

ESTIMATING FREEWAY TRAVEL TIME AS A FUNCTION OF DEMAND USING
SIMULATION

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2008

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To my parents

ACKNOWLEDGMENTS

I thank the University of Florida and the Department of Civil and Coastal Engineering for giving me the opportunity to participate in a Transportation Project and produce unique research. I thank my committee, comprising of Dr. Lily Elefteriadou, Associate Professor, Committee Chair, and primary advisor; Dr. Siva Srinivasan, Assistant Professor; and Dr. Yafeng Yin, Assistant Professor. I thank them for the advice, guidance, and feedback throughout the research and writing of the report. I thank the group of master's and doctoral candidates that provided me with the technical support and guidance when needed. Finally, I thank my friends and family for encouragement throughout this endeavor.

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LIST OF ABBREVIATIONS

T.T	Travel time
BFS	Basic freeway segment
BPR	Bureau of Public Roads
MTC	Metropolitan Transportation Commission
d	Demand
C	Capacity
C_d	Downstream segment capacity
q	Flow

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December 2008

Chair: Lily Elefteriadou
Major: Civil Engineering

Analytical T.T. models using demand have been developed in the past, and are applicable for both under-saturated and oversaturated conditions. These models are consistent with each other and make accurate T.T. predictions at lower demand levels or in unsaturated conditions. However, at high levels of demand or congestion these models are not consistent with each other and have not been compared with field data. Further, some of the existing models, such as BPR, consider flows greater than the capacity, which is unrealistic. Thus there is a need for further advancement in the T.T. estimation models which make accurate predictions at both saturated and unsaturated congestion levels. Moreover most of the existing models such as BPR and MTC do not consider the queuing phenomenon explicitly. Thus analytical models which consider formation and dissipation of queue and also consider the delay associated with these queues in estimation of T.T. is required.

Besides analytical models, simulation has also been used in the past for estimation of the T.T. given demand. However, analytical models of T.T. have not been developed using results obtained from simulation.

A preliminary list of variables that may affect the T.T. are considered. These variables are used for simulation so that the significant variables can be selected for further consideration. Not

all of the freeway segments require the same set of inputs to estimate travel time, therefore each segment type is considered separately. The Highway Capacity Manual (HCM) 2000 considers the following freeway segments: 1) Basic freeway segment 2) Merge segment 3) Diverge segment 4) Weaving segment.

Lane Width, number of lanes, driver Population, free flow speed (FFS, freeway demand, length of the freeway segment are considered as important variables that may affect the travel time of a basic freeway segment. The same variables which are considered for the basic freeway segment are also considered for all the other segments with the addition of the on-ramp demand and length of the entry segment for merge segment, with the addition of the off-ramp demand and length of the entry segment for diverge segment, with the addition of the on-ramp demand, off-ramp demand, and length of the entry segment for weave segment.

CHAPTER 1 INTRODUCTION

1.1 Background

Travel time (T.T.) estimation has been extensively researched because of its important applications, such as pre-trip traveler information (Jha et.al 1998), route trip guidance systems (Balke et.al 1995), and traffic management (Palen, 1997). Such applications require accurate short-term T.T. predictions, which have been made possible due to the advancement of surveillance technologies. These can measure and transmit information such as volume, speed and occupancy. These traffic parameters can be used for real time estimation of T.T. Most of the models developed thus far are based on speed to estimate short-term T.T.

However there are other important applications of T.T. estimation, for example planning applications. Planning applications essentially involve the assessment of the transportation infrastructure at a future time to estimate its performance. Based on appropriate performance measures, decisions can be made regarding improvement alternatives. Planning applications for freeways are very important as the congestion levels on intercity highways and freeways are high and are likely to increase further (TRB special report, 1991). Such high levels of congestion have serious impacts on the regional economic development (Bhat 1995).

Planning applications are based on future travel demand where speed data for those future conditions are not known. Analytical T.T. models using demand have been developed, and are applicable for both under-saturated (Davidson 1966, HCM 2000) and oversaturated conditions (Bureau of Public Roads 1964, Akcelik 2003). These models are consistent with each other and make accurate T.T. predictions at lower demand levels and unsaturated conditions. However, at high levels of demand and congested conditions, these models are not consistent with each other and have not been compared with field data (Akcelik 2003).

Most of the existing models do not consider queuing explicitly. Thus, further advancement in the T.T. estimation models is needed to improve prediction particularly for congested conditions. These models should also consider the formation and dissipation of queues.

1.2 Objectives and Scope

The objective of this thesis is to develop analytical models for estimating T.T. for freeway corridors as a function of demand. Given the difficulty in obtaining field data particularly with respect to demand, simulation will be used in the development of the analytical models.

The following tasks were undertaken:

1. Select important variables which may impact freeway corridor T.T. as identified in the literature
2. Using these variables, develop scenarios and simulate them to select the significant variables that affect freeway T.T.
3. Using the significant variables identified above, finalize the scenarios considered and simulate them to generate data for the development of analytical models
4. Develop analytical T.T. models based on the simulation results
5. Compare the analytical models developed in task 4 to other planning T.T. models

1.3 Organization

The rest of this document is organized as follows. Chapter 2 discusses the literature relevant to the topic. The methodology developed to achieve the stated objectives is described in Chapter 3. Chapter 4 describes the development and simulation of scenarios for generating the database. This data is used to develop T.T. analytical models, which are presented in Chapter 5. These analytical models are compared to other planning T.T. models and the results are presented in Chapter 6. Chapter 7 summarizes the important findings from this research.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews literature relevant to the topic. First, the state-of-the art on T.T. models used in planning applications are reviewed (Section 2.1). Next, the state-of-art on T.T. models for real time applications are reviewed in (Section 2.2). Various data collection techniques which can be used to estimate or measure T.T. are reviewed in Section 2.3. Section 2.4 discusses variables found to impact T.T. Finally a summary of the literature review findings is provided in Section 2.5.

2.1 Travel Time Models for Planning Applications

This section reviews literature on T.T. estimation for planning applications, and the advantages and disadvantages of each of these methods are studied.

T.T. estimation models for planning applications can be broadly classified on the basis of saturation levels considered. While some models can be applied only for unsaturated conditions, other models can be applied for both unsaturated conditions (demand/capacity < 1) and over saturated conditions (demand/capacity > 1). Models of the former type, such as the HCM speed flow curve, can be used to predict the T.T.s for unsaturated conditions. However these models cannot be used for oversaturated conditions, and thus they cannot be used to predict T.T.s in future years as the traffic demand in future years usually falls in oversaturated conditions (Singh 1999).

There are three T.T. estimation models which are applicable in over saturated conditions and each of these is discussed below

(1) Bureau of Public Roads (BPR) model (Bureau of Public Roads, 1964):

$$T = T_{ff} * \left(1 + 0.15 * \left(\frac{q}{C}\right)^4\right) \quad (2-1)$$

Where,

T = travel time

T_{ff} = free flow travel time

q = flow

C = Capacity

Spiess (1990) evaluated the popular BPR function and found several drawbacks. Some of the limitations of the BPR function are (1) they are not strictly increasing functions at low volume (2) there is no upper limit on the slope of the volume delay function. Developing on these drawbacks of the BPR function he investigated the set of necessary conditions which a valid volume delay function should satisfy. The functions which satisfy these conditions are called conical volume delay functions. He cited an application of these conical volume delay functions as an input to the traffic assignment for the city of Basel, Switzerland. He found that the convergence speed for traffic assignment was high for conical volume delay functions as compared to the BPR function.

The first limitation highlighted by Spiess (1990) is not validated by any field data. On the other hand, HCM 2000 describes the speed flow relation, based on field data, as a relatively flat curve under non congested conditions.

The BPR function models travel time for the study segment independent of the downstream conditions. When the downstream segment is a bottleneck, all the upstream segments of the bottleneck experience congested conditions. Thus, excluding the impact of the downstream conditions is one of the fundamental limitations of BPR function.

Miruchandani et al. (2003) have highlighted that the popular BPR model and the conical volume delay functions are limited to uninterrupted flow. Further, they have highlighted that analytical volume delay functions do not model congestion and dissipation effects.

(2) Metropolitan Transportation Commission (MTC) model (Singh et.al, 1995):

$$T = T_{ff} * (1 + 0.2 * (q/C)^{10}) \quad (2-2)$$

Where,

T = travel time

T_{ff} = free flow travel time

q = flow

C = Capacity

Akcelik (2003) argues that for oversaturated traffic conditions the T.T. should increase linearly with flow. Contrary to this argument the T.T. estimated using the MTC model varies exponentially with flow for oversaturated conditions. Thus the MTC model is not theoretically justified from queuing theory.

Similar to the BPR function, MTC function models travel time for the study segment independent of the downstream conditions. When the downstream segment is a bottleneck all the upstream segments of the bottleneck experience congested conditions. Thus, excluding the impact of the downstream conditions is one of the fundamental limitations of MTC function. Further, the length of the segment is also not considered by both BPR and MTC functions. As the length of the segment increases the percentage of the segment that experiences congestion keeps decreasing. Thus the length of the segment is also believed to be an important variable, which is not addressed by both BPR and MTC functions.

(3) Akcelik's model estimates average T.T. over a given time period:

$$t = t_0 + \{0.25\Delta t * [(q/C - 1) + \{(q/C - 1)^2 + (8J_a * (q/C - 1)/(C\Delta t)\}^{0.5}]\} \quad (2-3)$$

Where,

t = T.T.

t_0 = free flow T.T.

Δt = time period for which the specified demand persists

q = flow

C = capacity

J_a = Delay parameter

These three models estimate T.T. significantly different from one another. Singh (1999) studied the T.T. predicted by BPR, MTC, and Akcelik models for oversaturated conditions. The comparison of the BPR, MTC, Akcelik and 1994 HCM are shown in Figure 2-1 and Figure 2-2. It can be observed from Figure 2-1 and Figure 2-2 that under uncongested conditions, all the above four travel time functions make similar predictions. However, under congested conditions, these four travel time functions make different travel time predictions. While, the BPR function is insensitive to increases in flow for oversaturated conditions, the MTC model predicts T.T. which varies non-linearly with increase in flow. Akceliks model predicts T.T. which varies linearly with increase in flow. Singh (1999) concluded that Akceliks model best describes the T.T. for oversaturated conditions. The fundamental limitation of all the above four functions is that they do not consider the impact of the downstream conditions on the travel time of the study segment.

There are several differences between Akceliks travel time function and other functions (BPR and MTC). One key difference is that, while Akceliks travel time function considers the time period over which the average travel time is reported, BPR and MTC travel time functions do not consider the time period over which the average travel time is reported. Another difference is that, while the BPR and MTC functions are more macroscopic and mainly focus on planning applications, the Akceliks function is microscopic and focuses on making realistic estimate of travel time.

Miruchandani et al. (2003) have developed simulation-based T.T. estimation, for modeling the impacts of congestion, dissipation, and interrupted flow, using the CORSIM software. Their simulation modeling included several factors such as lane changing behavior, gap acceptance,

intersection control, start up loss times, vehicle headways, and pedestrian traffic. They used this simulation-based estimation of T.T., for their traffic assignment process.

2.2 Travel Time Estimation for Real-Time Applications

This section reviews literature on T.T. estimation models for real time applications. These models are for short term prediction of T.T. The advantages and disadvantages of each of the methods are also studied. Finally the usability of these models to planning applications is studied.

Most models estimate and report either T.T. or, its equivalent, speed. The most widely used methods for freeway T.T. prediction use data collected from loop detectors. For methods that use loop detector data, vehicle length is an important parameter for estimating speed (or T.T.). These models either use a constant value of effective vehicle length (Petty and Peter Bickel 1998) or use the vehicle length measured for each vehicle (Dailey 2004). Dailey (2004) claimed that models that use a constant effective vehicle length are inaccurate (greater than 80%) under high levels of congestion. While the models that use vehicle length for each individual vehicle for estimation of speed are more accurate (greater than 90%).

Instead of estimating speed and then T.T., T.T. can also be directly measured by vehicle re-identification. Using dual loop detectors the vehicle length can be directly estimated. Several approaches have been proposed to estimate vehicle length including Kalman filtering (Dailey 2004) and Exponential smoothed technique (Helling 2002). Once the vehicle length is known, the vehicle can be re-identified using its length as its signature (Coifman 1998). By identifying the vehicle at both the upstream and down-stream the T.T. can be measured. Mirchandani et al. (2004) have shown that instead of identifying a single vehicle, a platoon can be identified at both the upstream and down-stream points. Using this technique they could match 90 % of the platoons. Thus the T.T. of all vehicles in the platoon can be measured. The vehicle re-

identification technique works well only under congested conditions. Smith et al. (2004) conducted sensitivity analysis on T.T. estimation using single loop detector data. They estimated T.T. at various levels of congestion and found that T.T. is overestimated as the congestion level decreases, by as much as 1 minute per mile.

An important issue regarding T.T. estimation is the T.T. prediction interval, the time period for which the predictions are made (for example the next 10 minutes). Chien et al (2003) have shown that although accurate (97%) short term T.T. predictions have been possible using flow and speed data modeled using simple regression techniques, without considering the historical data accurate prediction of T.T.s for longer periods could not be made. This is attributed to the unknown flows that are to arrive for the next one hour, and the speeds of the vehicles that are to arrive, which is also unknown.

2.3 Travel Time Data Collection Techniques

In this section various T.T. data collection technologies and their applications for T.T. measurement are also reviewed.

There are numerous techniques for T.T. data collection. Kim et.al (1995) classified these techniques into three categories: 1) Spot speed measurement techniques (measure speed only) 2) Vehicle tracking techniques (measure vehicle T.T.s) 3) Trip maker tracking techniques (measure traveler trip times than vehicle trip times). Further, Kim et.al (1995) evaluated the relative advantages of the above three classes of techniques. Spot speed measurement techniques measure the instantaneous speed either at a fixed location, such as road side sensors, or at fixed time, such as aerial photography. These spot speed measurement techniques provide economically efficient solutions for acquiring large volumes of speed data at a given location. Vehicle tracking techniques measure T.T. along the trip. These techniques include the floating car technique, non-instrumented vehicle tracking, and passive probe technique. Microwave radar

detection systems (RTMS) use microwaves to detect traffic and measure traffic related parameters such as volume and speed. EIS traffic solutions (2006) have tested the accuracy with which RTMS can measure traffic by comparing the traffic data collected using RTMS with manually collected data. They found that RTMS can be used to accurately measure traffic in general (98%).

2.4 Variables for Scenario Development

This section reviews the literature to identify a preliminary list of variables that may affect the travel time. These variables will be used for simulation so that the significant variables can be selected for further consideration.

The Highway Capacity Manual (HCM) 2000 considers the following freeway segments: 1) Basic freeway segment, 2) Merge segment, 3) Diverge segment, and 4) Weaving segment. Not all of these segments require the same set of inputs to estimate travel time, therefore each segment type is considered separately.

For the basic freeway segment, the HCM 2000 lists the following variables as important for operational analysis:

- 1) Lane Width: If the lane widths are less than 12 ft, drivers tend to reduce their speed for driving close to one another laterally.
- 2) Number of lanes: Under moderately or heavily congested conditions, lane changing might facilitate faster travel.
- 3) Driver Population: Non commuter driver populations have different driving behavior compared to regular commuters (HCM 2000).
- 4) Free flow speed (FFS): Under uncongested conditions, with higher free flow speed, there is an opportunity to travel faster
- 5) The demand: the demand is directly related to T.T. as, higher traffic results in congestion and lower T.T.

In addition to the factors listed in HCM 2000, other factors that can impact travel time of a basic freeway segment are also considered. These factors are listed below.

- 6) Length of the freeway segment: The length of the segment would affect the T.T./mile as a function of the queue length or the congested portion of the segment.

For a merge segment, the HCM 2000 considers the same variables as the basic freeway segment with the addition of the following:

1. Demand from on-ramp: Higher the demand from on-ramp, the extent of merging will be higher and results in high levels of congestion thus resulting in higher T.T.
2. Length of the entry segment: The entry segment stores the queue that needs to get past the merging point bottleneck. With longer entry segment, more vehicles can be queued, which results in higher travel time.

For a diverge segment, the HCM 2000 considers the same variables as the basic freeway segment with the addition of the following:

1. Demand on off-ramp: Higher the demand on off-ramp, more vehicles exit out of the system. This reduces congestion thus resulting in lower T.T.
2. Length of the entry segment: The entry segment stores the queue that needs to get past the merging point bottleneck. With longer entry segment, more vehicles can be queued, which results in higher travel time.

For a weaving segment, the HCM 2000 considers the same variables as the basic freeway segment with the addition of the following:

- 1) Demand from on-ramp: Higher the demand from on-ramp the extent of merging will be higher and results in high levels of congestion thus resulting in higher T.T.
- 2) Demand on off-ramp: Higher the demand on off-ramp, more vehicles exit out of the system. This reduces congestion thus resulting in lower T.T.
- 3) Length of the entry segment: The entry segment stores the queue that needs to get past the merging point bottleneck. With longer entry segment, more vehicles can be queued, which results in higher travel time.
- 4) Weaving Length: The length of the weaving segment restricts the space under which all the required lane changes have to be made. Thus with decrease in weaving length, the intensity of lane changes increases and thus speed decreases. Thus, the resulting travel time increases (HCM 2000).

2.5 Summary and Conclusions

Analytical T.T. models using demand have been developed, and are applicable for both under-saturated and oversaturated conditions. These models are consistent with each other and make accurate T.T. predictions at lower demand levels or in unsaturated conditions. However, at high levels of demand or congestion these models are not consistent with each other and have not been compared with field data. Further, some of the existing models, such as BPR, consider flows greater than the capacity, which is unrealistic. Thus there is a need for further advancement in the T.T. estimation models which make accurate predictions at both saturated and unsaturated congestion levels. Moreover, most of the existing models (BPR and MTC) do not consider the queuing phenomenon explicitly. Thus analytical models which consider formation of queue and dissipation of queues and also consider the delay associated with these queues in estimation of T.T. is required.

Besides analytical models, simulation has also been used for direct estimation of T.T.. However, analytical models of T.T. have not been developed using results obtained from simulation.

A preliminary list of variables that may affect the travel time are considered. These variables will be used for simulation so that the significant variables can be selected for further consideration. Not all of the freeway segments require the same set of inputs to estimate travel time, therefore each segment type is considered separately. The Highway Capacity Manual (HCM) 2000 considers the following freeway segments: 1) Basic freeway segment, 2) Merge segment, 3) Diverge segment, and 4) Weaving segment.

Lane Width, number of lanes, driver Population, free flow speed (FFS), freeway demand, length of the freeway segment were considered as important variables that may affect the travel time of a basic freeway segment. The same variables which are considered for the basic freeway

segment are also considered with the addition of the on-ramp demand and length of the entry segment for merge segments, with the addition of the off-ramp demand and length of the entry segment for diverge segments, with the addition of the on-ramp demand, off-ramp demand, and length of the entry segment for weave segments.

