenario had equal density (per the DKS Associates 2007 definition) but varied land use mix.

Table 4-8 summarizes the characteristics of each scenario.

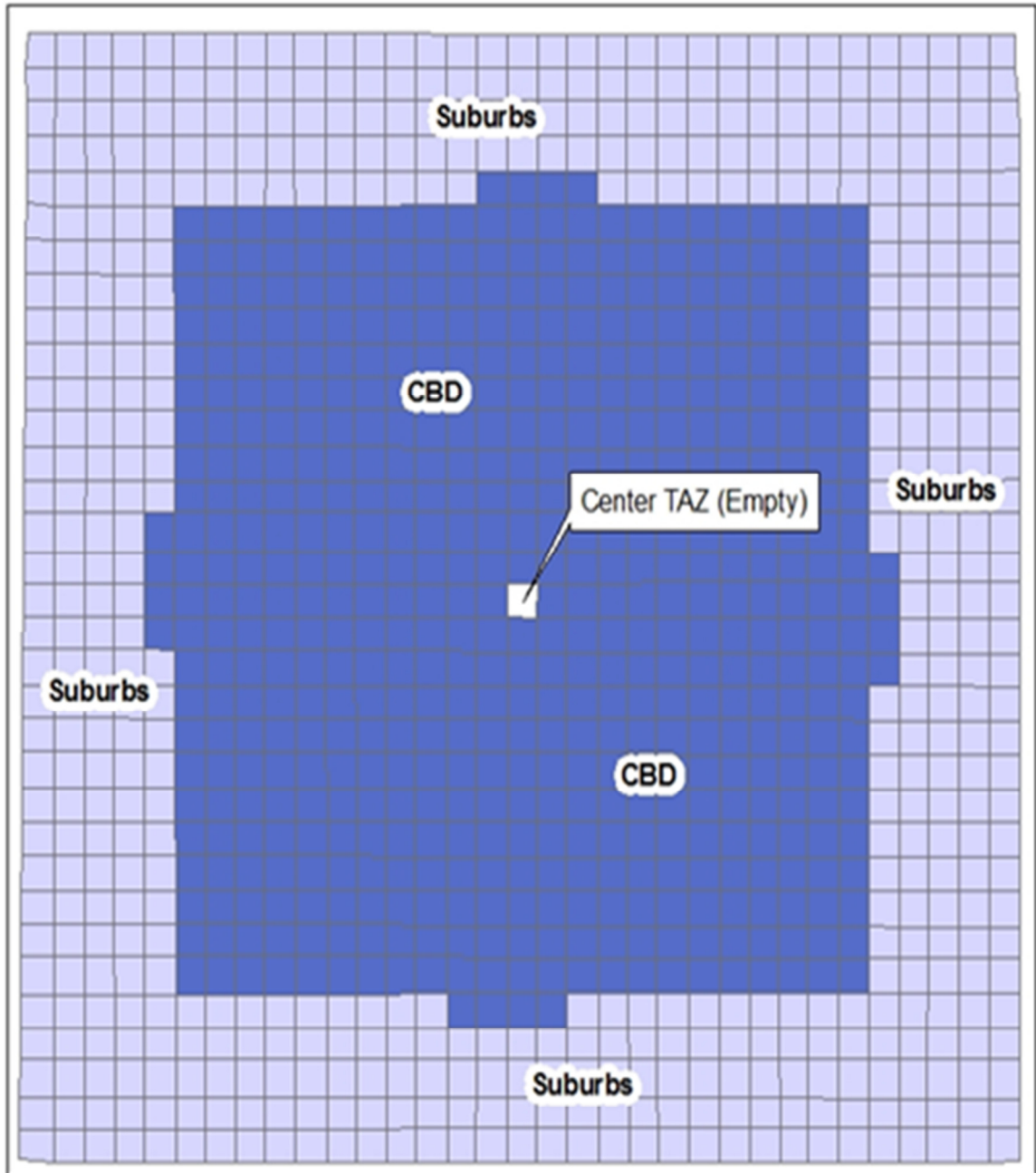


Figure 4-9: Mono-Centric City Land Use Mix Layout

Table 4-8: Mono-Centric City Land Use Mix Scenario Characteristics

Scenario	Suburb			CBD		
	Population/ TAZ	Employment/ TAZ	%LM ⁵	Population/ TAZ	Employment/ TAZ	%LM ²
Base	975	25	5%	25	975	5%
1	1000	1000	100%	1000	1000	100%
2	1050	950	95%	950	1050	95%
3	1100	900	90%	900	1100	90%
4	1150	850	85%	850	1150	85%
5	1200	800	80%	800	1200	80%
6	1250	750	75%	750	1250	75%
7	1300	700	70%	700	1300	70%
8	1350	650	65%	650	1350	65%
9	1400	600	60%	600	1400	60%
10	1450	550	55%	550	1450	55%
11	1500	500	50%	500	1500	50%
12	1550	450	45%	450	1550	45%
13	1600	400	40%	400	1600	40%
14	1650	350	35%	350	1650	35%
15	1700	300	30%	300	1700	30%
16	1750	250	25%	250	1750	25%
17	1800	200	20%	200	1800	20%
18	1850	150	15%	150	1850	15%
19	1900	100	10%	100	1900	10%

⁵ %LM calculated per Equation 4-5 as a percent

As shown in Figure 4-10, the average travel time decreased for all the trips produced in the suburbs decreased as the land use mix in the suburbs increased. This indicated that trips from the suburbs grew shorter (both in time and distance) as the employment in the suburbs increased.

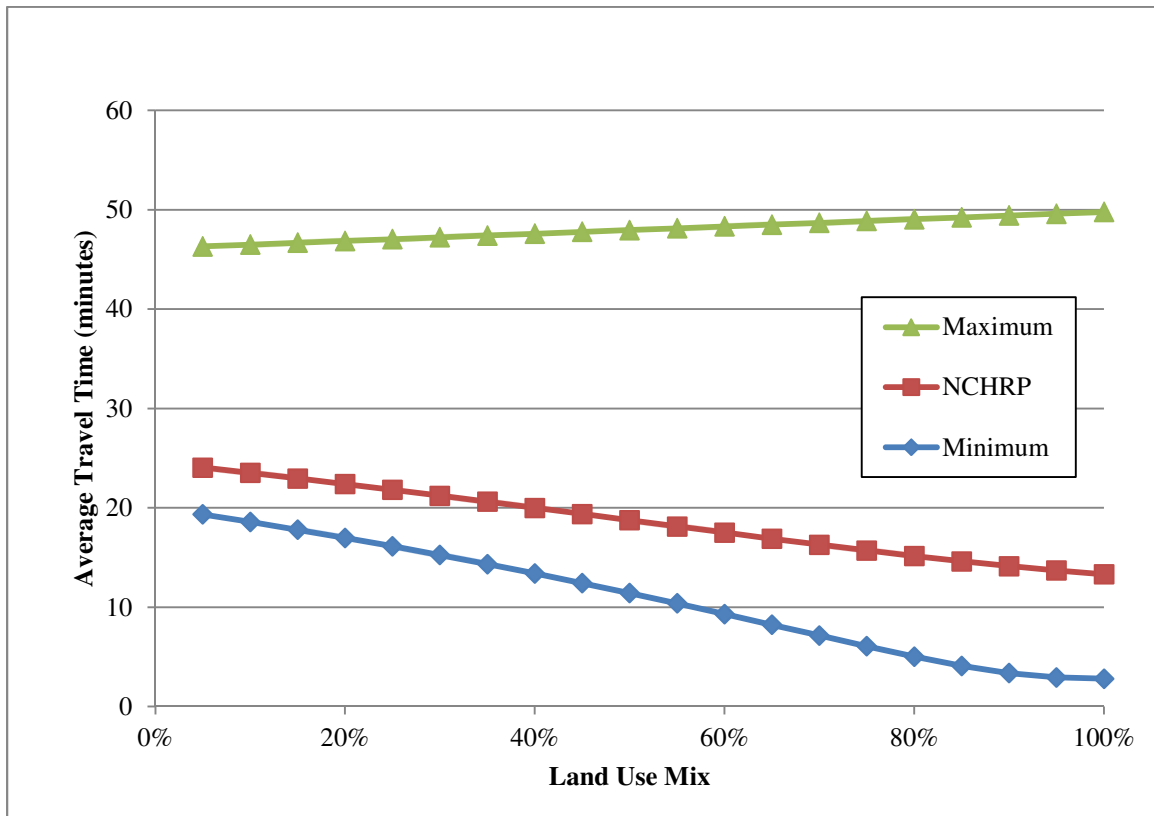


Figure 4-10: Mono-Centric City – Suburb Results

As shown in Figure 4-11, the average travel time did not vary greatly as the population in the CBD zones increased. This indicated that as long as the employment within a zone was greater than the population, a resident's average travel time would remain constant. The results from the mono-centric city land mix scenarios are given in Table 4-9.

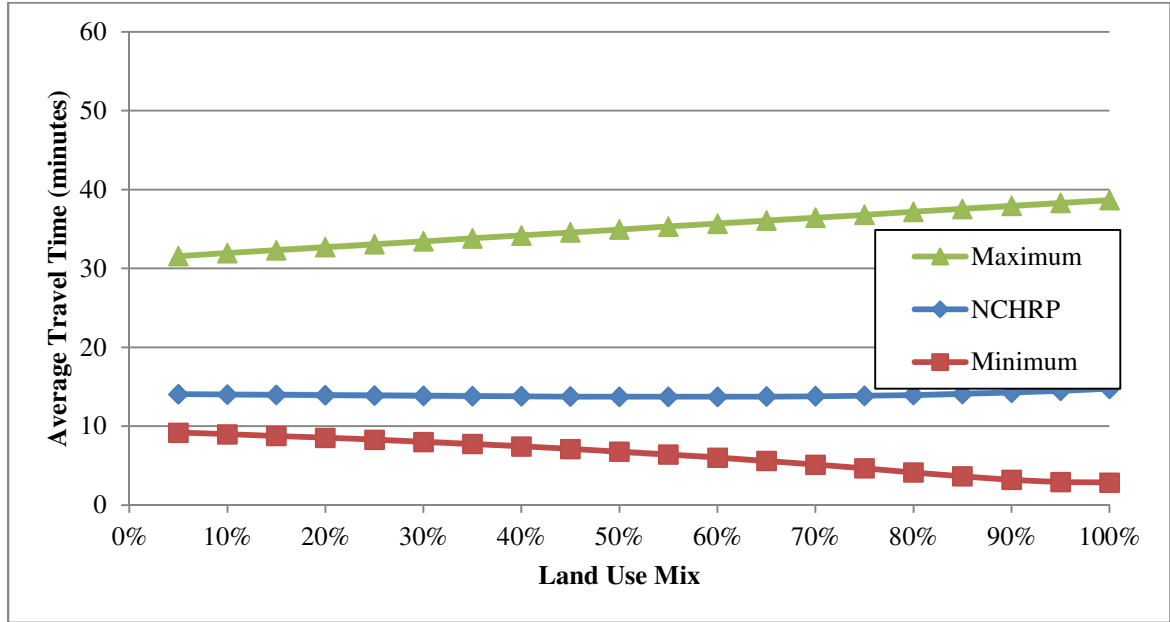


Figure 4-11: Mono-Centric City - CBD Results

Table 4-9: Mono-Centric City Land Use Mix Scenario Results

Scenario	Suburbs Average Travel Time (min)			CBD Average Travel Time (min)		
	Minimum	NCHRP	Entropy	Minimum	NCHRP	Entropy
Base	19.34	24.06	46.32	9.20	14.06	31.56
1	2.79	13.32	49.78	2.85	14.75	38.67
2	2.94	13.71	49.60	2.91	14.48	38.29
3	3.36	14.14	49.42	3.20	14.26	37.92
4	4.09	14.63	49.23	3.64	14.09	37.55
5	5.02	15.15	49.05	4.14	13.96	37.17
6	6.06	15.71	48.87	4.66	13.86	36.80
7	7.14	16.29	48.69	5.14	13.79	36.43
8	8.23	16.90	48.51	5.59	13.75	36.05
9	9.31	17.51	48.32	6.01	13.73	35.68
10	10.38	18.14	48.14	6.41	13.73	35.31
11	11.41	18.76	47.96	6.78	13.74	34.93
12	12.42	19.39	47.78	7.12	13.76	34.56
13	13.40	20.01	47.59	7.44	13.78	34.18
14	14.34	20.62	47.41	7.74	13.81	33.81
15	15.25	21.22	47.23	8.02	13.85	33.43
16	16.13	21.81	47.05	8.29	13.89	33.06
17	16.97	22.39	46.86	8.53	13.93	32.69
18	17.79	22.96	46.69	8.77	13.97	32.31
19	32.04	23.52	54.09	9.46	14.01	34.32
20	33.18	24.06	54.64	9.62	14.06	33.77

To determine the elasticity of the land use mix with respect to travel time, a linear (for arc elasticity) and logarithmic (for point elasticity) regression was run to determine the best fit to the data (see Appendix A for equations and calculations). The elasticity regression equations are plotted with model data in Figure 4-12 and Figure 4-13. The resulting arc elasticity and point elasticity for the mono-centric city layout are given in Table 4-10, along with the goodness of fit statistics for the functions.

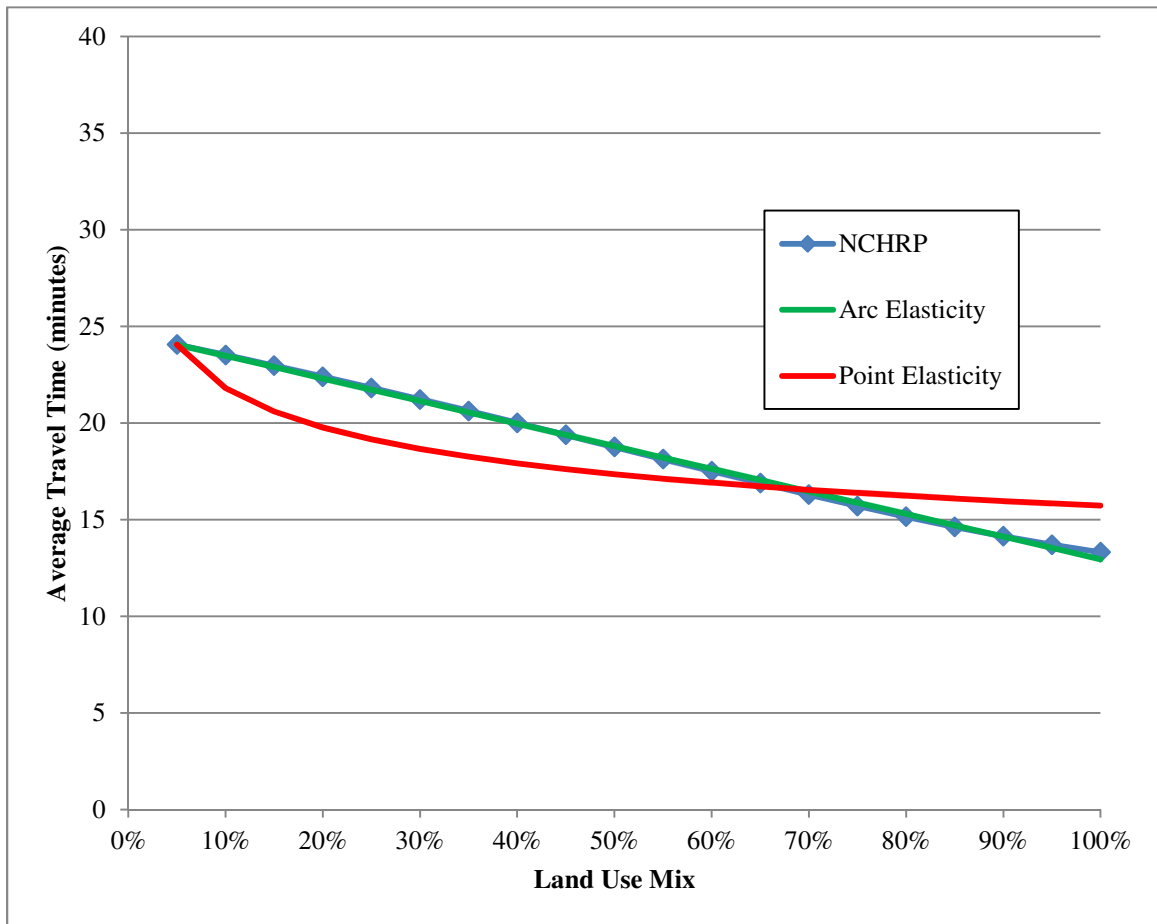


Figure 4-12: Mono-Centric City - Suburb Elasticity

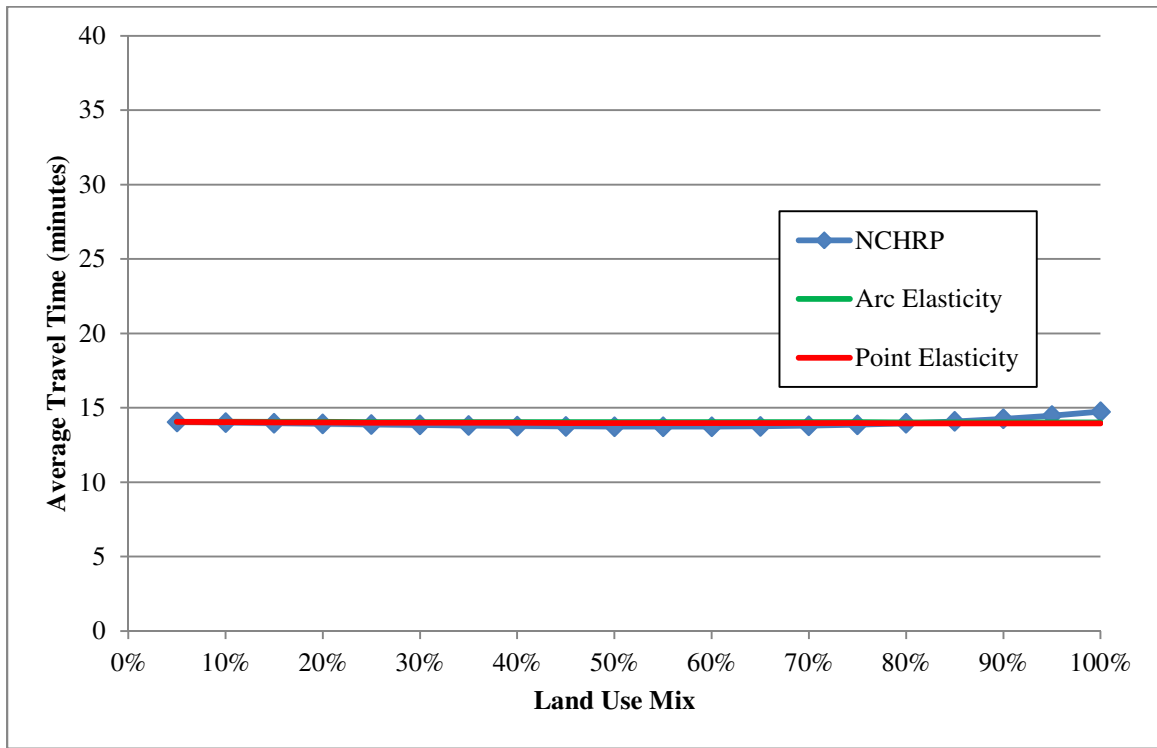


Figure 4-13: Mono-Centric City - CBD Elasticity

Table 4-10: Mono-Centric City Land Use Mix Scenario Statistics

	Suburbs		CBD	
	Point Elasticity	Arc Elasticity	Point Elasticity	Arc Elasticity
Base Year Travel Time (min)	24.058	24.058	14.056	14.056
Elasticity	-0.142	-0.024	-0.002	-0.0001
R ²	0.720	0.999	-0.064	-0.134
t - stat	-4.852	-112.121	-0.424	-0.163

As shown in Figure 4-13 and Table 4-10, the CBD TAZs again showed almost no sensitivity to changes in land use mix. This effect was similar to what was seen from the stratified city layout. Again, more discussion on the implications of this sensitivity will be discussed in the case study chapter.

Land Use Mix – Poly-Centric City: The third set of land use mix scenarios investigated was based on a poly-centric city layout. The layout was separated into four equal blocks of CBD TAZs, separated by suburbs (see Figure 4-14). The number suburb TAZs were equal to the number of CBD TAZs. Note that the center TAZ had no population or employment. This was done for the reasons discussed in the previous section. A base year and nineteen future scenarios were run on the layout. Each future scenario had equal density (per the DKS Associates 2007 definition) but varied land use mix. Table 4-11 summarizes the characteristics of each scenario.

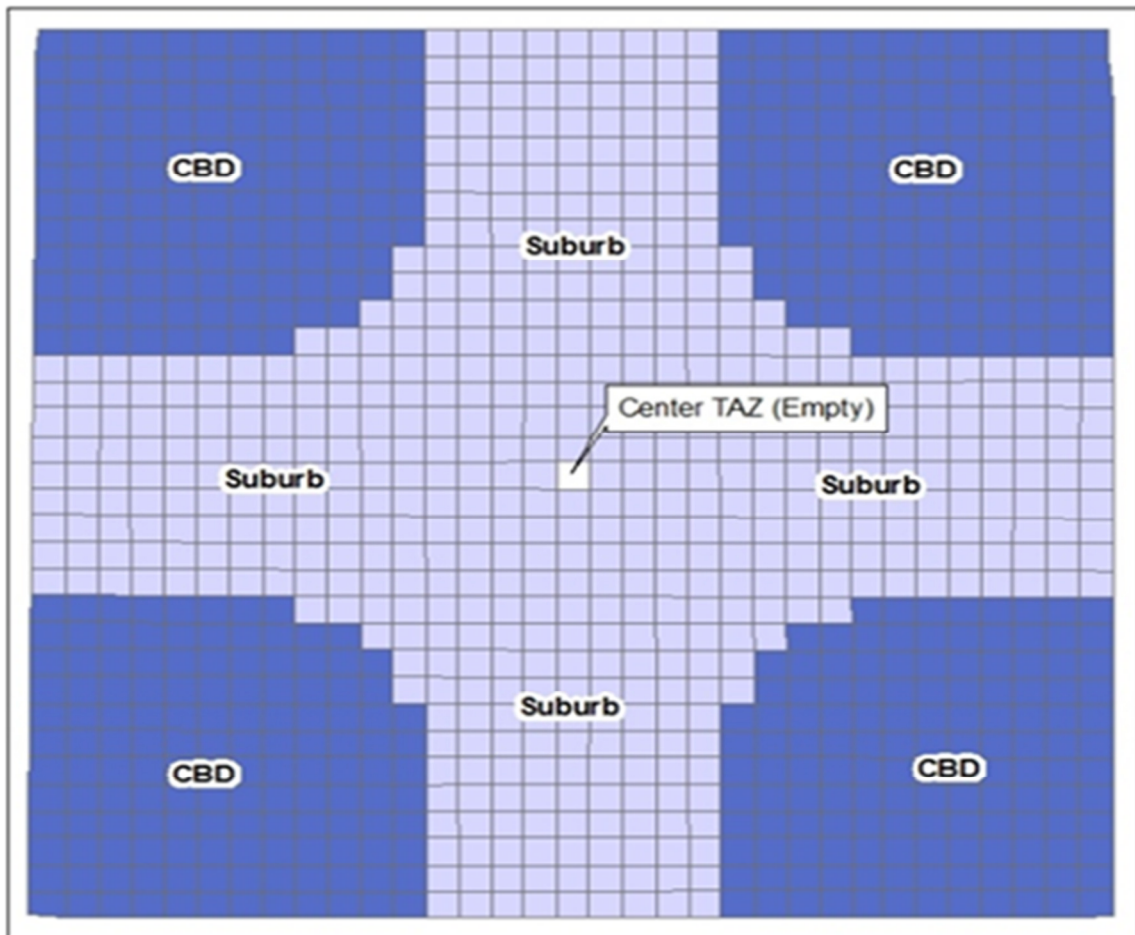


Figure 4-14: Poly-Centric City Land Use Mix Layout

Table 4-11: Poly-Centric City Land Use Mix Scenario Characteristics

Scenario	Suburb			CBD		
	Population/ TAZ	Employment/ TAZ	%LM ⁶	Population/ TAZ	Employment/ TAZ	%LM ²
Base	975	25	5%	25	975	5%
1	1000	1000	100%	1000	1000	100%
2	1050	950	95%	950	1050	95%
3	1100	900	90%	900	1100	90%
4	1150	850	85%	850	1150	85%
5	1200	800	80%	800	1200	80%
6	1250	750	75%	750	1250	75%
7	1300	700	70%	700	1300	70%
8	1350	650	65%	650	1350	65%
9	1400	600	60%	600	1400	60%
10	1450	550	55%	550	1450	55%
11	1500	500	50%	500	1500	50%
12	1550	450	45%	450	1550	45%
13	1600	400	40%	400	1600	40%
14	1650	350	35%	350	1650	35%
15	1700	300	30%	300	1700	30%
16	1750	250	25%	250	1750	25%
17	1800	200	20%	200	1800	20%
18	1850	150	15%	150	1850	15%
19	1900	100	10%	100	1900	10%

As shown in Figure 4-15, the average travel time decreased for the all the trip produced in the suburbs as the land use mix in the suburbs increased. This indicated that trips from the suburbs grew shorter (both in time and distance) as the employment in the suburbs increased.

⁶ %LM calculated per Equation 4 as a percent

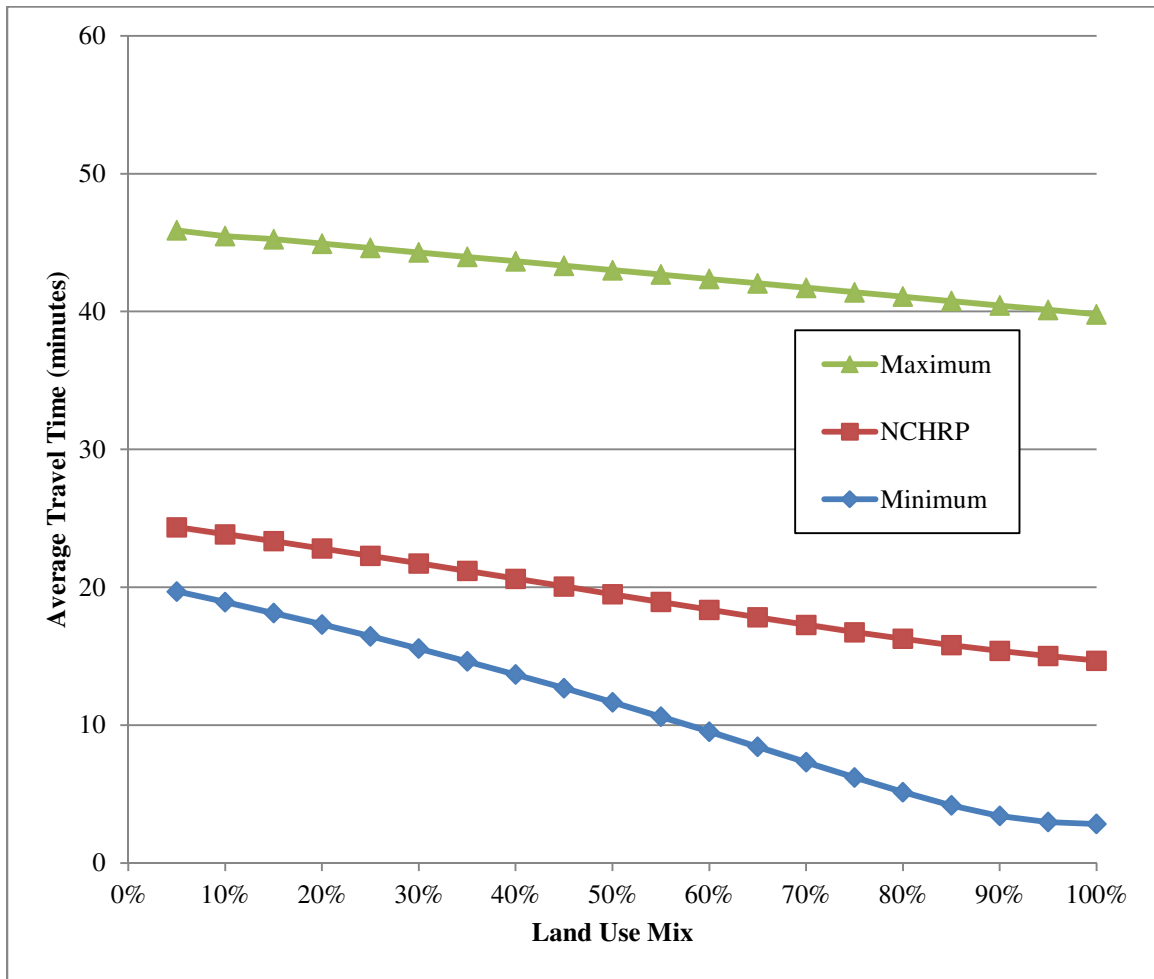


Figure 4-15: Poly-Centric City - Suburb Results

As shown in Figure 4-16, the average travel time did not very greatly as the population in the CBD zones increased. This indicated that as long as the employment within a zone was greater than the population, a resident's average travel time would remain constant. The results from the poly-centric city land mix scenarios are given in Table 4-12.