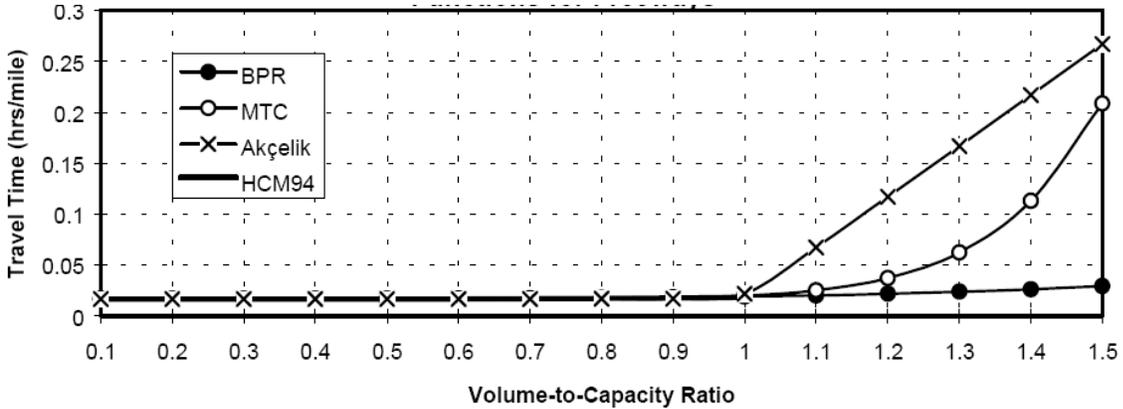


Figure 2-1. Comparison of BPR, MTC, Akcelik and 1994 HCM T.T. functions for $q/c < 1.5$ (source: Rupinder Singh, 1999)

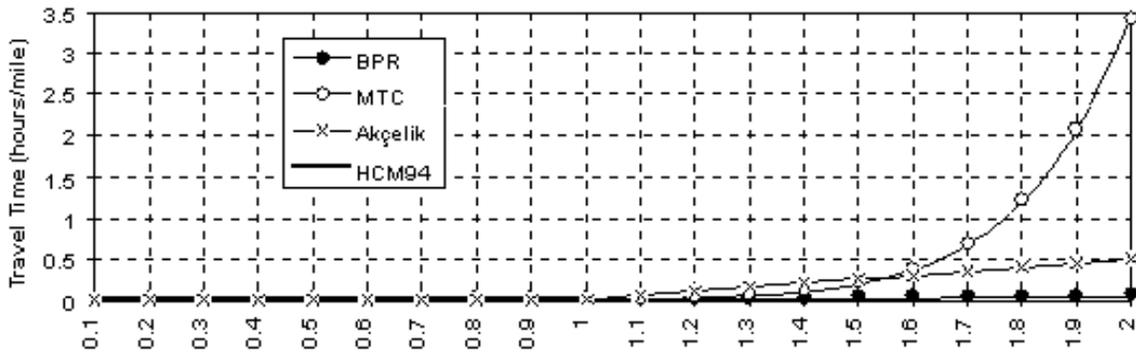


Figure 2-2. Comparison of BPR, MTC, Akcelik and 1994 HCM T.T. functions for $q/c < 2$ (source: Rupinder Singh, 1999)

CHAPTER 3 METHODOLOGY

This section presents the methodology developed to accomplish the objectives stated in Chapter 1. The methodology is outlined in Figure 3-1. First, a simulation model is selected to suit the needs of the project (Section 3.1). Next, scenarios are developed and simulated to identify the most important variables that may affect T.T. in the simulator (Section 3.2). Using these important variables, a set of scenarios is developed and simulated to obtain a database for analytical model development (Section 3.3). Analytical models are developed using this database (Section 3.4). Section 3.5 discusses the comparison of the proposed analytical models to other T.T. estimation models.

3.1 Simulation Model Selection

Although most of the micro-simulation packages available are capable of simulating large networks, they differ in the level of detail used to conduct analysis and also differ in the basic algorithms used (car following, lane changing, e.t.c.). Thus depending on the requirements of the application, appropriate software has to be selected.

There are several software packages, including AIMSUN, PARAMICS, VISSIM, and CORSIM, that suit the general requirements of this study. More specifically, the software should be able to replicate and provide T.T. for different types of freeway segments. Any of the above listed micro-simulation packages could be used for this purpose. The CORSIM software package was readily available for use for this study, thus the CORSIM software package was used.

CORSIM was developed by FHWA. It has a separate module for freeway analysis called FRESIM. It is widely used among transportation professionals, relatively well documented, and also requires only modest network coding. Moreover, the support from McTrans is readily

available for any problems that might arise while using CORSIM. It can also model freeway corridors under various levels of congestion.

3.2 Development and Simulation of Scenarios for Variable Selection

The study corridor is broken down in to freeway segments, as described in Section 2.4. Segmenting the corridor in to these segments enables easy estimation of analytical models for each of these three segments, as the number of variables remains relatively small. After developing analytical models for T.T. for each of the four classes of segments, the T.T. for the entire corridor is estimated as the sum of the T.T. of all the segments.

To develop the analytical models for each class of the freeway segments, first, important variables that can affect the T.T. for each segment are identified. For each of these variables, the possible range of values is selected within the normal field conditions. Within the range of possible values for each variable, a few values are selected and are considered for the development of scenarios. Once specific values are chosen for each variable, scenarios are developed using these values. A scenario represents a state where each variable is assigned a specific value among the possible values.

The variables selected for developing scenarios are classified into the following groups.

1. Basic freeway segment: Lane width, number of lanes, driver population, free flow speed (FFS), demand, and length of the freeway segment.
2. Merge segments: In addition to the variables considered for the basic freeway segment, the following variables are considered: Demand from on-ramp, length of the entry segment.
3. Diverge segment: In addition to the variables considered for the basic freeway segment, the following variables are considered: Demand on off-ramp, length of the entry segment.
4. Weaving segment: In addition to the variables considered for the basic freeway segment, the following variables are considered: Demand from on-ramp, demand on off-ramp, length of the entry segment, weaving Length.

In addition to the above variables, some other variables were also found to be important, such as: length of the acceleration and deceleration lane. However, both the length of the acceleration and deceleration lane are dependent on the free flow speed. As the free flow speed is varied, the length of the acceleration lane and deceleration lane is adjusted to its design length according to the guidelines mentioned in green book.

Lane width was not included for developing scenarios because it was already included in estimation of free flow speed. Driver population factor and percent of trucks were not included for developing scenarios to contain the number of scenarios within a reasonable range.

3.3 Scenarios for Database Development

Based on the results of the preliminary experiments, important variables are identified and the list of scenarios to be used is prepared. These scenarios are simulated and T.T. is extracted for each scenario. A database is developed using the simulated data. This database is in the form of an (MxN) matrix, where each of the “M” rows is a specific scenario and each of the “N” columns is a variable, either the T.T. itself or one of the several variables that have been considered in the development of scenarios. Such a database is developed for each segment type.

3.4 Development of Analytical T.T. Models

After simulating the scenarios and developing the database, analytical models are developed for each freeway segment type. Regression models are developed with T.T. as the dependent variable and the other variables used for developing scenarios as independent variables.

3.5 Comparison of Analytical Models to Simulator

The analytical models are applied to predict T.T. on freeway segments under saturated/congested conditions. Similarly, other analytical models from the literature are applied on freeway segments under saturated/congested conditions. Comparisons are drawn on the

predicted T.T. using the analytical models developed as part of this thesis along with other analytical models in literature.

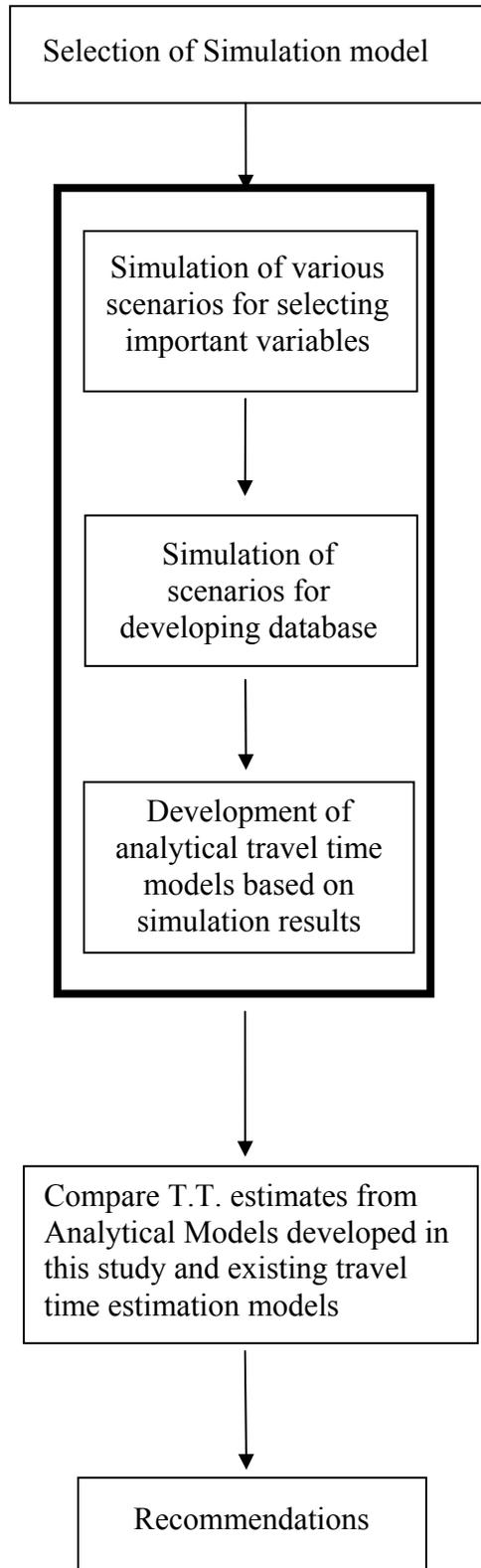


Figure 3-1. Methodology flow chart

CHAPTER 4 SIMULATION OF SCENARIOS

This chapter discusses the identification of variables for developing simulation scenarios, the simulation process, and the selection of variables for inclusion in the analytical models. The variables identified from the literature are discussed in Section 4.1. Next, the development and simulation of scenarios along with the selection of the variables found to affect T.T. in the simulation are presented in Section 4.2.

4.1 Identification of Variables and Their Range of Values

To develop the analytical models for each class of the freeway segments, first, the variables that may affect the T.T. for each type of segment identified from the literature (Section 2.4) are reviewed, and a reasonable range of values is obtained. The range of values is selected such that they reflect the commonly found values in field and also generate reasonable number of scenarios. These variables along with their range of values are listed in Table 4-1, Table 4-2, Table 4-3, and Table 4-4.

As discussed in Section 2.4, the downstream conditions can impact the traffic flow of the study segment, more so if the downstream segment is a bottleneck. In this study the impact of downstream segment is analyzed by varying its capacity. Although there is no standard procedure to design the downstream segment so that it reaches a particular capacity, five different road configurations were developed such that the throughput from the downstream segment varies uniformly over a large range of values. These different road configurations include, free flow speed of 15 mph and 25 mph, single lane closure, lane closure with rubber necking factor. Rubber necking factor reflects the intensity of the incident or work zone.

4.2 Development of Scenarios

This section presents the scenarios developed for each type of freeway segments, identified in Section 2.4.

4.2.1 Basic Freeway Segment

A basic freeway segment does not have any on-ramps or off-ramps. A sketch of a basic freeway segment is shown in Figure 4-1. The basic freeway segment shown in Figure 4-1 consists of two links, the subject freeway segment, which is located between the entry and exit points and the segment downstream of the subject segment. This downstream segment acts as a bottleneck and is used in this study to control the number of vehicles that can exit the subject freeway segment. This is achieved in the simulation by varying the geometry and driver behavior characteristics of the downstream segment.

Each variable under consideration was tested whether it has any influence on the T.T. per mile of the basic freeway segment. This was accomplished by varying the values of each variable systematically and observing the T.T. per mile. . It should be noted that, an initialization period of 15 minutes was used in all the simulation runs. Some of the simulation runs reached the equilibrium within the initialization period, while a majority of scenarios did not reach equilibrium within the initialization period. While the travel time derived from the simulation runs that did not reach equilibrium depend on the initialization period, this has not been considered in this study.

A detailed description of the variables evaluated is given below.

Demand per lane: Number of vehicles attempting to enter the subject segment. If the demand exceeds capacity then a queue is formed in the bottleneck and also upstream of the entrance of the subject segment. In this case the number of vehicles actually entering the segment

could be lower than the demand. Eight different values of demand are used, ranging from 1000 veh/hr/ln to 9999 veh/hr/ln.

Downstream capacity: The maximum number of vehicles exiting from the downstream section. Although there is no standard procedure to design the downstream segment so that it reaches a particular capacity, five different road configurations were developed such that the throughput varies uniformly over a large range of values.

Free-Flow speed: The average speed on a section when there is very low demand. Four different speeds were tested; 55 mph, 60 mph, 65 mph, and 70 mph.

Number of lanes: The number of through lanes in each direction. This study tested 2-lane segments, 3-lane segments, and 4-lane segments.

Length of the BFS segment: This study tested segment length equal to 5000 ft, 10,000 ft, 15,000 ft, 20,000 ft, and 25,000 ft.

The complete set of values tested is shown in Table 4-5, and scenarios were developed for each combination of these for a basic freeway segment.

2400 different scenarios were created for basic freeway segment. Each of these scenarios was simulated 10 times and the average travel time, density, and number of vehicles exiting the downstream segment were computed. The run time for simulating all of these 2400 scenarios 10 times was about 48 hrs on a “2.39 Ghz core 2 duo” CPU with 3 GB memory.

Preliminary analysis was conducted to evaluate the impacts of each of these variables on the T.T. per mile. Figure 4-2 shows that the T.T. remains relatively constant until demand reaches downstream capacity. The impact of demand per lane is very significant when the downstream segment has reduced capacity. Once demand reaches downstream capacity, T.T.

starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,250 veh/ln).

To find the impact of downstream capacity on T.T., the downstream capacity is varied from no capacity reduction (2250 veh/hr/ln) to very low capacity (848 veh/hr/ln). Figure 4-3 presents the relationship between downstream capacity and T.T. As shown, the T.T. plots consist of three parts. In the first part, when demand is lower than the downstream capacity, the relationship between T.T. and demand is relatively flat, i.e. T.T. is not affected by demand. In the second part, when demand exceeds the downstream segment capacity, T.T. starts increasing linearly with demand. In the third and final part, when demand exceeds downstream segment capacity considerably, the linearly increasing T.T. curve flattens out and eventually becomes a constant value.

As illustrated in Figure 4-3, the downstream capacity has a very significant impact on T.T. Because of the high impact of the reduced downstream capacity, the impact of the remaining variables on T.T. is presented in two cases; a) when there is no reduction in capacity of the downstream section and b) when there is reduction in the capacity of the downstream section.

To find the impact of free-flow speed on T.T., the free-flow speed is varied from 55 mph to 70 mph and the relationship between T.T. and demand for each of the free-flow speeds is observed. Figure 4-4 presents the relationship between T.T. and demand for different free-flow speeds when there is no downstream bottleneck. As shown there is significant difference in the T.T. per mile between each of the FFS. Therefore FFS is an important variable in the estimation of T.T. when there is no downstream bottleneck. As the speed increases, the T.T. per mile decreases. When there is no reduction in downstream segment capacity, with higher FFS the vehicles can travel faster and the T.T. decreases. The relationship between T.T. and demand is a

set of parallel lines, one for each speed. The T.T. increases linearly by a relatively small amount, with increasing demand.

To find the impact of free-flow speed on T.T. when there is a downstream bottleneck, the free-flow speed is varied from 55 mph to 70 mph and the relationship between T.T. per mile and demand is observed for each of these FFS. Figure 4-5 presents the relationship between T.T. and demand for different free-flow speeds when the downstream segment has reduced capacity equal to 1324 veh/hr/ln. As shown, as the FFS increases, the difference in T.T. per mile between each of the FFSs decreases until the demand reaches the downstream segment capacity. Once demand reaches the downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free flow conditions, and there is no change in T.T. with increase in FFS. As shown in the Figure 4-5, the T.T. remains relatively constant until demand reaches downstream capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

The downstream capacity is further reduced to 849 veh/hr/ln and the relationship between T.T. and demand for different free-flow speeds is presented in Figure 4-6. As shown in the Figure 4-6, as the FFS increases, the difference in T.T. per mile between each of the free flow speed decreases until the demand reaches downstream segment capacity. Once demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free-flow conditions, and there is no change in T.T. with increase in free-flow speed.

To find the impact of length of the BFS on T.T., the length of the BFS is varied from 5,000 ft to 25,000 ft and the relationship between T.T. and demand for each of the lengths of BFS is observed. Figure 4-7 presents the relationship between T.T. and demand for different lengths of BFS when there is no downstream bottleneck. As shown, there is no significant difference in the

T.T. per mile between each of the lengths of the basic freeway segment. Therefore the length of the basic freeway segment is not an important variable in the estimation of T.T. when there is no downstream bottleneck. This trend is observed because when the downstream segment has no reduction in capacity, free flow conditions prevail in the basic freeway segment. Thus the T.T. increases with the length of the BFS almost linearly, which results in a constant T.T. per mile for different lengths of the BFS. As shown in the Figure 4-7, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity.

To find the impact of the length of the BFS on T.T. when there is a downstream bottleneck, the length of the BFS is varied from 5,000 ft to 25,000 ft and the relationship between T.T. per mile and demand is observed for each of these lengths. Figure 4-8 presents the relationship between T.T. and demand for different free-flow speeds when the downstream segment has reduced capacity equal to 1324 veh/hr/ln. As shown, there is significant difference in the T.T. per mile between each of the lengths of the basic freeway segment. Therefore the length of the basic freeway segment is an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-8, the T.T. per mile decreases with increasing length of the segment. When the segment is very long the queuing of vehicles is mostly concentrated at the downstream end of the segment, with the upstream part operating at free flow conditions. As the segment length increases, the section with free flow conditions increases, thus the average speed of the segment increases and the T.T. decreases as shown in Figure 4-8. As shown in the Figure 4-8, the T.T. remains relatively constant until demand reaches downstream capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T.

The downstream capacity is further reduced to 849 veh/hr/ln and the relationship between T.T. and demand for different lengths of the basic freeway segment is presented in Figure 4-9. As shown, there is significant difference in the T.T. per mile between each of the lengths of the basic freeway segment. Therefore the length of the basic freeway segment is an important variable in the estimation of T.T. when there is no downstream bottleneck. As shown in the Figure 4-9, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,250 veh/ln).

To find the impact of the number of lanes on T.T. when there is no downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of those configurations is observed. Figure 4-10 presents the relationship between T.T. and demand as a function of the number of lanes when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of these configurations. Therefore the number of lanes is not an important variable in the estimation of T.T. when there is no downstream bottleneck. As shown in the Figure 4-10, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity. It should be noted that the demand here and everywhere else in the document refers to vehicles that are attempting to use the facility on a per lane basis. Thus, while testing the impact of number of lanes, demand refers to demand per lane and not the total demand.

To find the impact of the number of lanes on T.T. when there is a downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of these configurations is observed. Figure 4-11 presents the relationship between T.T. and demand as a function of number of lanes when there is a downstream

bottleneck. As shown, there is no significant difference in the T.T. per mile between each of these configurations. Therefore the number of lanes is not an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-11, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,250 veh/ln).

To find the impact of downstream capacity on the T.T. per mile of the downstream segment, the downstream capacity is varied from no capacity reduction (2240 veh/hr) to very low capacity (848 veh/hr). Figure 4-12 presents the relationship between downstream capacity and T.T per mile of the downstream segment. As shown in Figure 4-13, travel time per mile of the downstream segment decreases exponentially with downstream segment capacity.

To find the impact of downstream capacity on the T.T. per mile of the downstream segment, the downstream capacity is varied from no capacity reduction (2240 veh/hr) to very low capacity (848 veh/hr). Figure 4-13 presents the relationship between downstream capacity and T.T per mile of the downstream segment. As shown, the T.T. plots do not have a clear 3 part curve similar to the upstream travel time plots.