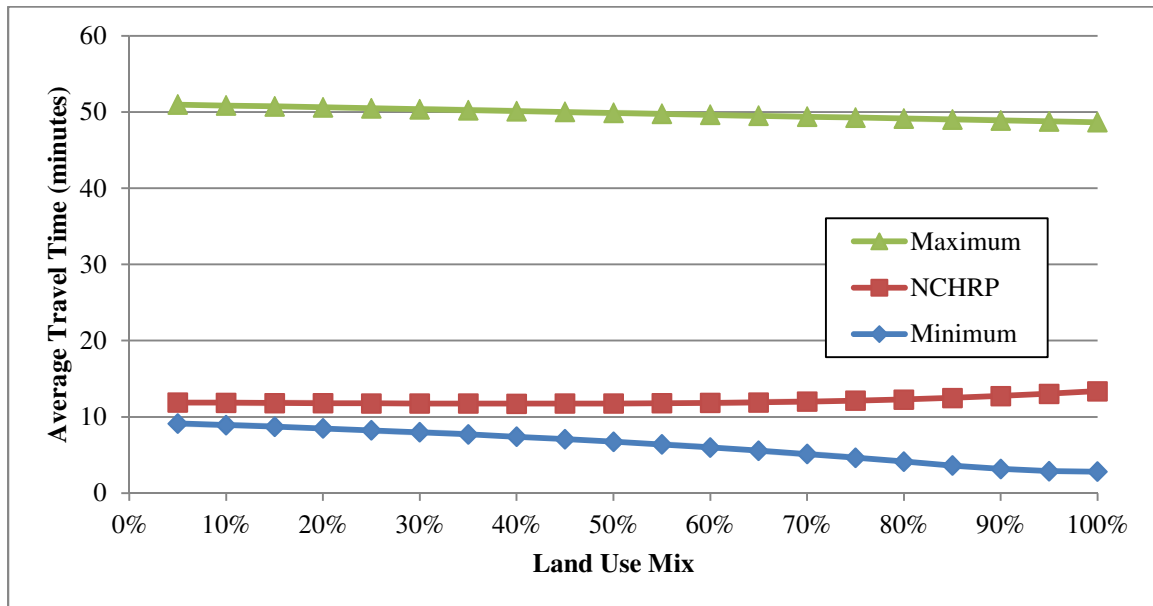


Figure 4-16: Poly-Centric City - CBD Results

Table 4-12: Poly-Centric City Land Use Mix Scenario Results

Scenario	Suburbs Average Travel Time (min)			CBD Average Travel Time (min)		
	Minimum	NCHRP	Entropy	Minimum	NCHRP	Entropy
Base	19.69	24.36	45.89	9.13	11.89	50.97
1	2.83	14.69	39.80	2.81	13.38	48.65
2	2.98	15.02	40.12	2.87	13.03	48.77
3	3.42	15.39	40.44	3.17	12.74	48.89
4	4.18	15.81	40.76	3.62	12.49	49.02
5	5.15	16.27	41.08	4.12	12.29	49.14
6	6.21	16.74	41.40	4.63	12.13	49.26
7	7.32	17.28	41.72	5.11	12.00	49.38
8	8.43	17.83	42.04	5.57	11.91	49.51
9	9.53	18.38	42.36	5.98	11.84	49.63
10	10.61	18.94	42.68	6.38	11.79	49.75
11	11.66	19.50	43.00	6.74	11.76	49.87
12	12.69	20.06	43.32	7.08	11.74	49.99
13	13.67	20.63	43.64	7.40	11.74	50.12
14	14.63	21.19	43.96	7.69	11.75	50.24
15	15.55	21.74	44.28	7.97	11.76	50.36
16	16.44	22.29	44.61	8.23	11.78	50.48
17	17.30	22.82	44.93	8.48	11.80	50.61
18	18.13	23.35	45.25	8.71	11.83	50.73
19	18.93	23.86	45.47	8.93	11.85	50.85

To determine the elasticity of the land use mix with respect to travel time, a linear (for arc elasticity) and logarithmic (for point elasticity) regression was run to determine the best fit to the data (see Appendix A for equations and calculations). The elasticity regression equations are plotted with model data in Figure 4-17 and Figure 4-18. The resulting arc elasticity and point elasticity for the poly-centric city layout are given in Table 4-13, along with the goodness of fit statistics for the functions.

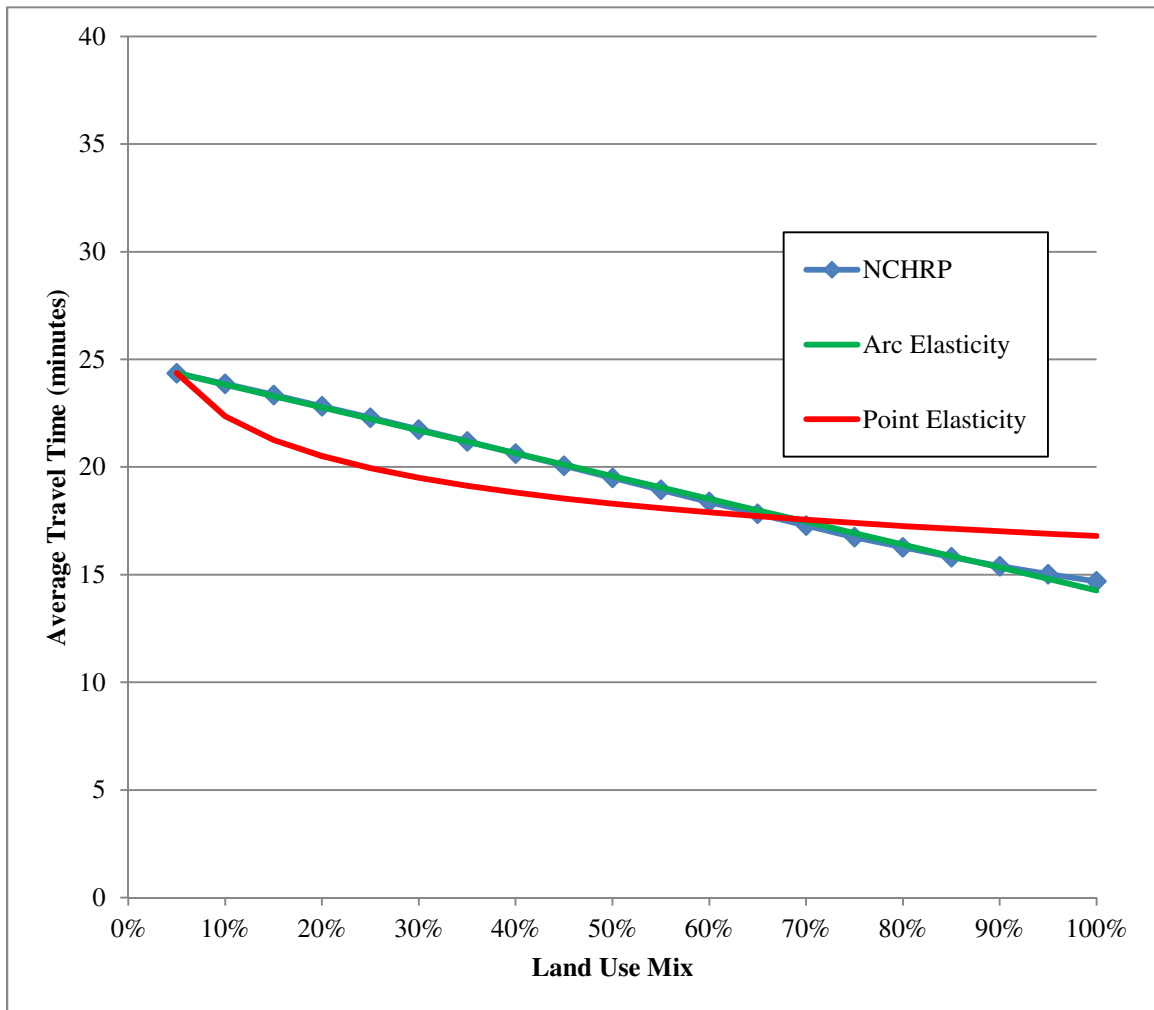


Figure 4-17: Poly-Centric City - Suburb Elasticity

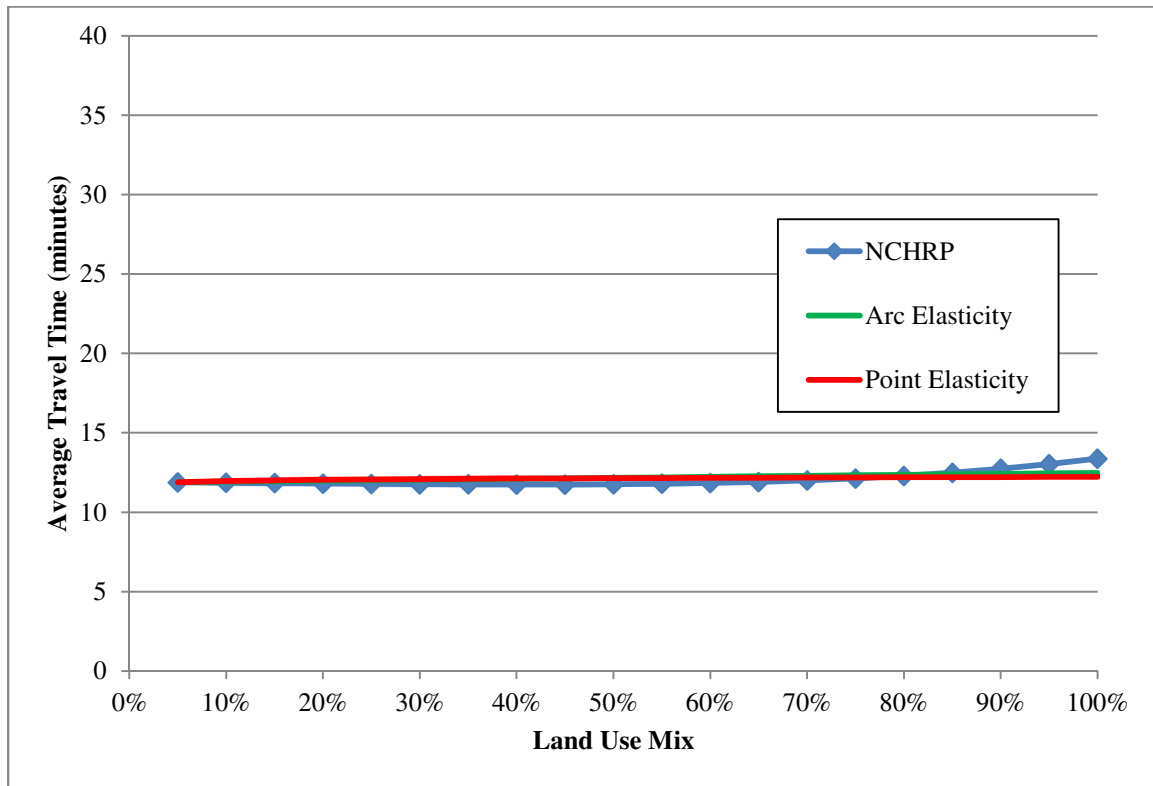


Figure 4-18: Poly-Centric City - CBD Elasticity

Table 4-13: Poly-Centric City Land Use Mix Scenario Statistics

	Suburbs		CBD	
	Point Elasticity	Arc Elasticity	Point Elasticity	Arc Elasticity
Base Year Travel Time (min)	24.360	24.360	11.886	11.886
Elasticity	-0.124	-0.022	0.009	0.003
R ²	0.736	0.998	0.164	0.397
t - stat	-5.095	-93.435	-0.927	-2.123

As shown in Figure 4-18 and Table 4-13, the CBD TAZs again showed almost no sensitivity to changes in land use mix. This effect was similar to what was seen from the stratified and mono-centric city layouts. Again, more discussion on the implications of this sensitivity will be discussed in the case study chapter.

Effects of Density

The effects of variation in density on trip distribution were analyzed in three different sets of scenarios. Each set of scenarios represented a general type of urban form, similar to the three general city layouts analyzed in the previous sections. For each scenario modeled, the average travel time was calculated according to the NCHRP 365 national average travel time distribution for work trips, along with the maximum and minimum possible *modeled* travel times. Again, the average travel time for all scenarios modeled using the NCHRP 365 distribution should theoretically be equal. The minimum and maximum travel times for each scenario were modeled using the same methods discussed in the land use mix sensitivity section. For all of the modeled scenarios, trips were distributed between the TAZs using the free flow travel times. No congestion costs were used. For each model run, each person was assumed to make one round trip to work per day. Therefore, the population and employment were made equal for every scenario. Similar to the land use mix scenarios, every layout contained a base year scenario and several future alternative scenarios. The total population and employment for all of the future scenarios was equal.

Density-Stratified City: The first set of density scenarios investigated was based on a stratified city layout. The general layout consisted of high-density CBD zones on one side and low-density suburb zones on the other. The density of the CBD zones was varied by varying the number of CBD zones, as shown in Figure 4-19. However, the total population (and employment) for each scenario was held constant. Also, the land use mix ratio for all of the TAZs in each scenario was 1.0 (or 100%). Scenario 1 represents a

sprawling urban area with population at 1090 in nearly every zone. Scenario 12 has 100 people per zone for most of the land area and a focused urban core with 29,800 people per zone. Table 4-14 summarizes the characteristics of each scenario analyzed. Note that for the base year the entire grid was assumed to be CBD.

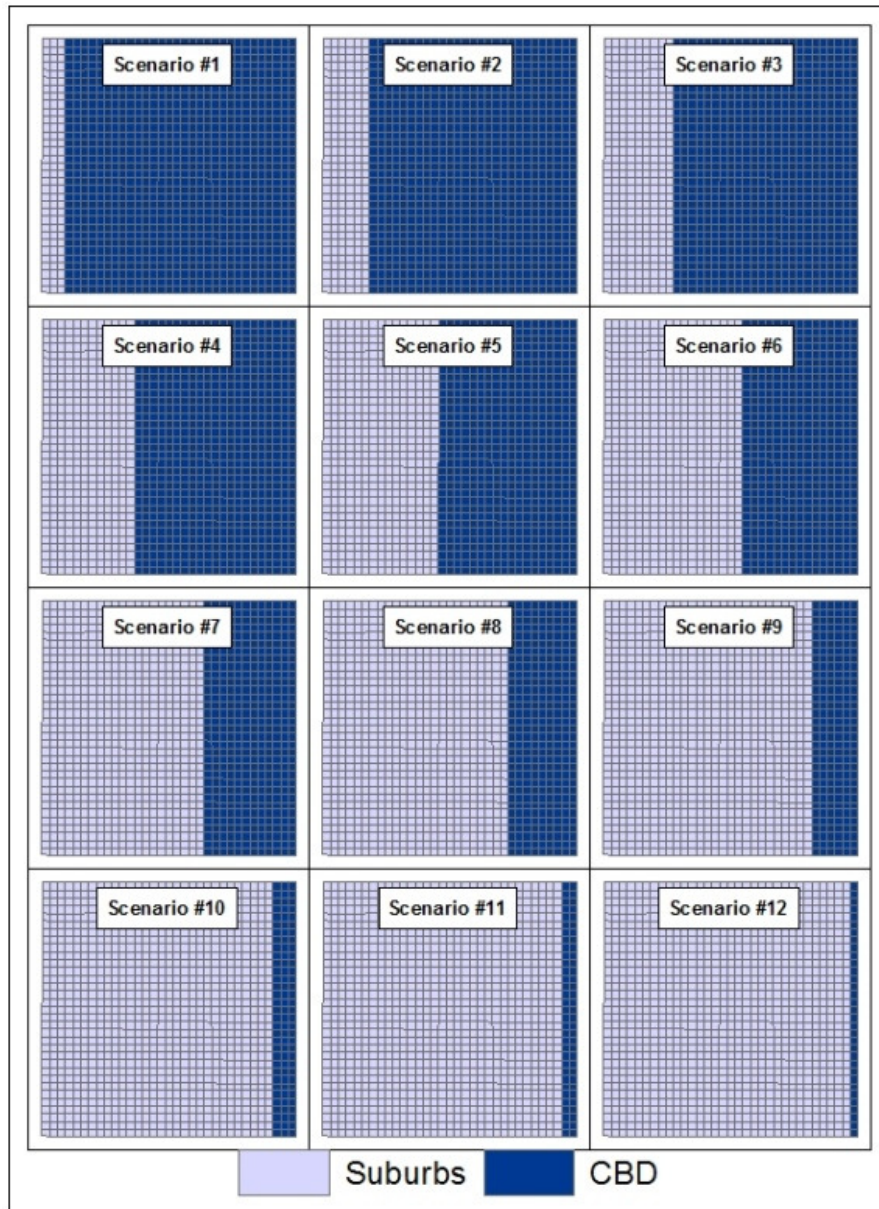


Figure 4-19: Stratified City Density Scenarios

Table 4-14: Stratified City Density Scenario Characteristics

Scenario	CBD			Suburbs		
	Population/ TAZ	Employment/T AZ	Density	Population/ TAZ	Employment/T AZ	Density
Base	1000	1000	2000	-	-	-
1	1090	1090	2180	100	100	200
2	1200	1200	2400	100	100	200
3	1338	1338	2675	100	100	200
4	1514	1514	3029	100	100	200
5	1750	1750	3500	100	100	200
6	2080	2080	4160	100	100	200
7	2575	2575	5150	100	100	200
8	3400	3400	6800	100	100	200
9	5050	5050	10100	100	100	200
10	10000	10000	20000	100	100	200
11	14950	14950	29900	100	100	200
12	29800	29800	59600	100	100	200

The results for the stratified city density scenarios are summarized in Table 4-15 and graphed in Figure 4-20 and Figure 4-21. Note that the average travel times for the suburb were simply plotted against the scenario number, as the density of the suburbs did not vary between scenarios.

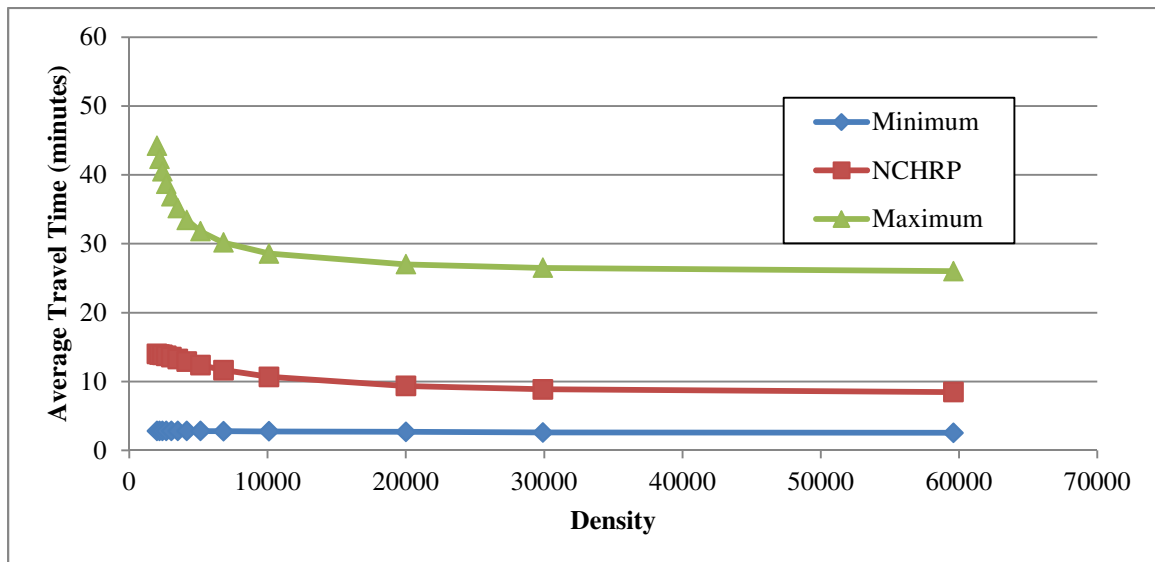


Figure 4-20: Stratified City - CBD Results

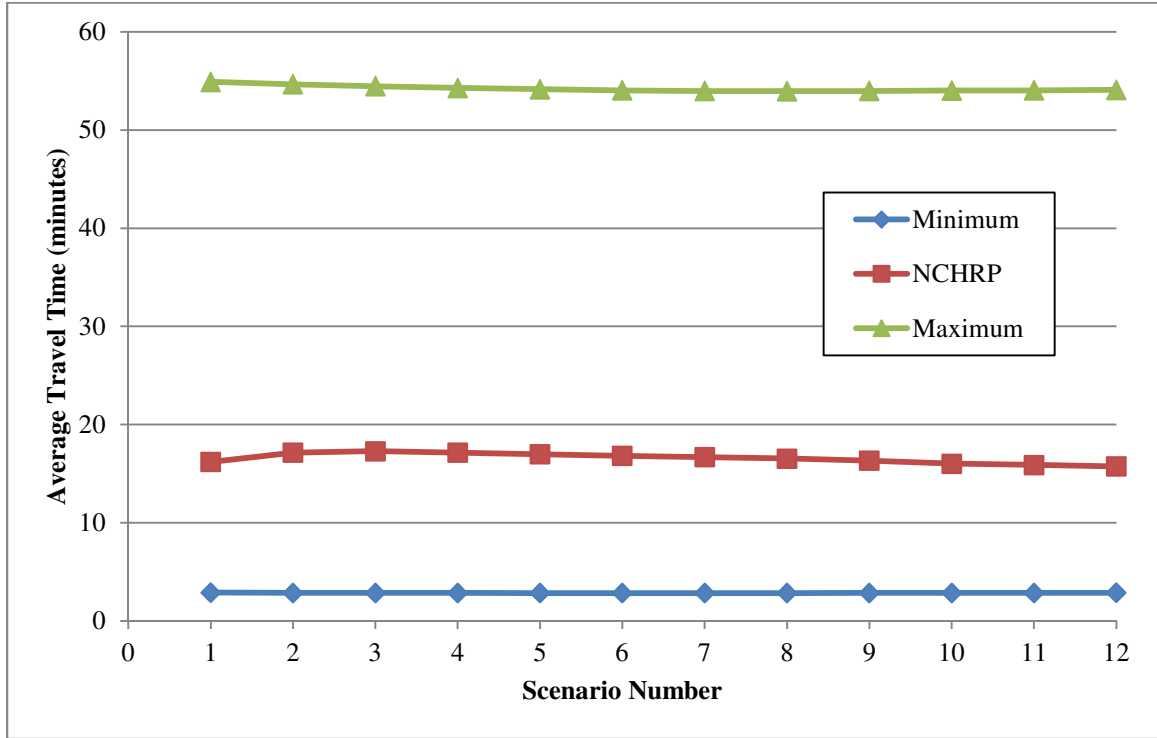


Figure 4-21: Stratified City - Suburb Results

Table 4-15: Stratified City Density Scenario Results

Scenario	CBD Average Travel Time (min)			Suburbs Average Travel Time (min)		
	Minimum	NCHRP	Maximum	Minimum	NCHRP	Maximum
Base	2.82	14.04	44.20	-	-	-
1	2.82	13.95	42.32	2.90	16.21	54.90
2	2.82	13.86	40.48	2.87	17.15	54.66
3	2.82	13.72	38.66	2.86	17.30	54.45
4	2.82	13.54	36.89	2.86	17.16	54.28
5	2.81	13.27	35.15	2.86	16.98	54.14
6	2.81	12.90	33.45	2.86	16.83	54.04
7	2.80	12.39	31.79	2.86	16.70	53.98
8	2.79	11.67	30.16	2.86	16.54	53.95
9	2.76	10.68	28.57	2.86	16.34	53.96
10	2.69	9.36	27.02	2.87	16.02	54.01
11	2.60	8.87	26.51	2.87	15.89	54.04
12	2.55	8.49	26.01	2.88	15.76	54.08

To determine the elasticity of the density with respect to travel time, linear (for arc elasticity) and logarithmic (for point elasticity) regressions were run to determine the best fit to the data (see Appendix A for equations and calculations). The elasticity regression equations are plotted with model data in Figure 4-22. The resulting arc and power elasticity for the stratified city layout are given in Table 4-16, along with the goodness of fit statistics for the functions. No regression analysis was run for the suburbs as the suburb density remained constant. However, the results shown in Figure 4-21 indicate that the average travel time for the suburbs remained fairly constant for all the scenarios. This shows that the increases in the density of the CBD as well as the decreasing of the total number of CBD zones (and corresponding increase in suburb zones) did not seriously impact the average travel time of the suburbs.

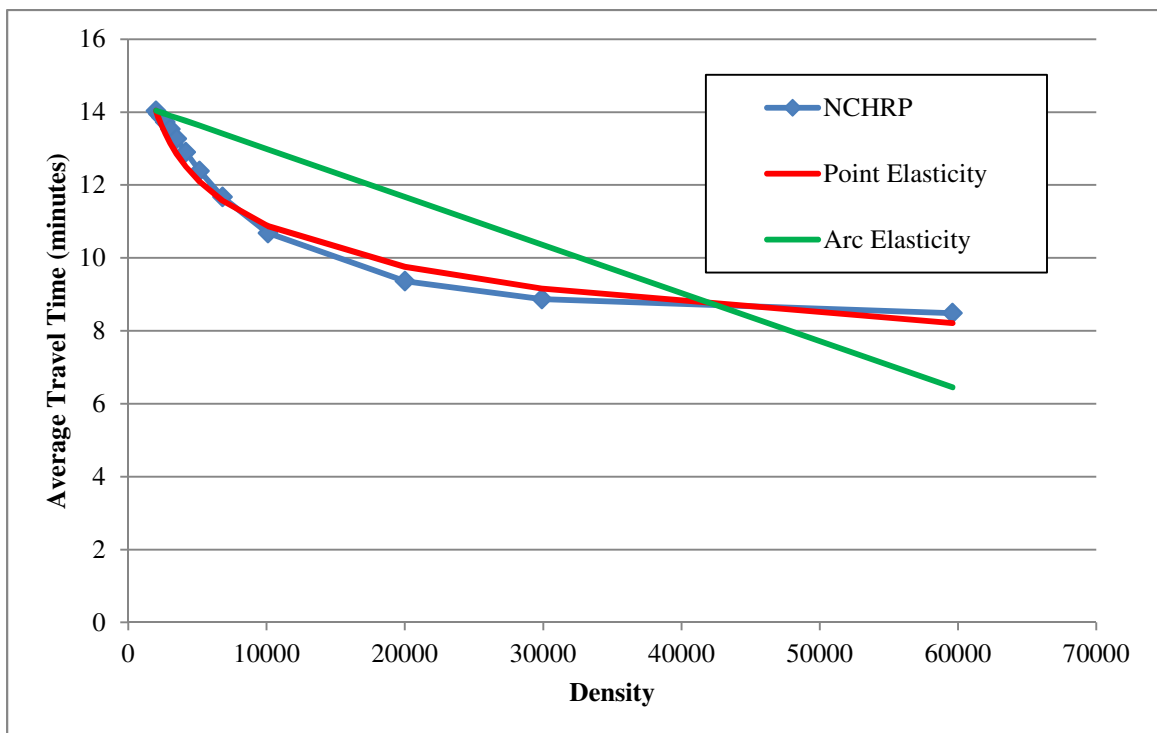


Figure 4-22: Stratified City - CBD Elasticity

Table 4-16: Stratified City Density Scenario Statistics

	CBD	
	Point Elasticity	Arc Elasticity
Base Year Travel Time (min)	14.039	14.039
Elasticity	-0.158	-0.019
R ²	0.979	0.547
t - stat	-21.526	-5.275

The data results show that there is a point elasticity relationship between density and average travel time for the stratified city layout. The results also indicate that the suburbs average travel time is not elastically dependent on the CBD density.

Density - Mono-Centric City: The second set of density scenarios investigated was based on a mono-centric city layout. The layout consisted of a CBD centered on the middle of the layout surrounded by low density suburbs. The density of the CBD was varied by varying the size of the CBD as shown in Figure 4-23. However, the total population (and employment) for each scenario was again held constant. Also, the land use mix ratio for all of the TAZs in each scenario was 1.0 (or 100%). Table 4-17 summarizes the characteristics of each scenario analyzed. Note that for the base year the entire grid was assumed to be CBD.

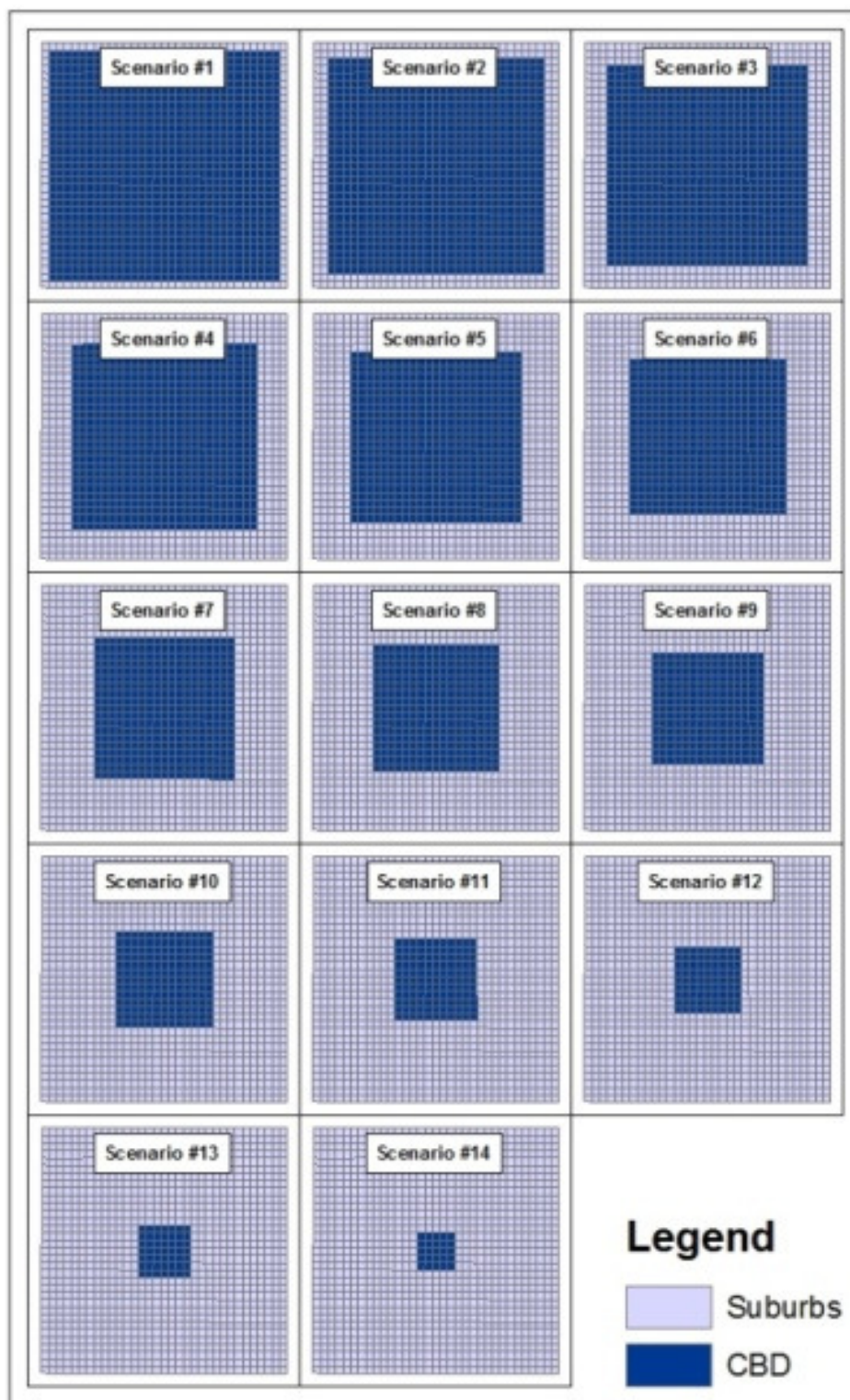


Figure 4-23: Mono-Centric City Density Scenarios

Table 4-17: Mono-Centric City Density Scenario Characteristics

Scenario	CBD			Suburbs		
	Population/ TAZ	Employment/T AZ	Density	Population/ TAZ	Employment/T AZ	Density
Base	1000	1000	2000	-	-	-
1	1067	1067	2133	500	500	1000
2	1147	1147	2295	500	500	1000
3	1247	1247	2494	500	500	1000
4	1371	1371	2742	500	500	1000
5	1529	1529	3059	500	500	1000
6	1735	1735	3469	500	500	1000
7	2008	2008	4017	500	500	1000
8	2384	2384	4768	500	500	1000
9	2920	2920	5840	500	500	1000
10	3722	3722	7444	500	500	1000
11	5000	5000	10000	500	500	1000
12	7222	7222	14444	500	500	1000
13	11612	11612	23224	500	500	1000
14	22280	22280	44560	500	500	1000

The results for the mono-centric density scenarios are summarized in Table 4-18 and graphed in Figure 4-24 and Figure 4-25. Note that the average travel times for the suburb were simply plotted against the scenario number, as the density of the suburbs did not vary between scenarios.