To find the impact of the number of vehicles in the is a downstream bottleneck on the T.T. of the downstream bottleneck, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-14, the T.T. per of the downstream bottleneck closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the downstream bottleneck is found to be an important variable in the estimation of T.T. within the downstream bottleneck when there is a downstream bottleneck. As shown in the Figure 4-14,

once downstream bottleneck gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

To find the impact of the number of vehicles in the is a upstream segment on the T.T. of the upstream segment, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-15, the T.T. per of the upstream segment closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the upstream segment is found to be an important variable in the estimation of T.T. within the upstream segment when there is a upstream segment. As shown in the Figure 4-15, once upstream segment gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

Summary: Based on the investigation made from the plots (Figure 4-2 to Figure 4-15) describing the variation of T.T. as a function of several factors, the following observations were made:

- 1) The relationship between T.T. and demand (Figure 4-2) can be characterized by the following; (1) when demand is less than the downstream segment capacity the T.T. remains relatively constant (2) when demand is equal to downstream capacity the T.T. starts to increase at an exponential rate (3) when the exponentially increasing T.T. suddenly starts to flatten and reaches a maximum T.T. Although the shape of the T.T. plot against demand is relatively similar to the BPR and other functions, when the demand is less than the capacity, the shape differs significantly in the congested region. While the traditional models predict exponentially increasing T.T. once the demand exceeds capacity, the analysis conducted in this study suggests that the T.T. curve flattens after a particular point.
- 2) The capacity of the downstream segment plays a key role in the prediction of T.T. The variation of T.T. with demand varies significantly depending on whether the demand is greater than or less than the downstream capacity (Figure 4-3). Thus the impact of all other variables is broken-down into 2 cases: (1) when there is no downstream bottleneck (2) when there is a downstream segment bottleneck.
- 3) FFS significantly affects T.T. when there is no downstream bottleneck (Figure 4-4). However if there is a downstream bottleneck, the FFS does not impact the T.T. (Figure 4-5 & Figure 4-6).

- 4) The length of the basic freeway segment is not significant when there is not bottleneck (Figure 4-7). However when there is a downstream bottleneck, the length of basic free flow segment becomes significant, under congested conditions (Figure 4-8 and Figure 4-9). It is observed that as the length of the basic freeway segment increases, the T.T. decreases for a given demand. For segments with higher length, the impact of downstream congestion on the upstream end is lower than that of a shorter segment, and thus higher average speeds are reported for longer segments.
- 5) The number of lanes shows no significant impact on T.T. neither for presence of a downstream segment bottleneck nor when there is no bottleneck (Figure 4-10 & Figure 4-11).

From the simulation analysis in this section, it is observed that variation of T.T. with demand primarily depends on whether or not demand exceeds the downstream segment capacity. It is also observed that the impact of any variable (with the exception of downstream segment capacity) on T.T. of any freeway segment depends on the downstream segment capacity. Table 4-6 summarizes the impact of each of the variables on travel time when there is no downstream segment bottleneck and when there is a downstream segment bottleneck.

4.2.2 Merge Segment

The merge segment tested consists of four freeway links and a ramp link. The first link is the entry link which spans from the beginning of the merge segment to the point where the ramp meets the freeway (Figure 4-16). The second link is the merging section, which spans along the length of the acceleration lane. The third link is immediately downstream of the merging section and extends till the exit point. The fourth and final link is the downstream section, which starts from the exit point of the merge segment and spans for a fixed length (2000 ft). This downstream segment is used to control the number of vehicles that can move out of the merge segment, in other words the downstream capacity. This is achieved in the simulation by varying the geometry, traffic control, and driver behavior characteristics of the downstream segment. A brief description of the variables considered to develop merge operating scenarios is given below.

Demand per lane: Number of vehicles attempting to enter the subject segment. If the demand exceeds capacity then a queue is formed upstream of the entrance of the subject segment. In this case the number of vehicles actually entering the segment could be lower than the demand. Eight different values of demand are used, ranging from 1000 veh/hr/ln to 9999 veh/hr/ln.

Downstream capacity: The maximum number of vehicles exiting from the downstream section. Although there is no standard way to design the downstream segment to achieve a particular capacity, five different road configurations were developed such that the throughput varies uniformly over a large range of values.

Ramp Demand per lane: Number of vehicles attempting to enter the ramp segment. Three different values of demand are used: 100, 300, and 500 veh/hr/ln.

FFS: The average speed on a section when there is very low demand. Four different speeds were tested; 55 mph, 60 mph, 65 mph, and 70 mph.

Number of lanes: The number of through lanes in each direction. This study tested 2-lane segments, 3-lane segments, and 4-lane segments.

Length of the entry segment: The length of the section of road starting from the entry point of the merge segment to the beginning of the acceleration lane.

The complete set of values tested is provided in Table 4-7, and scenarios are developed for each combination of these for a merge segment.

6075 different scenarios were created for merge freeway segment. Each of these scenarios is simulated 10 times and the average travel time, density, and number of vehicles exiting the system are computed. The run time for simulating all of these 3375 scenarios 10 times takes about 150 hrs on a core 2 duo CPU with 3 GB memory.

Preliminary analysis was conducted to evaluate the impacts of each of these variables on the T.T. per mile. Figure 4-17 shows that the T.T. remains relatively constant until demand reaches downstream capacity. The impact of demand per lane is very significant when the downstream segment has reduced capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then flatten out to a maximum value of T.T. (at approximately 2,250 veh/ln).

To find the impact of downstream capacity on the T.T., the downstream capacity is varied from full capacity (4500 veh/hr/ln) to very low capacity (250 veh/hr/ln). Figure 4-18 presents the relationship between downstream capacity and the T.T. As shown in Figure 4-18 the T.T. plot with demand has two characteristic points similar to the basic freeway segment.

As illustrated in Figure 4-18 the downstream capacity has a very significant impact on T.T. Similar to the basic freeway segment case, the impact of remaining variables on T.T. is presented in two cases; no reduction in capacity and reduction in capacity.

To find the impact of free-flow speed on T.T., the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. and demand for each of the free-flow speeds is observed. Figure 4-19 presents the relationship between T.T. and demand for different free-flow speeds when there is no downstream bottleneck. Similar to the basic freeway segment case, FFS is found as an important variable in the estimation of T.T., when there is no downstream bottleneck, and the relationship between T.T. and demand is a set of parallel lines, one for each speed. The T.T. linearly increases, by a very minimal value, with increase in demand.

To find the impact of free-flow speed on T.T. when there is a downstream bottleneck, the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. per mile and demand is observed for each of these FFS. Figure 4-20 presents the relationship between T.T.

and demand for different free-flow speeds when the downstream segment has reduced capacity equal to 1689 veh/hr/ln. As shown, as the FFS increases, the difference in T.T. per mile between each of the FFS decreases until the demand reaches the downstream segment capacity. Once demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free flow conditions. Thus there is no change in T.T. with increase in FFS. As shown in the Figure 4-20, the T.T. remains relatively constant until demand reaches downstream capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln)

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different free-flow speeds is presented in Figure 4-21. As shown, as the FFS increases, the difference in T.T. per mile between each of the FFS starts increasing after the demand reaches downstream segment capacity. As shown in the Figure 4-21, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of on-ramp demand on T.T., the length ramp-demand is varied from 100 veh/hr/ln to 500 veh/hr/ln and the relationship between T.T. and demand for each value of on-ramp demand is observed. Figure 4-22 presents the relationship between T.T. and demand for different on-ramp demand when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the on-ramp demands. Therefore on-ramp demand is not an important variable in the estimation of T.T. when there is no downstream bottleneck.

To find the impact of on-ramp demand on T.T. when there is a downstream bottleneck, the ramp-demand is varied from 100 veh/hr/ln to 500 veh/hr/ln and the relationship between T.T. and demand for each value of on-ramp demand is observed. Figure 4-23 presents the relationship between T.T. and demand for different on-ramp demand when there is a downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the on-ramp demands. Therefore on-ramp demand is not an important variable in the estimation of T.T. when there is no downstream bottleneck.

To find the impact of free-flow speed on T.T. when there is a downstream bottleneck, the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. per mile and demand is observed for each of these FFS. Figure 4-23 presents the relationship between T.T. and demand for different free-flow speeds when the downstream segment has 1321 veh/hr/ln as reduced capacity.

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different on-ramp demands is presented in Figure 4-24. As shown, as the FFS increases, the difference in T.T. per mile between each of the on-ramp demand starts increasing after the demand reaches downstream segment capacity. As shown in the Figure 4-24, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of number of lanes on T.T. when there is no downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of the number of lanes is observed. Figure 4-25 presents the relationship between T.T. and demand for different number of lanes when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the number of lane

configurations. Therefore number of lanes segment is not an important variable in the estimation of T.T. when there is no downstream bottleneck. As shown in the Figure 4-25, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity.

It should be noted that the demand here and everywhere else in the document refers to vehicles that are attempting to use the facility on a per lane basis. Thus, while testing the impact of number of lanes, demand refers to demand per lane and not the total demand.

To find the impact of the number of lanes on T.T. when there is a downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of the number of lanes is observed. Figure 4-26 presents the relationship between T.T. and demand for different number of lanes when there is a downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the number of lane configurations. Therefore number of lanes segment is not an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-26, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,250 veh/ln).

To find the impact of length of the entry segment on T.T. per mile of merge segment, the length of the entry segment is varied from 500 ft to 10,000ft and for each length we plot the graph between T.T. and demand, as shown in Figure 4-27. As shown, there is no significant variation in T.T. per mile for different series of length of the entry segment when the downstream segment has no reduction in capacity. This trend is observed because when the downstream segment has no reduction in capacity, uncongested conditions prevail in the merge segment. Thus the T.T. increases with length of the entry segment almost linearly, which results in a constant T.T. per mile for different lengths of the entry segment.

To find the impact of length of the entry segment on T.T. per mile of merge segment when there is a downstream bottleneck, the length of the entry segment is varied from 500 ft to 10,000ft and for each length we plot the graph between T.T. and demand, as shown in Figure 4-28. As shown in Figure 4-28, there is significant variation in T.T. per mile for different series of length of the entry segment when the downstream segment has a reduction in capacity. As shown in the Figure 4-28, the T.T. remains relatively constant until demand reaches downstream capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,250 veh/ln)

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different lengths of the entry segment is presented in Figure 4-29. As shown, there is significant difference in the T.T. per mile between each of the lengths of the entry segment. Therefore length of the entry segment is an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-29, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of the number of vehicles in the is a downstream bottleneck on the T.T. of the downstream bottleneck, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-30, the T.T. per of the downstream bottleneck closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the downstream bottleneck is found to be an important variable in the estimation of T.T. within the downstream bottleneck when there is a downstream bottleneck. As shown in the Figure 4-30,

once downstream bottleneck gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

To find the impact of the number of vehicles in the upstream segment on the T.T. of the upstream segment, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-31, the T.T. per of the upstream segment closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the upstream segment is found to be an important variable in the estimation of T.T. within the upstream segment when there is a upstream segment. As shown in the Figure 4-31, once upstream segment gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

Summary: Based on the investigation made from the plots (Figure 4-17 to Figure 4-40) describing the variation of T.T. with several factors, the following observations were made:

- 1) The variation of T.T. with demand has a step curve (Figure 4-17) as opposed to the popular exponentially increasing curve (as in BPR or MTC models). The step curve can be characterized by two points; (1) when demand equals downstream segment, until this point the T.T. remains relatively constant and after this point the T.T. suddenly starts to increase at an exponential rate (2) when the exponentially increasing T.T. suddenly starts to flatten and reaches a maximum T.T. Although the shape of the T.T. plot against demand is relatively similar when the demand is less than the capacity, the shape differs significantly in the congested region. While the traditional models predict exponentially increasing T.T.s once the demand exceeds capacity, the analysis conducted in this study suggests that the T.T. curve flattens after a particular point.
- 2) Capacity of the downstream segment plays a key role in the prediction of T.T. The variation of T.T. with demand varies significantly depending on whether the demand is greater than or less than the downstream capacity (Figure 4-18). Thus the impact of all other variables is broken-down into 3 cases: (1) when there is a downstream bottleneck (2) when there is no downstream bottleneck.
- 3) FFS shows up significant variation in T.T. when there is no downstream bottleneck (Figure 4-19). However if there is a downstream bottleneck, it is found that as the FFS increases, the T.T. per mile increases until the demand reaches downstream segment capacity. Once demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free flow conditions. Thus the FFS no longer impacts the T.T. (Figure 4-20 & Figure 4-21).

- 4) On-ramp demand doesn't show up significant variation in T.T. when there is no downstream bottleneck (Figure 4-22). However if there is a downstream bottleneck, it is observed that T.T. per mile at a given demand is different for different values of on-ramp demand (Figure 4-23 & Figure 4-24). Moreover it is also observed that this difference in T.T. (for different values of on ramp demand) keeps increasing with demand until the demand reaches downstream capacity. Once the demand reaches the downstream capacity the difference in T.T. per mile (for different values of on-ramp demand) remains fixed with demand. It is also observed that the T.T. per mile is higher for higher on-ramp demand.
- 5) Length of the entry segment doesn't show up significant variation in T.T. per mile when there is no downstream bottleneck (Figure 4-28). However, it is found that the length of the entry segment is an important variable when there is no downstream bottleneck, as shown in Figure 4-29 and Figure 4-30. It is observed from Figure 4.29 that the T.T. per mile decreases with increase in length of the segment. This phenomenon can be explained as follows: when the segment length is large the queuing of vehicles is mostly concentrated at the downstream end of the segment, leaving the upstream segment at free flow conditions. As the segment length increases, the section with free flow conditions increase, thus the average speed of the segment increases and in-turn the T.T. decreases as shown in Figure 4-29 and Figure 4-30
- 6) The number of lanes does not have a significant impact on T.T. neither when there is no downstream bottleneck nor when there is a downstream bottleneck (Figure 4-10, Figure 4-11, & Figure 4-12)

From the simulation analysis in this section, it is observed that variation of T.T. with demand primarily depends on whether or not demand exceeds the downstream segment capacity. It is also observed that the impact of any variable (with the exception of downstream segment capacity) on T.T. of any freeway segment depends on the downstream segment capacity.

4.2.3 Diverge Segment

A sketch of a diverge freeway segment is shown in Figure 4-31. The diverge segment network consists of four freeway links and an off-ramp link. The first link is the entry link which spans from the beginning of the diverge segment to the start of deceleration lane, as shown in Figure 4-31. The second link is the diverging section, it spans along the length of the deceleration lane. The third link is immediately downstream of the diverging section till the exit point of the diverge segment. The fourth and final link is the downstream section, which starts from the exit point of diverge segment and spans for a fixed length (2000 ft). This downstream

segment is used in this study to control the number of vehicles that can move out of the diverge segment, in other words the downstream capacity. This is achieved in the simulation by varying the geometry, traffic control, and driver behavior characteristics of the downstream segment. The picture of the diverge freeway segment considered is shown in Figure 4-31.

In order to generate the scenarios for a diverge segment the following values for each variable were chosen. The picture of the Diverge freeway segment considered is shown in Figure 4-31

A brief description of the variables considered to develop scenarios is given below.

Demand per lane: Number of vehicles attempting to enter the subject segment. If the demand exceeds capacity then a queue is formed upstream of the entrance of the subject segment. In this case the number of vehicles actually entering the segment could be lower than the demand. Eight different values of demand are used, ranging from 1000 veh/hr/ln to 9999 veh/hr/ln.

Downstream capacity: The maximum number of vehicles exiting from the downstream section. Although there is no standard procedure to design the downstream segment, so that it reaches a particular capacity, five different road configurations were developed such that the throughput varies uniformly over a large range of values.

FFS: The average speed on a section when there is very low demand. Four different speeds were tested; 55 mph, 60 mph, 65 mph, and 70 mph.

Off-Ramp exit %: The fraction of vehicles exiting to off ramp at the diverge point. In this study for diverge segment, three different values of off-ramp exit % are used: 100, 300, and 500 veh/hr/ln.

Number of lanes: The number of through lanes in each direction. This study tested 2 lane segments, 3 lane segments, and 4 lane segments.

Length of the entry segment: The length of freeway section located between the entry point of the merge segment to the beginning of the acceleration lane.

The complete set of values tested is in Table 4-9, and scenarios are developed for each combination of these for a diverge segment.

The complete set of values tested is shown in Table 4-9, and scenarios are developed for each combination of these for a diverge segment.

6,075 different scenarios were created for merge freeway segment. Each of these scenarios is simulated 10 times and the average travel time, density, and number of vehicles exiting the system are computed. The run time for simulating all of these 6,075 scenarios 10 times was about 150 hrs on a “2.39 Ghz core 2 duo” CPU with 3 GB memory.

Preliminary analysis was conducted to evaluate the impacts of each of these variables on the T.T. per mile. It was found that the impact of demand per lane is very significant when the downstream segment has reduced capacity. Figure 4-33 shows that the T.T. remains relatively constant until demand reaches downstream capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of downstream capacity on T.T., the downstream capacity is varied from no capacity reduction (2137 veh/hr/ln) to very low capacity (1323 veh/hr/ln). Figure 4-34 presents the relationship between downstream capacity and T.T. As shown in the previous figure, the T.T. plots consist of three parts. In the first part, when demand is lower than the downstream capacity, the relationship between T.T. and demand is relatively flat. In the second part, when

demand exceeds downstream segment, T.T. suddenly starts increasing linearly with demand. In the third and final part, when demand starts approaching 2250 veh/hr/ln, the linearly increasing T.T. curve flattens out and tends to a constant T.T.

As illustrated in Figure 4-34 the downstream capacity has a very significant impact on T.T. Because of the high impact of the reduced downstream capacity, the impact of the remaining variables on T.T. is presented in two cases; a) when there is no reduction in capacity of the downstream section and b) when there is reduction in capacity of the downstream section.

To find the impact of free-flow speed on T.T., the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. and demand for each of the free-flow speeds is observed. Figure 4-35 presents the relationship between T.T. and demand for different free-flow speeds when there is no downstream bottleneck. As shown there is significant difference in the T.T. per mile between each of the FFS. Therefore FFS is an important variable in the estimation of T.T. when there is no downstream bottleneck. As the speed increases, the T.T. per mile decreases. When there is no reduction in downstream segment capacity, with higher FFS the vehicles can travel faster and the T.T. decreases. The relationship between T.T. and demand is a set of parallel lines, one for each speed. The T.T. linearly increases, by a very minimal value, with increase in demand.

To find the impact of free-flow speed on T.T. when there is a downstream bottleneck, the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. per mile and demand is observed for each of these FFS. Figure 4-36 presents the relationship between T.T. and demand for different free-flow speeds when the downstream segment has reduced capacity equal to 1689 veh/hr/ln. As shown, the FFS increases, the difference in T.T. per mile between each of the FFS decreases until the demand reaches the downstream segment capacity. Once

demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free flow conditions. Thus there is no change in T.T. with increase in FFS. As shown in the Figure 4-36, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different free-flow speeds is presented in Figure 4-37. As shown, once demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free-flow conditions. In these cases there is no change in T.T. with increase in free-flow speed. As shown in the Figure 4-37, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T.

To find the impact of percentage of vehicles exiting through off ramp on T.T., the exit percentage is varied from 5 % to 20 % and the relationship between T.T. and demand for each of the exit percentages is observed. Figure 4-38 presents the relationship between T.T. and demand for different exit percentages when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the exit percentages. Therefore exit percentage is not an important variable in the estimation of T.T. when there is no downstream bottleneck. As shown in the Figure 4-38, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity.

To find the impact of percentage of vehicles exiting through off ramp on T.T. when there is a downstream bottleneck, the exit percentage is varied from 5 % to 20 % and the relationship between T.T. and demand for each of the exit percentages is observed. Figure 4-39 presents the

relationship between T.T. and demand for different exit percentages, when the downstream segment has reduced capacity equal to 1689 veh/hr/ln. As shown, as the exit percentage increases, the difference in T.T. per mile between each of the exit percentages decreases until the demand reaches the downstream segment capacity. As shown in the Figure 4-39, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different exit percentages is presented in Figure 4-40. As shown, there is no change in T.T. with increase in exit percentage. As shown in the Figure 4-40, once demand exceeds downstream capacity, T.T. curve flattens out to a maximum value of T.T.

To find the impact of length of entry segment on T.T., the length of entry segment is varied from 500 ft to 10,000 ft and the relationship between T.T. and demand for each of the length of entry segment is observed. Figure 4-41 presents the relationship between T.T. and demand for different lengths of entry segments when there is no downstream bottleneck. As shown there is no significant difference in the T.T. per mile between each of the length of entry segment. Therefore length of entry segment is not an important variable in the estimation of T.T. when there is no downstream bottleneck. The relationship between T.T. and demand is a set of parallel lines, one for each length of entry segment. The T.T. linearly increases, by a very minimal value, with increase in demand.

To find the impact of the length of the entry segment on T.T. when there is a downstream bottleneck, the length of the entry segment is varied from 500 ft to 10,000 ft and the relationship between T.T. per mile and demand is observed for each of these lengths of the entry segment. Figure 4-42 presents the relationship between T.T. and demand for different lengths of entry

segment when the downstream segment has reduced capacity equal to 1689 veh/hr/ln. As shown, there is significant difference in the T.T. per mile between each of the lengths of the entry segment. Therefore the length of the entry segment is an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-42, the T.T. per mile decreases with increasing length of the segment. When the segment is very long the queuing of vehicles is mostly concentrated at the downstream end of the segment, with the upstream part operating at free flow conditions. As the segment length increases, the section with free flow conditions increase, thus the average speed of the segment increases and in-turn the T.T. decreases as shown in Figure 4-42. As shown in the Figure 4-42, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different lengths of the entry segment is presented in Figure 4-43. As shown, there is significant difference in the T.T. per mile between each of the lengths of the entry segment. Therefore length of the entry segment is an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-43, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of number of lanes on T.T. when there is no downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of the number of lanes is observed. Figure 4-44 presents the relationship between T.T. and demand for different number of lanes when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the number of lane

configurations. Therefore number of lanes segment is not an important variable in the estimation of T.T. when there is no downstream bottleneck. As shown in the Figure 4-44, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity.

It should be noted that the demand here and everywhere else in the document refers to vehicles that are attempting to use the facility on a per lane basis. Thus, while testing the impact of number of lanes, demand refers to demand per lane and not the total demand.

To find the impact of number of lanes on T.T. when there is a downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of the number of lanes is observed. Figure 4-45 presents the relationship between T.T. and demand for different number of lanes when there is a downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the number of lane configurations. Therefore number of lanes segment is not an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-45, the T.T. remains relatively constant with increasing demand, when there is reduction in downstream capacity.

To find the impact of the number of vehicles in the is a downstream bottleneck on the T.T. of the downstream bottleneck, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-46, the T.T. per of the downstream bottleneck closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the downstream bottleneck is found to be an important variable in the estimation of T.T. within the downstream bottleneck when there is a downstream bottleneck. As shown in the Figure 4-46, once downstream bottleneck gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

To find the impact of the number of vehicles in the upstream segment on the T.T. of the upstream segment, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-47, the T.T. per of the upstream segment closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the upstream segment is found to be an important variable in the estimation of T.T. within the upstream segment when there is a upstream segment. As shown in the Figure 4-47, once upstream segment gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

Summary: Based on the investigation made from the plots (Figure 4-32 to Figure 4-47) describing the variation of T.T. with several factors, the following observations were made:

- 1) The variation of T.T. with demand has a step curve (Figure 4-33) as opposed to the popular exponentially increasing curve (as in BPR or MTC models). The step curve can be characterized by two points; (1) when demand equals downstream segment, until this point the T.T. remains relatively constant and after this point the T.T. suddenly starts to increase at an exponential rate (2) when the exponentially increasing T.T. suddenly starts to flatten and reaches a maximum T.T. Although the shape of the T.T. plot against demand is relatively similar when the demand is less than the capacity, the shape differs significantly in the congested region. While the traditional models predict exponentially increasing T.T.s once the demand exceeds capacity, the analysis conducted in this study suggests that the T.T. curve flattens after a particular point.
- 2) Capacity of the downstream segment plays a key role in the prediction of T.T. The variation of T.T. with demand varies significantly depending on whether the demand is greater than or less than the downstream capacity (Figure 4-34). Thus the impact of all other variables is broken-down into 3 cases: (1) when there is no downstream bottleneck (2) when there is a downstream bottleneck.
- 3) FFS shows up significant variation in T.T. when there is no reduction in capacity of the downstream segment (Figure 4-35). However if there is a downstream bottleneck, it is found that as the FFS increases, the T.T. per mile increases until the demand reaches downstream segment capacity, as shown in Figure 4-36 & Figure 4-37.
- 4) Off-ramp exit % shows up no significant variation in T.T. when there is no downstream bottleneck (Figure 4-38). Thus off-ramp exit % is not an important variable in the estimation of T.T. when there is no downstream bottleneck. However when there is a downstream bottleneck, it is observed that T.T. per mile at a given demand is different for different values of off-ramp exit %. Moreover it is also observed that this difference in T.T. (for different values of off-ramp exit %) keeps increasing with demand until the

demand reaches downstream capacity. Once the demand reaches the downstream capacity the difference in T.T. per mile (for different values of off-ramp exit %) starts to decrease until it reaches the capacity of the diverge segment and then remains fixed with demand. It is also observed that the T.T. per mile is higher for lower off-ramp exit %. When the downstream segment has full reduction in capacity, it is found that for a given off-ramp exit %, there is no change in T.T. per mile with main line demand, as shown in Figure 4-40. Moreover at any given main line demand value the value of T.T. per mile is lower for higher off-ramp exit %.

- 5) Length of the entry segment doesn't show up significant variation in T.T. when there is no downstream bottleneck (Figure 4-41). However if when there is a downstream bottleneck, it is found that the length of the entry segment is an important variable when the downstream segment has reduced capacity as shown in Figure 4-42 and Figure 4-43. It is observed from Figure 4-43 that the T.T. per mile decreases with increase in length of the segment. This phenomenon can be explained as follows: when the segment length is large the queuing of vehicles is mostly concentrated at the downstream end of the segment, leaving the upstream segment at free flow conditions. As the segment length increases, the section with free flow conditions increases, thus the average speed of the segment increases and in-turn the T.T. per mile decreases as shown in Figure 4-42.
- 6) The number of lanes shows no significant impact on T.T. independent of the downstream bottleneck (Figure 4-44, & Figure 4-45)

4.2.4 Weaving segment

The weaving segment network developed for testing consists of four freeway links and two ramp links. The first link is the entry link, that spans from the beginning of the weaving segment to the point where the ramp meets the freeway, as shown in Figure 4-47. The second link is the weaving section, where weaving takes place. The third link is immediately downstream of the weaving section till the exit point of the weaving segment. The fourth and final link is the downstream section, which starts from the exit point of weaving segment and extends for a fixed length (2000 ft). This downstream segment is used in this study to control the number of vehicles that can move out of the diverge segment, in other words the downstream capacity. This is achieved in the simulation by varying the geometry, traffic control, and driver behavior characteristics of the downstream segment.

A brief description of the variables considered to develop scenarios is given below.

Demand per lane: Number of vehicles attempting to enter the subject segment. If the demand exceeds capacity then a queue is formed upstream of the entrance of the subject segment. In this case the number of vehicles actually entering the segment could be lower than the demand. Eight different values of demand are used, ranging from 1000 veh/hr/ln to 9999 veh/hr/ln.

Downstream capacity: The maximum number of vehicles exiting from the downstream section. Although there is no standard procedure to design the downstream segment, so that it reaches a particular capacity, five different road configurations were developed such that the throughput varies uniformly over a large range of values.

FFS: The average speed on a section when there is very low demand. Four different speeds were tested; 55 mph, 60 mph, 65 mph, and 70 mph.

Off-Ramp exit %: The fraction of vehicles exiting to off ramp at the diverge point. In this study for diverge segment, three different values of off-ramp exit % are used: 100, 300, and 500 veh/hr/ln.

Number of lanes: The number of through lanes in each direction. This study tested 2 lane segments, 3 lane segments, and 4 lane segments.

Length of the entry segment: The length of freeway section located between the entry points of the merge segment to the beginning of the acceleration lane.

The complete set of values tested is in Table 4-11, and scenarios are developed for each combination of these for a weaving segment.

The complete set of values tested is shown in Table 4-11, and scenarios are developed for each combination of these for a weaving segment. In order to generate the scenarios for weaving

segment the following values for each variable were chosen. 30,375 different scenarios were created for weaving freeway segment. Each of these scenarios is simulated 10 times and the average travel time, density, and number of vehicles exiting the system are computed. The run time for simulating all of these 30,375 scenarios 10 times was about 400 hrs on a “2.39 Ghz core 2 duo” CPU with 3 GB memory.

Preliminary analysis was conducted to evaluate the impacts of each of these variables on the T.T. per mile. It was found that the impact of demand per lane is very significant when the downstream segment has reduced capacity. Figure 4-48 shows that the T.T. remains relatively constant until demand reaches downstream capacity. Once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of downstream capacity on T.T., the downstream capacity is varied from no capacity reduction (2209 veh/hr/ln) to very low capacity (1326 veh/hr/ln). Figure 4-49 presents the relationship between downstream capacity and T.T. As shown in the previous figure, the T.T. plots consist of three parts. In the first part, when demand is lower than the downstream capacity, the relationship between T.T. and demand is relatively flat. In the second part, when demand exceeds downstream segment, T.T. suddenly starts increasing linearly with demand. In the third and final part, when demand starts approaching 2250 veh/hr/ln, the linearly increasing T.T. curve flattens out and tends to a constant T.T.

As illustrated in Figure 4-49 the downstream capacity has a very significant impact on T.T. Because of the high impact of the reduced downstream capacity, the impact of the remaining variables on T.T. is presented in two cases; a) when there is no reduction in capacity of the downstream section and b) when there is reduction in capacity of the downstream section.

To find the impact of free-flow speed on T.T., the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. and demand for each of the free-flow speeds is observed. Figure 4-50 presents the relationship between T.T. and demand for different free-flow speeds when there is no downstream bottleneck. As shown there is significant difference in the T.T. per mile between each of the FFS. Therefore FFS is an important variable in the estimation of T.T. when there is no downstream bottleneck. As the speed increases, the T.T. per mile decreases. When there is no reduction in downstream segment capacity, with higher FFS the vehicles can travel faster and the T.T. decreases. The relationship between T.T. and demand is a set of parallel lines, one for each speed. The T.T. linearly increases, by a very minimal value, with increase in demand.

To find the impact of free-flow speed on T.T. when there is a downstream bottleneck, the free-flow speed is varied from 50 mph to 70 mph and the relationship between T.T. per mile and demand is observed for each of these FFS. Figure 4-51 presents the relationship between T.T. and demand for different free-flow speeds when the downstream segment has reduced capacity equal to 1696 veh/hr/ln. As shown, the FFS increases, the difference in T.T. per mile between each of the FFS decreases until the demand reaches the downstream segment capacity. Once demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free flow conditions. Thus there is no change in T.T. with increase in FFS. As shown in the Figure 4-51, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln)

The downstream capacity is further reduced to 1326 veh/hr/ln and the relationship between T.T. and demand for different free-flow speeds is presented in Figure 4-52. As shown, once

demand reaches downstream segment capacity, congestion starts to occur and vehicles can no longer travel at free-flow conditions. In these cases there is no change in T.T. with increase in free-flow speed. As shown in the Figure 4-52, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T.

To find the impact of percentage of vehicles exiting through off ramp on T.T., the exit percentage is varied from 5 % to 15 % and the relationship between T.T. and demand for each of the exit percentages is observed. Figure 4-53 presents the relationship between T.T. and demand for different exit percentages when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the exit percentages. Therefore exit percentage is not an important variable in the estimation of T.T. when there is no downstream bottleneck. As shown in the Figure 4-53, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity.

To find the impact of percentage of vehicles exiting through off ramp on T.T. when there is a downstream bottleneck, the exit percentage is varied from 5 % to 15 % and the relationship between T.T. and demand for each of the exit percentages is observed. Figure 4-54 presents the relationship between T.T. and demand for different exit percentages, when the downstream segment has reduced capacity equal to 1696 veh/hr/ln. As shown in Figure 4-54, there is no significant impact of exit percentage on travel time per mile until demand reaches downstream segment capacity. Once demand exceeds downstream segment capacity, exit percentage has significant impact on travel time per mile. As shown in Figure 4-54, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

The downstream capacity is further reduced to 1326 veh/hr/ln and the relationship between T.T. and demand for different exit percentages is presented in Figure 4-55. As shown in Figure 4-55, there is no significant impact of exit percentage on travel time per mile until demand reaches downstream segment capacity. Once demand exceeds downstream segment capacity, exit percentage has significant impact on travel time per mile. As shown in Figure 4-55, once demand exceeds downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of length of entry segment on T.T., the length of entry segment is varied from 500 ft to 10,000 ft and the relationship between T.T. and demand for each of the length of entry segment is observed. Figure 4-56 presents the relationship between T.T. and demand for different lengths of entry segments when there is no downstream bottleneck. As shown in Figure 4-56, there is no significant difference in the T.T. per mile between each of the length of entry segment. Therefore length of entry segment is not an important variable in the estimation of T.T. when there is no downstream bottleneck. The relationship between T.T. and demand is a set of parallel lines, one for each length of entry segment. The T.T. linearly increases, by a very minimal value, with increase in demand.

To find the impact of the length of the entry segment on T.T. when there is a downstream bottleneck, the length of the entry segment is varied from 500 ft to 10,000 ft and the relationship between T.T. per mile and demand is observed for each of these lengths of the entry segment. Figure 4-57 presents the relationship between T.T. and demand for different lengths of entry segment when the downstream segment has reduced capacity equal to 1696 veh/hr/ln. As shown in Figure 4-57, there is no significant impact of lengths of the entry segment on travel time per mile until demand reaches downstream segment capacity. Once demand exceeds downstream

segment capacity, length of the entry segment has significant impact on travel time per mile. Therefore the length of the entry segment is an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-57, the T.T. per mile decreases with increasing length of the segment. When the segment is very long the queuing of vehicles is mostly concentrated at the downstream end of the segment, with the upstream part operating at free flow conditions. As the segment length increases, the section with free flow conditions increase, thus the average speed of the segment increases and in-turn the T.T. decreases as shown in Figure 4-57. As shown in the Figure 4-57, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

The downstream capacity is further reduced to 1326 veh/hr/ln and the relationship between T.T. and demand for different lengths of the entry segment is presented in Figure 4-58. As shown, there is significant difference in the T.T. per mile between each of the lengths of the entry segment. Therefore length of the entry segment is an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-58, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of number of lanes on T.T. when there is no downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of the number of lanes is observed. Figure 4-59 presents the relationship between T.T. and demand for different number of lanes when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the number of lane configurations. Therefore number of lanes segment is not an important variable in the estimation

of T.T. when there is no downstream bottleneck. As shown in the Figure 4-59, the T.T. remains relatively constant with increasing demand, when there is no reduction in downstream capacity.

It should be noted that the demand here and everywhere else in the document refers to vehicles that are attempting to use the facility on a per lane basis. Thus, while testing the impact of number of lanes, demand refers to demand per lane and not the total demand.

To find the impact of number of lanes on T.T. when there is a downstream bottleneck, the number of lanes is varied from 2 lanes to 4 lanes and the relationship between T.T. and demand for each of the number of lanes is observed. Figure 4-60 presents the relationship between T.T. and demand for different number of lanes when there is a downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the number of lane configurations. Therefore number of lanes segment is not an important variable in the estimation of T.T. when there is a downstream bottleneck. As shown in the Figure 4-60, the T.T. remains relatively constant with increasing demand, when there is reduction in downstream capacity.

To find the impact of on-ramp demand on T.T., the length ramp-demand is varied from 100 veh/hr/ln to 500 veh/hr/ln and the relationship between T.T. and demand for each value of on-ramp demand is observed. Figure 4-61 presents the relationship between T.T. and demand for different on-ramp demand when there is no downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the on-ramp demands. Therefore on-ramp demand is not an important variable in the estimation of T.T. when there is no downstream bottleneck.

To find the impact of on-ramp demand on T.T. when there is a downstream bottleneck, the ramp-demand is varied from 100 veh/hr/ln to 500 veh/hr/ln and the relationship between T.T. and demand for each value of on-ramp demand is observed. Figure 4-62 presents the relationship

between T.T. and demand for different on-ramp demand when there is a downstream bottleneck. As shown, there is no significant difference in the T.T. per mile between each of the on-ramp demands. Therefore on-ramp demand is not an important variable in the estimation of T.T. when there is no downstream bottleneck.

The downstream capacity is further reduced to 1324 veh/hr/ln and the relationship between T.T. and demand for different on-ramp demands is presented in Figure 4-63. As shown, as the FFS increases, the difference in T.T. per mile between each of the on-ramp demand starts increasing after the demand reaches downstream segment capacity. As shown in the Figure 4-63, once demand reaches downstream capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T. (at approximately 2,000 veh/ln).

To find the impact of the number of vehicles in the is a downstream bottleneck on the T.T. of the downstream bottleneck, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-64, the T.T. per of the downstream bottleneck closely follows the trend of the number of vehicles in the downstream bottleneck. Therefore the number of vehicles in the downstream bottleneck is found to be an important variable in the estimation of T.T. within the downstream bottleneck when there is a downstream bottleneck. As shown in the Figure 4-64, once downstream bottleneck gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

To find the impact of the number of vehicles in the is a upstream segment on the T.T. of the upstream segment, a particular combination of demand and downstream segment capacity values are chosen such that a queue is formed after the simulation is run for a while. As shown in the Figure 4-65, the T.T. per of the upstream segment closely follows the trend of the number of

vehicles in the downstream bottleneck. Therefore the number of vehicles in the upstream segment is found to be an important variable in the estimation of T.T. within the upstream segment when there is a upstream segment. As shown in the Figure 4-65, once upstream segment gets saturated with traffic, T.T. starts to flatten out to a maximum value of T.T.

Summary: Based on the investigation made from the plots (Figure 4-48 to Figure 4-65) describing the variation of T.T. with several factors, the following observations were made:

- 1) The variation of T.T. with demand has a step curve (Figure 4-48) as opposed to the popular exponentially increasing curve (as in BPR or MTC models). The step curve can be characterized by two points; (1) when demand equals downstream segment, until this point the T.T. remains relatively constant and after this point the T.T. suddenly starts to increase at an exponential rate (2) when the exponentially increasing T.T. suddenly starts to flatten and reaches a maximum T.T. Although the shape of the T.T. plot against demand is relatively similar when the demand is less than the capacity, the shape differs significantly in the congested region. While the traditional models predict exponentially increasing T.T.s once the demand exceeds capacity, the analysis conducted in this study suggests that the T.T. curve flattens after a particular point.
- 2) Capacity of the downstream segment plays a key role in the prediction of T.T. The variation of T.T. with demand varies significantly depending on whether the demand is greater than or less than the downstream capacity (Figure 4-49). Thus the impact of all other variables is broken-down into 3 cases: (1) when there is no downstream bottleneck (2) when there is a downstream bottleneck.
- 3) FFS shows up significant variation in T.T. when there is no reduction in capacity of the downstream segment (Figure 4-50). However if there is a downstream bottleneck, it is found that as the FFS increases, the T.T. per mile increases until the demand reaches downstream segment capacity, as shown in Figure 4-51 and Figure 4-52.
- 4) Off-ramp exit % shows up no significant variation in T.T. when there is no downstream bottleneck (Figure 4-53). Thus off-ramp exit % is not an important variable in the estimation of T.T. when there is no downstream bottleneck. However when there is a downstream bottleneck, it is observed that T.T. per mile at a given demand is different for different values of off-ramp exit %. Moreover it is also observed that this difference in T.T. (for different values of off-ramp exit %) keeps increasing with demand until the demand reaches downstream capacity. Once the demand reaches the downstream capacity the difference in T.T. per mile (for different values of off-ramp exit %) starts to decrease until it reaches the capacity of the diverge segment and then remains fixed with demand. It is also observed that the T.T. per mile is higher for lower off-ramp exit %. When the downstream segment has full reduction in capacity, it is found that for a given off-ramp exit %, there is no change in T.T. per mile with main line demand, as shown in

Figure 4-54 and Figure 4-55. Moreover at any given main line demand value the value of T.T. per mile is lower for higher off-ramp exit %.