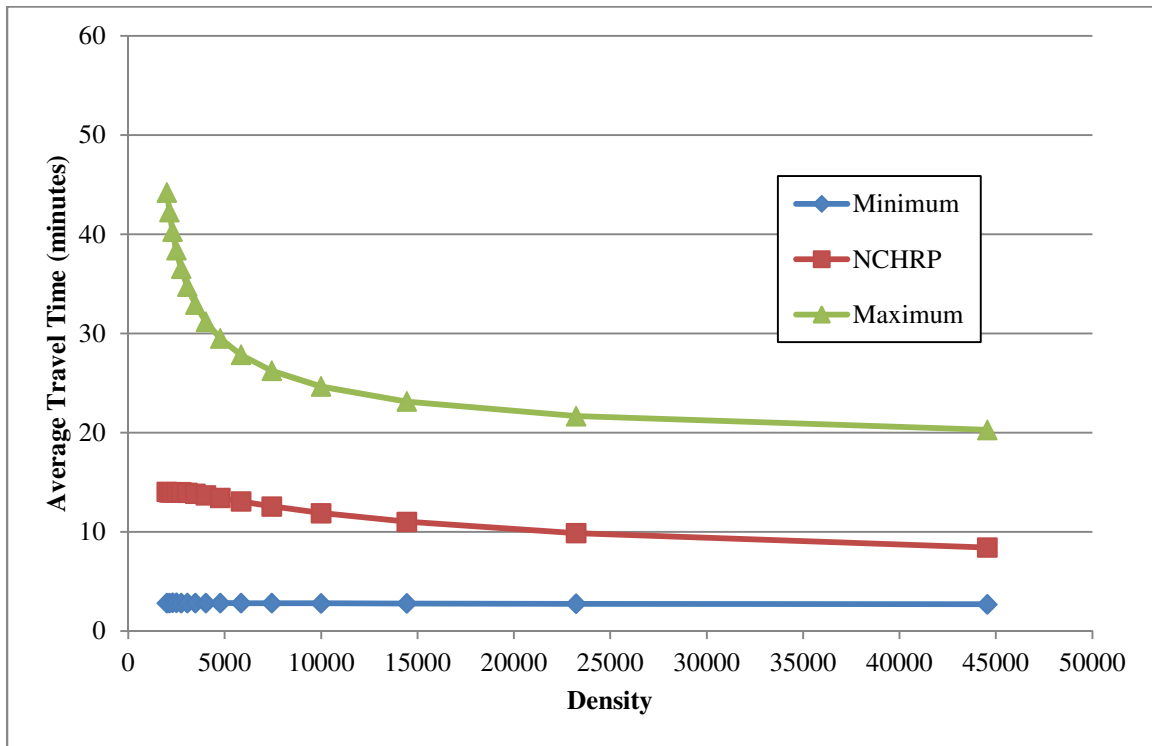


Figure 4-24: Mono-Centric City - CBD Results

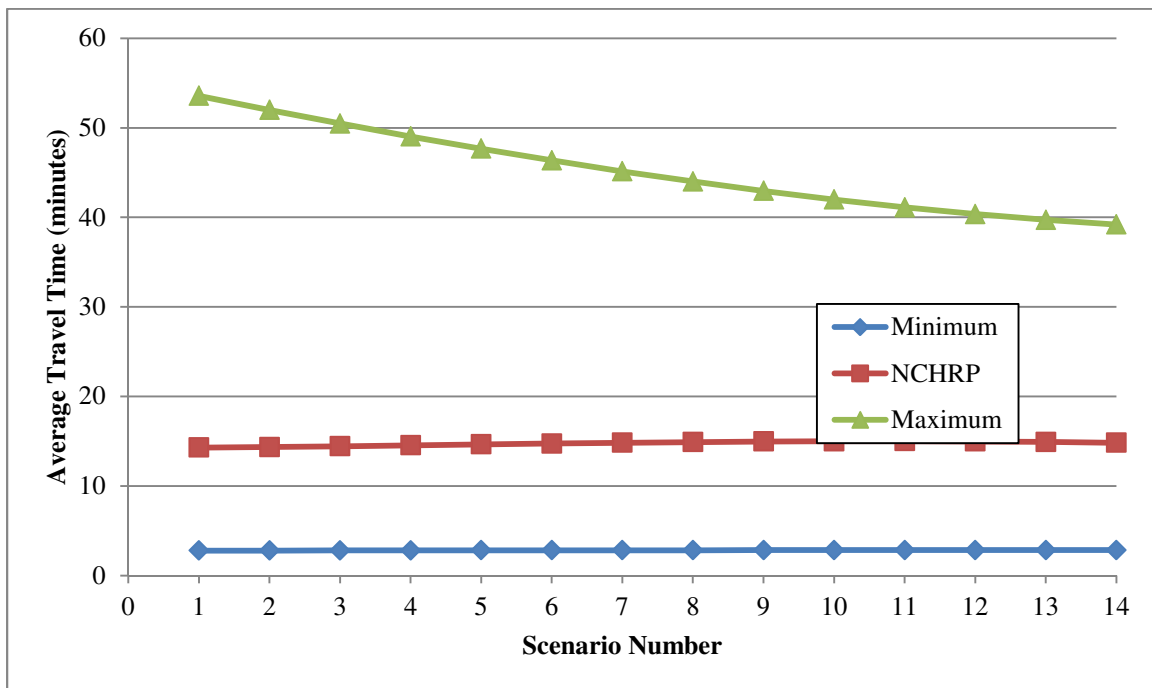


Figure 4-25: Mono-Centric City - Suburb Results

Table 4-18: Mono-Centric City Density Scenario Results

Scenario	CBD Average Travel Time (min)			Suburbs Average Travel Time (min)		
	Minimum	NCHRP	Entropy	Minimum	NCHRP	Entropy
Base	2.82	14.03	44.20	-	-	-
1	2.83	13.98	42.22	2.78	14.30	53.57
2	2.84	13.99	40.28	2.79	14.35	51.99
3	2.84	14.00	38.38	2.80	14.44	50.48
4	2.84	14.00	36.52	2.81	14.54	49.03
5	2.84	13.96	34.70	2.82	14.64	47.66
6	2.83	13.86	32.92	2.82	14.74	46.36
7	2.83	13.69	31.19	2.83	14.83	45.14
8	2.82	13.44	29.49	2.83	14.90	44.00
9	2.82	13.07	27.84	2.83	14.96	42.94
10	2.81	12.57	26.22	2.83	14.99	41.98
11	2.80	11.90	24.65	2.83	15.00	41.12
12	2.78	11.02	23.13	2.84	14.97	40.36
13	2.75	9.87	21.66	2.84	14.91	39.72
14	2.71	8.42	20.28	2.84	14.82	39.19

To determine the elasticity of the density with respect to travel time, a linear and logarithmic regression were run to determine the best fit to the data (see Appendix A for equations and calculations). The elasticity regression equations are plotted with model data in Figure 4-26. The resulting arc elasticity and point elasticity for the mono-centric city layout are given in Table 4-19, along with the goodness of fit statistics for the functions. No regression analysis was run for the suburbs as the suburb density remained constant. However, the results in Table 4-18 indicate that the average travel time for the suburbs remained fairly constant for all the scenarios. This shows that the increases in the density of the CBD as well as the decreasing of the total number of CBD zones (and corresponding increase in suburb zones) did not seriously impact the average travel time of the suburbs.

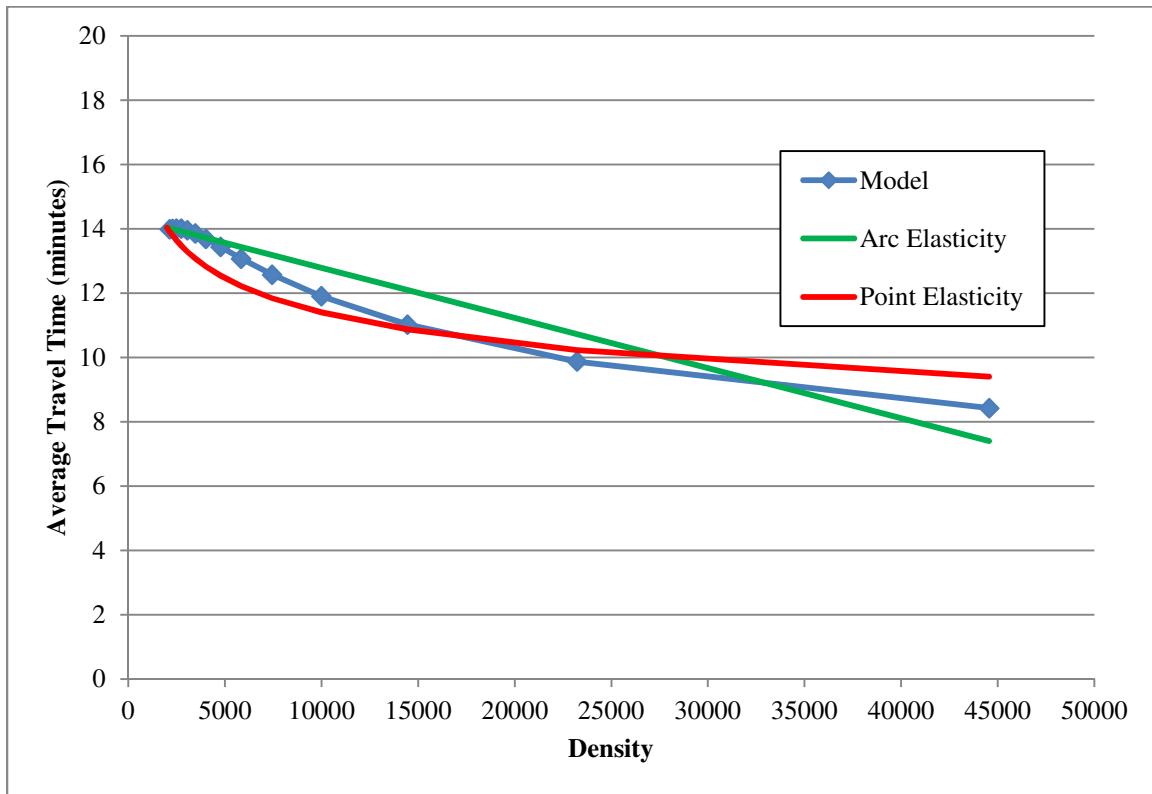


Figure 4-26: Mono-Centric City - CBD Elasticity

Table 4-19: Mono-Centric City Density Scenario Statistics

	CBD	
	Point Elasticity	Arc Elasticity
Base Year Travel Time (min)	14.034	14.034
Elasticity	-0.129	-0.022
R ²	0.877	0.900
t - stat	-8.110	-11.665

The data results show that there is definitely elasticity between average travel time and density for the mono-centric city layout. However, the arc elasticity regression was only a marginally better fit to the data than the point elasticity. The average travel

times for the suburbs were not analyzed through regression for the reasons discussed earlier.

Density – Poly-Centric City: The third set of density scenarios investigated was based on a poly-centric city layout. The layout consisted of four CBDs located at the four corners of the layout. The CBDs were surrounded by low density suburbs. The density of the CBDs was varied by varying the size of each CBD as shown in Figure 4-27. However, the total population (and employment) for each scenario was held constant. Also, the land use mix ratio for all of the TAZs in each scenario was 1.0 (or 100%). Table 4-20 summarizes the characteristics of each scenario analyzed.

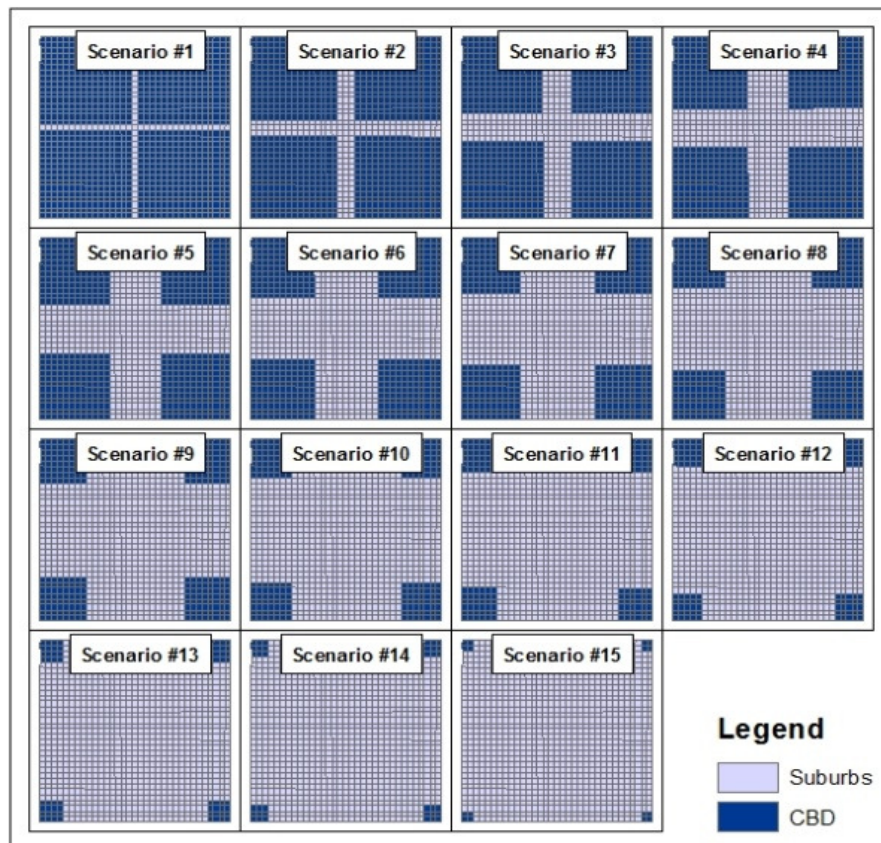


Figure 4-27: Poly-Centric City Density Scenarios

Table 4-20: Poly-Centric City Density Scenario Characteristics

Scenario	CBD			Suburbs		
	Population/ TAZ	Employment/T AZ	Density	Population/ TAZ	Employment/T AZ	Density
Base	1000	1000	2000	-	-	-
1	1057	1057	2114	500	500	1000
2	1189	1189	2378	500	500	1000
3	1350	1350	2700	500	500	1000
4	1550	1550	3100	500	500	1000
5	1802	1802	3603	500	500	1000
6	2125	2125	4250	500	500	1000
7	2550	2550	5101	500	500	1000
8	3125	3125	6250	500	500	1000
9	3929	3929	7857	500	500	1000
10	5101	5101	10201	500	500	1000
11	6906	6906	13813	500	500	1000
12	9901	9901	19802	500	500	1000
13	15414	15414	30828	500	500	1000
14	27325	27325	54650	500	500	1000
15	61356	61356	122713	500	500	1000

The results for the poly-centric density scenarios are summarized in Table 4-21 and graphed in Figure 4-28 and Figure 4-29. Note that the average travel times for the suburb were simply plotted against the scenario number, as the density of the suburbs did not vary between scenarios.

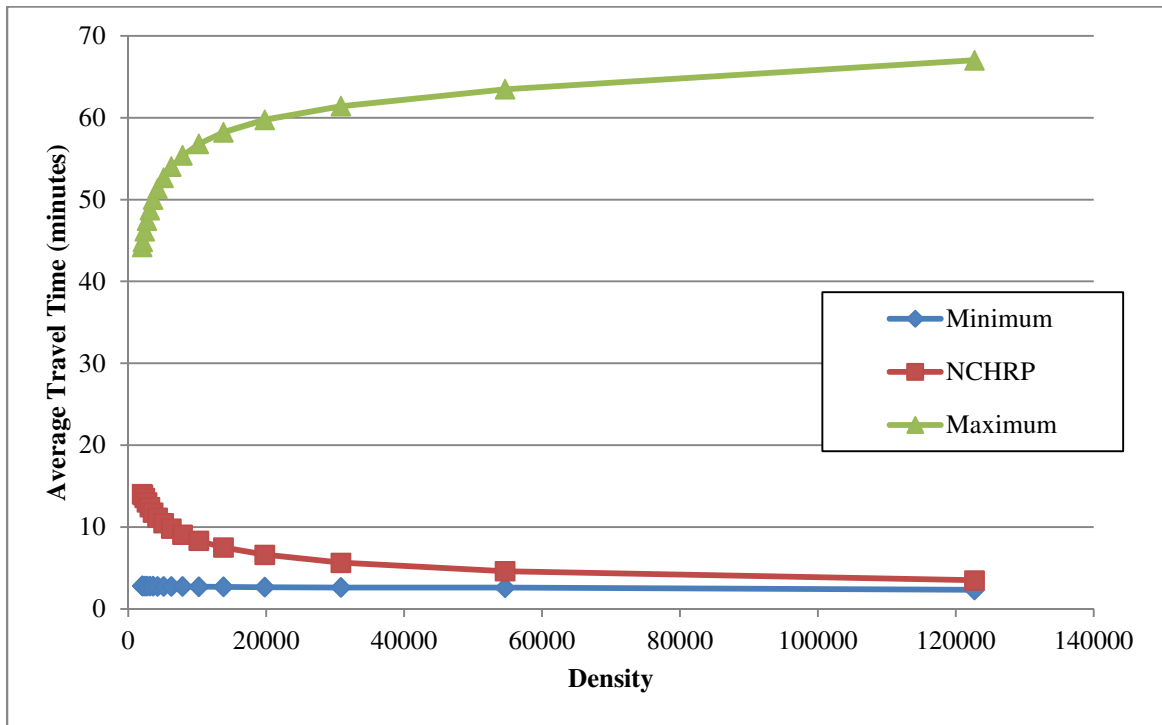


Figure 4-28: Poly-Centric City - CBD Results

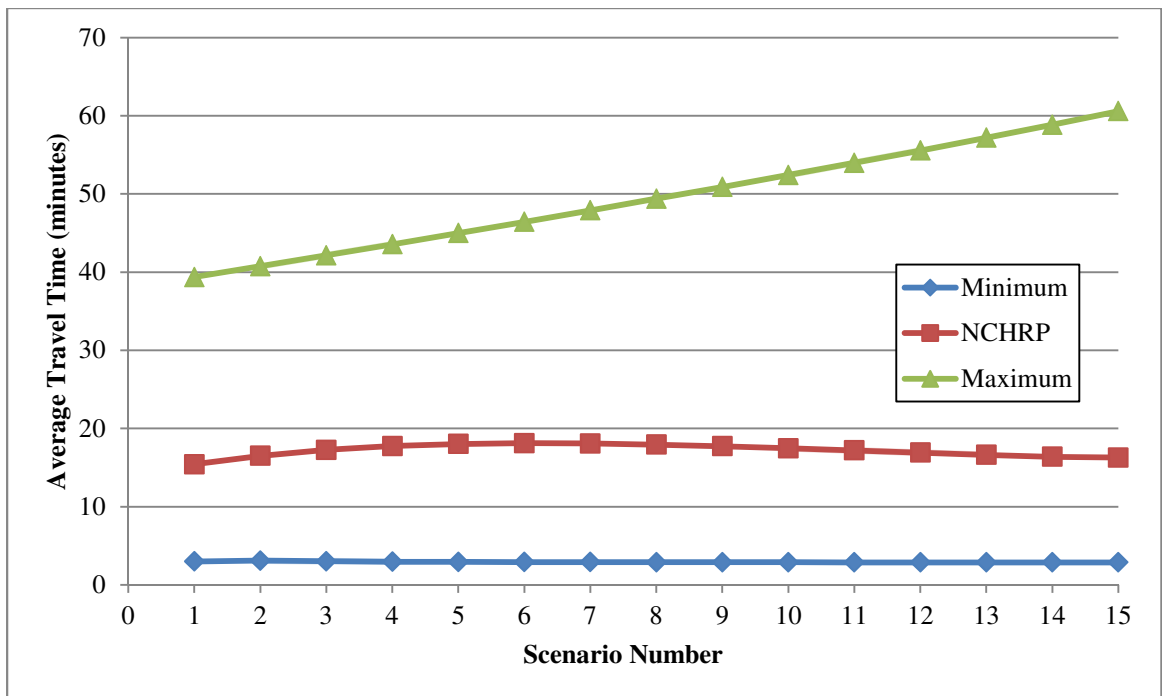


Figure 4-29: Poly-Centric City - Suburb Results

Table 4-21: Poly-Centric City Density Scenario Results

Scenario	CBD Average Travel Time (min)			Suburbs Average Travel Time (min)		
	Minimum	NCHRP	Entropy	Minimum	NCHRP	Entropy
Base	2.82	14.04	44.20	-	-	-
1	2.82	13.94	44.84	2.99	15.42	39.37
2	2.80	13.57	46.12	3.10	16.50	40.75
3	2.79	13.04	47.41	3.01	17.25	42.14
4	2.79	12.43	48.71	2.96	17.75	43.56
5	2.78	11.80	50.02	2.94	18.02	44.99
6	2.78	11.16	51.34	2.92	18.11	46.43
7	2.77	10.50	52.68	2.91	18.08	47.90
8	2.76	9.83	54.03	2.90	17.94	49.38
9	2.75	9.10	55.39	2.89	17.73	50.89
10	2.74	8.34	56.78	2.89	17.47	52.42
11	2.71	7.52	58.22	2.88	17.19	53.97
12	2.68	6.64	59.74	2.88	16.90	55.56
13	2.64	5.67	61.41	2.87	16.62	57.18
14	2.61	4.63	63.48	2.87	16.38	58.84
15	2.34	3.51	67.02	2.86	16.28	60.58

To determine the elasticity of the density with respect to travel time, linear and logarithmic regressions were run to determine the best fit to the data (see Appendix A for equations and calculations). The elasticity regression equations are plotted with the modeled data in Figure 4-30. The resulting arc elasticity and power elasticity for the poly-centric city layout are given in Table 4-22, along with the goodness of fit statistics for the functions. Note again that no regression was run for the suburbs, as the density of the suburbs remained constant throughout all the scenarios. The modeling results in Table 4-21 indicate that the average travel time for the suburbs did not vary too significantly between scenarios.

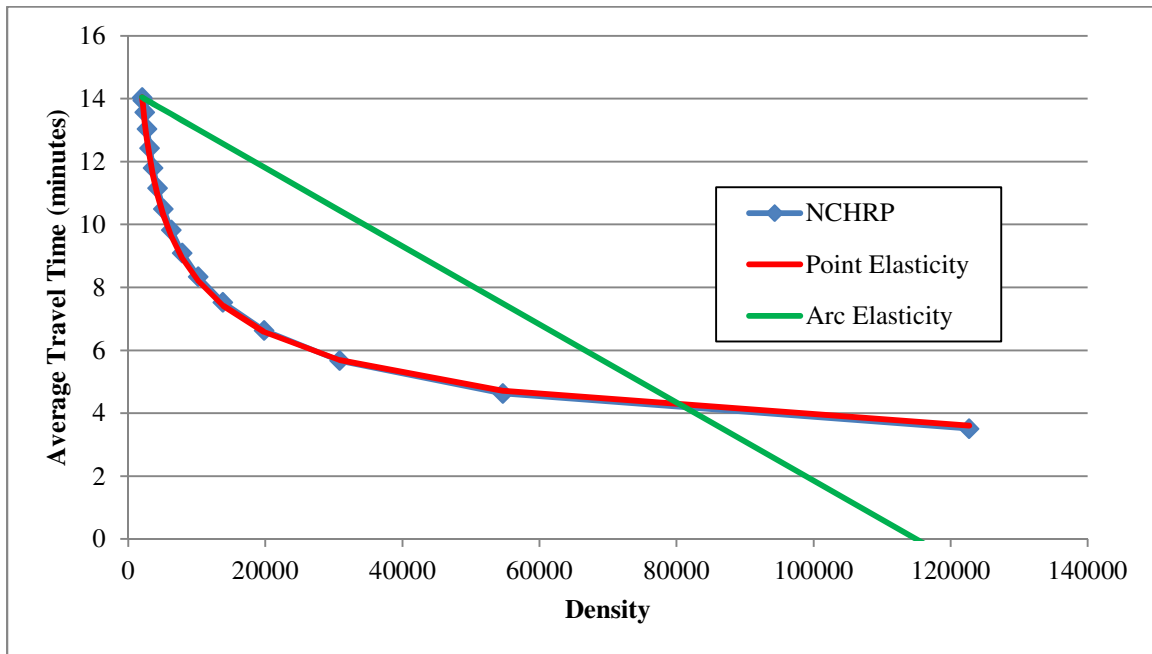


Figure 4-30: Poly-Centric City - CBD Elasticity

Table 4-22: Poly-Centric City Density Scenario Statistics

	CBD	
	Point Elasticity	Arc Elasticity
Base Year Travel Time (min)	14.039	14.039
Elasticity	-0.330	-0.018
R ²	0.998	-0.038
t - stat	-81.006	-4.175

The data results show that there is a point elasticity relationship between density and average travel time for the poly-centric city layout. The results also indicate that the suburbs average travel time is not elastically dependent on the CBD density.

Sensitivity Summary

The sensitivity of the doubly-constrained gravity model to changes in the urban form variables of land use mix and density are summarized in Table 4-23 and Table 4-24. The three types of city layouts investigated in this analysis do not represent all possible city layouts. However, they do represent a very general sample of the different possible layouts for a study region. More research could be used to determine the elasticities of more specific regional layouts.

Table 4-23: Density Sensitivity

City Layout	Density		
	Elasticity	Type	Equation ⁷
Stratified	-0.158	Point	$t_{i,avg} = \frac{t_{i,base}}{D_{i,base}^{-0.158}} \times D_i^{-0.158}$
Mono-Centric	-0.022	Arc	$t_{i,avg} = -0.022 \times \frac{t_{i,base}}{D_{i,base}} \times D_i + (1.022) \times t_{bi}$
Poly-Centric	-0.330	Point	$t_{i,avg} = \frac{t_{i,base}}{D_{i,base}^{-0.330}} \times D_i^{-0.330}$

Table 4-24: Land Use Mix Sensitivity

City Layout	Land Use Mix		
	Elasticity	Type	Equation ⁸
Stratified	-0.033	Arc	$t_{i,avg} = -0.033 \times \frac{t_{i,base}}{LM_{i,base}} \times LM_i + (1.033) \times t_{bi}$
Mono-Centric	-0.024	Arc	$t_{i,avg} = -0.024 \times \frac{t_{i,base}}{LM_{i,base}} \times LM_i + (1.024) \times t_{bi}$
Poly-Centric	-0.022	Arc	$t_{i,avg} = -0.022 \times \frac{t_{i,base}}{LM_{i,base}} \times LM_i + (1.022) \times t_{bi}$

⁷ Where $t_{i,avg}$ is the average travel time for TAZ i, $t_{i,base}$ is the base year travel time for TAZ i, D_i is the density of or around TAZ i, and $D_{i,base}$ is the base year density of or around TAZ i.

⁸ Where LM_i is the Land Use Mix for TAZ i, and $LM_{i,base}$ is the base year Land Use Mix for TAZ i.

It should be noted that the density and land use mix variables used in these equations are better defined for the density and land use mix in and near each TAZ. The average travel times modeled were always the average for all of the TAZs with a specific density. Variations in the average travel time between specific TAZs of the same mix or density were not taken into account. Therefore, these elasticities should only be applied to specific TAZs when the density and land use mix for the TAZ account for the urban form of the surrounding area. Also, the TAZs did not vary in size. When analyzing a region with TAZs of different sizes the land use mix and density variables for each TAZ should be calculated for roughly the same size area for each zone. Table 4-25 shows the updated elasticity table for the project, with the inherent model elasticity values added. The elasticity due to density is given as the arc elasticity for each scenario, calculated using the point elasticity equation for a poly-centric city derived in this chapter.

Table 4-25: Elasticities

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 5.11)	Modified Model Resulting Elasticity (Ch. 5.12)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04	None	None		
	Land Use Mix	-0.06	None	None		
Average Trip Length (per trip)	Density	-0.05	-0.021 (ALT) -0.236 (BAU)	-0.212 (ALT) -0.437 (BAU)		
	Land Use Mix	-0.05		-0.022		

For a poly-centric city (as is the case for the Bozeman, Belgrade, and Four Corners area) the inherent elasticity of the trip distribution step was determined to be a

point elasticity of -0.33. However, the literature elasticity of trip length to density is arc elasticity. Therefore, the expected inherent elasticity of the basic model between trip length and density was converted to resulting arc elasticity for both future scenarios. The expected inherent elasticity of trip length to density for the two future scenarios was calculated using as shown in Equation 4-13 and Equation 4-14. Note that average trip length was substituted for average travel time, as in the idealized scenarios these variables were directly related.

$$e_{arc,BAU} = \frac{\% \Delta l_{base-BAU}}{\% \Delta D_{base-BAU}} = \frac{\frac{\frac{l_{base}}{D_{base}^{-0.330}} \times D_{BAU}^{-0.330} - l_{base}}{l_{base}} \times 100\%}{\frac{D_{BAU} - D_{base}}{D_{base}} \times 100\%}$$

$$= \frac{\frac{6.781}{5057^{-0.33}} \times 3276^{-0.33} - 6.781}{\frac{3276 - 5057}{5057}} = -0.437$$

Equation 4-13

$$e_{arc,ALT} = \frac{\% \Delta l_{base-ALT}}{\% \Delta D_{base-ALT}} = \frac{\frac{\frac{l_{base}}{D_{base}^{-0.330}} \times D_{ALT}^{-0.330} - l_{base}}{l_{base}} \times 100\%}{\frac{D_{ALT} - D_{base}}{D_{base}} \times 100\%}$$

$$= \frac{\frac{6.781}{5057^{-0.33}} \times 9608^{-0.33} - 6.781}{\frac{9608 - 5057}{5057}} = -0.212$$

Equation 4-14

Where:

l_{base} = The average base year trip length in miles

D_{base} = *The average base year population density*

D_{BAU} = *The average BAU scenario population density*

D_{ALT} = *The average ALT scenario population density*

The inherent elasticity of the four-step model can now be used to improve the accuracy of the process with respect to changes in urban form. The next chapter is the case study for the Sonoran Institute. The model used in the case study will be modified to account for the inherent elasticity of the four-step model, leading to better comparison between the two future scenarios.

CHAPTER 5

DEVELOPMENT OF A MODIFIED MODEL AND APPLICATION TO CASE STUDY: ENVISION TOMORROW PROJECT WITH SONORAN INSTITUTE

Introduction

Our modified travel demand model was developed for a project sponsored by the Sonoran Institute. The model inputs were restricted to the output provided by the Sonoran Institute's land use planning program, Envision Tomorrow, and data available through the state, county, and city GIS departments in Montana. The following sections will detail how the model was developed and implemented with real urban form data.