- 5) Length of the entry segment doesn't show up significant variation in T.T. when there is no downstream bottleneck (Figure 4-56). However if when there is a downstream bottleneck, it is found that the length of the entry segment is an important variable when the downstream segment has reduced capacity as shown in Figure 4-57 and Figure 4-58. It is observed from Figure 4-58 that the T.T. per mile decreases with increase in length of the segment. This phenomenon can be explained as follows: when the segment length is large the queuing of vehicles is mostly concentrated at the downstream end of the segment, leaving the upstream segment at free flow conditions. As the segment length increases, the section with free flow conditions increases, thus the average speed of the segment increases and in-turn the T.T. per mile decreases as shown in Figure 4-58.
- 6) The number of lanes shows no significant impact on T.T. independent of the downstream bottleneck (Figure 4-59, & Figure 4-60)

Table 4-1. Range of values for each variable that may affect T.T. along basic freeway segments

Variable	Minimum value	Maximum value
Number of Lanes	2	4
Demand/lane on Main line	1000	9999 (veh/hr)
Speed	55	70 (mph)
Length of Segment	5000 (ft)	25,000 (ft)
Capacity of Downstream Segment	No blockage	1 Lane blocked and 95% rubber necking factor for rest of the lanes

Table 4-2. Range of values for each variable that may affect T.T. along merge segment

Variable	Minimum value	Maximum value
Number of Lanes	2	5
Demand on Main line	1000	9999 (veh/hr)
Demand on Ramp	100	500 (veh/hr)
Speed	50	70 (mph)
Distance from link start to the On-ramp location	1500	3000
Capacity of Downstream Segment	No blockage	1 Lane blocked and 95% rubber necking factor for rest of the lanes

Table 4-3. Range of values for each variable that may affect T.T. along diverge segment

Variable	Minimum value	Maximum value
Number of Lanes	2	5
Demand on Main line	1000	9999 (veh/hr)
Speed	50	70 (mph)
Percent of vehicles passing through	80	100
Distance from link start to the On-ramp location	1500	3000
Distance between On-ramp and Off-ramp	200	2000 (ft)
Capacity of Downstream Segment	No blockage	1 Lane blocked and 95% rubber necking factor for rest of the lanes

Table 4-4. Range of values for each variable in weaving segment

Variable	Minimum value	Maximum value
Number of Lanes	2	4
Demand on Main line	1500	9999 (veh/hr)
Demand on Ramp	100	500 (veh/hr)
Speed	50	70 (mph)
Percent of vehicles passing through	80	100
Distance from link start to the On-ramp location	1500	3000
Length of weaving section	500	2500 (ft)
Capacity of Downstream Segment	No blockage	1 Lane blocked and 99% rubber necking factor for rest of the lanes

Table 4-5. Input values simulated for basic freeway segments

Demand per lane	Downstream capacity	FFS	Length of the segment	Number of lanes
1000	No Blockage	55	5000	2
1250	1 Lane Blocked	60	10000	3
1500	1 Lane Blocked and 90% rubber necking factor	65	15000	4
1750	1 Lane Blocked and 95% rubber necking factor	70	20000	
2000	FFS of 25 mph		25000	
2250	FFS of 15 mph			
2500				
9999				
8 values	5 values	4 values	5 values	3 values
# Scenarios = $8*5*4*5*3 = 2400$ scenarios				

Table 4-6. Impact of study variables on T.T. of BFS

Variable	Unrestricted downstream segment capacity	Restricted downstream segment capacity
FFS	Significant	Not significant
length of BFS	Not significant	Significant
# Lanes	Not significant	Not significant
Demand	Significant	Significant
Downstream Capacity	N/A	N/A

Table 4-7. Input values simulated for a merge segment

Freeway demand per lane	Downstream Capacity	Demand per lane (Ramp)	FFS	# Lanes	Length of the entry section
1000	No Blockage	100	50	2	500
1200	1 Lane Blocked	300	60	3	1000
1400	1 Lane Blocked and 90% rubber necking factor	500	70	4	1500
1500	FFS of 20 mph				2500
1600	FFS of 10 mph				5000
1800					
2000					
2500					
3000					
9 values	5 values	3 values	3 values	3 values	5 values
Scenarios = $9*5*3*3*3*5 = 6075$ scenarios					

Table 4-8. Impact of study variables on T.T. of merge segment

Variable	Unrestricted downstream segment capacity	Restricted downstream segment capacity
Demand per lane (Ramp)	Not significant	Significant
FFS	Significant	Not significant
# Lanes	Not significant	Not significant
Length of the entry section	Not significant	Significant
Demand	Significant	Significant
Downstream Capacity	N/A	N/A

Table 4-9. Input values simulated for a diverge segment

Demand per Lane (main line) (veh/hr/ln)	Downstream Capacity (veh/hr/ln)	Speed (mph)	Off-ramp Exit %	# Lanes	Length of Entry Segment (ft)
1000	No Blockage	50	5	2	500
1200	1 Lane Blocked	60	10	3	1,000
1400	1 Lane Blocked and 90% rubber necking factor	70	20	4	1,500
1500	FFS of 25 mph				2,500
1600	FFS of 15 mph				5,000
1800					
2000					
2500					
3000					
9 values	5 values	3 values	3 values	3 values	5 values
# Scenarios = $9*5*3*3*3*5 = 6,075$ scenarios					

Table 4-10. Impact of study variables on T.T. of diverge segment

Variable	Unrestricted downstream segment capacity	Restricted downstream segment capacity
FFS	Significant	Not significant
Off-ramp Exit %	Not significant	Significant
# Lanes	Not significant	Not significant
Length of Entry Segment (ft)	Not significant	Significant
Demand	Significant	Significant
Downstream Capacity	N/A	N/A

Table 4-11. Variable values for weaving segment

Demand/Lane (main line)	Demand (Ramp)	Off Ramp Demand	Length of weaving section	Speed	# Lanes	Length of entry segment
1000	100	85	1000	50	2	500
1200	300	90	1500	60	3	1000
1400	500	95	2000	70	4	1500
1500	750		2500			2500
1600	1000		3000			5000
1800						
2000						
2500						
3000						
9 values	5 values	3 values	5 values	3 values	3 values	5 values
Total Scenarios = $9*5*3*5*3*3*5 = 30,375$ scenarios						

Table 4-12. Impact of study variables on T.T. of weaving segment

Variable	Unrestricted downstream segment capacity	Restricted downstream segment capacity
FFS	Significant	Not significant
Off-ramp Demand	Not significant	Significant
On-ramp Demand	Not significant	Significant
# Lanes	Not significant	Not significant
Length of Entry Segment (ft)	Not significant	Significant
Demand	Significant	Significant
Downstream Capacity	N/A	N/A

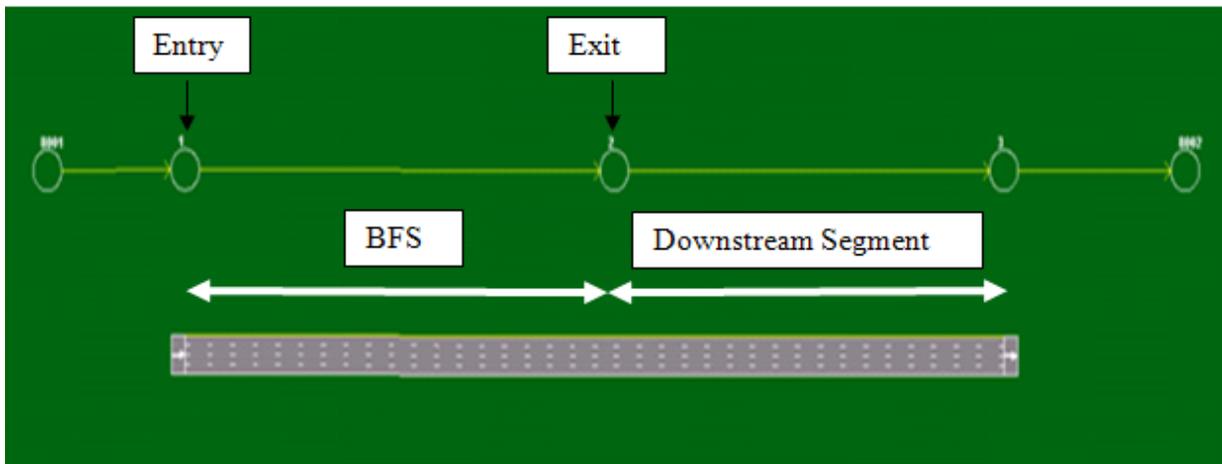


Figure 4-1. Picture of a basic freeway segment.

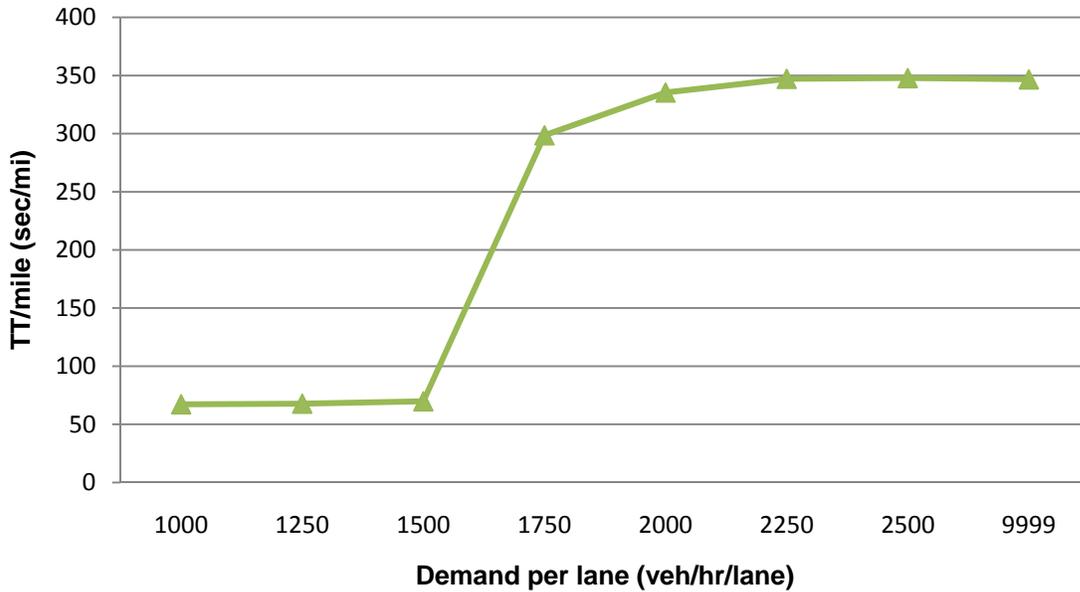


Figure 4-2. Variation of TT per mile with demand (lanes = 2, FFS = 50 mph, length of basic freeway segment = 5000 ft, and downstream capacity = 1515 veh/hr/lane)

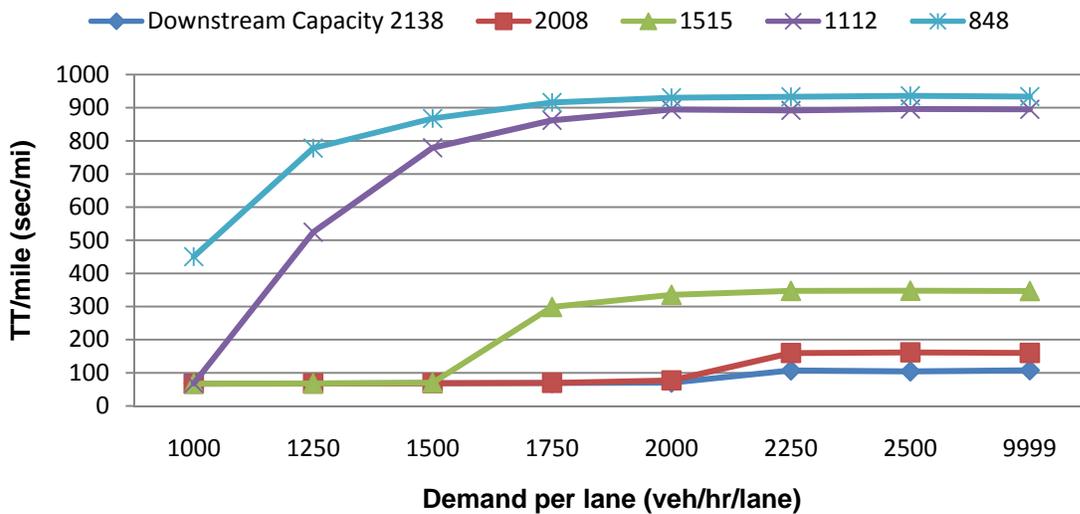


Figure 4-3. Variation of TT per mile with demand for various values of downstream capacity (lanes = 2, length of basic freeway segment = 5000 ft and FFS is 55 mph)

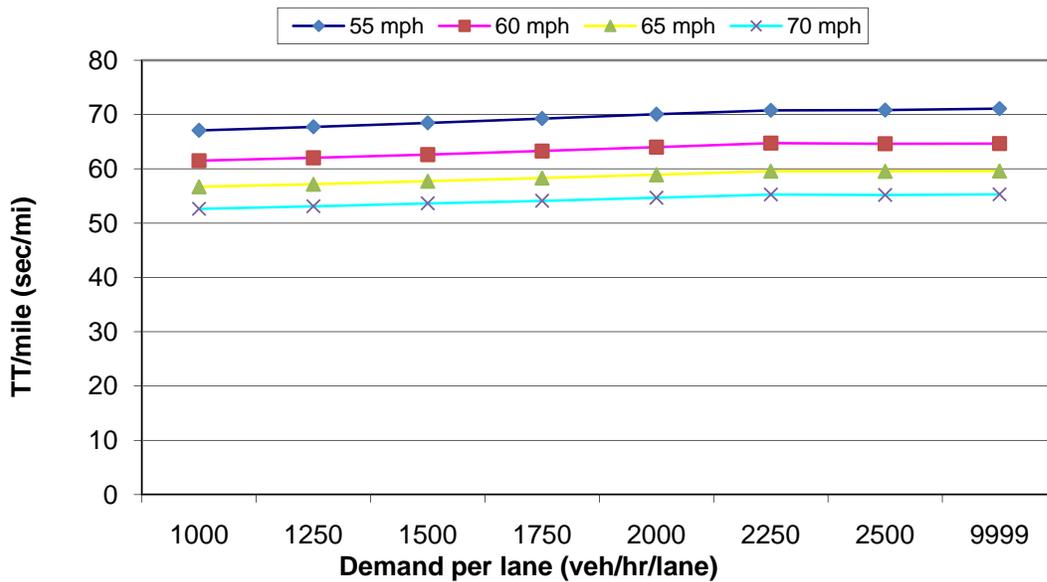


Figure 4-4. Variation of TT per mile with demand for different values of speed (Lanes = 2, length of basic freeway Segment = 5000 ft, and downstream capacity = 2250 veh/hr/lane)

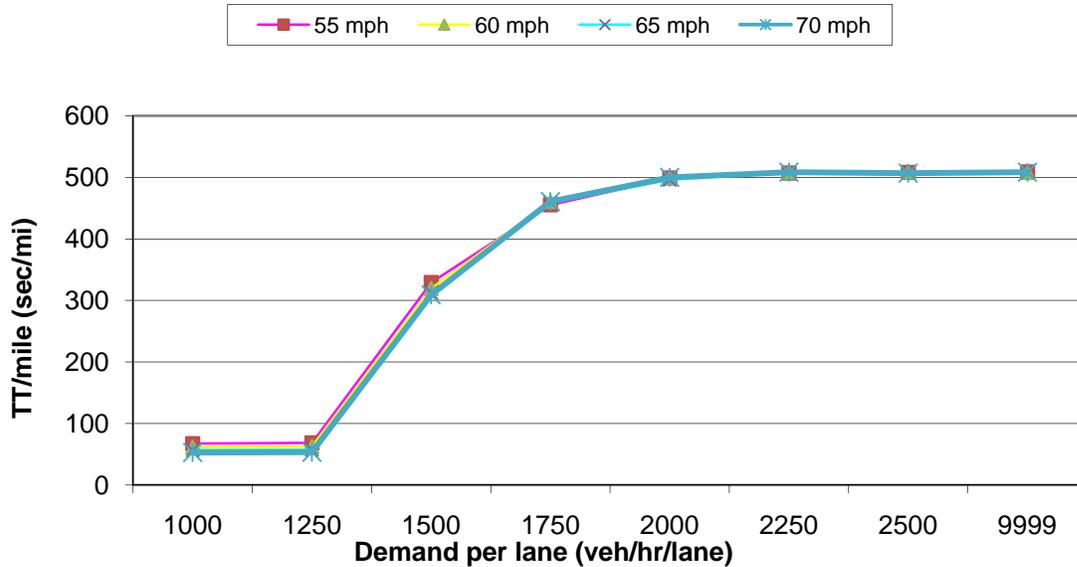


Figure 4-5. Variation of TT per mile with different values of speed (lanes = 2, length of basic freeway segment = 5000 ft and downstream capacity = 1324 veh/hr/lane)

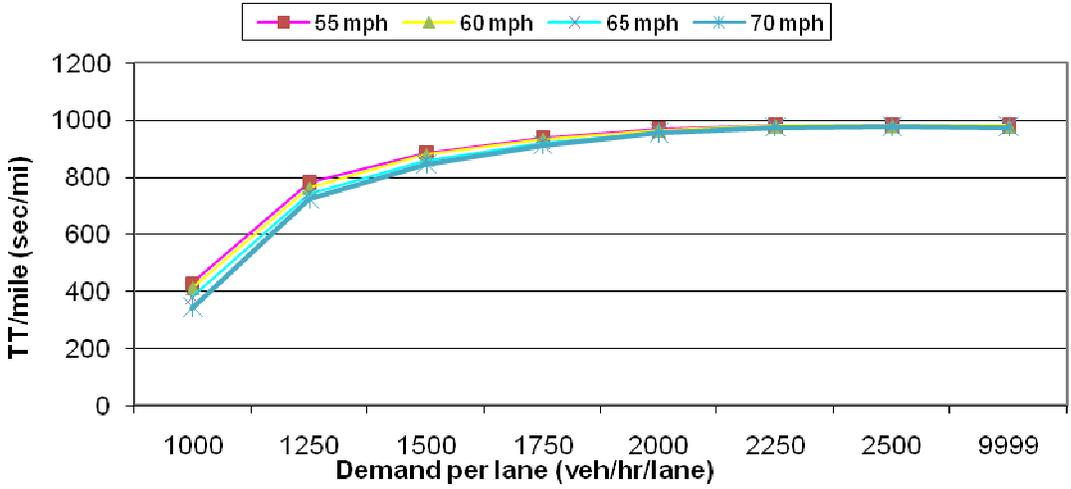


Figure 4-6. Variation of TT per mile with different values of speed (lanes = 2, length of basic freeway segment = 5000 ft and downstream capacity = 849 veh/hr/lane)

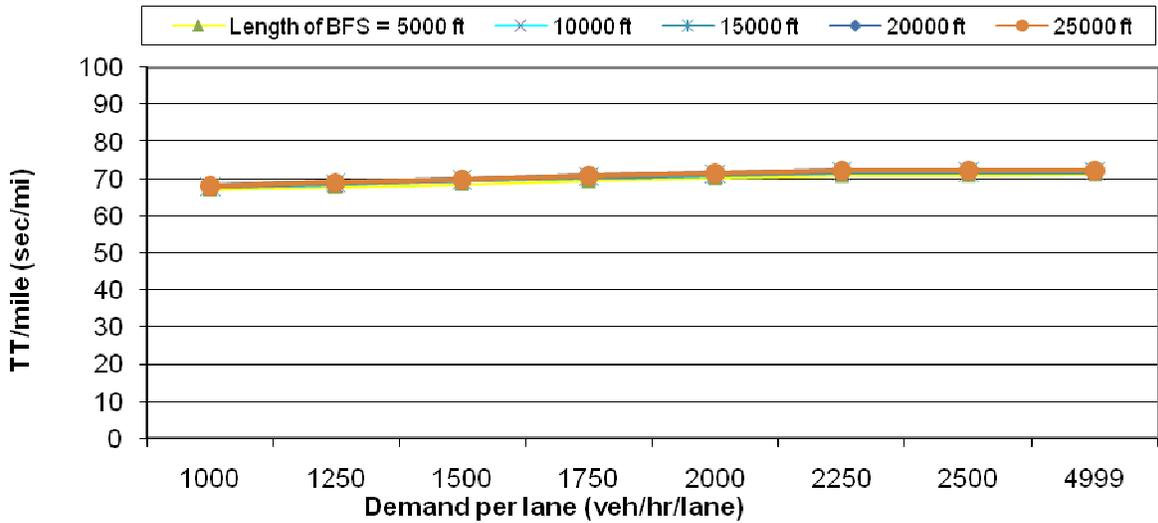


Figure 4-7. Variation of TT per mile with demand for different lengths of the BFS (lanes = 2, length of basic freeway segment = 5000 ft and downstream capacity = 2250 veh/hr/lane)

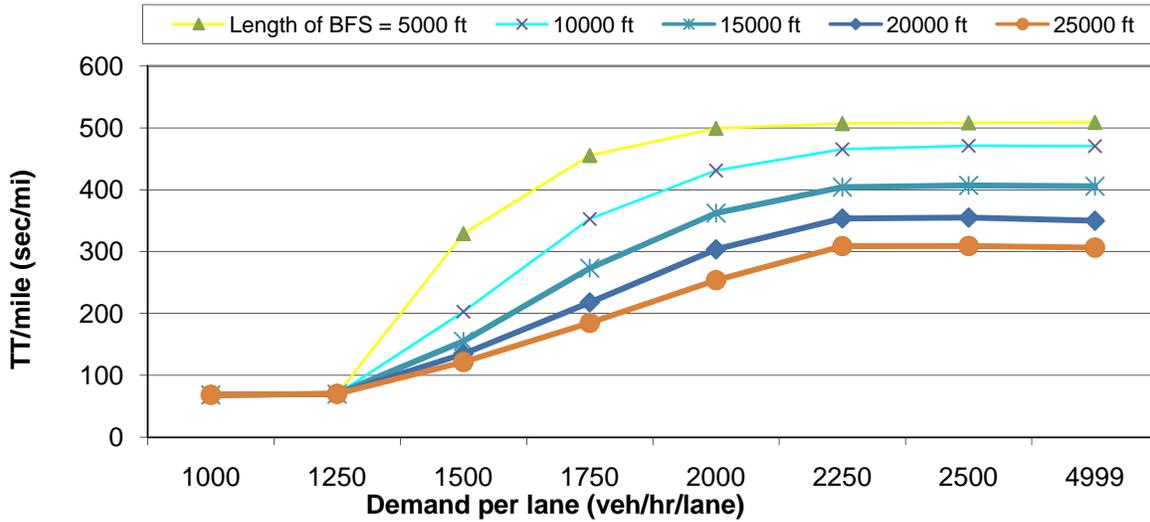


Figure 4-8. Variation of TT per mile with demand for different lengths of the BFS (lanes = 2, FFS = 55 mph, and downstream capacity = 1324 veh/hr/lane)

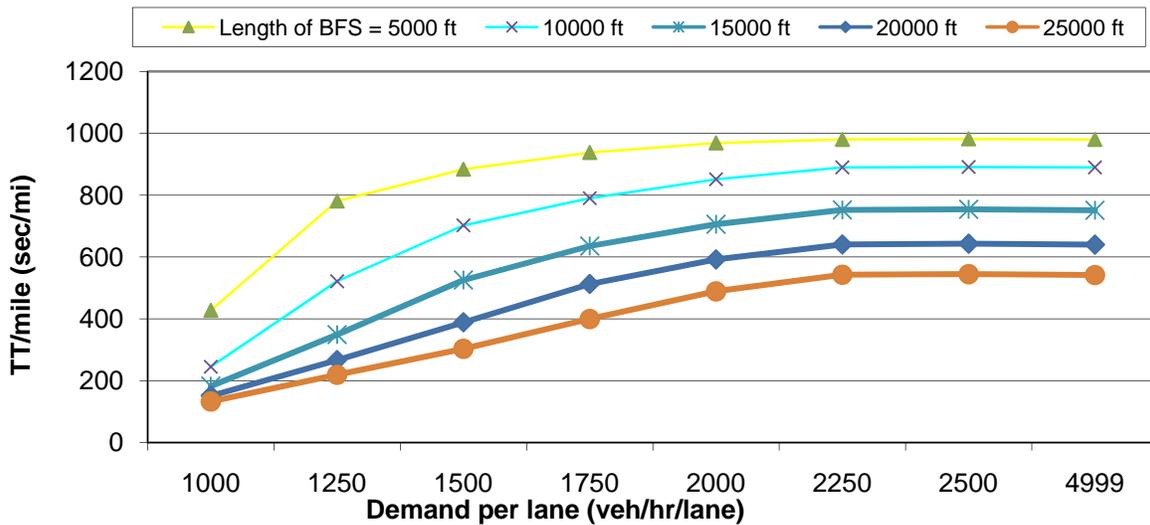


Figure 4-9. Variation of TT per mile with demand for various lengths of the BFS (lanes = 2, FFS = 55 mph, and downstream capacity = 849 veh/hr/lane)

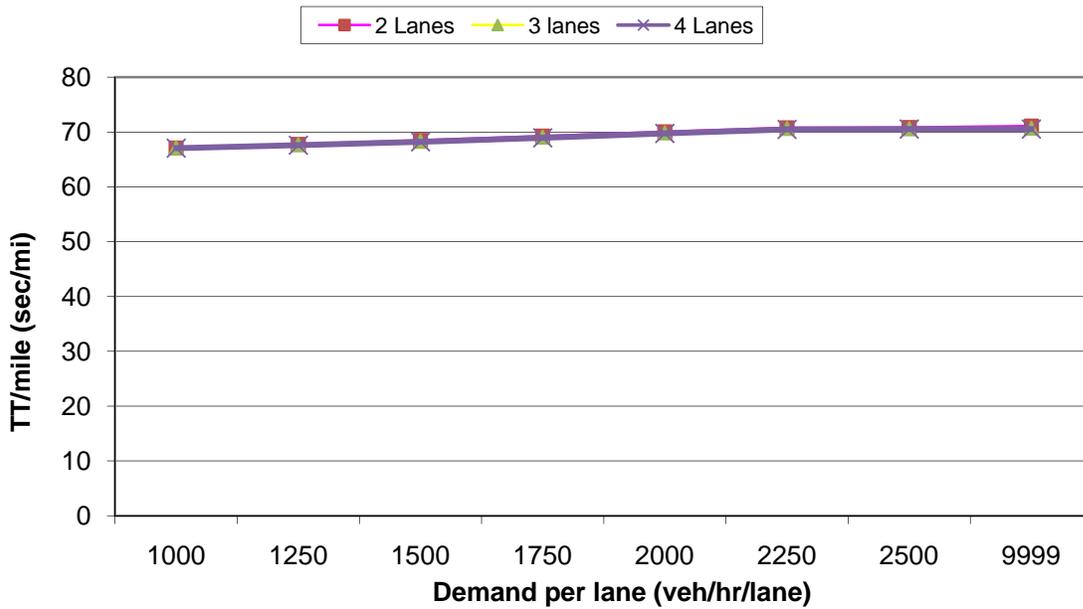


Figure 4-10. Variation of TT per mile with demand for various values of number of lanes of the BFS (FFS = 55 mph, length of basic freeway segment = 5000 ft and downstream capacity = 2250 veh/hr/lane)

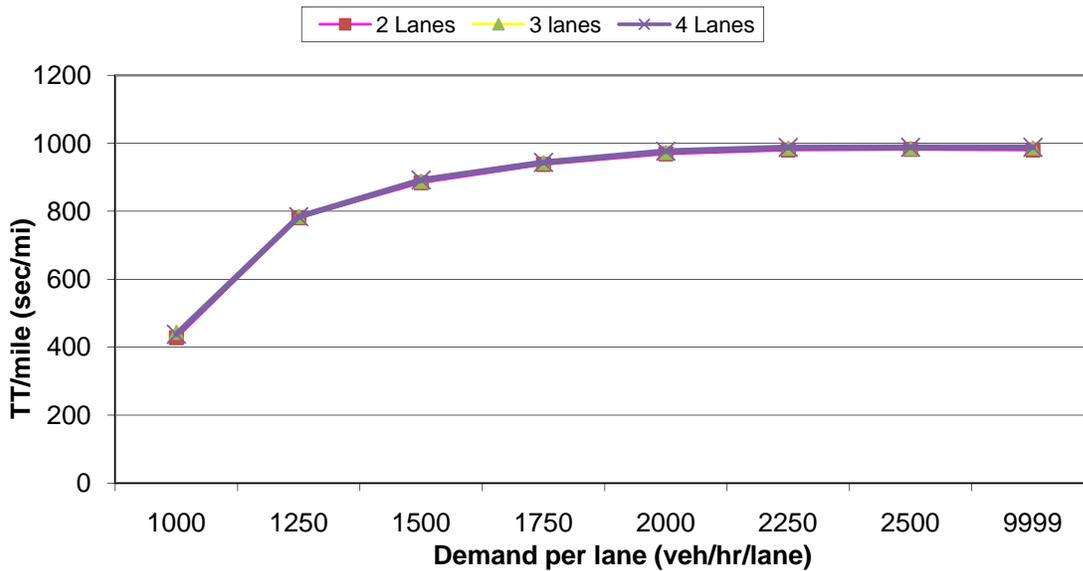


Figure 4-11. Variation of TT per mile with demand for various values of number of lanes of the BFS (FFS = 55 mph, length of basic freeway segment = 5000 ft and downstream capacity = 850 veh/hr/ane)

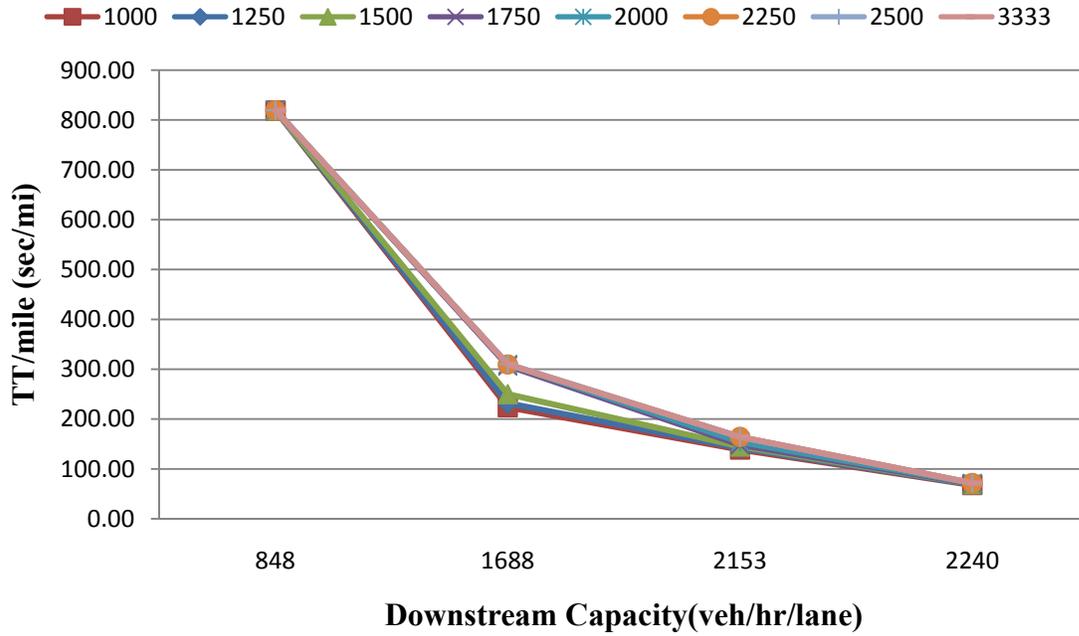


Figure 4-12. Variation of TT per mile with demand for the downstream segment with (number of lanes = 2, FFS = 55 mph)

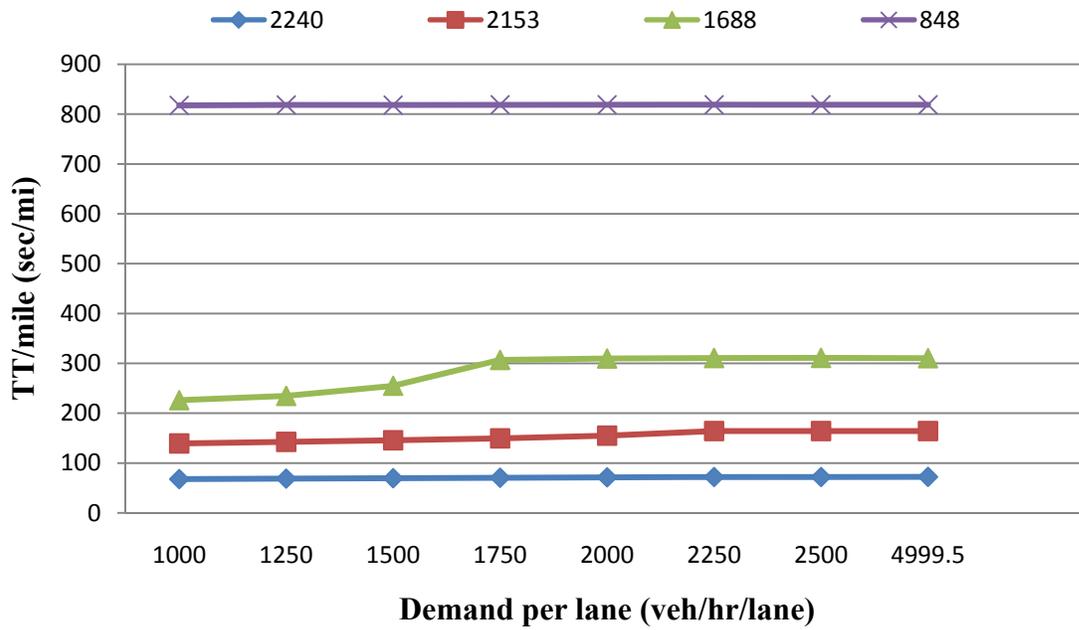


Figure 4-13. Variation of TT per mile with demand for the downstream segment with (number of lanes = 2, FFS = 55 mph)

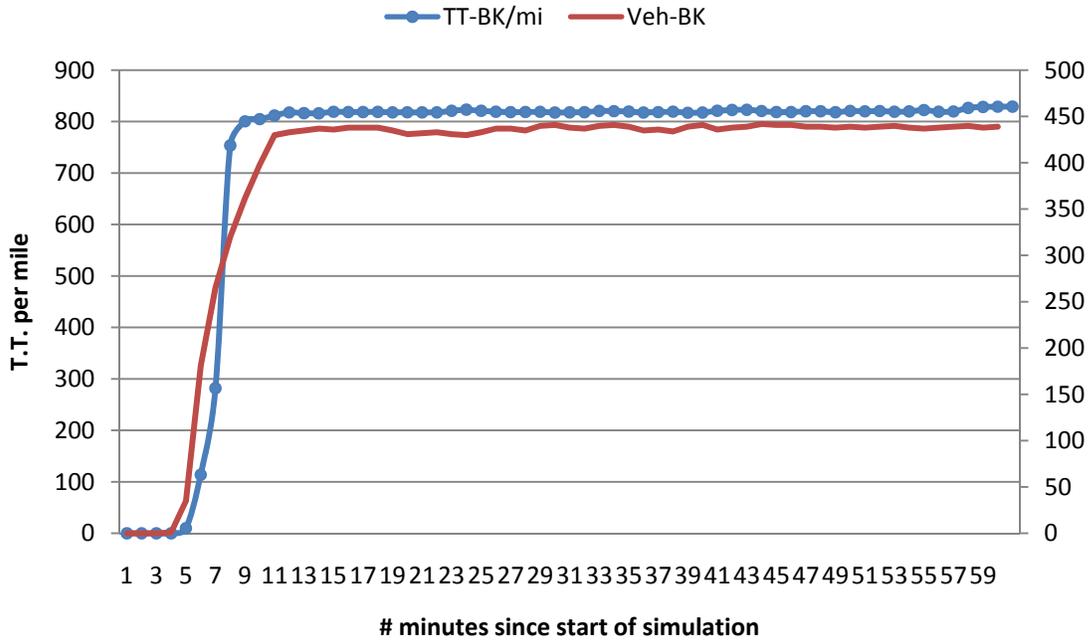


Figure 4-14. Time series plot between TT per mile of the downstream bottleneck and the number of vehicles in the downstream bottleneck

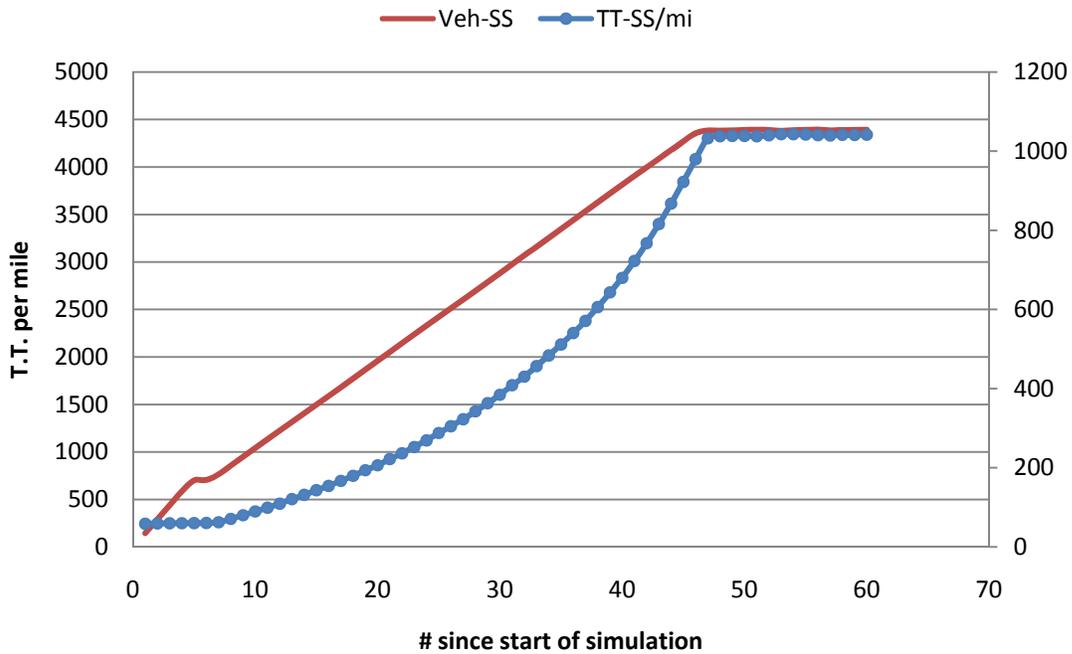


Figure 4-15. Time series plot between TT per mile of the upstream segment and the number of vehicles in the upstream segment

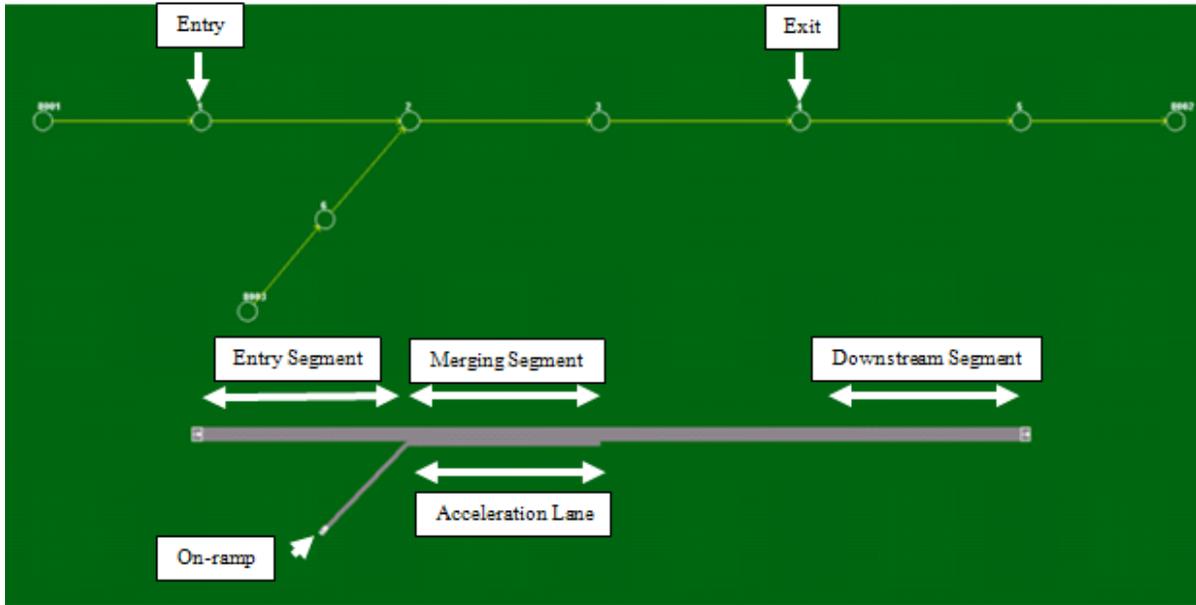


Figure 4-16. Sketch of a merge freeway segment.