Background

The Sonoran Institute helped create the Envision Tomorrow program to provide counties with a tool for planning future land development. The project was developed in response to concerns about the land consumption and traffic congestion issues arising from the recent rapid growth in areas like Gallatin County, most especially in the Bozeman, Belgrade, and Four Corners "Golden Triangle" area (see Figure 5-1).

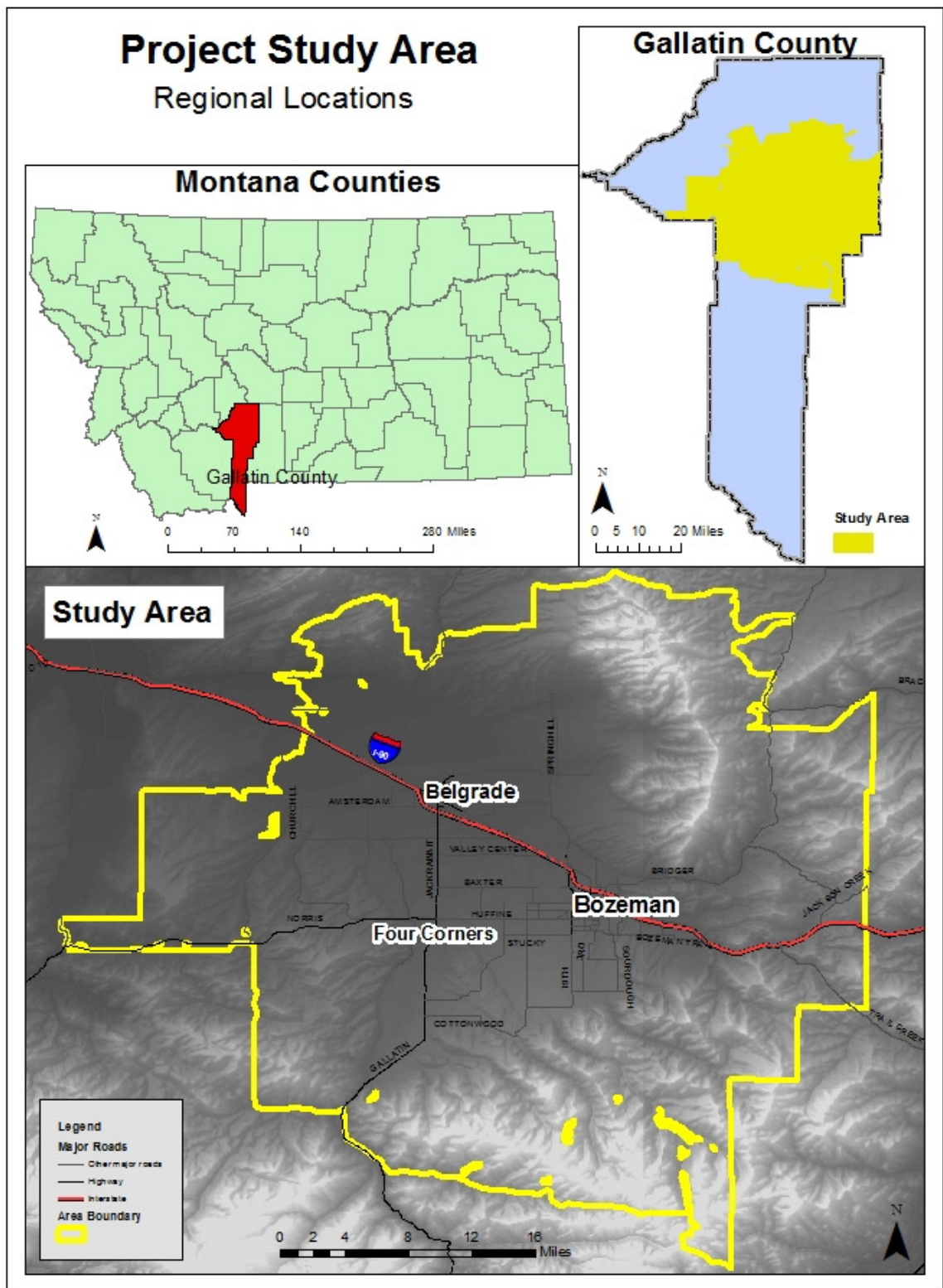


Figure 5-1: Study Area

To utilize Envision Tomorrow in Gallatin County in order to encourage community awareness and involvement in the urban form planning process, the Sonoran Institute organized a workshop in early May of 2010. This workshop brought together community leaders and planners with the goal of developing different future growth scenarios for the Golden triangle area for the year 2049. The workshop used the Envision Tomorrow land use planning tool (a GIS linked database program) to build land development scenarios detailed to the parcel level. Using the data obtained urban form scenarios for the year 2049. One scenario was created assuming that growth would continue in the current pattern (called the “Business As Usual” scenario) and the other (called the “Alternate” scenario) was created focused on more centralized, high density and high mix development (see Figure 5-2).

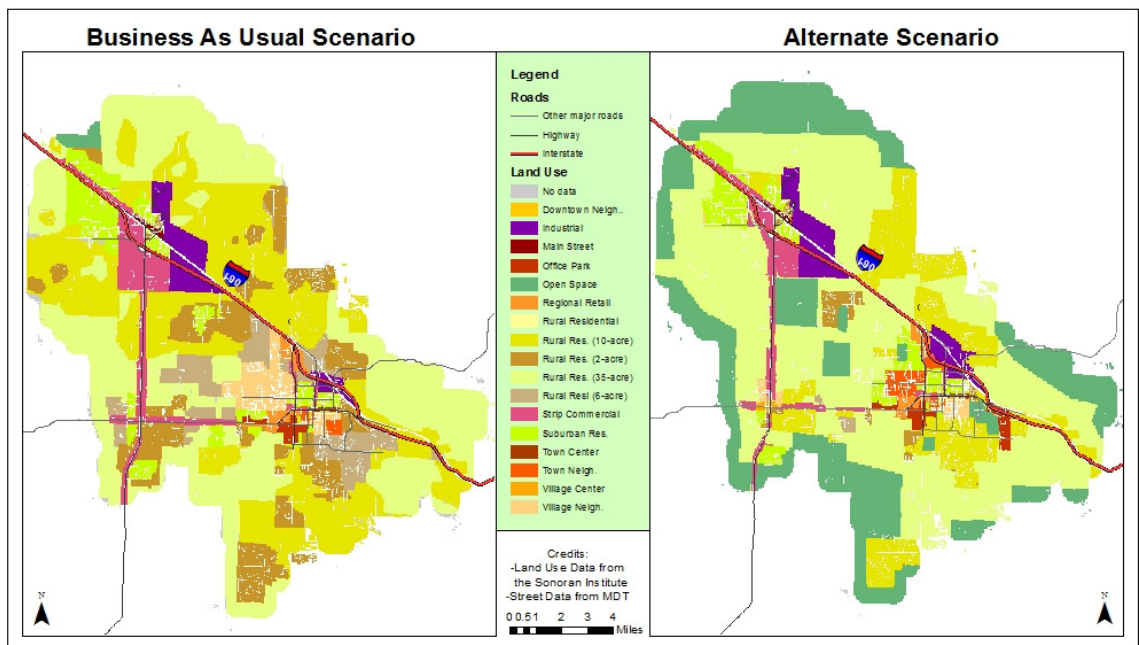


Figure 5-2: Future Scenarios by Development Type

This project involved developing a travel demand model that could predict future vehicle miles traveled for the two future scenarios. The model was constrained to be dependent on the land use, housing, and employment data output by the Envision Tomorrow program. However, a travel demand model must have a base year to provide validation and calibration data. The Sonoran Institute did not provide any base year data. Rather, base year data was obtained from a wide variety of sources. As the goal of the model was to provide a cheap yet sensitive model for rural areas, the base year's data sources were selected based on minimum costs (i.e. mostly free clearinghouse data).

Spatial/Modeling Software

The modified travel model was developed using the four-step process. However, some changes were made to incorporate more sensitivity to density and land use mix in the process. These changes were based on the research and modeling results presented in previous chapters. The model was built and run using the TransCad software from Caliper. TransCad is GIS platform software that also incorporates specific travel demand modeling statistical tools. TransCad has the ability to read any GIS file that can be read in the ESRI ArcGIS format, both vector and raster datasets. TransCad also projects all spatial data files into the same coordinate system. The project used the North American Geographic Coordinate System (NAD 1983) as the coordinate system. This coordinate system was selected because it was the same as the system used by both the Sonoran Institute and Alan Vanderwey of the Montana Department of Transportation (MDT) Planning Division in their modeling projects.

Data Preparation

Every four-step process travel demand model aggregates travel into traffic analysis zones (TAZs). Alan Vanderwey provided the TAZ data for the project area (see Figure 5-3 for example). The TAZs were roughly spatially equivalent to the census blocks of the area. The area of the TAZs varied depending on the population density of the region. For example, the TAZs in downtown Bozeman were the size of a city block, while TAZs in the extremely rural farmland southeast and northeast of Bozeman had areas of more than one square mile. The TAZ data included year 2010 total and occupied

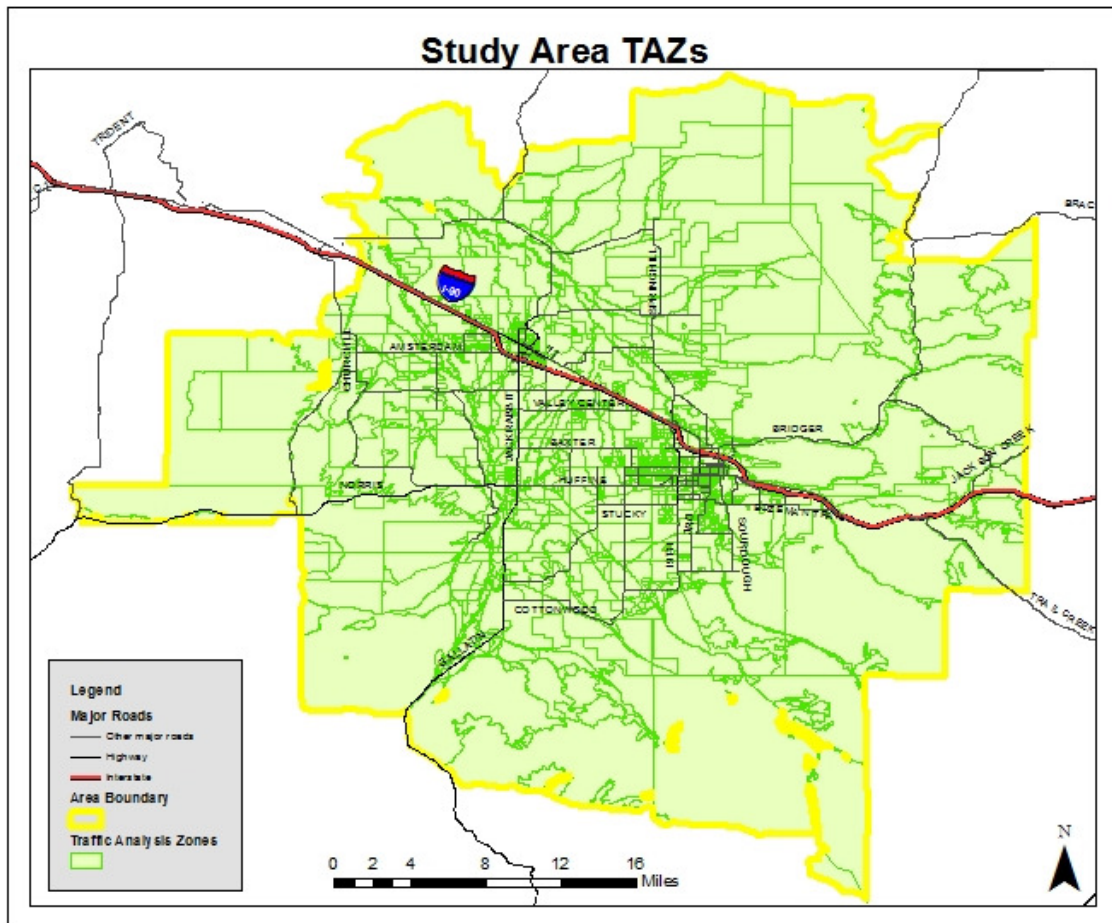


Figure 5-3: TAZ Layout (based off MDT zones)

housing, 2010 zone population new housing from 2001-2010 (all from 2000 and 2010 census block data), and retail and nonretail employment for 2010. As these zones contained most of the data that would be used for the model, they were selected as the TAZs. The study area ended up containing 4144 TAZs and 9 external stations (discussed further in Chapter 3).

Before the travel demand modeling process could begin, the variables necessary to run the model had to be selected and obtained. The Envision Tomorrow output contained housing type, employment (retail, office, and industrial), and development type (city center, village center, open space, etc.). After thorough research of the free GIS data available for the targeted base year, the spatial data variables shown in Table 5-1 were selected for the model.

Table 5-1: Spatial Data Variables Selected

Variable	Purpose	Spatial Unit	Year Available
Single-family housing unit	Used to calculate home-based trips	Per Census Block Group	2000
Multi-family housing unit	Used to calculate home-based trips	Per Census Block Group	2000
Townhome (condo) housing unit	Used to calculate home-based trips	Per Census Block Group	2000
Retail Employment	Used to calculate trip ends	Per TAZ	2010
Non-retail Employment	Used to calculate trip ends	Per TAZ	2010
Measured Average Annual Daily Traffic (ADT)	Used to validate and calibrate model	For all links with available data	1990-2010

The following subsections detail how each of the variables listed in Table 5-1 were acquired and refined for each year required. The data dictionary for the spatial datasets used is given in Appendix D.

Housing

The Sonoran Institutes future scenario provides three type of housing: single-family, multi-family, and townhome (condominium) housing units. Trip rates (discussed further in Chapter 3) are available for these three housing types. To take advantage of the sensitivity to urban form found when using these housing types (see Chapter 4) they were selected as the base year housing units. However, housing type data was not readily available for the base year. Therefore, a combination of county building type data and year 2000 and 2010 census block and block group data was used to estimate the housing units by type in each TAZ. All of the data used was obtained for free from clearinghouse websites maintained either by the state of Montana or Gallatin County. Although the housing unit data was not available at the TAZ level, the combined data from the previously mentioned sources allowed for fairly accurate housing type estimation for the year 2010 for all the TAZs. The most problematic housing type was the townhome. However, the building data from Gallatin County was sufficient to provide estimation for each TAZ.

Employment

The Sonoran Institute's Envision Tomorrow scenarios output office, industrial, and retail employment (these summed to the total employment). However, the data used for the base year of 2010 (provided by Alan Vanderwey) only contained retail and non-

retail employment. To better match the base year the Sonoran Institute's employment data was combined into retail and non-retail (office, services, and industrial).

Density and Land Use Mix

As discussed in the literature review, population density and land use mix have been shown to impact average trip length. The density used for this model was employment plus population per square mile (based on the DKS equations discussed in Chapter 2). As discussed in Chapter 2, the urban form around a housing unit (or a TAZ) effects the travel generated within that TAZ. Therefore, a suitable "area of influence" around each TAZ was used to determine the urban form characteristics for the TAZ. For this project, an area of influence of approximately 0.4 square miles was used. The size of this area was determined to be approximately equivalent to the area created by a 1km network radius around a typical point in the region. The area of influence for each TAZ was calculated by summing the areas of all of the TAZs with a centroid within 0.25 miles of the boundary of the TAZ of interest. The area of the TAZ of interest was also included in this area. The population and employment of the TAZs within the area of influence were calculated using the aggregation tool in the TransCad software. The population and employment within each influence area was then used to calculate the density and land use mix for each TAZ by Equation 5-1 and Equation 5-2.

$$Density = \frac{Population + Employment}{Area}$$

Equation 5-1

Land Use Mix =

$$= \begin{cases} 1 - \frac{b \times \text{Population} - \text{Employment}}{b \times \text{Population} + \text{Employment}}, & \text{Employment} < b \times \text{Population} \\ 1.0, & \text{Employment} \geq b \times \text{Population} \end{cases}$$

Equation 5-2

Where $b = \frac{\text{Total Regional Employment}}{\text{Total Regional Population}}$

The population, employment, and area variables used in Equation 5-1 and Equation 5-2 are calculated from the influence area in and around the TAZ of interest. The density for the base year is shown in Figure 5-4 and the land use mix is shown in Figure 5-5.

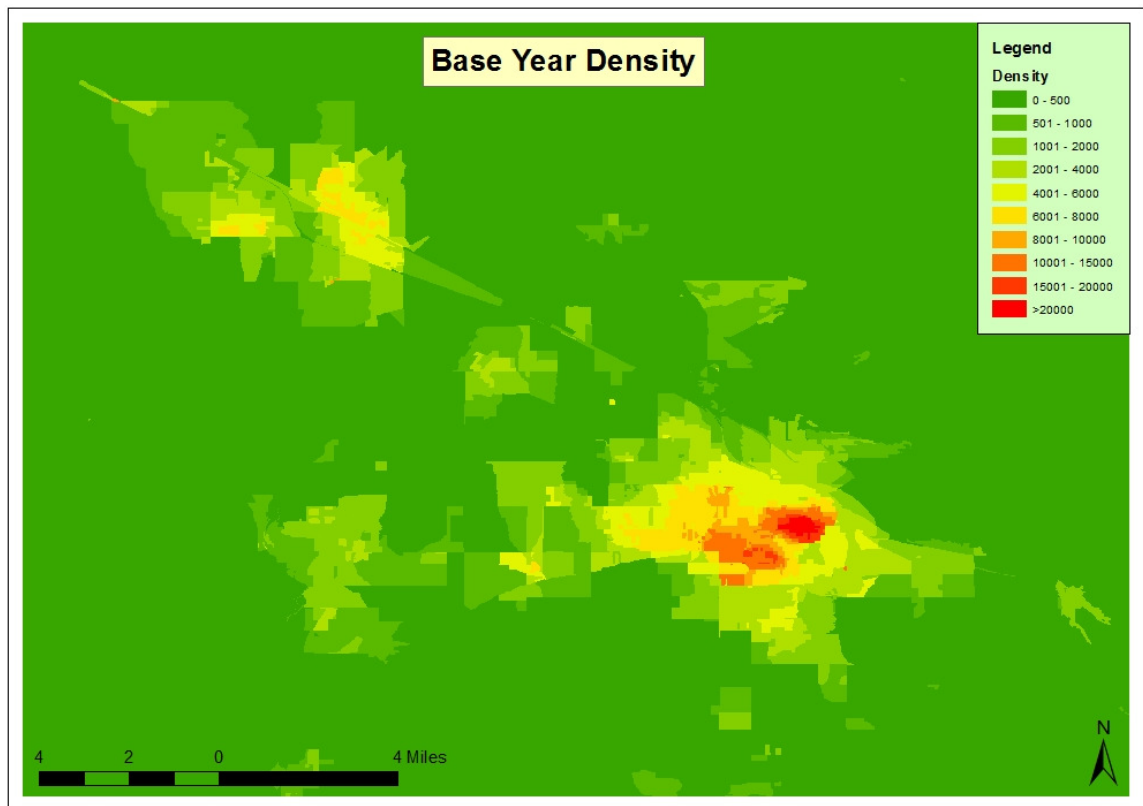


Figure 5-4: Base Year Influence Density Map

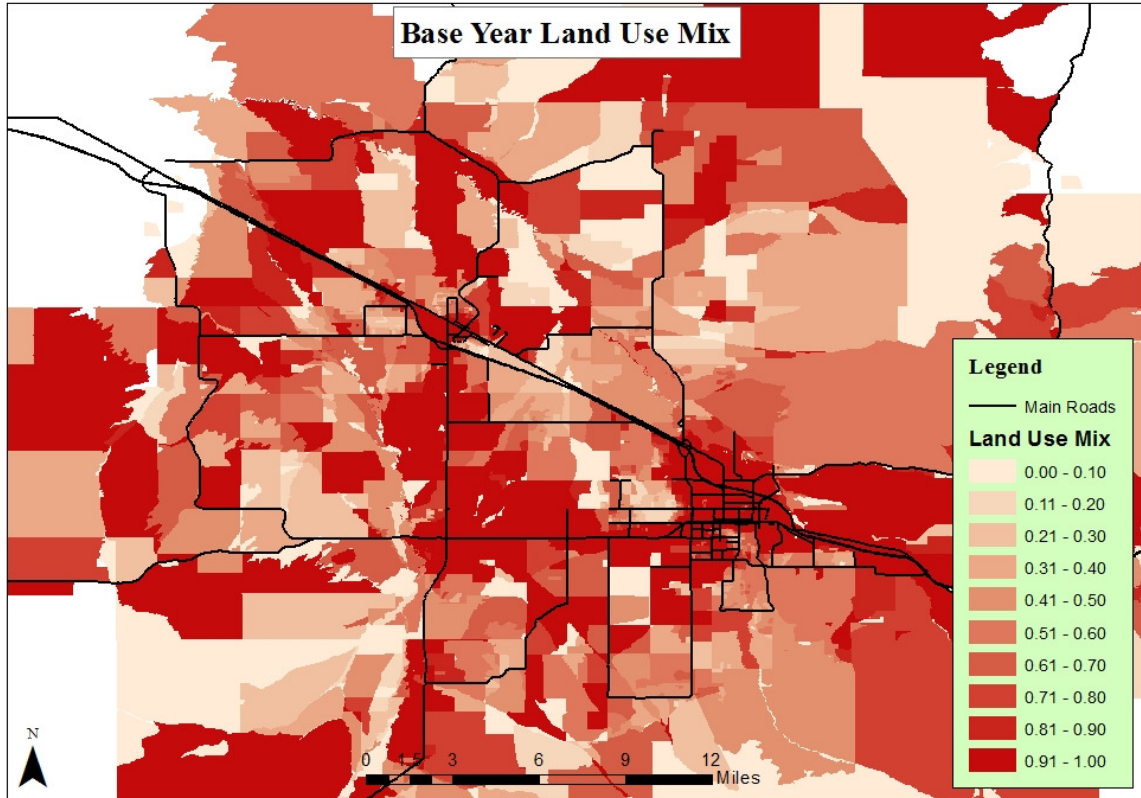


Figure 5-5: Base Year Influence Land Use Mix Map

Average Daily Traffic

The Montana Department of Transportation (MDT) maintains traffic counts at several locations within Gallatin County. Alan Vanderwey provided the average annual traffic (ADT) data for all of the links containing an MDT counting station. These ADT counts were for the year 2010, and would be used to validate and calibrate the base year model (see Section 3.7 for details).

General Process

The model used the four-step travel demand modeling process, with some modifications to the general method used by most agencies (including MDT). The four

steps of the process are trip generation, trip distribution, mode choice/time of day, and traffic assignment (as discussed in detail in Chapter 3). The model did include a calibration feedback loop to adjust trip generation, but no feedback into the trip distribution (i.e. updating travel times accounting for congestion). The model development and application process is outlined in Figure 5-6 and Figure 5-6.

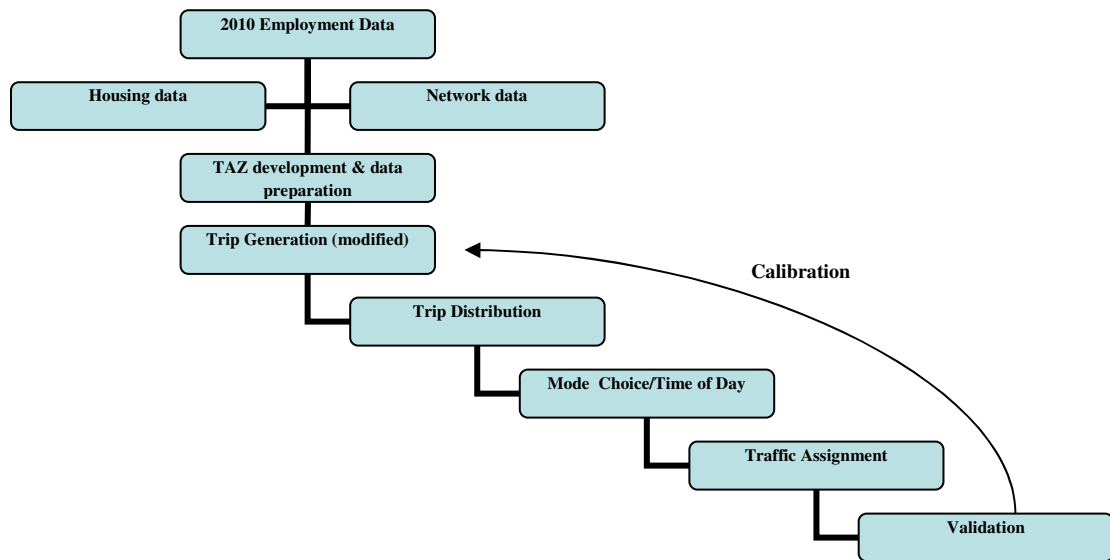


Figure 5-6: Model Development

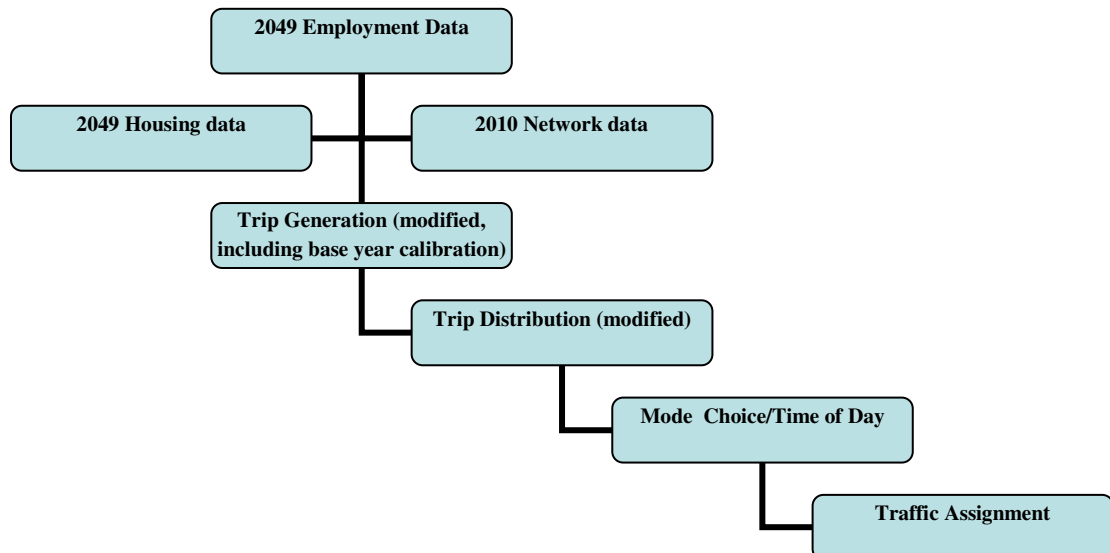


Figure 5-7: Model Application

The model was run for the base year modified trip rates (discussed in detail in the following section). The ADT outputs of the model were validated against the available 2010 ADT data and used to determine a single calibration factor applied to the trip generation rates. The model was then run again with the adjusted trip rates, and the resulting ADT values were satisfactory. The model was validated and calibrated with base year data and traffic was then applied to the future housing and employment data to predict future traffic.

Trip Generation

The first step of the four-step process was trip generation. In this step person-trip productions and attractions are calculated within the each of the model analyses zones. As discussed earlier, the model used TAZ files obtained from MDT. These TAZs were approximately equivalent to census blocks. The Sonoran Institute's scenario data was all at the parcel level and could therefore be easily aggregated up into the TAZs.

The next step involved connecting the TAZs to the network. This involved exporting the TAZ layer to a centroids (point) spatial layer linked to the TAZ database. The centroids were automatically created by TransCad approximately in the center of every TAZ. The centroids were then linked to the network through centroid connectors. Centroid connectors are essentially imaginary roads used to housing and employment destinations of each zone to the network. TransCad has a tool for automatically connecting centroids to the network. However, the centroid connectors for the external stations had to be created by hand. Centroids were not connected with roads that had a functional class of 1 or 2, as these functional classes represented interstates and

highways, which are rarely directly fed by driveways (another way of imagining centroid connectors). Figure 5-8 shows some of the centroid connectors used in the model.

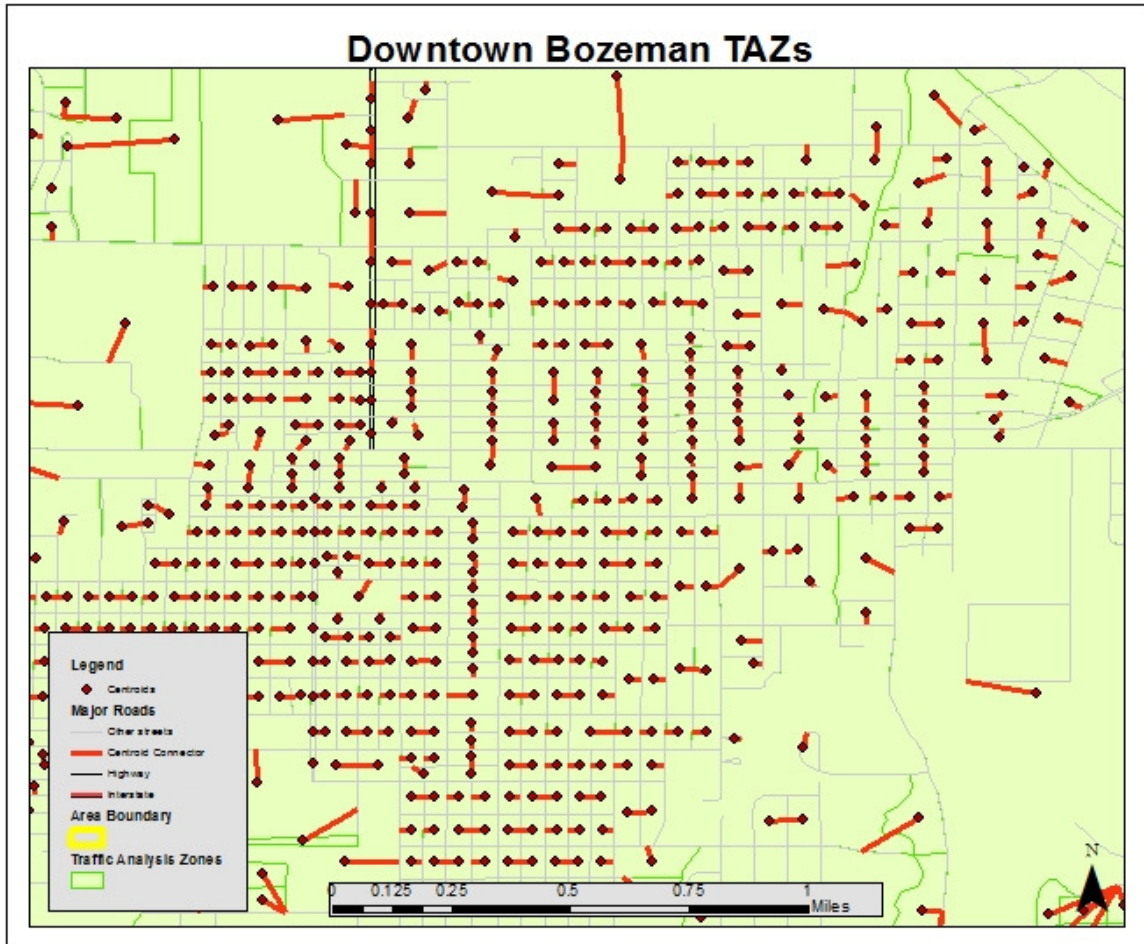


Figure 5-8: Downtown Bozeman Centroid Connectors

The centroid connectors were forced to connect at midblock (a more common location for driveways). The centroid connectors were all assigned a travel time of 0.5 minutes, as they were imaginary roads and their length was irrelevant. Therefore, the minimum possible travel time between two TAZs was fixed at 1.0 minutes. The 0.5

minutes represented an approximation of the time it would take for a vehicle to traverse a driveway and leave the block.

Base Trip Rates

The purpose of the productions and attractions was to create trip beginnings and ends. Trips are expected to form between productions and attractions. The model used three types of housing (multi-family, single family, and townhome (condo) housing units), retail employment, and non-retail employment to calculate the productions and attractions for each zone. These variables were selected based on the available base year data and the output from the Envision Tomorrow scenarios. The variables were derived as described in Chapter 3.

The productions and attractions for each TAZ were calculated for each of the three trip types: home-based work trips, home-based other trips, and non-home based trips. Home-based work trips are work trips that start and end at home, home-based other trips are all other trips that start and end at home, and non-home-based trips are trips that start and end away from the home. The trip types were divided into productions and attractions using trip rates and trip type percentages combining the ITE Trip Generation Manual, a rural travel study performed in Oregon, and NCHRP 365. The original trip rates used are detailed in Table 5-2 (note that these are the un-calibrated trip rates). The trip generation rate equation derivation is detailed in Appendix B.

Table 5-2: Trip Rate Equations

Trip Type	Equation
Home-Based Work Production	$2.11 * HU$ ($HU = SF + MF + TH$ = total housing units)
Home-Based Work Attraction	$1.5 * EMP$ (EMP = retail + non-retail employment)
Home-Based Other Production	$4.17 * SF + 2.31 * MF + 1.75 * TH$ (SF = single-family housing unit, MF = multi-family housing unit, TH = townhome housing unit)
Home-Based Other Attraction	$8.28 * RET + 0.9 * HU$ (RET = retail employment)
Non-Home-Based Production	$1.57 * RET + 1.46 * SF + 0.75 * MF + 0.53 * TH$
Non-Home-Based Attraction	$1.57 * RET + 0.95 * NRET$ ($NRET$ = non-retail employment)

It is important to note here that all of the trips generated for the model were based off studies focused on vehicle only traffic. These trip rates left out transit and pedestrian/bicycling trips at the very beginning of the modeling process. Therefore, the only sensitivity of the model to shifts in travel mode would be captured in by the different trip generation rates for the three types of housing units. For example, multi-family homes generally produce more alternate mode trips per housing unit than single-family homes. The model captures some of this mode shift effect by fewer home-based other auto trips (i.e. 4.17 auto trips per SF versus 2.31 per MF).

Special Generators

Special rates were used for the Montana State University Campus and the Gallatin Field Airport using the ITE trip generation rates for these specific land uses. These two areas were designated as special generators (see Chapter 3 for definition). The university

trip rates were based off the student population of the university, and the airport trip rates were based off the average number of commercial flights per day arriving and departing. The trip rates for the two special generators are detailed in Table 5-3.

Table 5-3: University Special Generator Trip Rate Equations

Trip Type	University Generator	Airport Generator
HBW Productions/Attractions	$0.25 * 0.16 * 1.4 * 2.38 * \text{Students}$	$0.25 * 0.16 * 1.4 * 122.21 * \text{Commercial Flights/day}$
HBO Productions/Attractions	$0.25 * 0.61 * 1.9 * 2.38 * \text{Students}$	$0.25 * 0.61 * 1.9 * 122.21 * \text{Commercial Flights/day}$
NHB Productions/Attractions	$0.25 * 0.23 * 1.6 * 2.38 * \text{Students}$	$0.25 * 0.23 * 1.6 * 122.21 * \text{Commercial Flights/day}$

Note that the trip types were calculated by simply multiplying the total trip rate by a fixed percentage of a trip type (the percentages were the same as used by MDT split up trips by type). The locations and sizes of the special generators are shown in Figure 5-9.

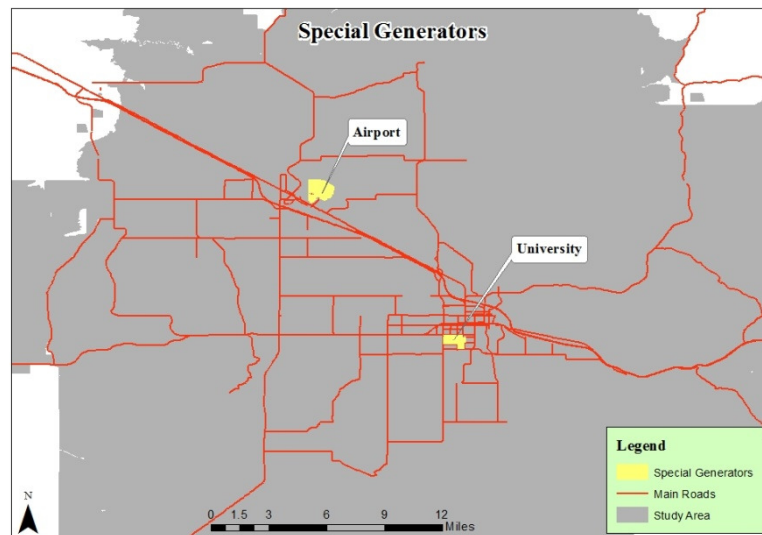


Figure 5-9: Special Generators

In the model application to the future scenarios, the number of students attending the university and their housing location was provided by the Sonoran Institute, allowing for the same special generator trip rates to be used for the university. The airport was covered by residential development in both future scenarios, so this special generator was removed in the future scenario model application.

External Stations

The model included nine external stations. External stations capture traffic from major roads leading into and out of a modeled study region (See Chapter 3 for more detailed definition). The productions and attractions for the external stations was calculated based on the year 2010 ADT counts for the links represented by the stations using the MDT external station trip rate calculation method. The full calculations for the external stations are included in Appendix C. However, the model also used the NCHRP 365 through-trip calculation process to calculate how many of the I-90 trips would go straight through the study area (about 42%). These trips were removed from first two steps of the four step process and included in the third step (see Section 3.5). All of the production and attraction rates were ultimately derived from vehicle trips rates. Figure 5-10 shows the locations and Table 5-4 summarizes ADTs for the external stations.

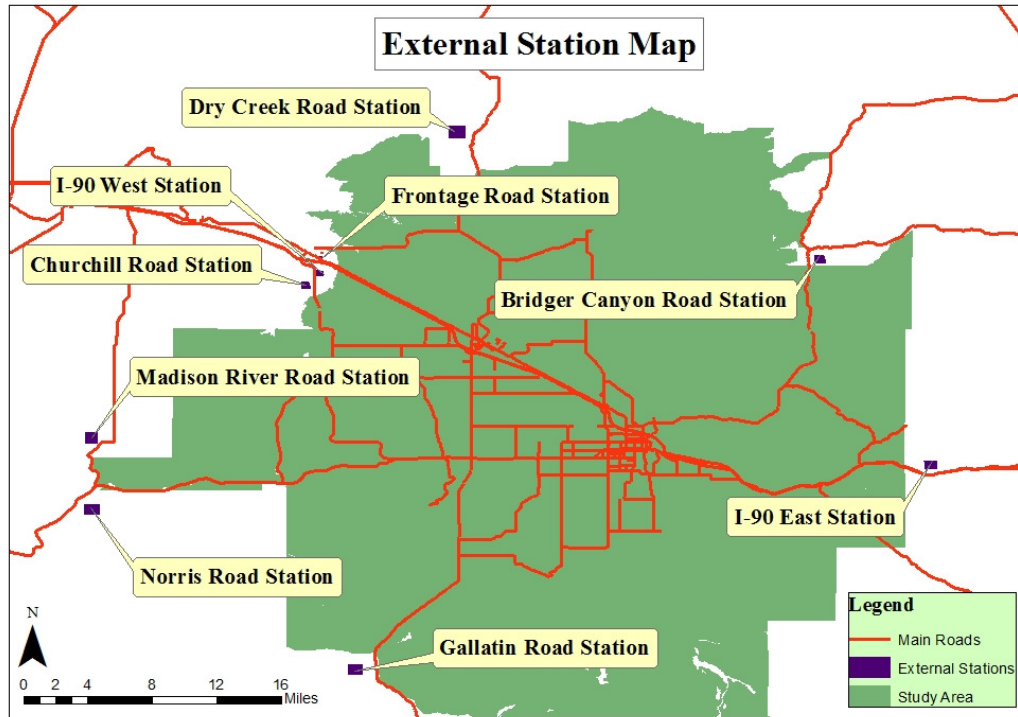


Figure 5-10: External Stations

Table 5-4: External Station ADT

Station	2010 ADT	2049 Predicted ADT
I-90 East Station	12750	27413
Gallatin Road Station	5840	12556
Norris Road Station	1720	3698
Madison River Road Station	80	172
Churchill Road Station	1090	2344
I-90 West Station	12543	26967
Frontage Road Station	1580	3397
Bridger Canyon Station	770	1656
Dry Creek Road Station	190	409

Balancing

Each production and attraction represented a two-way person trip. It should be noted here that this leads to one of the main limitations of the four-step process.

Essentially, the model can only account for two-way trips, trips that go from an origin to a destination and back to the origin with no stops in between. However, this modeling process has been shown to provide fairly satisfactory results and is used by most Metropolitan Planning Organizations (MPOs).

To complete the trip generation process, the productions and attractions had to be balanced. Balancing productions and attractions simply means that there must be an equal number of productions and attractions for each trip type for the entire study region (but not within each zone). The productions and attractions were balanced by holding the productions constant and scaling the attractions to equal the productions total. The trips were balanced to the productions because the housing data was much more accurate than the employment data. As the productions were primarily dependent on the housing data (with the exception of the non-home-based trips) the productions were assumed to be more accurate. However, the attractions were held constant for the special generators and the external stations, as the trip rates for these zones were more likely to be. The balancing process was completed using the TransCad trip balancing tool.

Trip Distribution

The second step of the four-step process is trip distribution. In this step the productions and attractions developed in the trip generation step are paired. The methods

of pairing the productions and attractions again vary between models but generally use some type of assignment method involving the travel relative attractiveness (i.e. more attractions than other areas) of other zones. Some type of impedance is used to incorporate the cost (in travel time) of the trips. The results of trip distribution can be represented in matrices matching productions to attractions, thus forming a table of round trips between zones.

The model used the doubly constrained gravity model to distribute the trips between the zones. Different impedance values were assigned to every possible origin-destination (O-D) pair using a gamma function (discussed in the following section) that represented a typical travel time distribution for an urban area. These impedance values were calculated using a skim matrix of the shortest travel times from each zone to every other zone as the cost matrix for the impedance function. The travel times for each link had already been calculated using the average free flow speed and length of each link (provided in the street network file). Each TAZ was assigned an inter-zonal travel time of 10000 minutes. As the TAZs were generally the size of a city block and all of the productions and attractions, although calculated as person trips, were originally derived from vehicle trip rates it was decided that the probability of inter-zonal vehicle trips was highly unlikely based on the small size of the TAZs. People don't generally use their cars to drive to their neighbor's houses. The 10000 minute interzonal travel time effectively forced all trips generated within a TAZ to go to other TAZs. This method was also used by Alan Vanderwey of MDT when working with TAZs of this size

The four step model distributes trips according to different travel time distributions. These travel time distributions are typically the same for the base year and

future scenarios. Many models use travel time distributions based off local travel surveys, while others use a trip distribution function representing the national travel time distribution for each trip type (when travel time survey data is unavailable). The travel time distributions are used to calculate friction factors representing the relative cost of travel between zones.

As shown in Chapter 4, the doubly-constrained gravity model is sensitive to urban form. However, studies have shown that the actual sensitivity of travel length specifically to urban form is much higher than the sensitivity provided by the unmodified doubly-constrained gravity model. Therefore, the trip distribution step was modified to adjust travel length for urban form. To perform this adjustment the average travel time of a distribution would have to become a function of the changes in urban form around a zone. To derive this function the travel time distribution had to be changed into a functional form. The modeling of the travel time distribution is detailed in the following sections.

The “Gamma Function”

For a model without local travel time distribution data available for each trip type, the so-called “Gamma Function” is used to determine the friction factors for the free-flow travel times between each zone (see Equation 5-3). The form of the actual gamma probability distribution function is shown in Equation 5-4.

$$f_{ij} = at_{ij}^{-b}e^{-ct_{ij}}$$

Equation 5-3

Where:

t_{ij} = Travel time between zones i and j ,

a , b , and c = Constants determined by the trip type

f_{ij} = The friction factor representing the cost of travel

$$f(x) = \frac{\lambda^r x^{r-1} e^{-\lambda x}}{\Gamma(r)}$$

Equation 5-4

Where:

$$r > 0$$

$$\lambda > 0$$

$$\Gamma(r) = \int_0^{\infty} x^{r-1} e^{-x} dx$$

Although the actual Gamma function in Equation 5-4 may be more statistically accurate, the version in Equation 5-3 provides a close approximation with a needed simplicity and was therefore used for this project. The constant values in Table 5-5 are used to model the national average travel time distribution for HBW, HBO, and NHB trips. Figure 5-11 shows the graphs of these three distributions.

Table 5-5: NCHRP Gamma Function Coefficients

Trip Type	a coefficient	b coefficient	c coefficient
HBW	28507	0.02	0.123
HBO	139137	1.285	0.094
NHB	219113	1.332	0.100

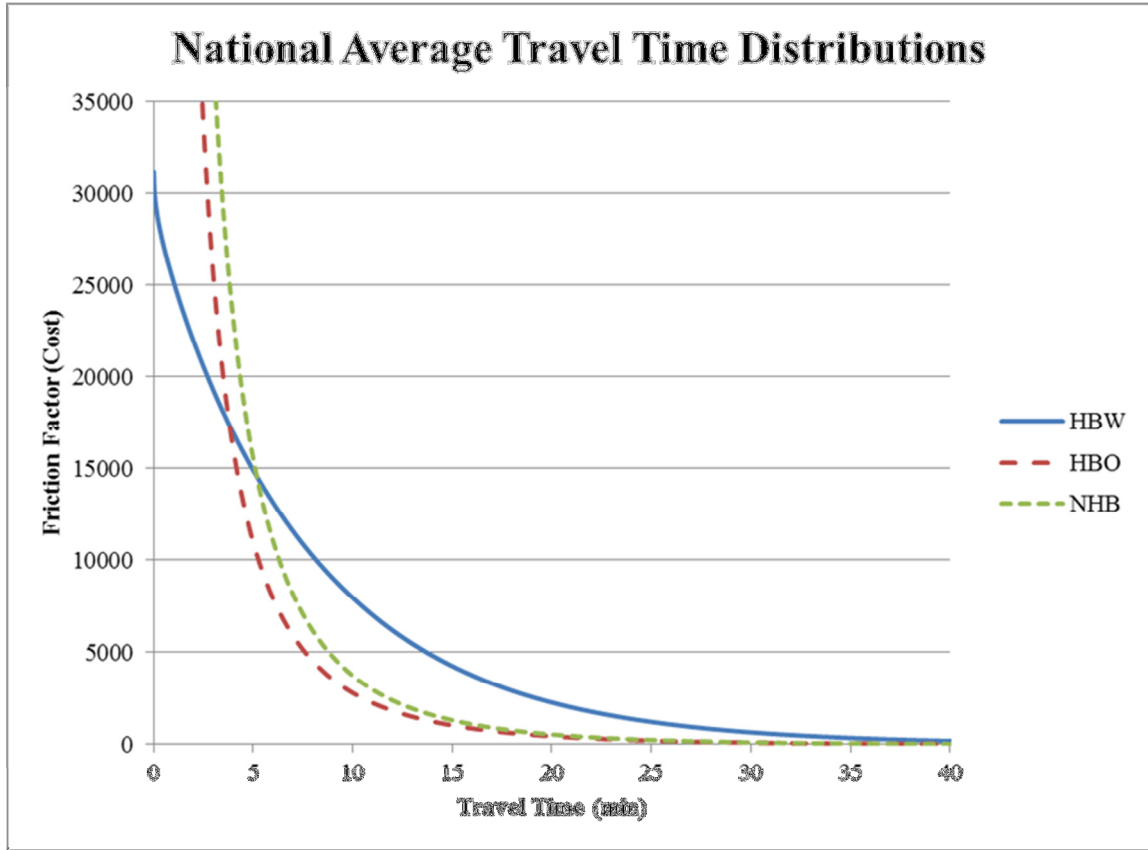


Figure 5-11: NCHRP Friction Factors

If the gamma function was really a gamma function, the average travel time for each distribution could be calculated as shown in Equation 5-6. This equation is derived from the equation for the average value a gamma probability distribution function shown in Equation 5-5.

$$\mu = \frac{r}{\lambda}$$

Equation 5-5

When $\mu = t_{avg}$, $r = 1 - b$, and $\lambda = c$

$$t_{avg} = \frac{1 - b}{c}$$

Equation 5-6

However, for travel modeling purposes, this does not represent the average travel time of the distribution, as the minimum travel time possible is the twice the centroid connector time. Also, this relationship only holds true if $b < 1.0$ (since $r > 0$ for the gamma probability distribution). As b is greater than 1.0 for HBO and NHB travel time distributions, a different method was developed to calculate the average travel time for each distribution.

To be able to adjust the travel time for a given zone (based on urban form) an approximation method, detailed in Appendix E, was utilized. Essentially, the distributions shown in Figure 5-11 were adjusted left or right to keep a similar shape but adjust the average travel time. This was adjusted by adjusting one of the coefficients of the gamma function for each trip type, as summarized in Table 5-6.

Table 5-6: Gamma Function Adjustments

Trip Type	Adjustment Coefficient	Equation
HBW	c-value	$c(t_{avg}) = \begin{cases} 0.0001, & t_{avg} > 30.0 \text{ min} \\ -0.00401t_{avg} + 0.12011, & 17.5 \text{ min} < t_{avg} < 30.0 \text{ min} \\ 2.22707t_{avg}^{-1.32650}, & 17.5 \text{ min} \geq t_{avg} > 2.0 \text{ min} \\ 1.0, & t_{avg} < 2.0 \text{ min} \end{cases}$
HBO	b-value	$b(t_{avg}) = \begin{cases} 0.12, & t_{avg} > 57.0 \text{ min} \\ -0.02838t_{avg} + 1.73860, & 15.5 \text{ min} < t_{avg} < 57.0 \text{ min} \\ 3.70697t_{avg}^{-0.38270}, & 15.5 \text{ min} \geq t_{avg} > 2.0 \text{ min} \\ 3.0, & t_{avg} < 2.0 \text{ min} \end{cases}$
NHB	b-value	$b(t_{avg}) = \begin{cases} 0.01, & t_{avg} > 60.0 \text{ min} \\ -0.02843t_{avg} + 1.73945, & 15.5 \text{ min} < t_{avg} < 60.0 \text{ min} \\ 3.70836t_{avg}^{-0.38284}, & 15.5 \text{ min} \geq t_{avg} > 2.0 \text{ min} \\ 3.0, & t_{avg} < 2.0 \text{ min} \end{cases}$

Model Application

The goal of the sensitivity built into the trip distribution step was make the travel time distribution sensitive to the changes in urban form around each TAZ. The urban form of an area affects the travel behavior of the area's residents. Therefore, the sensitivities of the travel time distribution to changes in urban form would only be applied to the trips produced in each TAZ. For example, residents of a TAZ with high density and a high land use mix would have a shorter average trip length. However, trips attracted to the TAZ would not necessarily have a shorter average trip length, depending on the changes in urban form of the neighborhood where they originated.

To apply an elasticity function to the model, a base travel time had to be developed for each TAZ. For the base year, trips were distributed using the NCHRP travel time distribution friction factors (national average travel time distribution) and the doubly-constrained gravity model. After the trips were distributed, the average travel time for each zone was calculated by trip type. The average travel times for all of the trips produced in each TAZ were then calculated using Equation 5-7.

$$t_{i-avg} = \frac{\sum_{j=1}^n P_{ij} t_{ij}}{\sum_{j=1}^n P_{ij}}$$

Equation 5-7

Where:

t_{i-avg} = average travel time for TAZ i

P_{ij} = the productions of the trip type distributed from zone i to zone j

t_{ij} = the free flow travel time between zones i and j

The resulting travel times for each trip type were used as the base year travel times for each TAZ. Average trip length has an arc elastic relationship to land use mix and density, as discussed in Chapter 2. The elasticity of these two variables against trip length is shown in Table 5-7.

Table 5-7: DKS Associates (2007) Elasticity Values

Variable	Effectuated Variable	Elasticity
Land Mix	Travel Length	-0.05
Population + Employment Density	Travel Length	-0.05

However, the doubly constrained gravity model does have some inherent elasticity between average travel time, land use mix, and density (see Chapter 4). The average travel time is roughly proportional to the average trip length, as the doubly constrained gravity model used for this model distributed trips using free-flow travel times. Therefore, the sensitivity of the doubly constrained gravity model was modified to account for this this inherent elasticity. Because the Gallatin Valley most closely resembled a poly-centric layout, the inherent elasticities of a poly-centric layout (see Table 4-23 and Table 4-24) were used in the model.

No adjustments were made to the base year model. Trips were distributed using the national average travel time distribution, and no other modifications were made in the trip distribution step. However, the future scenarios contained many changes in urban form. Therefore, the density and land use mix (which had already been calculated for the base year) were calculated for the future scenarios, using the same influence areas and

TAZs. Once these urban form variables were calculated, the average travel time for all trips produced within each TAZ were recalculated using the base year travel time, literature elasticities, and base and future scenario land use mix and density values (see Equation 5-8). The travel times for each trip type were recalculated using these equations.

$$t_i = t_{i,0} \left\{ [-0.05 - (-0.022)] \times \frac{LM_i - LM_{i,0}}{LM_{i,0}} + \left[-0.05 - \left(\frac{\frac{t_{i,0}}{D_{i,0}^{-0.330}} \times D_i^{-0.330} - t_{i,0}}{\frac{t_{i,0}}{\frac{D_i - D_{i,0}}{D_{i,0}}}} \right) \right] \times \frac{D_i - D_{i,0}}{D_{i,0}} + 1 \right\}$$

Equation 5-8

Where:

t_i = the average travel time for trip produced in zone i ($t_{i,0}$ = base year)

LM and D are as defined previously

The model attempts to bring the inherent sensitivity to land use mix (arc elasticity of -0.022) to the sensitivity of travel found in literatures (arc elasticity of -0.05).

Additionally, the sensitivity inherent to density (point elasticity of -0.33) is also modified to the sensitivity of travel found in literature (arc elasticity of -0.05).

The trip distribution adjustment is done for the household travel starting in each zone. First, the base year travel times for all of the trips starting in each zone are determined using the base year model results. Next, the predicted average trip length (in

travel time) is calculated using Equation 5-8. The predicted average travel time is the average travel time expected for the zone based on the urban form.

Once the future scenario desired travel times were determined, the equations shown in Table 5-6 were used to calculate the coefficient required in the gamma function to build a travel time distribution with the specific average travel time. These coefficients were then combined with the travel times from the shortest path matrix to calculate the friction factors for every possible trip match for the TAZ. This process was run for every TAZ. The end result was a friction factor table that modeled a separate travel time distribution for each TAZ. Note that the friction factors were applied only to the trips produced in a TAZ. Trips attracted to a TAZ were not directly affected by the travel time distribution of the trips produced in the TAZ. This method effectively implemented urban form elasticities into the trip distribution while accounting for the inherent elasticities of the doubly-constrained gravity model. The end result of the trip distribution step was person trip matrix for the entire study region.

Time of Day/Mode Choice

The third step of the four step process is time of day/mode choice. The goal of this step is to convert the production and attraction round trips into an origins and destinations while also moving from person trips to vehicle trips. Mode choice data is used to incorporate vehicle occupancy into the model. Future mode choice data can be projected by using base year percentages (i.e. the percent of all trips taken with transit will not change over time), by multinomial logit calculations, or other mode split prediction calculation methods. The trips are sometimes also divided up by time of day

using some daily travel split distribution, to find the peak hour traffic flows. More detail into the mode choice step is given in Chapter 3.

This step was simplified for the model by assuming that all trips generated by the model were vehicle trips, a fair assumption given the fact that the productions and attractions were generated based on vehicle trip rates (as discussed earlier) and the transit mode split share in Bozeman is very low (less than 0.5% of all trips, according to the Streamline bus website). The model used the same vehicle occupancy rates as used by the Montana Department of Transportation (MDT) Planning Division (see Table 5-8).

Table 5-8: MDT Vehicle Occupancy by Trip Type

Trip Type	Average Assumed Vehicle Occupancy
Home-Based Work	1.4
Home-Based Other	1.9
Non-Home-Based	1.6

As the primary focus of the model was total vehicle miles traveled (VMT), no time of day analysis was used initially in the base year model. For better network accuracy, the model could be broken down into trips by hour. However, this process would be time consuming and not make any significant difference in the VMT output from the model. The end result of the time of day/mode choice step was an origin-destination (O-D) matrix of vehicle trips between all of the TAZs in the model. It should also be noted that the I-90 through trips removed from the external stations during the trip generation step were now re-inserted by hand into the final model O-D matrix.

Traffic Assignment

The final step in the four-step process is trip assignment, also called route choice. The goal of this step is to establish the link flows between the analyses zones. These flows are calculated from the origin destination matrix, using the least costly (shortest travel time) routes for each trip. The link capacities can be considered in this step (but in this case were not) which may lead to some updating for the time components of the equations used in the distribution step.

Trips were initially assigned to the streets of the study area using the all or nothing (AON) method, which essentially places assigns all O-D pairs to the shortest available routes based on free flow travel times (essentially ignoring congestion effects). TransCad can also assign traffic with some sensitivity to congestion. However as the model was only concerned with daily traffic and the daily capacity of the network links was far higher than the expected model daily flows, no congestion effects were accounted for initially. This simplification was also justified by the ultimate goal of the model to produce a total VMT for the study area, a number not likely to be effected by slight traffic shifts during peak hours. The TransCad traffic assignment tool created a data table containing the daily traffic flow and VMT for all of the links in the network. These results were used for the model calibration and validation. It should be noted here that later on in the calibration process, the trips were assigned to the network accounting for at least some of the congestion effects. The assignment method used, called user equilibrium, is based off the assumption that drivers will select their routes based on congested travel times until all routes with any traffic between an origin-destination pair

have an equal and lowest possible travel time. This method uses the Bureau of Public Roads (BPR) function to account for the effects of congestion on travel time. More detail into this traffic assignment method is not necessary as it was used merely as a validation check on the model after some calibration.

Validation/Calibration

The validation and calibration portion of travel modeling varies greatly depending on what type of travel data is available for the study region. As the only travel data available was 2010 ADT, a validation method commonly used by Alan Vanderwey of MDT was performed on the model. To calibrate the model, the ratio of the model ADT to the year 2010 measured AADT of all of the links with year 2010 ADT data was calculated. The resulting ratio indicated that the modeled travel was initially about 16% too high. Therefore, the trip production and attractions calculated in trip generation were adjusted by the inverse of this ratio and the entire four-step process was re-run with these recalculated trips. The resulting ADT ratio was 0.003% too high, which was more than acceptable.

The percent root mean square error (%RMSE, see Equation 3-2) was also calculated for all links within the study area with 2010 ADT data available. The RMSE measure captures both the ratio of model to actual ADT and the deviation of the specific link ADT volumes. Many states recommend a maximum RMSE of 30%. The calibrated base year model had an RMSE of 46%. However, a second validation check was run accounting for some of the effects of congestion.

The base year trips were divided by hour in the time of day/mode choice step, resulting in 24 O-D matrices, one for each hour of the day. The proportion of daily trips assigned to each hour was determined using a national average time of day trip distribution for the three different trip types (HBW, HBO, and NHB). Then the trips were assigned to the network using user-equilibrium (see Chapter 3). Each hour was assigned separately, and the effects of congestion on travel time were account for through the BPR function. These coefficients were used to calculate the congested travel times during the user equilibrium assignment. The user-equilibrium method provided a much better %RMSE value (31.5%). Again, as the focus of the model was on VMT and not specific link travel, this value was determined to be more than acceptable. Table 5-9 summarizes the iterations performed, calibrations applied, and validation results for the base year model. Figure 5-12 shows the model to actual ADT ratios for the base year after the final iteration. It should be noted that the traffic flow on all of the principal connectors between the three main urban areas in the model were modeled very close to the actual base year measured traffic.

Table 5-9: Validation and Calibration Summary

	Initial Model	Iteration 1	Iteration 2
$ADT_{\text{model,avg}}/ADT_{\text{actual,avg}}$	1.16	1.00	1.07
%RMSE	51.59%	46.38%	31.30%
Calibration Adjustment	None	Multiply Trip Rates by 0.866	User Equilibrium Assignment

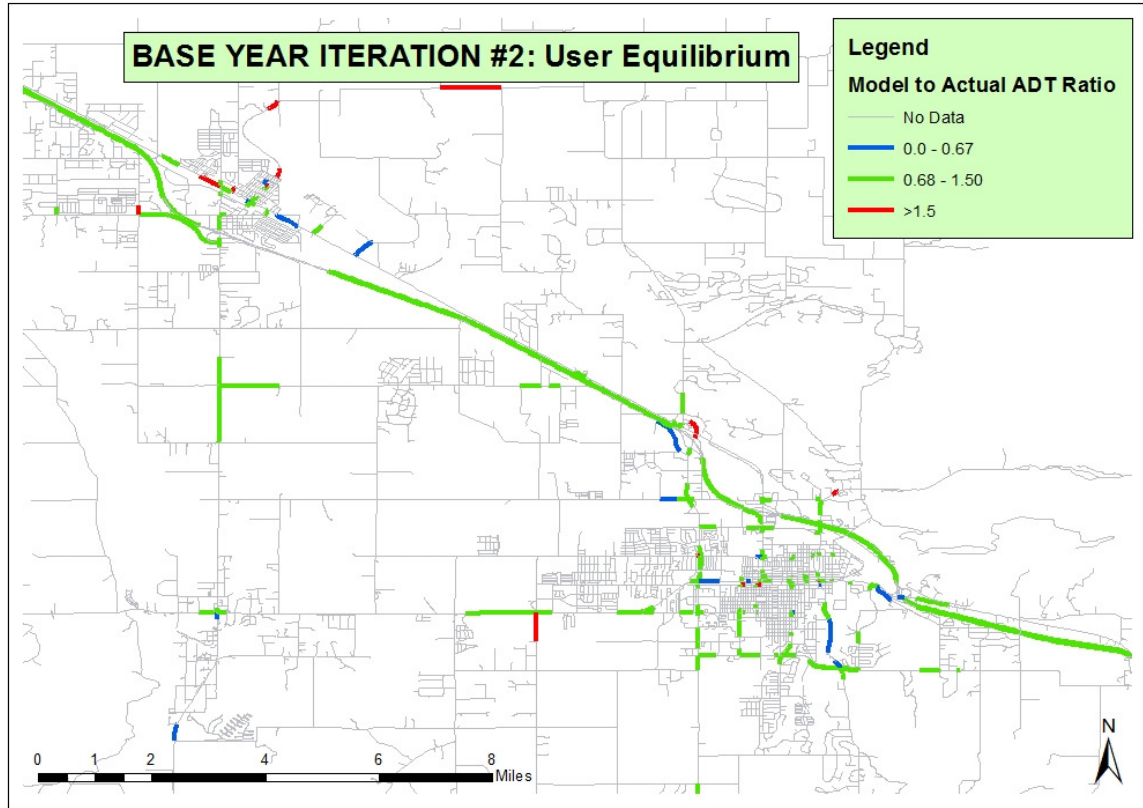


Figure 5-12: Final Iteration ADT Ratio Map

The end result of the base year model was the ADT for the network in 2010. The ADT was used to calculate the daily VMT for the project area. Figure 5-13 shows the base year ADT for the project network.