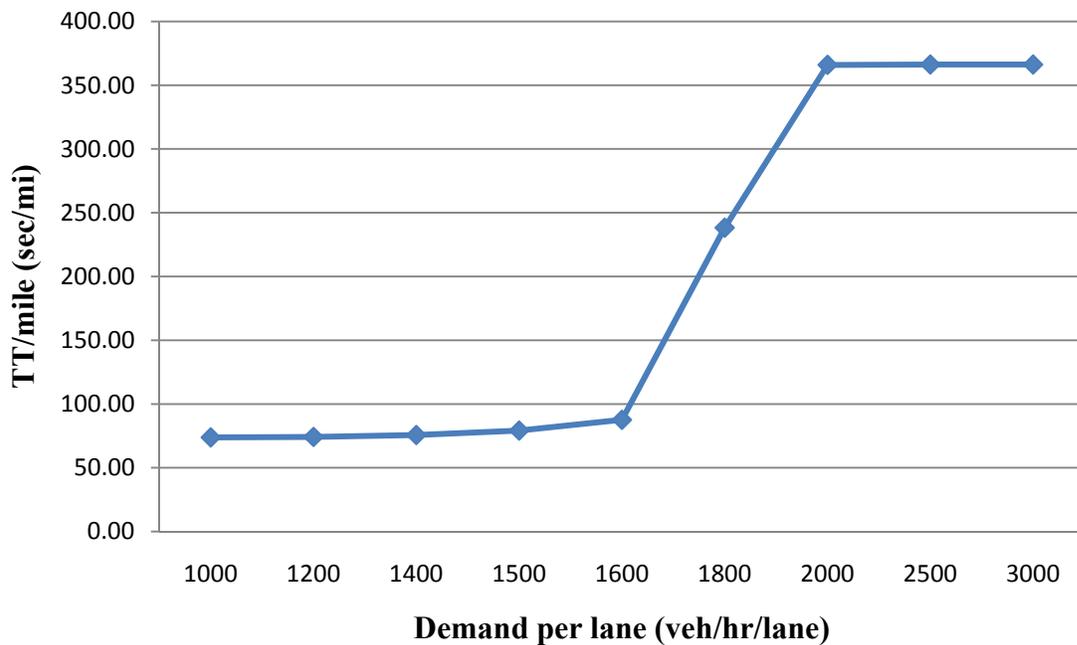


Figure 4-17. Variation of TT per mile with demand (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, ramp demand = 100 veh/hr/ln, and downstream capacity = 1689 veh/hr/lane)

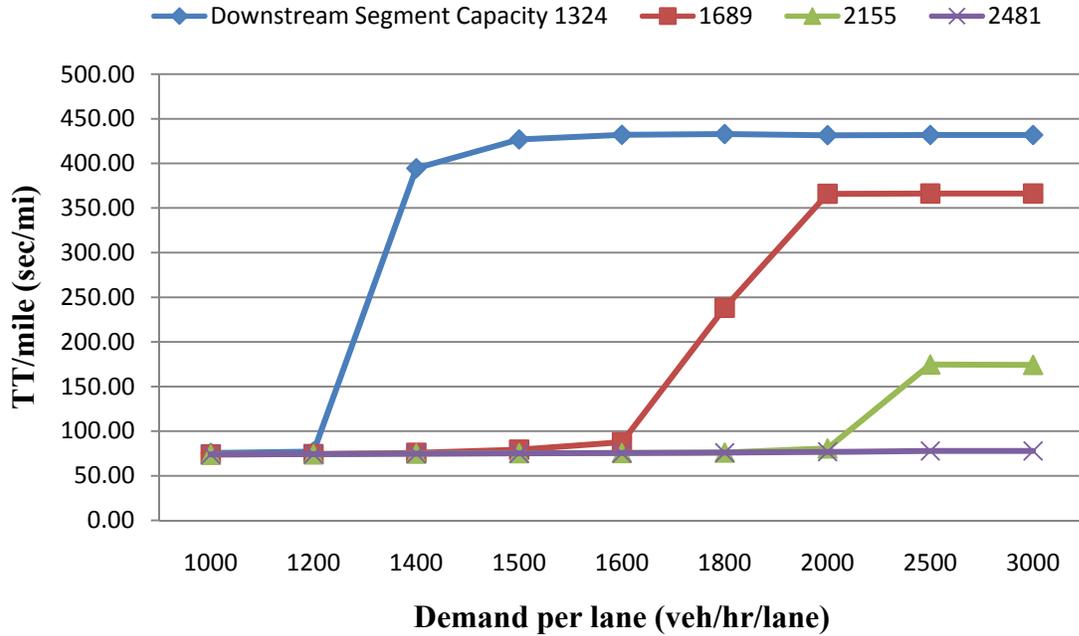


Figure 4-18. Variation of TT per mile with demand (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp demand = 100 veh/hr/ln)

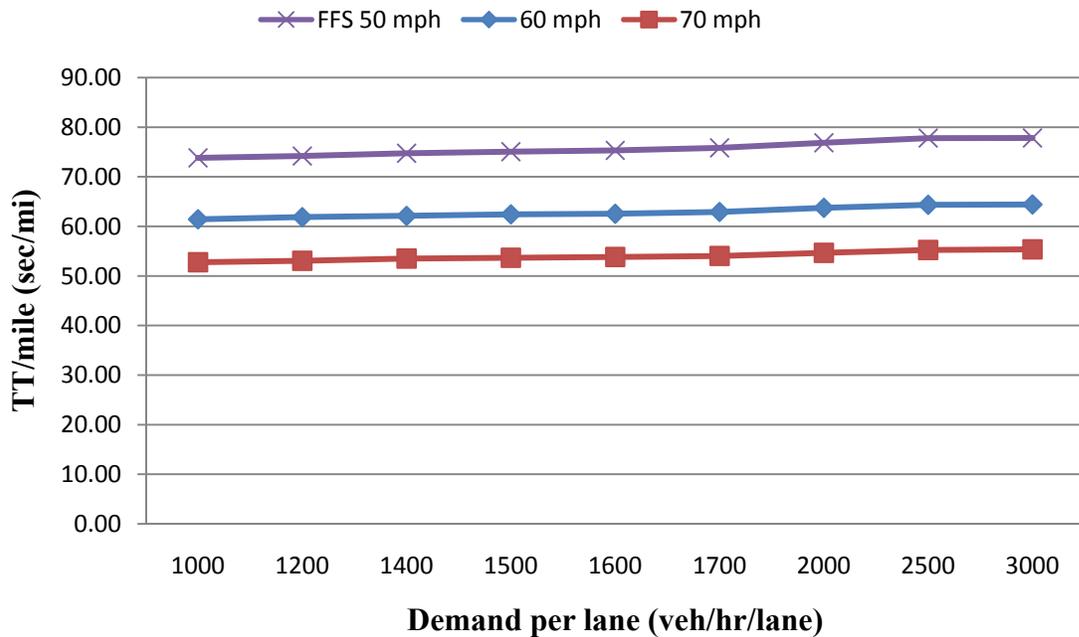


Figure 4-19. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp demand = 100 veh/hr/ln, and downstream capacity = 2400 veh/hr/lane)

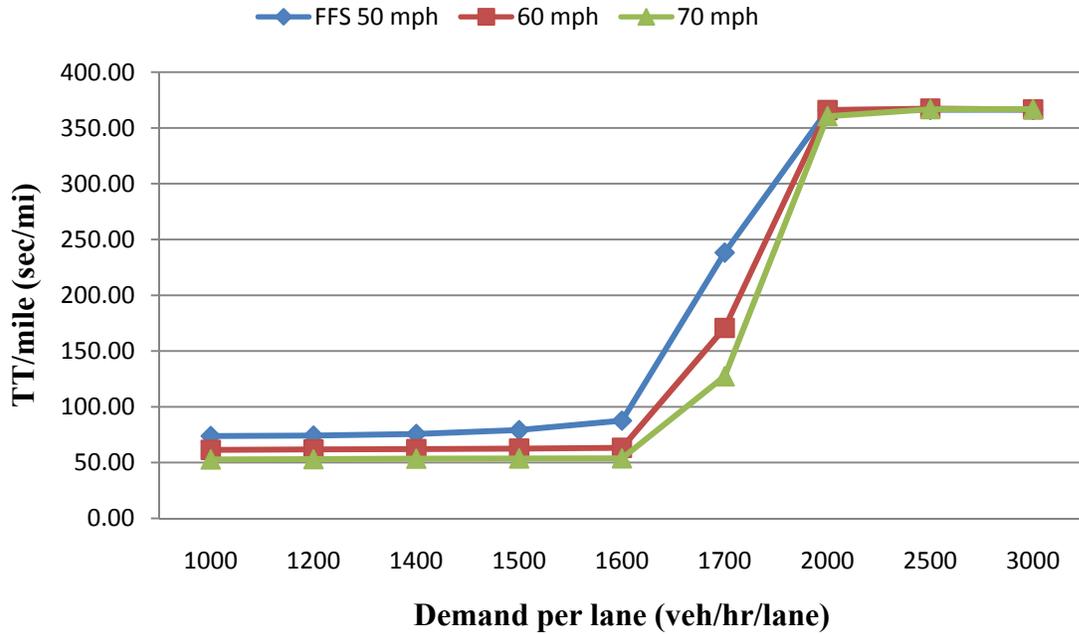


Figure 4-20. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp demand = 100 veh/hr/ln, and downstream capacity = 1689 veh/hr/lane)

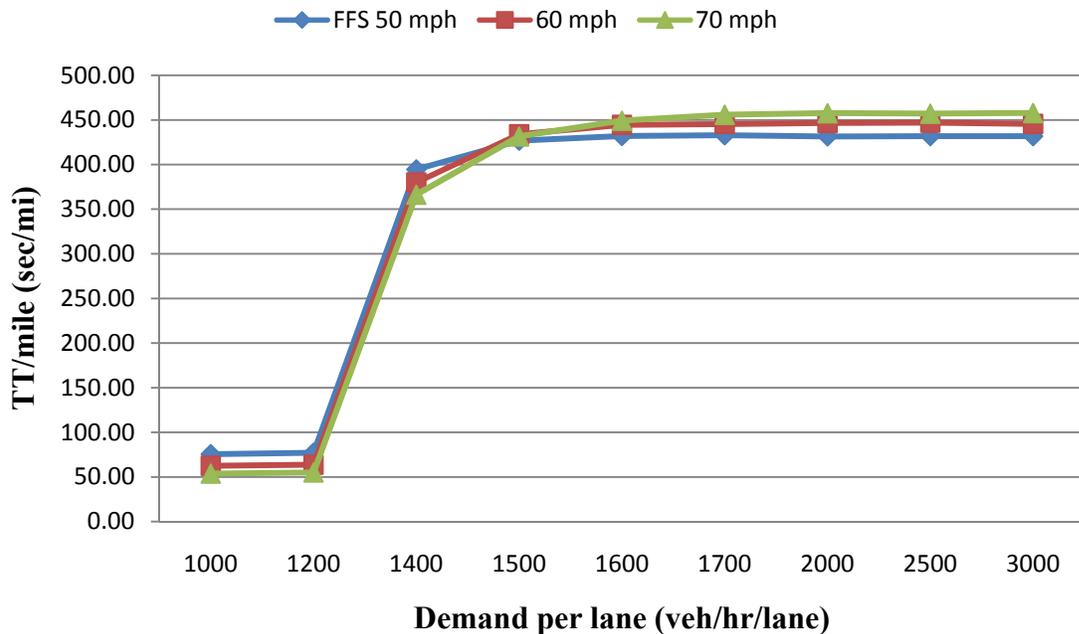


Figure 4-21. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp demand = 100 veh/hr/ln, and downstream capacity = 1324 veh/hr/ln)

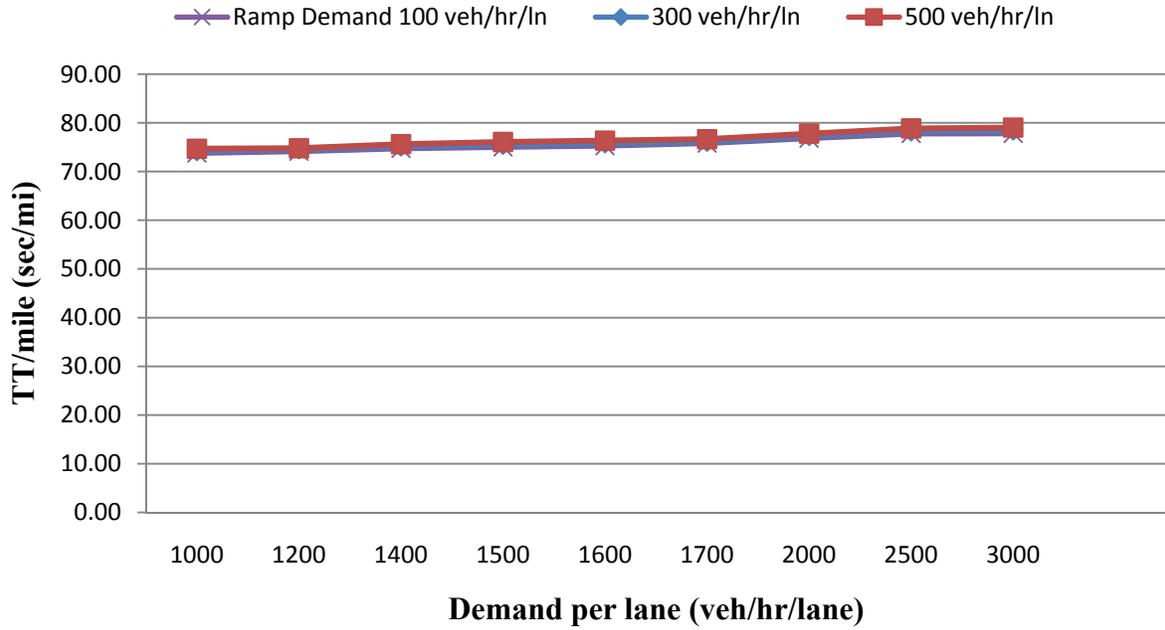


Figure 4-22. Variation of TT per mile with demand for different values of ramp demand (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 2491 veh/hr/lane)

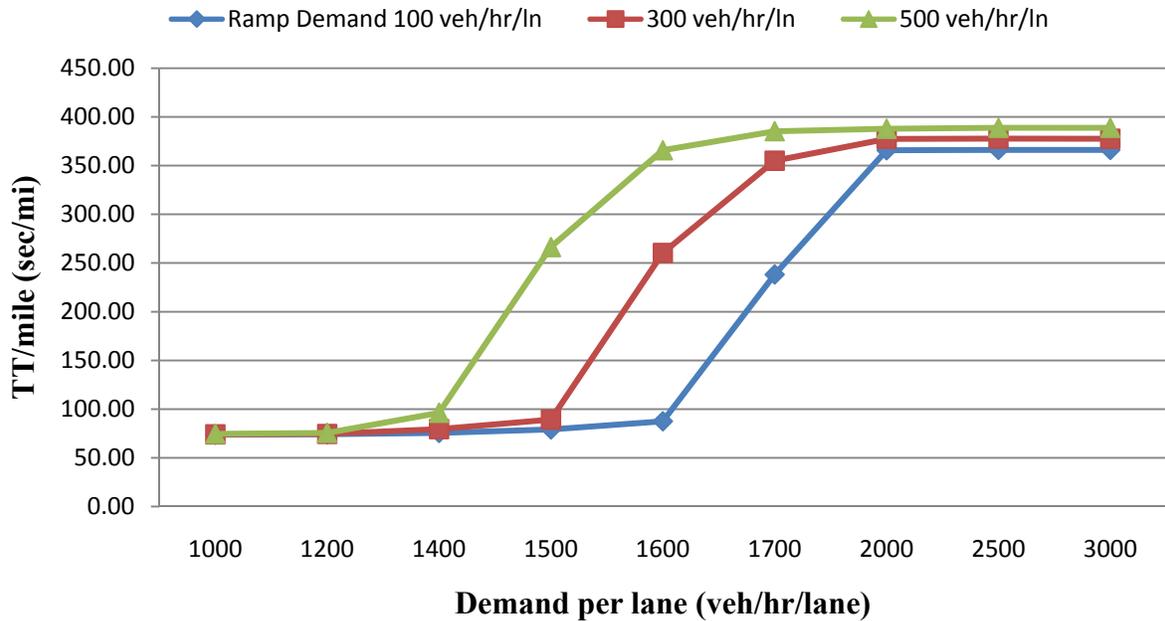


Figure 4-23. Variation of TT per mile with demand for different values of ramp demand (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1689 veh/hr/lane)