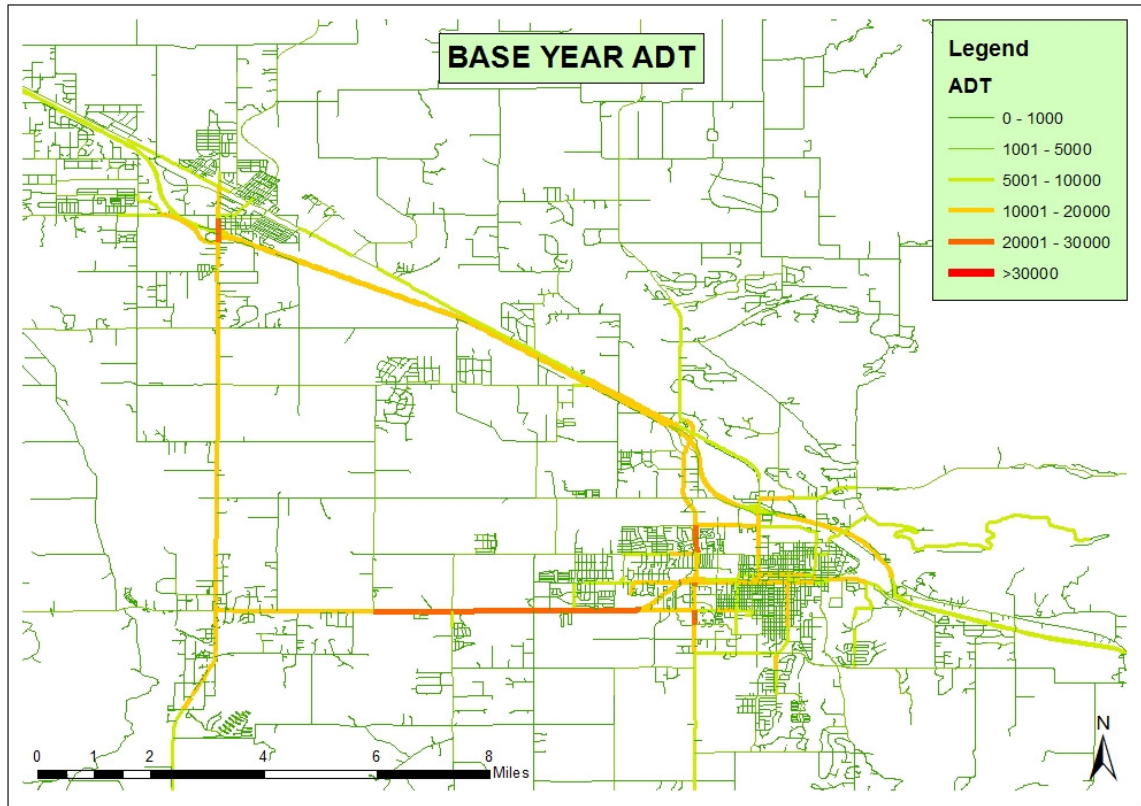


Figure 5-13: Base Year (2010) Model ADT

Future Scenarios

The future urban form scenarios were provided by the Sonoran Institute, as discussed in previously. The two scenarios had very different development patterns. The Business As Usual (BAU) scenario attempted to follow the current growth patterns in the Golden Triangle Area. The Alternate (ALT) scenario was developed using more smart growth oriented techniques, centering development on high land use mix and high density urban centers. The general demographic data for the two future scenarios is summarized in Table 5-10.

Table 5-10: Scenario Demographics

	Base	ALT	BAU
Population	82,463	159,471	158,103
Total Employment	53,366	156,810	143,555
Retail Employment	28,563	91,284	88,829
Non-Retail Employment	24,803	655,527	54,726
Total Housing	32,344	54,889	54,346
SF	18,994	26,585	42,488
MF	11,632	23,533	5,501
TH	2,302	4,772	6,357

The influence density for each zone in both future scenarios is shown in Figure 5-14 and Figure 5-15. The influence land use mix for each zone in both future scenarios is shown in Figure 5-16 and Figure 5-17. Note that the urban form variables shown in these figures are calculated for each zone based on the urban form influence area described previously.

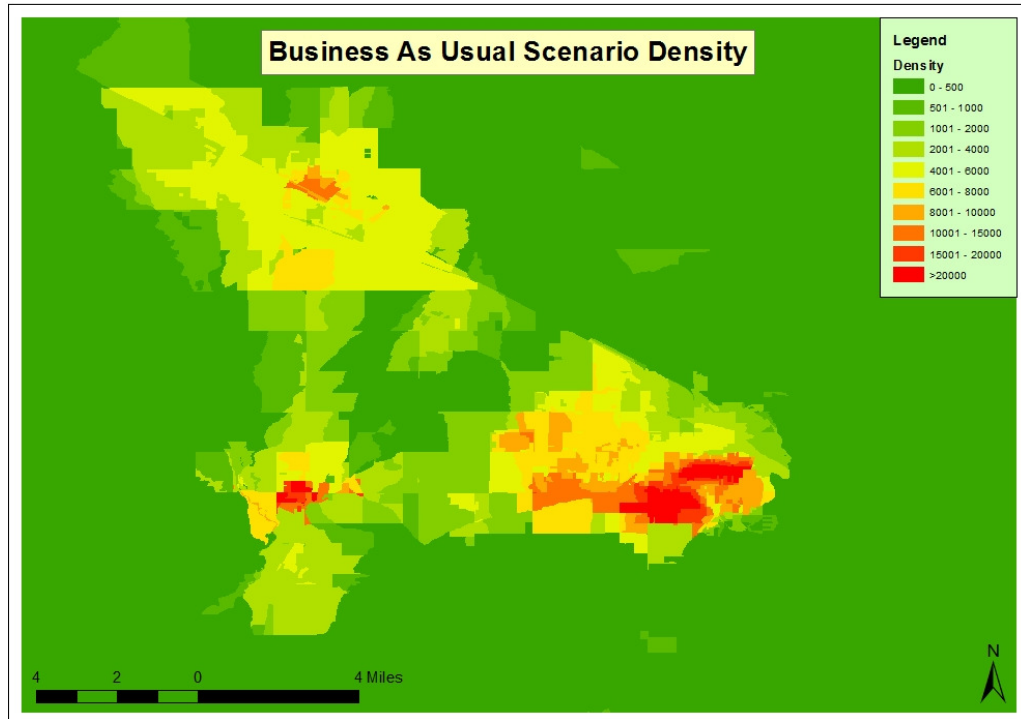


Figure 5-14: BAU Density Influence Map

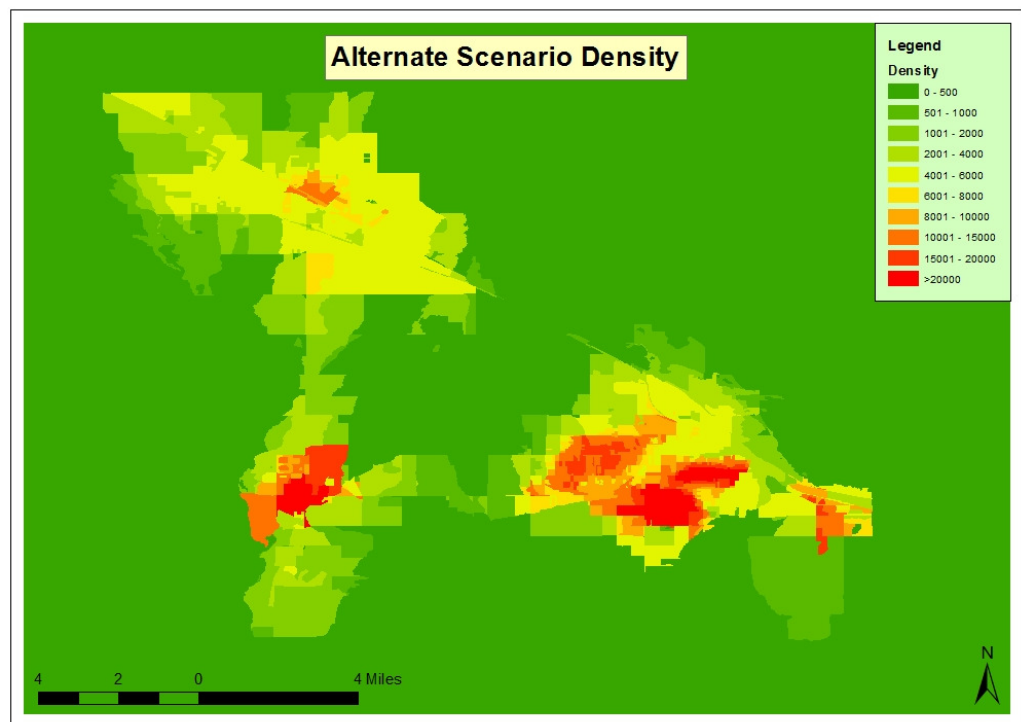


Figure 5-15: Alternate Scenario Density Influence Map

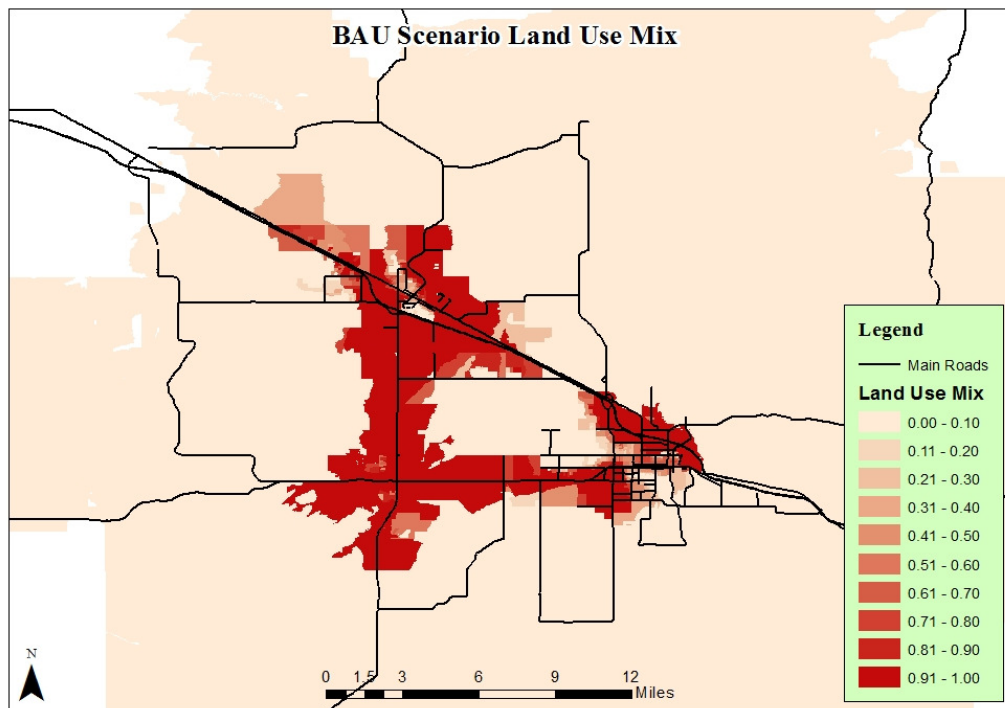


Figure 5-16: BAU Scenario Land Use Mix Influence Map

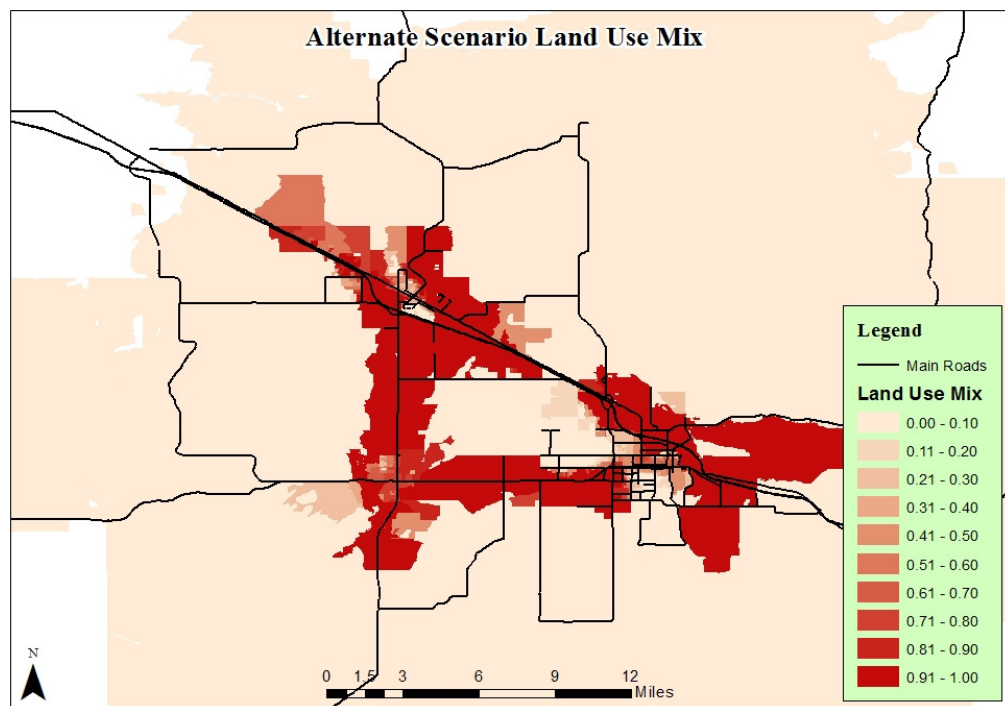


Figure 5-17: Alternate Scenario Land Use Mix Influence Map

The future scenarios were modeled using the same process as the base year model, with the exceptions detailed in the following sections.

External Stations

The ADT for the external stations was calculated based on the ADT growth between 2000 and 2010. ADT data from 2000 through 2010 was available for all of the external stations. This growth rate was then assumed to hold constant through the next 39 years, and the ADT for the year 2049 was then calculated based on this growth rate (see Table 5-4 for 2049 external station ADT). The 2049 ADT was then used to calculate the productions and attractions for each external station using the process described in Appendix C. The through trips for I-90 were again calculated using the process described in Appendix C. Note that the percent through trips for I-90 decreased for the year 2049, as the total population of the study area increased markedly. However, it should also be noted that for comparison purposes the external station trips produced and attracted were equal for both the future scenarios.

Special Generators

The MSU special generator was treated in the same way as in the base year model for both the BAU and ALT scenarios. As discussed earlier, the Sonoran Institute provided the data for the total number of additional student in the year 2049 (6000 students for both scenarios). However, the size of the MSU special generator varied between the two future scenarios (see Figure 5-18).

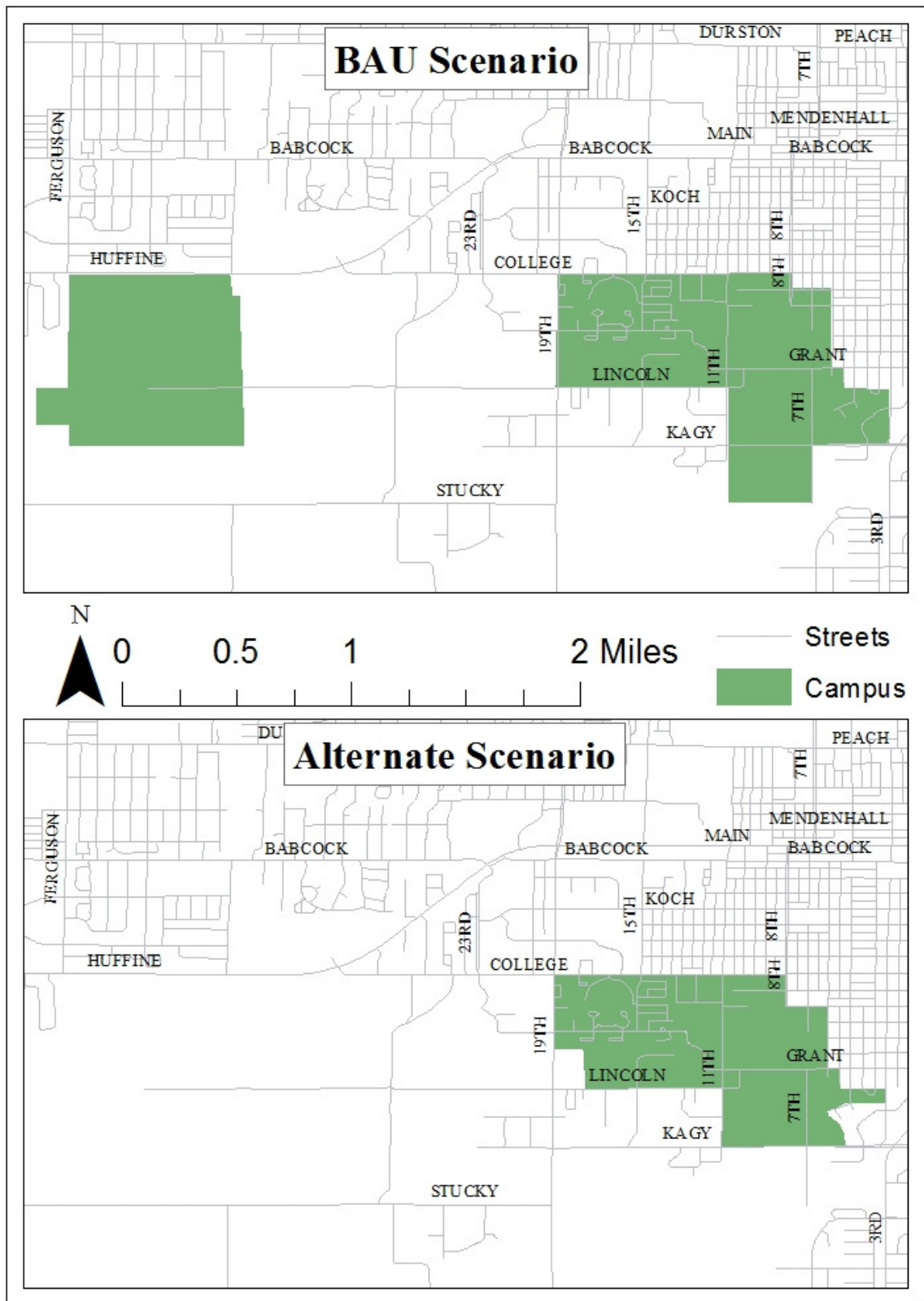


Figure 5-18: Future Scenarios Campus Special Generator

constant during the trip balancing to remain consistent with the base year modeling process. Both of the future scenarios replaced the airport with housing. Although this development change is not likely, the primary focus of the model was a comparison of VMT between the two future scenarios. As both scenarios eliminated the airport, the comparative impact of removing the airport special generator would be non-existent. Therefore, the airport special generator was removed from the future scenarios and the airport TAZ was treated like any other non-special generator TAZ in the model.

Trip Distribution

The trip distribution step was modified using the base year average travel times, base and future densities and land use mixes for each TAZ (as discussed in more detail previously). Therefore, the BAU and ALT scenarios used different travel time distributions for almost every TAZ. However, the travel time distributions for both future scenarios were both always partially dependent on the base year travel time and urban form for each TAZ.

Calculating changes in urban form between the two scenarios led to a rather unique challenge. While the base year data was based on census and employment spatial data, the future scenarios were based on hypothetical development. This hypothetical development became problematic when it did not account for housing or employment already in a location. For example, the BAU future scenario attempted to replicate the base year plus additional growth. However, some TAZs inevitably were overlooked, resulting in previously well populated zones losing all of their housing and employment within 39 years. This then led to drastic decreases in density in some areas. The Alternate

scenario compounded this issue, as many suburban developments were completely eliminated. To prevent these excessive (and rather unlikely) swings in urban form from having a serious impact on the model the adjusted average travel times were capped at reasonable minimum and maximum values. Again, the primary focus of the model was comparison between two future scenarios, so the minimum and maximum modeled average travel times were capped at 1.5 minutes and 60 minutes respectively to prevent anomalies between the base and future scenarios from having too great an effect on the comparison.

Additional Modifications

The mode choice step was performed in exactly the same manner as in the base year model. The trips were not broken down by time of day. The traffic assignment was performed using AON. Congestion was not taken into account as the future growth was so large that the current network would become severely over capacity, resulting in enormous congestion detours. Realistically, the future growth predicted in the future models would be combined with some increases in network capacity. Again, total VMT being the primary focus of the model congestion was not taken into account. Finally, no calibration or validation was performed in the future scenarios as there was no real or predicted ADT data to validate against.

CHAPTER 6

RESULTS

The results from base year and future development scenarios are presented in this section. The output traffic flows for the alternate and business as usual scenarios are shown in Figure 6-1 and Figure 6-2.

Table 6-1 summarizes the results from the base and future models.

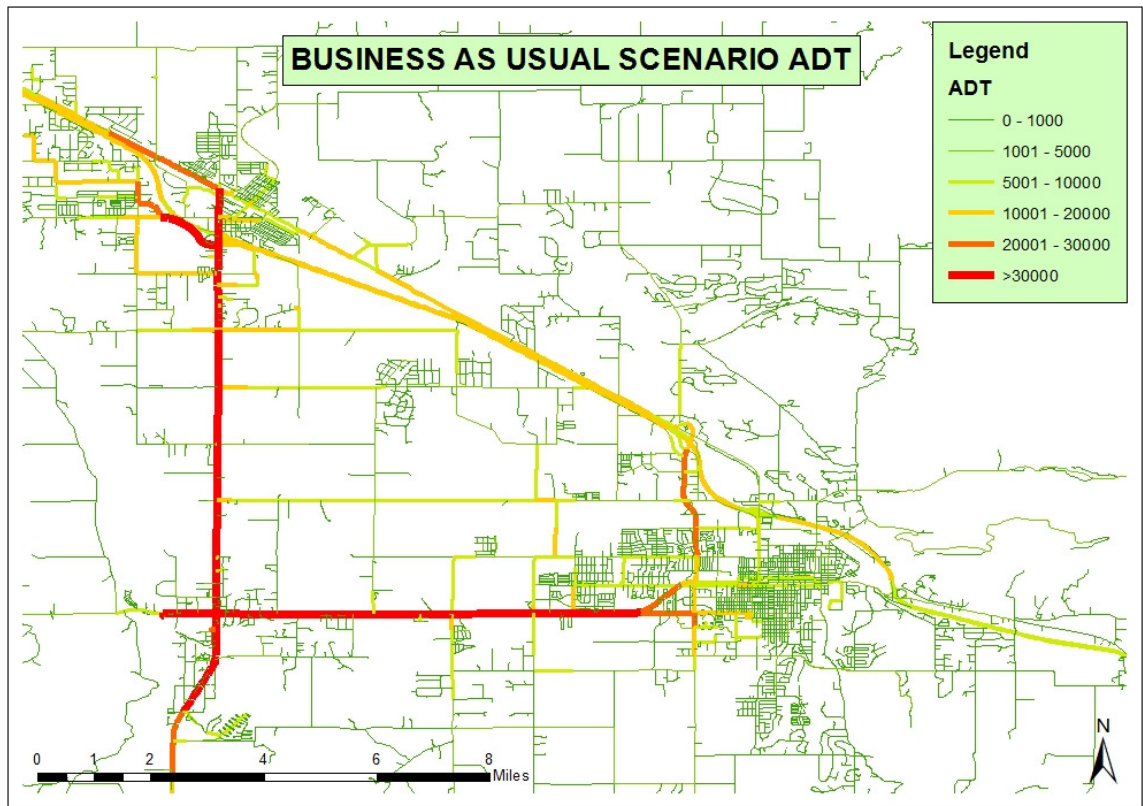


Figure 6-1: BAU Scenario Future (2049) ADT

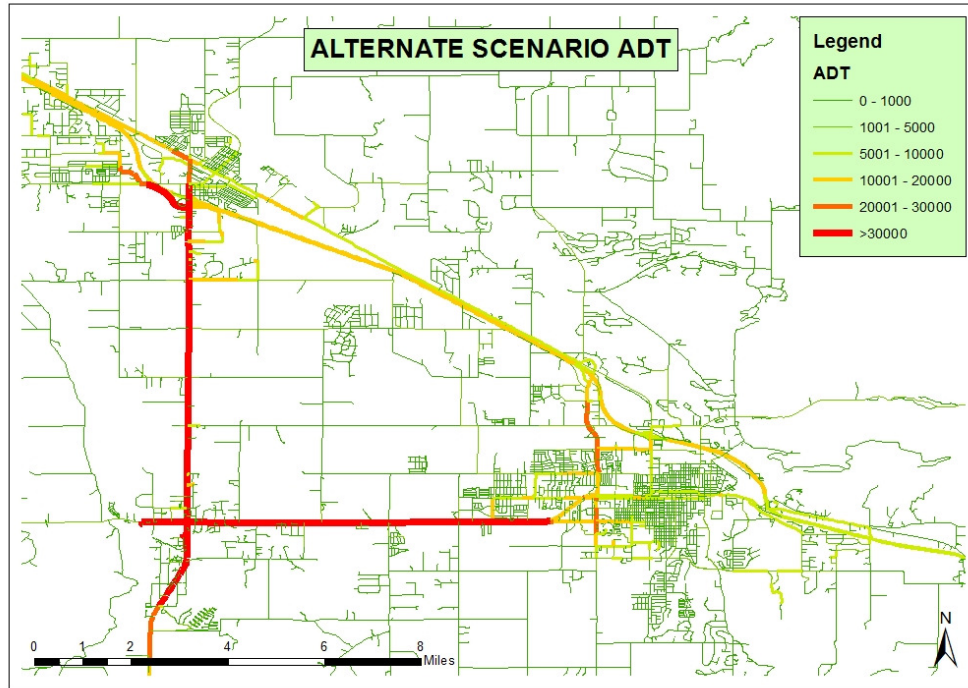


Figure 6-2: Alternate Scenario Future (2049) ADT

Table 6-1: Model Results

	Base		ALT		BAU	
	Modified	Basic	Modified	Basic	Modified	Basic
Weighted Density	5,057	5,057	9,608	9,608	3,276	3,276
Weighted Mix	0.670	0.670	0.496	0.496	0.457	0.457
HBW Average Travel Time (min)	11.10	11.26	10.23	10.19	11.73	11.54
HBO Average Travel Time (min)	9.82	9.51	9.11	8.58	10.48	10.81
NHB Average Travel Time (min)	6.66	6.55	6.96	8.32	6.86	5.86
Total VMT	2,057,507	2,169,999	2,967,681	3,666,503	3,528,576	4,253,495
Total Average Travel Time (all trip types, min)	10.29	10.29	9.12	9.18	9.75	11.07
Total Trips	304,287	320,017	436,039	548,061	499,572	543,001
Average Trip Length	6.76	6.78	6.81	6.69	7.06	7.83
Trips/HU	9.41	9.89	7.94	9.98	9.19	9.99

The modeling results indicate that the total VMT increased for both the BAU and Alternate scenarios using both the basic and the modified method. The total VMT for the Alternate scenario was significantly lower than the BAU VMT, regardless of the method used. This result indicates first that mixed use, high density development reduce modeled VMT, and second, the basic four-step modeling process does have some sensitivity to changes in urban form already.

Table 6-2 shows the final VMT, trip, trip rate, and average trip length comparative results for the BAU versus the Alternate scenario, using both the basic and modified methods. The results initially indicate that the modified model increased the sensitivity of trip rate to changes in urban form while decreasing the sensitivity of trip length. However, the elasticity comparison between the methods provides a better understanding of the impact of the modified modeling method (discussed later).

Table 6-2: Final VMT Results

	Basic Model			Modified Model		
	BAU	Alternate	%Δ	BAU	Alternate	%Δ
Total Trips	543001	548061	+0.93%	499572	436039	-12.71%
Trips/HU	9.99	9.98	-0.10%	9.19	7.94	-13.60%
Total VMT	4253495	3666503	-13.80%	3528576	2967681	-15.90%
Average Trip Length	7.83	6.69	-14.56%	7.06	6.81	-3.54%

The average added elasticity for the modified model was calculated with the weighted average density and land use mix for the base year and each future scenario and Equation 5-8, substituting average trip length for average travel time. The resulting expected added elasticity to the average trip length is shown in Table 6-3.

Table 6-3: Elasticities

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 5.11)	Modified Model Resulting Elasticity (Ch. 5.12)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04	None	None	-0.086	
	Land Use Mix	-0.06	None	None	None	
Average Trip Length (per trip)	Density	-0.05	-0.021 (ALT) -0.236 (BAU)	-0.212 (ALT) -0.437 (BAU)	+0.162 (ALT) +0.388 (BAU)	
	Land Use Mix	-0.05		-0.022	-0.028 (ALT) -0.028 (BAU)	

It should be again noted that the inherent elasticity of the model between density and average trip length was found to be point elasticity, not arc elasticity. Therefore, the elasticity added to the model for density and trip length should vary between scenarios with different average densities. Equation 4-13 and Equation 4-14 demonstrate how the inherent density varies between scenarios. As the literature elasticity calls for constant arc elasticity for any scenario, the elasticity added to correct the inherent elasticity (in column D) also must vary. Equation 6-1 summarizes the goal of column D.

$$\text{Column C} + \text{Column D} = \text{Column A to help Column E} = \text{Column A}$$

Equation 6-1

Table 6-4 gives the final elasticity values for the modified model, allowing for comparison between the basic and modified methods.

Table 6-4: Final Elasticity Values

VMT Variable	Urban Form Variable	Literature Elasticity (Ch. 2)	Un-modified Model Resulting Elasticity (Ch. 3)	Inherent Elasticity (Ch. 4)	Modified Model Elasticity Correction (Ch. 6)	Modified Model Resulting Elasticity (Ch. 6)
	Column	A	B	C	D	E
Trip Rate (per HU/day)	Density	-0.04	None	None	-0.086	-0.173 (ALT) +0.065 (BAU)
	Land Use Mix	-0.06	None	None	None	None
Average Trip Length (per trip)	Density	-0.05	-0.021 (ALT) -0.236 (BAU)	-0.212 (ALT) -0.437 (BAU)	+0.162 (ALT) +0.388 (BAU)	+0.010 (ALT) -0.066 (BAU)
	Land Use Mix	-0.05		-0.022	-0.028 (ALT) -0.028 (BAU)	

At first glance the modifications to the basic model appear to have actually decreased the sensitivity of the average trip length to the two urban form variables. However, note the difference between the average trip length average elasticity values for the modified model (column E) and then for the basic model (column B). In the basic model, the BAU scenario had a far higher sensitivity between average trip length and density and land use mix than the Alternate scenario. The BAU scenario was nearly five times more sensitive to density and land use mix than the literature indicated (see column A). The modified model results did still contain different sensitivities between the two future scenarios (see column E). However, the difference in average elasticity was only a third of the difference in sensitivity between the two scenarios resulting from the basic model. As the goal of the project was to compare the VMT of the two future scenarios,

the modified model clearly provides a much more accurate comparison. The modification to the trip distribution definitely increased the accuracy of the model.

The model contained many inaccuracies due to the inconsistent development patterns of the future scenarios. The BAU scenario attempted to build on the base year development. However, some zones were completely de-populated, leading to some nearly impossible changes in urban form. The Alternate scenario had even more issues, as the future development did try to match up to the base year population locations. These inconsistencies led to drastically decreased population densities around some zones with higher base year populations. These inconsistencies can explain much of the discrepancy between the inherent elasticity for the basic model (column B) and the inherent elasticity found from the idealized scenarios investigated in Chapter 4 (column C). These inconsistencies can also explain why the modified model sensitivity still varied between the BAU and Alternate scenarios.

The trip rate sensitivity went from non-existent in the basic model (column B) to widely variable between the two future scenarios. However, the trip rates were based on the most detailed data available (housing types only, with no vehicle ownership or income data). Therefore, the modified model results may still be considered more accurate than the basic model whose trip rates were based solely on housing units.

CHAPTER 7

RECOMMENDATIONS

The results from the case study indicate that the modified method does increase the sensitivity of the trip distribution step to changes in urban form. The output from the modified method is still conservative when compared to expected decreases in average trip length. However, the modifications to the process do provide a better sensitivity to changes in urban form, and when combined with the sensitivity of housing types to trip rates also effect the changes in total VMT. However, the housing type modification sensitivity does not match up well to researched trip rate elasticity values. Given a more detailed data set, a method involving influence areas similar to the trip distribution modification method could easily be developed to modify trip rate equations based on changes in urban form, rather than simply relying on the housing type to capture these changes.

The process is fairly accurate, at least given the base year results. However, unless future road improvement data is available the model should not be used to determine specific link flows as the AON traffic assignment can lead to traffic shift issues. User equilibrium assignment may be used with an updated road network. Also, more accuracy might be achieved through a feedback loop to the travel time matrix. However, hourly attraction and productions are required to complete the travel time feedback loop, so the increased link flow accuracy resulting from loop would require fairly detailed data.

The best use of the model is as a quick and easy way to compare the effects of different growth scenarios in a rural area. The model can capture some of the effects of

changes in urban form on travel behavior, better modeling the positive effects of smart growth techniques on VMT. Overall, the model is flexible and could be applied to any rural region providing some sort of housing, employment, and traffic data is available. Also, the city types used for estimating the effects of urban form on the model due to the gravity model should be selected based on the general layout of the study region and at the discretion of the travel modeler.

CHAPTER 8

CONCLUSION

The project was extremely successful, as shown in the results. The model developed is relatively simple to run, but still fairly accurate and sensitive to changes in urban form. The final model met all of the original goals for the project while also providing some useful measure of the sensitivity of a traditional four-step travel model to urban form. The model output indicated that smart growth techniques do decrease total travel for a region. Higher reductions might be measured using land use models that match up better to the base year development.

The basic model analysis proved that there is indeed some inherent sensitivity (through average trip length) to changes in some urban form variables within the basic four-step process. However, this sensitivity does not match the researched sensitivity for these variables. The modified model increased the accuracy of the sensitivity of the four-step model to changes in the urban form variables investigated (land use mix and density), while providing some additional although not very accurate sensitivity to the trip generation rates. The increased accuracy of the average trip length sensitivity did help increase the comparative analysis capability of the modified model.

This project has opened several avenues of future research and model development. More research could be performed into determining the effects of density and land use mix on the doubly constrained gravity model, possibly determining a way to calculate the inherent elasticity for any layout using the entropy (maximum) and

minimum average travel times for the area. More city layouts could also be analyzed to provide a wider assortment of options for incorporating inherent sensitivity.

The model could also be modified to include transit travel, and the sensitivity of the transit mode choice to changes in urban form could be incorporated into the trip generation or mode choice steps. As discussed in the recommendations section, the model accuracy could be increased through a travel time feedback loop.

Overall, the model met the goal of providing an easy, quick, and accurate way for comparing VMT for future land development scenarios. The model is flexible enough to be applied to other rural communities, and with further research could be applied to a much wider range of projects.

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APPENDICES

APPENDIX A

SAMPLE REGRESSION EQUATIONS

The following calculation example was taken from CBD analysis of Poly-centric land mix scenarios.

Arc Elasticity Regression (Linear Function):

	P	A	NCHRP tt (y)	Land Use Mix (x)	Y_{hat}	SS_{error}	SS_{total}	SS_{xtotal}
1	50	1950	11.89	5%	11.89	0.00	0.04	0.23
2	100	1900	11.85	10%	11.92	0.00	0.05	0.18
3	150	1850	11.83	15%	11.95	0.01	0.06	0.14
4	200	1800	11.80	20%	11.98	0.03	0.07	0.11
5	250	1750	11.78	25%	12.01	0.05	0.09	0.08
6	300	1700	11.76	30%	12.04	0.08	0.10	0.05
7	350	1650	11.75	35%	12.07	0.11	0.11	0.03
8	400	1600	11.74	40%	12.10	0.13	0.11	0.02
9	450	1550	11.74	45%	12.14	0.15	0.11	0.01
10	500	1500	11.76	50%	12.17	0.17	0.10	0.00
11	550	1450	11.79	55%	12.20	0.17	0.08	0.00
12	600	1400	11.84	60%	12.23	0.15	0.06	0.01
13	650	1350	11.91	65%	12.26	0.13	0.03	0.02
14	700	1300	12.00	70%	12.29	0.08	0.01	0.03
15	750	1250	12.13	75%	12.32	0.04	0.00	0.05
16	800	1200	12.29	80%	12.35	0.00	0.05	0.08
17	850	1150	12.49	85%	12.38	0.01	0.17	0.11
18	900	1100	12.74	90%	12.42	0.10	0.44	0.14
19	950	1050	13.03	95%	12.45	0.34	0.91	0.18
20	1000	1000	13.38	100%	12.48	0.81	1.70	0.23

$e = -0.002620321$ (by solver)

$y_0 = 11.889$ (from the data)

$x_0 = 5\%$ (from the data)

$n = 20$ (all scenarios i)

$v = n-2 = 18$

$\beta_0 = (e-1)*y_0 = 11.855184$

$$\beta_1 = e * y_0 / x_0 = 0.622919919$$

$$y_{\text{hat},i} = \beta_1 * x_i + \beta_0$$

$$y_{\text{bar}} = \sum y_i / n = 12.073552$$

$$SS_{\text{error}} = \sum (y_i - y_{\text{hat},i})^2 = 2.577209384$$

$$SS_{\text{total}} = \sum (y_i - y_{\text{bar}})^2 = 4.272248306$$

$$R \text{ squared} = 1 - SS_{\text{error}} / SS_{\text{total}} = 0.396755713$$

$$\sigma^2 = SS_{\text{error}} / v = 0.143178299$$

$$x_{\text{bar}} = \sum x_i / n = 0.525$$

$$SS_{x\text{total}} = \sum (x_i - x_{\text{bar}})^2 = 1.6625$$

$$\alpha = 0.05 \text{ (95\% confidence)}$$

$$T_0 = \beta_1 / \sqrt{(\sigma^2 * SS_{x\text{total}})} = (2.122630725$$

$$t_{0.025,v} = 2.086 \text{ (t-stat lookup for } v = 18)$$

Point Elasticity Regression (Power Function):

Scenario	NCHRP tt (y)	%LM (x)	ln(Y)	ln(X)	ln(Y _{hat})	SS _{error}	SS _{ytotal}	SS _{xtotal}
1	11.89	5%	2.475	-2.996	2.475	0.000	0.000	4.481
2	11.85	10%	2.473	-2.303	2.482	0.000	0.000	2.027
3	11.83	15%	2.470	-1.897	2.486	0.000	0.000	1.037
4	11.80	20%	2.468	-1.609	2.488	0.000	0.000	0.534
5	11.78	25%	2.466	-1.386	2.490	0.001	0.001	0.257
6	11.76	30%	2.465	-1.204	2.492	0.001	0.001	0.106
7	11.75	35%	2.464	-1.050	2.494	0.001	0.001	0.029
8	11.74	40%	2.463	-0.916	2.495	0.001	0.001	0.001
9	11.74	45%	2.463	-0.799	2.496	0.001	0.001	0.006
10	11.76	50%	2.465	-0.693	2.497	0.001	0.001	0.035
11	11.79	55%	2.467	-0.598	2.498	0.001	0.001	0.079
12	11.84	60%	2.471	-0.511	2.499	0.001	0.000	0.136
13	11.91	65%	2.477	-0.431	2.499	0.001	0.000	0.201
14	12.00	70%	2.485	-0.357	2.500	0.000	0.000	0.273
15	12.13	75%	2.495	-0.288	2.501	0.000	0.000	0.350
16	12.29	80%	2.508	-0.223	2.501	0.000	0.000	0.430
17	12.49	85%	2.525	-0.163	2.502	0.001	0.001	0.513
18	12.74	90%	2.545	-0.105	2.502	0.002	0.003	0.598
19	13.03	95%	2.567	-0.051	2.503	0.004	0.006	0.685
20	13.38	100%	2.594	0.000	2.503	0.008	0.011	0.773

$e = -0.00938$ (by solver)

$y_0 = 11.889$ (from the data)

$x_0 = 5\%$ (from the data)

$n = 20$ (all scenarios i)

$v = n - 2 = 18$

$\beta_0 = y_0 / (x_0^e) = 12.225$

$\beta_1 = e = -0.00938$

$LN(y_{\text{hat},i}) = LN(\beta_0) + LN(x_i) * \beta_1$

$y_{\text{bar}} = \sum LN(y_i) / n = 2.490$

$$SS_{\text{error}} = \sum [\text{LN}(y_i) - \text{LN}(y_{\text{hat},i})]^2 = 0.023$$

$$SS_{\text{total}} = \sum [\text{LN}(y_i) - y_{\text{bar}}]^2 = 0.028$$

$$R \text{ squared} = 1 - SS_{\text{error}}/SS_{\text{total}} = 0.164$$

$$\sigma^2 = SS_{\text{error}}/v = 0.001$$

$$x_{\text{bar}} = \sum \text{LN}(x_i)/n = -0.879$$

$$SS_{\text{xtotal}} = \sum [\text{LN}(x_i) - x_{\text{bar}}]^2 = 12.550$$

$$\alpha = 0.05 \text{ (95\% confidence)}$$

$$T_0 = \beta_1 / \sqrt{(\sigma^2 * SS_{\text{xtotal}})} = 0.927$$

$$t_{0.025,v} = 2.086 \text{ (t-stat lookup for } v = 18)$$

APPENDIX B

TRIP GENERATION RATE CALCULATIONS

Rate Sources and Values:

Rate	Units	Source
1.51	Workers/HH	ACS (American Community Survey for Gallatin County)
1.5	Person Trips/day/EMP	Oregon's rural travel behavior survey
9.57	Veh. Trip Ends/SF/Weekday	ITE-TGM, Code 210
6.72	Veh. Trip Ends/MF/Weekday	ITE-TGM, Code 220
5.86	Veh. Trip Ends/TH/Weekday	ITE-TGM, Code 230
42.96	Veh. Trip Ends/1000 sq. ft. GLA/Weekday for a Retail Shopping Center	ITE-TGM, Code 820
3.5	Veh. Trip Ends/OFF/Weekday for an Office Park Building	ITE-TGM, Code 750
1.4	workers/veh	
1.9	persons/hbo veh	
1.6	persons/nhb veh	NCHRP 365 Table 37 (Population 50,000-199,999)
1.4	Workers/Vehicle	Oregon's rural travel behavior survey
31.50 %	%non-work trips per HH that are NHB trips	Oregon's rural travel behavior survey
68.50 %	%non-work trips per HH that are HBO trips	Oregon's rural travel behavior survey
0.9	HBO person-trips/weekday that go to another home	NCHRP 365
333	Sq. ft. GLA/RET	Denver TDM Study
0.07	% workers that work at home	Gallatin County US Census Data (2000)

Equations Explanations:

HBW Productions = $1.51(\text{workers/HH}) * 1.50(\text{person-trips/worker}) * [1 - 0.07(\text{percent working at home})] * \text{HU} = 2.11 * \text{HU}$ person-trip productions per weekday

HBW Attractions = $1.50(\text{person-trips/worker}) * \text{EMP} = 1.50 * \text{EMP}$ person-trip attractions per weekday

HBO Productions = $68.5\%(\% \text{non-work trips that are HBO}) * \{ [9.57(\text{veh. trip ends/SF}) * 1.9(\text{persons/veh.}) / 2(\text{converts to two-way person-trips})] - 2.11(\text{two-way work trips/SF}) - 0.9(\text{HBO person-trips attracted to the HU}) \} * \text{SF} + 68.5\% * \{ [6.72(\text{veh. trip ends/MF}) * 1.9/2] - 2.11 - 0.9 \} * \text{MF} + 68.5\% * \{ [5.86(\text{veh. trip ends/TH}) * 1.9/2] - 2.11 - 0.9 \} * \text{TH} = 3.12 * \text{SF} + 1.67 * \text{MF} + 1.23 * \text{TH}$ person-trip productions per weekday

HBO Attractions = $68.5\%(\%HBO \text{ vs NHB trips}) * \{ [42.96(\text{veh. trip ends}/1000 \text{ sq. ft. GLA Retail}) * 1.9(\text{persons}/\text{veh.}) * 333(\text{sq. ft. GLA}/\text{RET})/2(\text{to convert to two way person trips}) - 1.5(\text{person trips}/\text{day}/\text{RET}) \} * \text{RET} + 0.9(\text{HBO person-trips}/\text{weekday that go to another home}) * \text{HU} = 8.28 * \text{RET} + 0.9 * \text{HU}$ person-trip attractions per weekday

NHB Productions = $31.5\%(\%NHB \text{ vs HBO trips}) * \{ [42.96(\text{veh. trip ends}/1000 \text{ sq. ft. GLA Retail}) * 1.6(\text{persons}/\text{veh.}) * 333(\text{sq. ft. GLA}/\text{RET})/2(\text{to convert to two way person trips}) - 1.5(\text{person trips}/\text{day}/\text{RET}) \} * \text{RET} + 31.5\%(\% \text{non-work trips that are NHB}) * \{ [9.57(\text{veh. trip ends}/\text{SF}) * 1.6(\text{persons}/\text{veh.})/2(\text{converts to two-way person-trips}) - 2.11(\text{two-way work trips}/\text{SF}) - 0.9(\text{HBO person-trips attracted to the HU}) \} * \text{SF} + 31.5\% * \{ [6.72(\text{veh. trip ends}/\text{MF}) * 1.6/2] - 2.11 - 0.9 \} * \text{MF} + 31.5\% * \{ [5.86(\text{veh. trip ends}/\text{TH}) * 1.6/2] - 2.11 - 0.9 \} * \text{TH} = 1.57 * \text{RET} + 1.46 * \text{SF} + 0.75 * \text{MF} + 0.53 * \text{TH}$ person-trip productions per weekday

NHB Attractions = $31.5\%(\%NHB \text{ vs HBO trips}) * \{ [42.96(\text{veh. trip ends}/1000 \text{ sq. ft. GLA Retail}) * 1.6(\text{persons}/\text{veh.}) * 333(\text{sq. ft. GLA}/\text{RET})/2(\text{to convert to two way person trips}) - 1.5(\text{person trips}/\text{day}/\text{RET}) \} * \text{RET} + [3.5(\text{veh. trips}/\text{OFF}) * 1.4(\text{workers}/\text{veh.})/2(\text{converts to two-way person-trips})] * \text{NRET} = 1.57 * \text{RET} + 0.95 * \text{NRET}$ person-trip attractions per weekday

Final Equations:

$$\text{HBW_P} = 2.11 * \text{HU}$$

$$\text{HBW_A} = 1.50 * \text{EMP}$$

$$\text{HBO_P} = 4.17 * \text{SF} + 2.31 * \text{MF} + 1.75 * \text{TH}$$

$$\text{HBO_A} = 8.28 * \text{RET} + 0.9 * \text{HU}$$

$$\text{NHB_P} = 1.57 * \text{RET} + 1.46 * \text{SF} + 0.75 * \text{MF} + 0.53 * \text{TH}$$

$$\text{NHB_A} = 1.57 * \text{RET} + 0.95 * \text{NRET}$$

APPENDIX C

EXTERNAL STATION CALCULATIONS

From MDT:

Trip Type	Vehicle Occupancy	% of Total Trips
HBW	1.4	16%
HBO	1.9	61%
NHB	1.6	23%

External Station Trip Generation Equations:

HBW Productions/Attractions = (HBW veh. Occupancy) * (% of total trips that are HBW) * 0.25 (converts one-way vehicle trips to half of a person two-way round trip) * ADT (average daily traffic on the highway represented by the external station for the analysis year) = **1.4*0.16*0.25*ADT**

HBO Productions/Attractions = (HBO veh. Occupancy) * (% of total trips that are HBO) * 0.25 (converts one-way vehicle trips to half of a person two-way round trip) * ADT (average daily traffic on the highway represented by the external station for the analysis year) = **1.9*0.61*0.25*ADT**

NHB Productions/Attractions = (NHB veh. Occupancy) * (% of total trips that are NHB) * 0.25 (converts one-way vehicle trips to half of a person two-way round trip) * ADT (average daily traffic on the highway represented by the external station for the analysis year) = **1.6*0.23*0.25*ADT**

Through trips for I-90 calculations:

$$Y_i = 76.76 + 11.2 \times I - 25.74 \times PA - 42.18 \times MA + 0.00012 \times ADT_i + 0.59 \\ \times PTKS_i - 0.48 \times PPS_i - 0.000417 \\ \times POP \text{ (Equation 5.1, NCHRP 365)}$$

Where:

Y_i = percentage of the ADT at external station i that are through trips (as a percentage)

I = interstate (1 if yes, 0 if no)

PA = principal arterial (1 if yes, 0 if no)

MA = minor arterial (1 if yes, 0 if no)

ADT_i = average daily traffic at external station i

$PTKS_i$ = percentage of trucks excluding vans and pickups at external station i

PPS_i = percentage of vans and pickups at external station i

POP = population inside the cordon area (project analysis region)

The percent through trips for all of the non-interstate stations was low enough to ignore, as these external stations were either principle arterials or minor arterials, all with fairly low ADT. Therefore, the percent through trips were only calculated for the two I-90 stations.

Given:

$I = 1.0$ (interstate)

$PA = 0$

$MA = 0$

$ADT = 12750$ for East I-90, 12543 for West I-90

$PTKS$ and $PPS = 0$ (no future year data for these percentages, no base year data for PPS)

$POP = 82,463$

$$Y_{east\ I-90\ STA} = 76.76 + 11.2 \times 1.0 - 25.74 \times 0 - 42.18 \times 0 + 0.00012 \times 12750 + 0.59 \times 0 - 0.48 \times 0 - 0.000417 \times 82463 = 55.10\%$$

$$Y_{west\ I-90\ STA} = 76.76 + 11.2 \times 1.0 - 25.74 \times 0 - 42.18 \times 0 + 0.00012 \times 12543 + 0.59 \times 0 - 0.48 \times 0 - 0.000417 \times 82463 = 55.08\%$$

The goal was to calculate only the percent of through trips that remained on I-90 through the study area. Therefore, a second equation from the NCHRP 365 report was used as follows:

$$Y_{ij} = -2.70 + 0.21 \times PTTDES_j + 67.86 \times RTECON_{ij} \text{ (Equation 5.2, NCHRP 365)}$$

Where:

Y_{ij} = percentage distribution of through-trip ends from origin station i to destination station j

$PTTDES_j$ = percentage through-trip ends at destination station j

$RTECON_{ij}$ = route continuity between stations i and j , 1 if yes, 0 if no

$$Y_{west-east\ I-90} = -2.70 + 0.21 \times PTTDES_{east\ I-90} + 67.86 \times RTECON_{west-east\ I-90} = -2.70 + 0.21 \times 55.10 + 67.86 \times 1.0 = \mathbf{76.73\%}$$

$$Y_{east-west\ I-90} = -2.70 + 0.21 \times PTTDES_{west\ I-90} + 67.86 \times RTECON_{east-west\ I-90} = -2.70 + 0.21 \times 55.08 + 67.86 \times 1.0 = \mathbf{76.73\%}$$

Therefore, the percent of trips that remain on I-90 through the project study area is as follows:

$$\%I-90\ \text{only through trips} = 0.767 \times 0.551 = \mathbf{42.3\%}$$

The same calculations were performed for the future scenarios using the year 2049 predicted ADT and population.

APPENDIX D

PROJECT DATA DICTIONARY

ALT Gallatin

Source: Sonoran Institute Envision Tomorrow Alternate Growth Scenario (year 2049) – Provided by Cameron Ellis on May 27, 2011

Description: vector data, polygons of land parcels, used to determine project study area extent and required variables, State Plane Coordinate System - Lambert Conformal Conic Projection (NAD 1983, meters), 1:40,000 scale accuracy

Attributes of ALT Gallatin table

	<u>Field</u>	<u>Type</u>	<u>Description</u>
parcel	SF	Double	Number of single-family housing units in a
parcel	MF	Double	Number of multi-family housing units in a
	TH	Double	Number of townhome housing units in a parcel
	RET	Double	Retail employees employed in a parcel
	EMP	Double	Total employees employed in a parcel

BAU Gallatin

Source: Sonoran Institute Envision Tomorrow Alternate Growth Scenario (year 2049) – Provided by Cameron Ellis on May 27, 2011

Description: vector data, polygons of land parcels, used to determine project study area extent and required variables, State Plane Coordinate System - Lambert Conformal Conic Projection (NAD 1983, meters), 1:40,000 scale accuracy

Attributes of ALT Gallatin table

	<u>Field</u>	<u>Type</u>	<u>Description</u>
parcel	SF	Double	Number of single-family housing units in a
parcel	MF	Double	Number of multi-family housing units in a
	TH	Double	Number of townhome housing units in a parcel
	RET	Double	Retail employees employed in a parcel
	EMP	Double	Total employees employed in a parcel

Dataset: Bozeman Existing Rds

Source: Alan VanderWey, Montana Department of Transportation Planning Division – Provided on April 21, 2011

Description: vector data, lines and nodes representing streets and intersections, updated to include 2010 street improvements, scale unknown, GCS NAD 1983 (no projection)

Attributes of Bozeman Existing Rds table

<u>Field</u>	<u>Type</u>	<u>Description</u>
Length	Double	Represents the length of a road segment in miles
Dir	Integer	Value representing the direction of flow

Value Field

Value Description

1	One-way flow in the topological direction of the segment
0	Two-way flow
-1	One-way flow opposing the topological direction of the segment

[FUNCTIONAL CLASS]	Integer	Road type classification
--------------------	---------	--------------------------

<u>Value Field</u>	<u>Value Description</u>
1	Interstate
2	State Highway
3	Primary Arterial
4	Secondary Arterial
5	Collector
6	Local Road
7	ON/OFF Ramp
9	Centroid Connector

Capacity	Double	Daily two-way street capacity in vehicles (range 10 to 54400)
Speed	Double	Free flow travel speed in mph
Travel_Time	Double	Free flow travel time in minutes
ALPHA	Double	Coefficient of the BRP function
BETA	Double	Coefficient of the BPR function
ADT	Double	Measured 2010 Average Daily Traffic

Dataset: E Belgrade proj update TAZ
Source: Alan VanderWey, Montana Department of Transportation Planning Division- Provided July 29, 2011
Description: vector data, polygons representing TAZs, based on year 2010 Census blocks, used for model Traffic Analysis Zones, GCS NAD 1983 (no projection), 1:100,000 scale accuracy

Attributes of E Belgrade proj update TAZ Table

<u>Field</u>	<u>Type</u>	<u>Description</u>
Area	Double	Area of the TAZ in square miles
POPTOTAL	Double	Total 2010 TAZ population
Total_housing	Double	Total 2010 TAZ housing units
Occ_housing	Double	Total 2010 TAZ occupied housing units
Retail_2010	Double	Estimated 2010 TAZ retail employment
NonRetail_2010	Double	Estimated 2010 TAZ non-retail

employment

Dataset: Structures
Source: Montana Base Map Service Center, Department of Administration, Information Technology Services Division – updated continuously

Description: vector data, points representing 2011 Gallatin County structures, State Plane Coordinate System – Lambert Conformal Conic Projection (NAD 1983, meters), 1:40000 scale accuracy

Attributes of Structures Table

<u>Field</u>	<u>Type</u>	<u>Description</u>
FUNCTIONID	Integer	Residence type classification

Values of Interest

<u>Value Field</u>	<u>Value Description (from metadata)</u>
101	Dwelling, single-family
102	Dwelling, multi-family
103	Institutional residence / dorm / barrack

Dataset: Structures

Source: Gallatin County GIS database, updated 08/25/2010

Description: vector data, points representing 2011 Gallatin County structures in unincorporated areas, State Plane Coordinate System – Lambert Conformal Conic Projection (NAD 1983, meters), 1:40000 scale accuracy

Attributes of Structures

<u>Field</u>	<u>Type</u>	<u>Description</u>
CONDO	Text	Boolean values (N = not a condo, null = yes a condo)

Dataset: CountyLines

Source: Database of Montana Counties, updated 10/05/09

Description: vector data, lines representing Montana county boundaries, State Plane Coordinate System – Lambert Conformal Conic Projection (NAD 1983, meters), 1:24000 scale accuracy

Attributes of Structures Table

No Attributes were required from this data, it was only used to help show the geographic location of the study area.

Dataset: ccBlockGroup

Source: Caliper Data CD, compiled from year 2000 Census TIGER files – Published 2001

Description: vector data, polygons representing year 2000 Census Block Groups, GCS NAD 1983 (no projection), 1:100,000 scale accuracy

<u>Field</u>	<u>Type</u>	<u>Description</u>
16+_Mean travel time to work	Double	Average block group average commute time for persons age 16 and older
HU_1 unit, detached	Integer	Detached housing units per block group
HU_1 unit, attached	Integer	Attached housing units per block group
HU_2 units	Integer	2 unit housing per block group

HU_3-4 units	Integer	3-4 unit housing per block group
HU_5-9 units	Integer	5-9 unit housing per block group
HU_10-19 units	Integer	10-19 unit housing per block group
HU_20+ units	Integer	20+ unit housing per block group

Dataset: ccBlock
Source: Caliper Data CD, compiled from year 2000 Census TIGER files – Published 2001
Description: vector data, polygons representing year 2000 Census Blocks, GCS NAD 1983 (no projection), 1:100,000 scale accuracy

<u>Field</u>	<u>Type</u>	<u>Description</u>
Area	Double	Area of the block in square miles
Population	Integer	Census block population
Occupied Housing	Integer	Census block occupied housing units

Dataset: National Elevation Dataset (NED)
Source: U.S. Geological Survey, published 2009
Description: raster dataset representing elevations in meters, 1:100000 scale, Geographic Coordinate System North American Datum (NAD 1983), six 80 km tiles with approximately 22 meter cells

32-bit pixels, black (minimum) to white (maximum) color bands representing elevations in meters

Dataset: Lower Gallatin Valley Color Infrared Orthophotos, 2001
Source: Montana State Library, published 06/12/2006
Description: raster dataset, 1:24000 Montana State Plane coordinate system (NAD 1983, meters), Lambert Conformal Conic Projection, 41 approximately 7.6 km tiles

24-bit pixels, 3 band color (RGB) represent brightness values 0 - 255

APPENDIX E

GAMMA FUNCTION MODIFICATIONS

HBW Distribution

For the HBW distribution, the c coefficient was found to be related to the average travel time. The NCHRP coefficients were used as the a and b coefficients, and the c coefficient was varied in small increments. The average travel time of the distribution was calculated for each c value by the trapezoid area method. The distribution was analyzed for values between 1.0 and 120 minutes (the minimum and maximum travel times possible for the model). The resulting relationship between the c coefficient and the average travel time of the distribution is shown in Figure E-0-1.

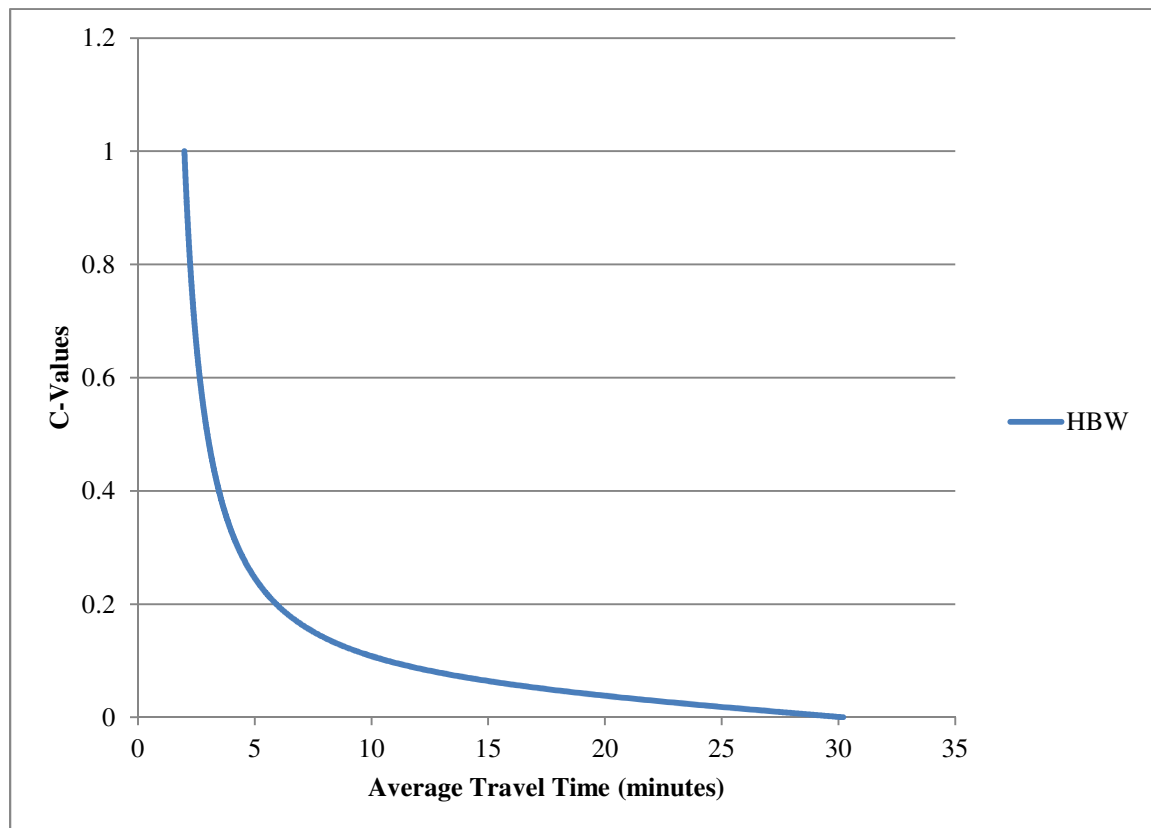


Figure E-0-1: HBW c vs Average Travel Time

The relationship between the c coefficient and the average travel time of the distribution was approximately linear for a certain range of average travel times, and a more exponential decay function for another range. The ranges were selected by guess and check, using different range values to find where the linear function could apply. See Figure E-0-2 for the selected ranges.

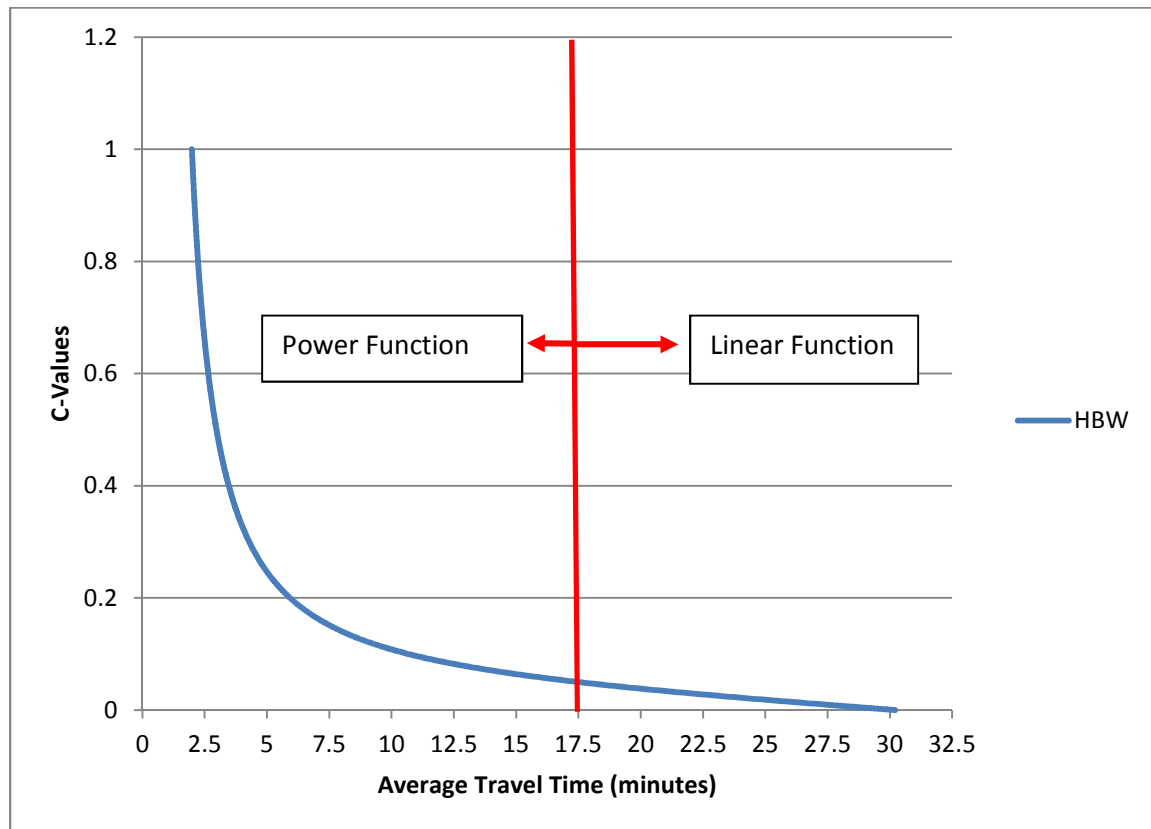


Figure E-0-2: HBW Average Travel Time Ranges

The relationship between the c coefficient and average travel time of the distribution was modeled for each range using ordinary least squares, with the range break value 17.5 minutes as a fixed point of the function. The coefficient c was made a function of the average travel time as shown in Equation E-1, while Table E-0-1 summarizes the statistics for the equations.

$$c(t_{avg}) = \begin{cases} -0.00401t_{avg} + 0.12011, & 17.5 \text{ min} < t_{avg} < 30.0 \text{ min} \\ 2.22707t_{avg}^{-1.32650}, & 17.5 \text{ min} \geq t_{avg} > 2.0 \text{ min} \end{cases}$$

Equation E-1

If $t_{avg} > 30.0$ minutes then $c = 0.0001$ and if $t_{avg} < 2.0$ minutes then $c = 1.0$

Table E-0-1: HBW c value statistics

Equation Type	Equation Range	R ²	t ₀	t _{0/2,v}
Constant	$30.0 \text{ min} \geq t_{avg}$	N/A	N/A	N/A
Linear	$17.5 \text{ min} < t_{avg} < 30.0 \text{ min}$	0.9946	169.004	1.960
Power	$2.0 \text{ min} < t_{avg} \leq 17.5 \text{ min}$	0.9938	382.320	1.960
Constant	$t_{avg} \leq 2.0 \text{ min}$	N/A	N/A	N/A

Figure E-0-3 shows the modeled and actual relationships of the c coefficient and the average travel time of the distribution. Note that for HBW trips the maximum possible average travel time is 30 minutes. To model distributions with a higher average travel time the b coefficient would have to be varied. For the purposes of this model, this maximum possible average travel time of the HBW distribution was very acceptable, as the travel time between from any location in the analysis zone to the nearest CBD would be less than 30 minutes.

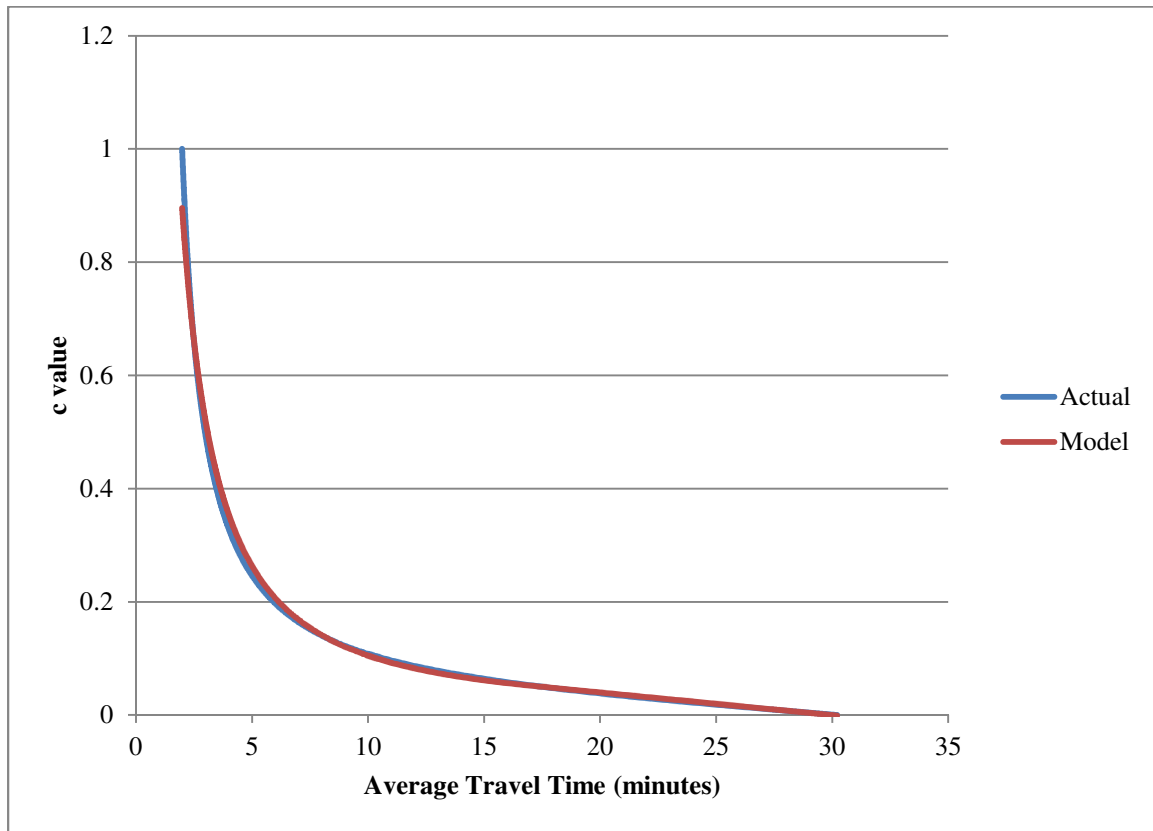


Figure E-0-3: HBW Average Travel Time Relationship Results

HBO Distribution

For the HBO distribution, the b coefficient was found to be related to the average travel time. The NCHRP coefficients were used as the a and c coefficients, and the b coefficient was varied in small increments. The average travel time of the distribution was calculated for each b value by the trapezoid area method. The distribution was analyzed for values between 1.0 and 120 minutes (the minimum and maximum travel times possible for the model). The resulting relationship between the b coefficient and the average travel time of the distribution is shown in Figure E-0-4.

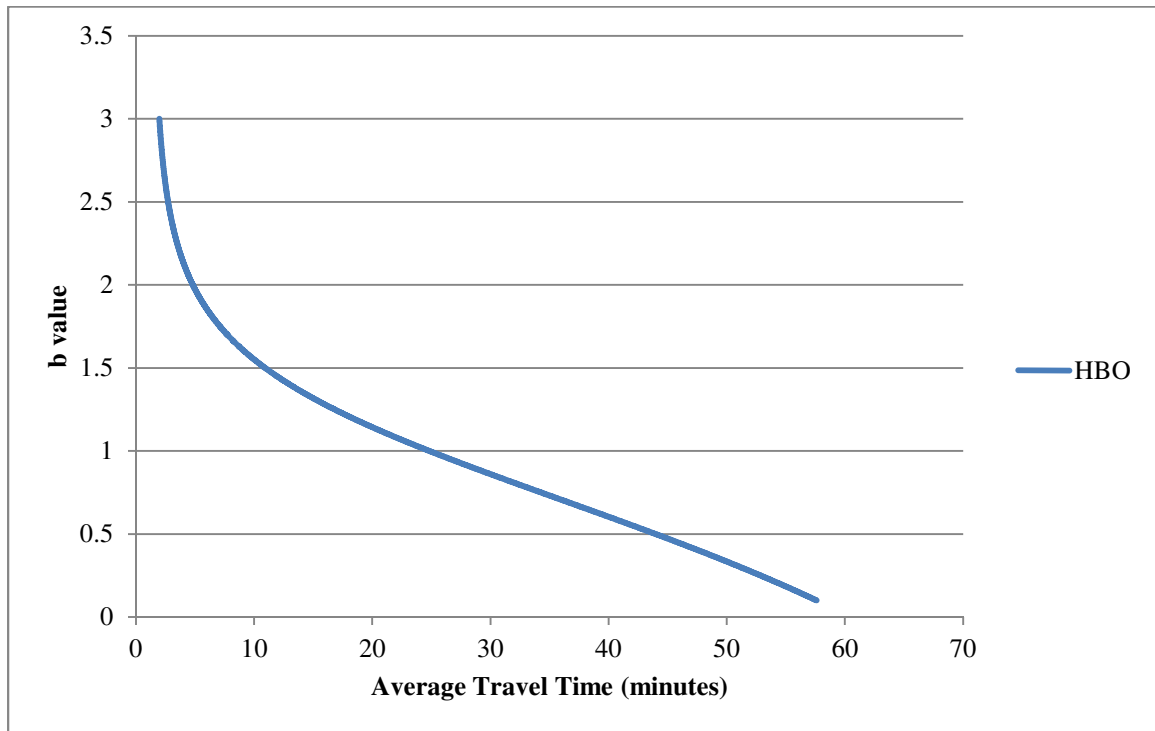


Figure E-0-4: HBO b vs Average Travel Time

The relationship between the b coefficient and the average travel time of the distribution was approximately linear for a certain range of average travel times, and more of an exponential decay function for another range. The ranges were selected by guess and check, using different range values to find where the linear function could apply. See Figure E-0-5 for the selected ranges.

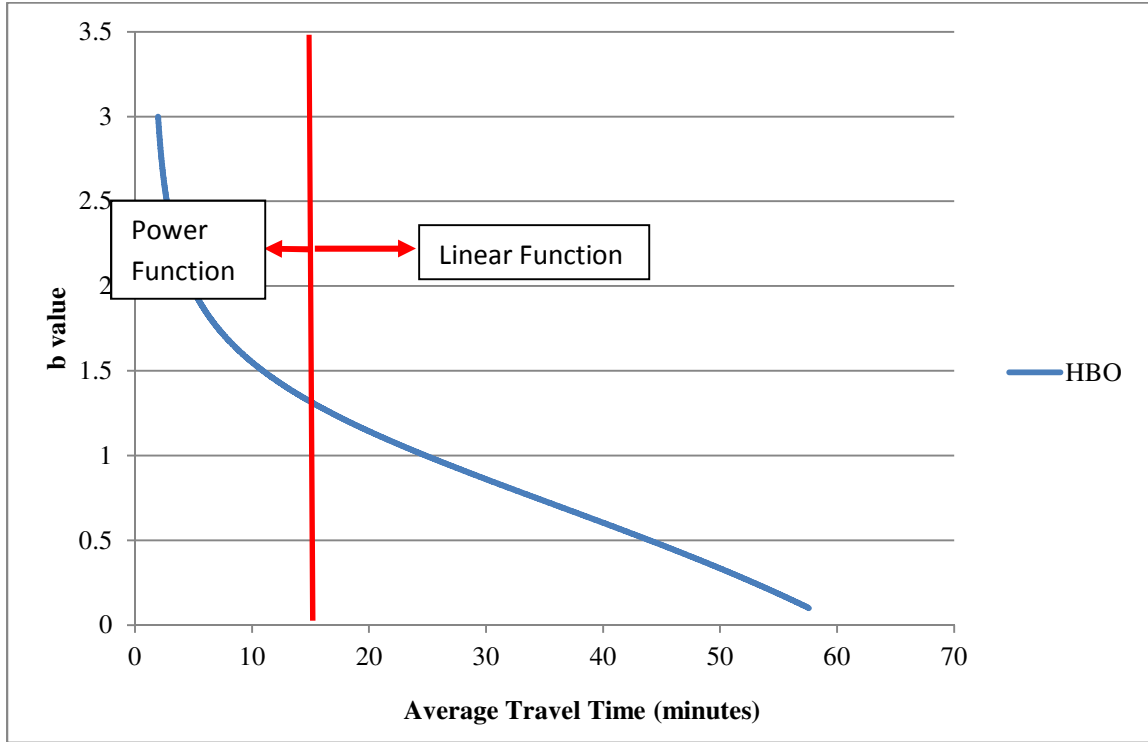


Figure E-0-5: HBO b vs Average Travel Time Ranges

The relationship between the b coefficient and average travel time of the distribution was modeled for each range using ordinary least squares regression, with the range break value 15.5 minutes as a fixed point of the function. The coefficient b was made a function of the average travel time as shown in Equation E-2, while **Table E-0-2** summarizes the statistics for the equations.

$$b(t_{avg}) = \begin{cases} -0.02838t_{avg} + 1.73860, & 15.5 \text{ min} < t_{avg} < 57.0 \text{ min} \\ 3.70697t_{avg}^{-0.38270}, & 15.5 \text{ min} \geq t_{avg} > 2.0 \text{ min} \end{cases}$$

Equation E-2

If $t_{avg} > 57.0$ minutes then $b = 0.12$ and if $t_{avg} < 2.0$ minutes then $b = 3.0$

Table E-0-2: HBO b Value Statistics

Equation Type	Equation Range	R^2	$ t_0 $	$t_{a/2,v}$
Constant	$57.0 \text{ min} \geq t_{avg}$	N/A	N/A	N/A
Linear	$15.5 \text{ min} < t_{avg} < 57.0 \text{ min}$	0.9969	642.858	1.960
Power	$2.0 \text{ min} < t_{avg} \leq 15.5 \text{ min}$	0.9948	564.479	1.960
Constant	$t_{avg} \leq 2.0 \text{ min}$	N/A	N/A	N/A

Figure E-0-6 shows the modeled and actual relationships of the b coefficient and the average travel time of the distribution. Note that for HBO trips, the maximum possible average travel time is 57 minutes. To model distributions with a higher average travel time the b coefficient would have to be varied. For the purposes of this model, this maximum possible average travel time of the HBO distribution was very acceptable, as the travel time between from any location in the analysis zone to the nearest CBD would be less than 57 minutes.

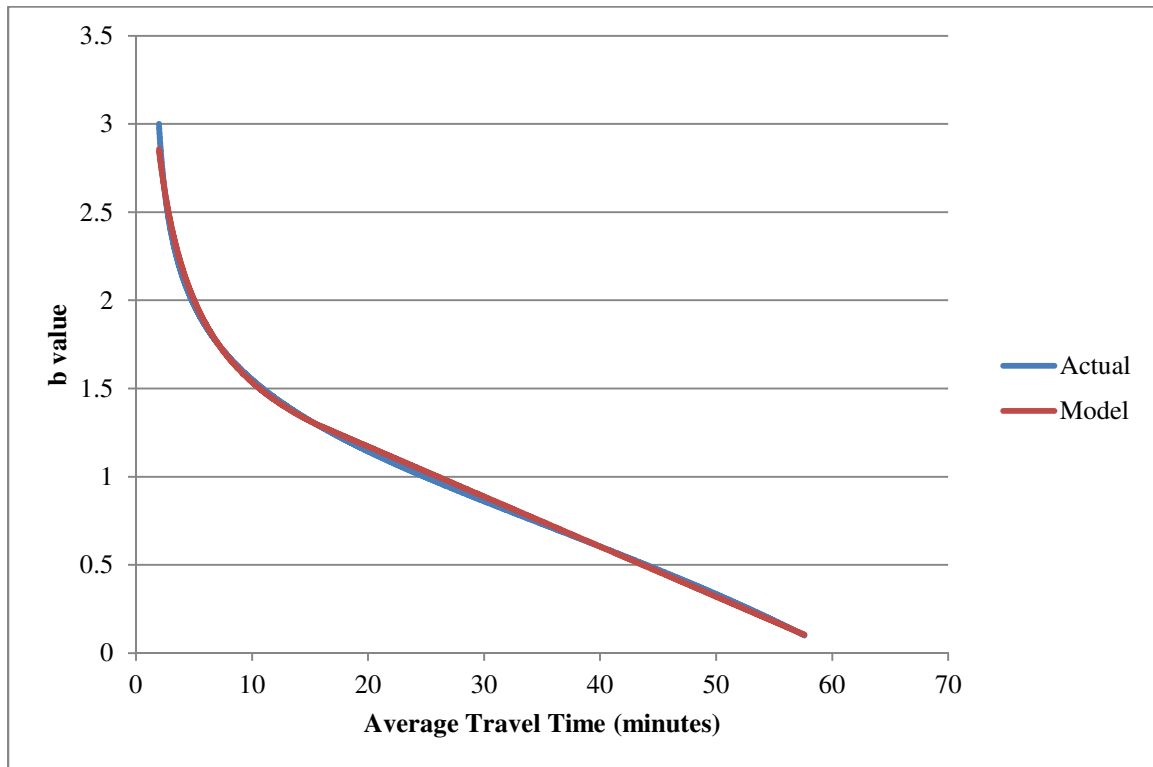


Figure E-0-6: HBO b vs Average Travel Time Relationship Results

NHB Distribution

For the NHB distribution, the b coefficient was found to be related to the average travel time. The NCHRP coefficients were used as the a and c coefficients, and the b coefficient was varied in small increments. The average travel time of the distribution was calculated for each b value by the trapezoid area method. The distribution was analyzed for values between 1.0 and 120 minutes (the minimum and maximum travel times possible for the model). The resulting relationship between the b coefficient and the average travel time of the distribution is shown in Figure E-0-7.

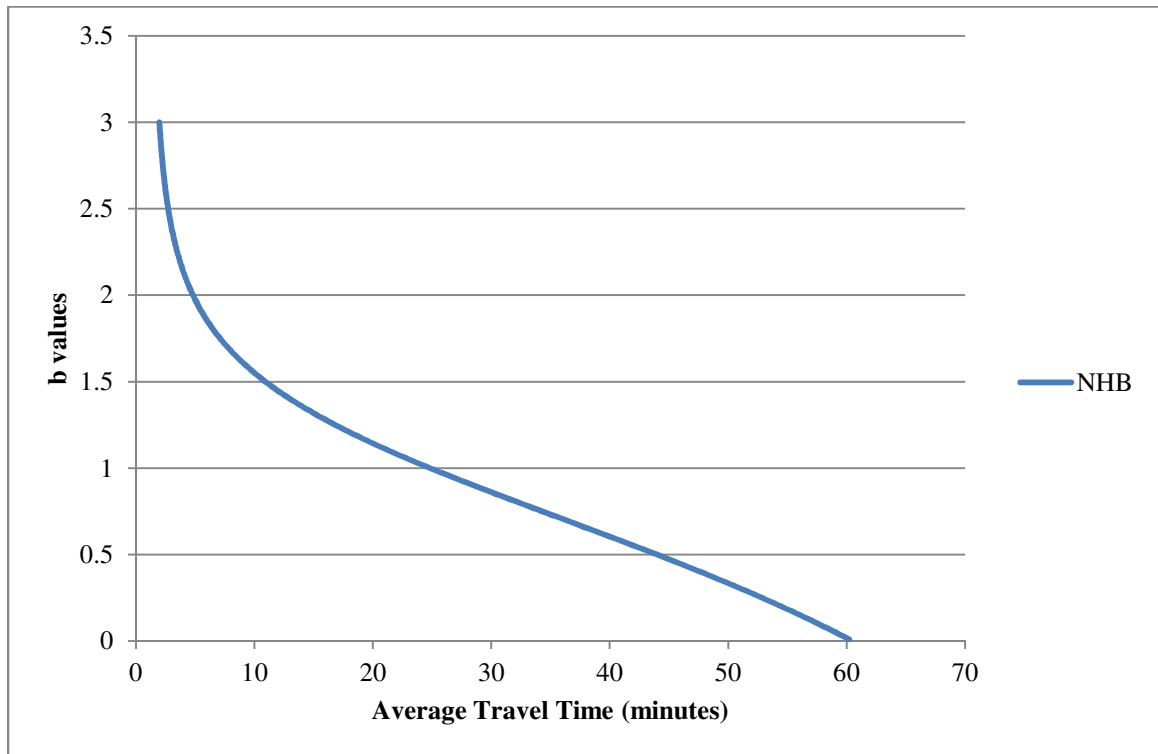


Figure E-0-7: NHB b vs Average Travel Time

The relationship between the b coefficient and the average travel time of the distribution was approximately linear for a certain range of average travel times, and more of an exponential decay function for another range. The ranges were selected by guess and check, using different range values to find where the linear function could apply. See Figure E-0-8 for the selected ranges.

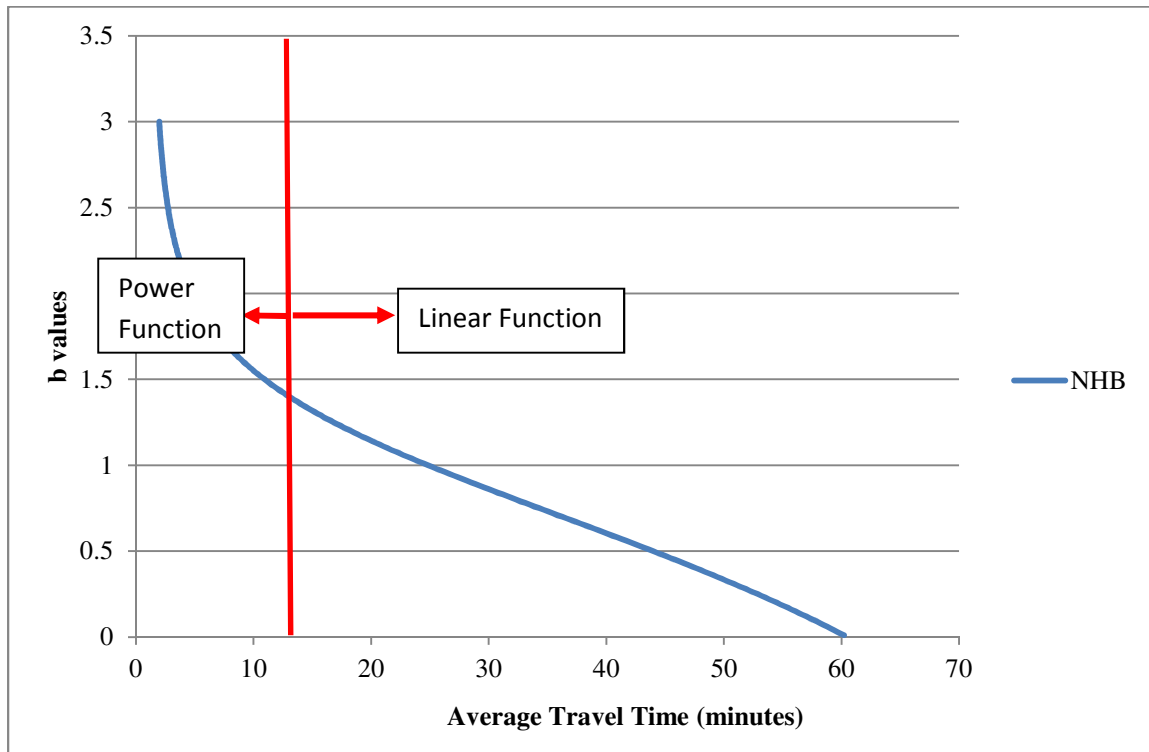


Figure E-0-8: NHB b vs Average Travel Time Ranges

The relationship between the b coefficient and average travel time of the distribution was modeled for each range using ordinary least squares regression, with the range break value 15.5 minutes as a fixed point of the function. The coefficient b was made a function of the average travel time as shown in Equation E-3, while Table E-0-3 summarizes the statistics for the equations.

$$b(t_{avg}) = \begin{cases} -0.02843t_{avg} + 1.73945, & 15.5 \text{ min} < t_{avg} < 60.0 \text{ min} \\ 3.70836t_{avg}^{-0.38284}, & 15.5 \text{ min} \geq t_{avg} > 2.0 \text{ min} \end{cases}$$

Equation E-3

If $t_{avg} > 60.0$ minutes then $b = 0.01$ and if $t_{avg} < 2.0$ minutes then $b = 3.0$

Table E-0-3: NHB b Value Statistics

Equation Type	Equation Range	R^2	$ t_0 $	$t_{a/2,v}$
Constant	$60.0 \text{ min} \geq t_{avg}$	N/A	N/A	N/A
Linear	$15.5 \text{ min} < t_{avg} < 60.0 \text{ min}$	0.9975	231.537	1.960
Power	$2.0 \text{ min} < t_{avg} \leq 15.5 \text{ min}$	0.9947	177.592	1.960
Constant	$t_{avg} \leq 2.0 \text{ min}$	N/A	N/A	N/A

Figure E-0-9 shows the modeled and actual relationships of the b coefficient and the average travel time of the distribution. Note that for NHB trips, the maximum possible average travel time is 57 minutes. To model distributions with a higher average travel time the b coefficient would have to be varied. For the purposes of this model, this maximum possible average travel time of the NHB distribution was very acceptable, as the travel time between from any location in the analysis zone to the nearest CBD would be less than 57 minutes.

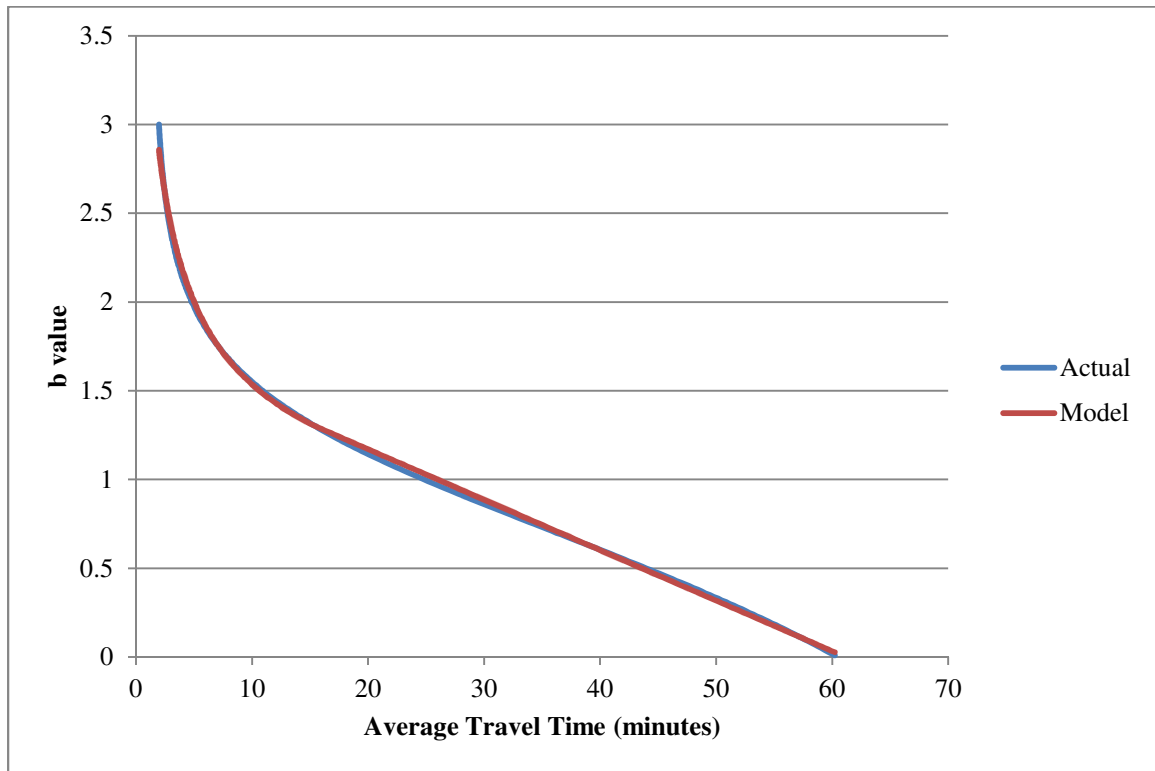


Figure E-0-9: NHB b vs Average Travel Time Relationship Results