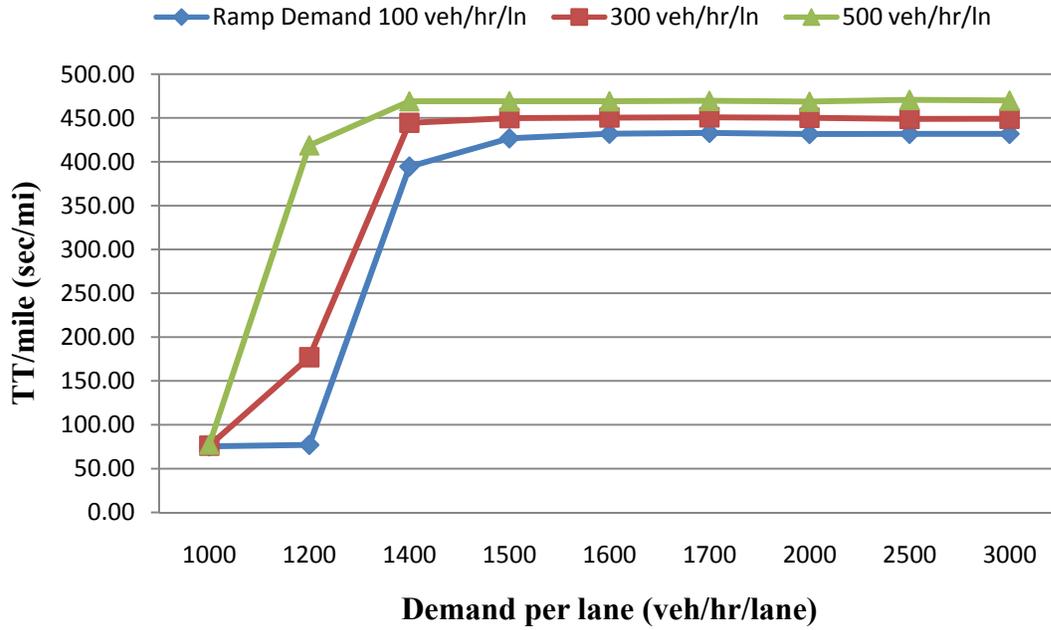


Figure 4-24. Variation of TT per mile with demand for different values of ramp demand (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1324 veh/hr/lane)

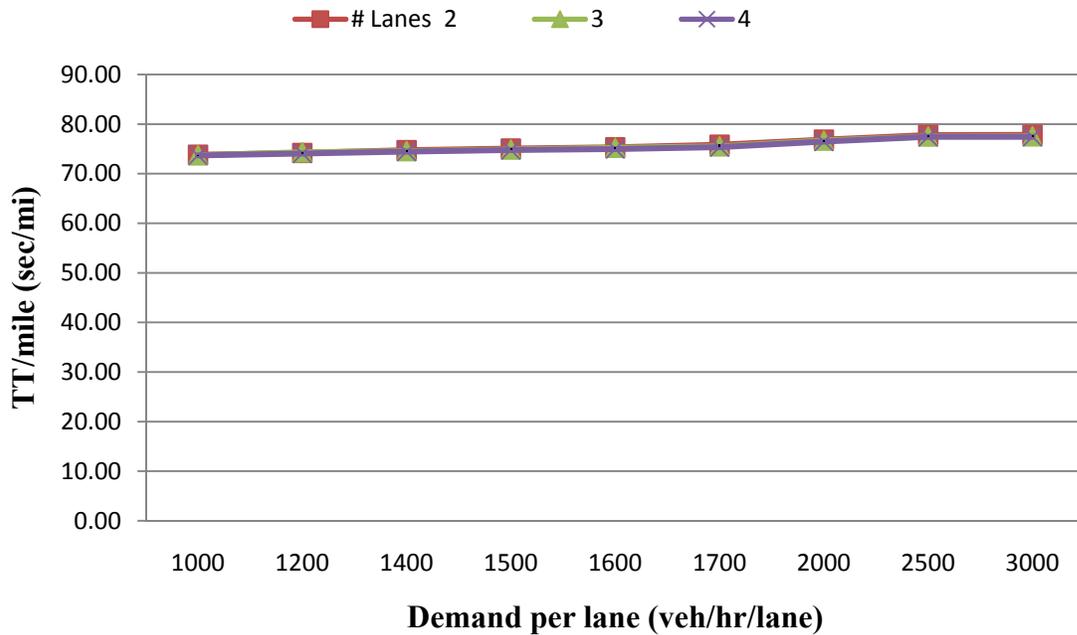


Figure 4-25. Variation of TT per mile with demand for different values of # lanes (length of entry section = 500 ft, and FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 2400 veh/hr/lane)

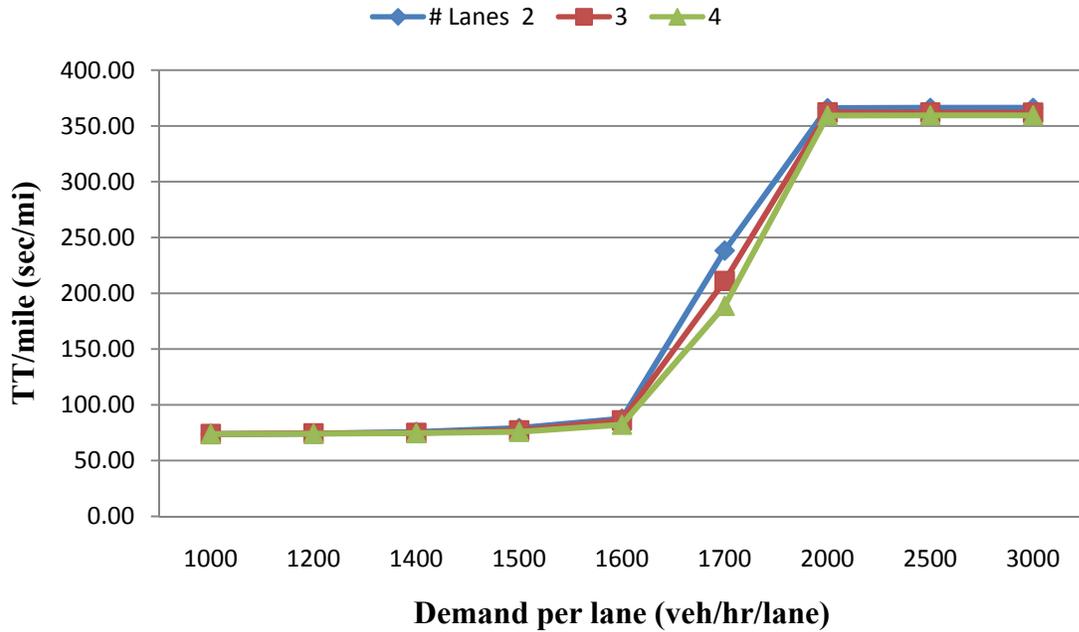


Figure 4-26. Variation of TT per mile with demand for different values of # lanes (length of entry section = 500 ft, and FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1685 veh/hr/lane)

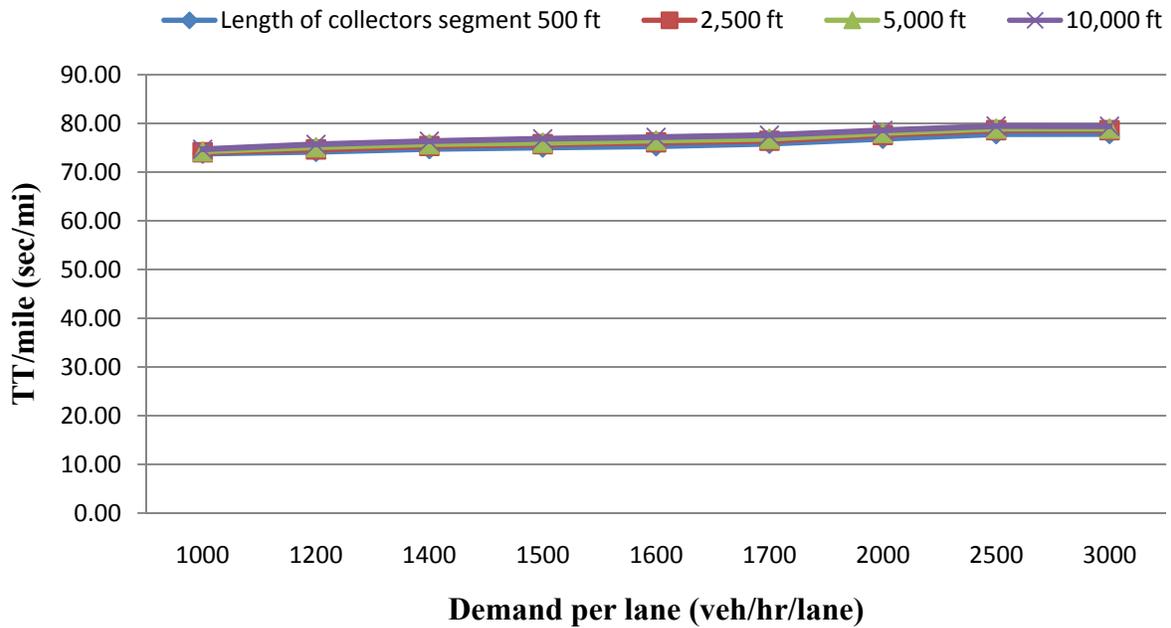


Figure 4-27. Variation of TT per mile with demand for different values of length of entry section (# Lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 2400 veh/hr/lane)

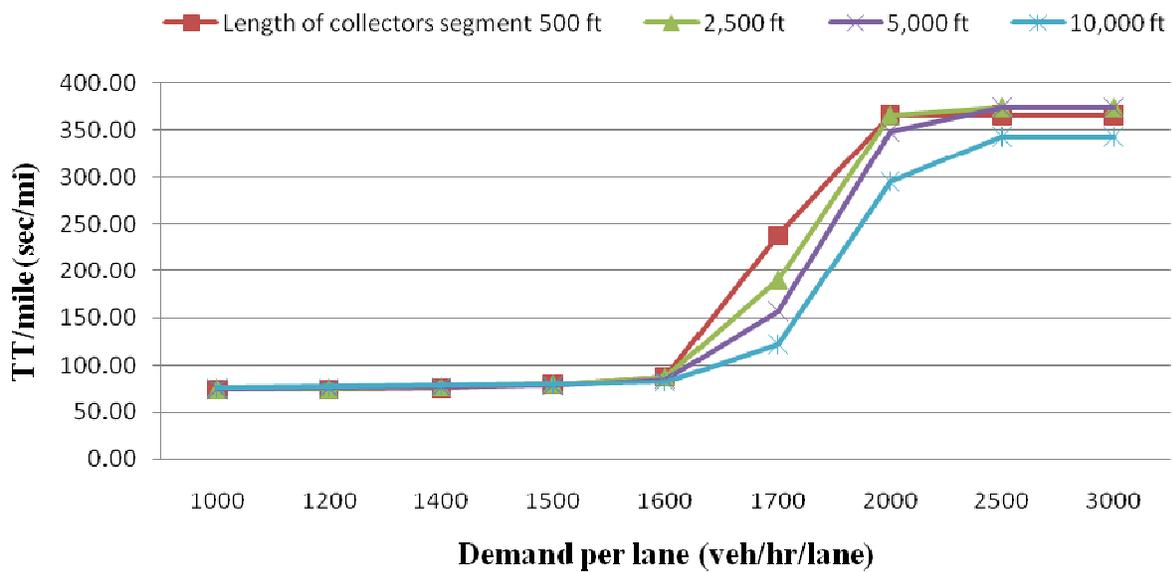


Figure 4-28. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1689 veh/hr/lane)

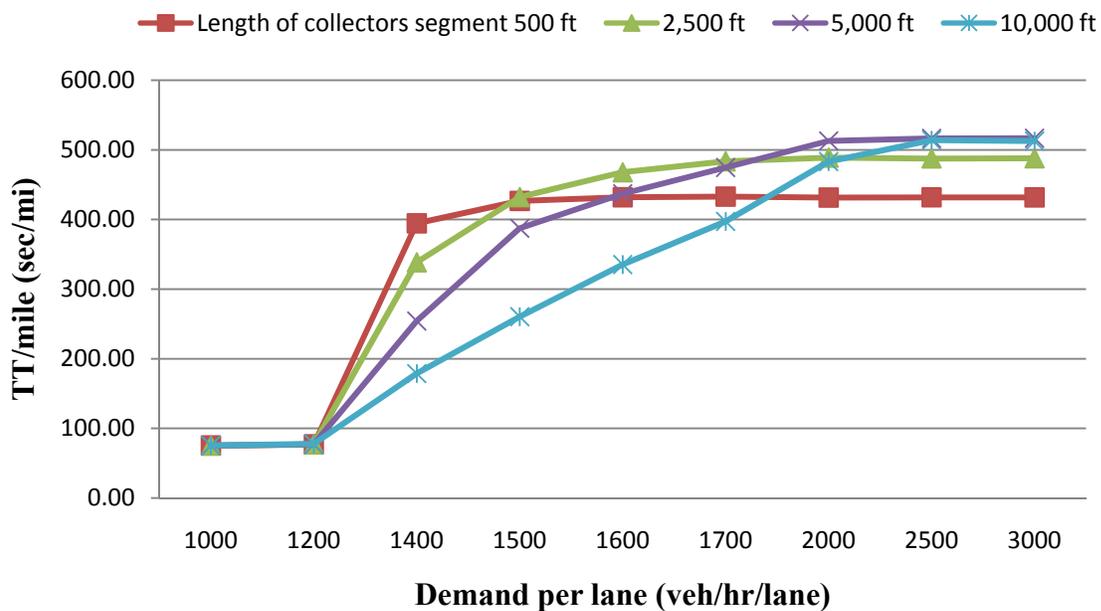


Figure 4-29. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1324 veh/hr/lane)

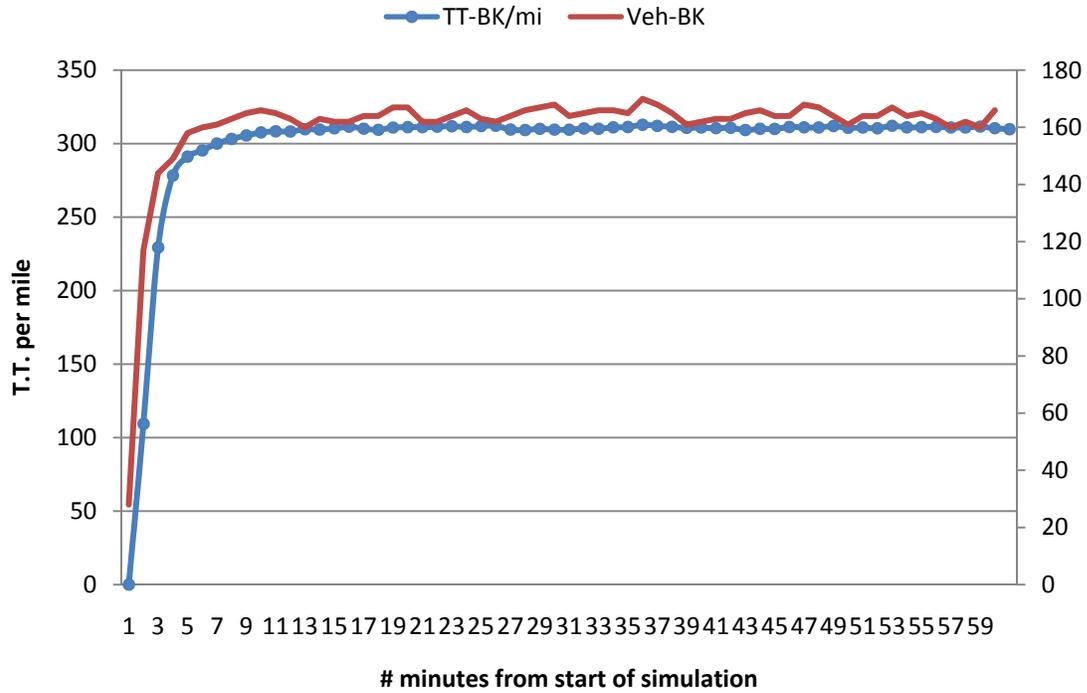


Figure 4-30. Time series plot between TT per mile of the downstream bottleneck and the number of vehicles in the downstream bottleneck

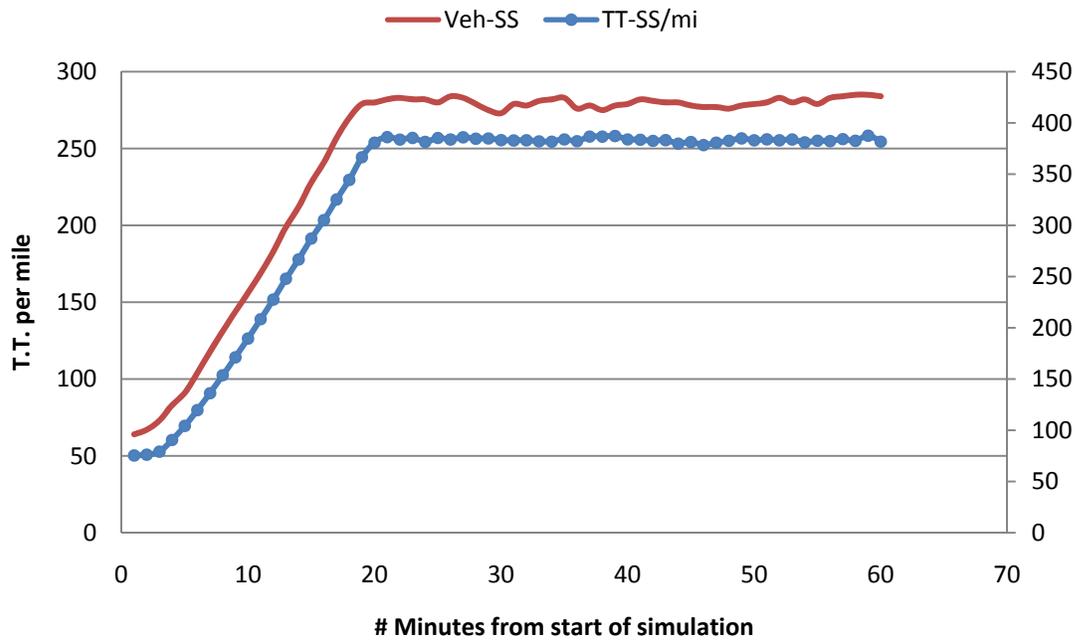


Figure 4-31. Time series plot between TT per mile of the upstream segment and the number of vehicles in the upstream segment

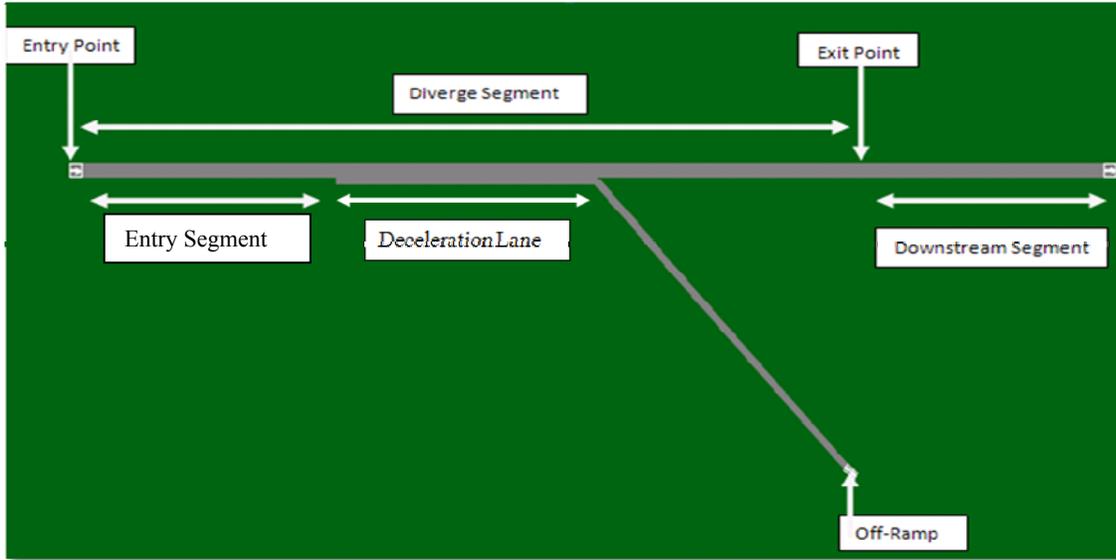


Figure 4-32. Sketch of a diverge freeway segment.

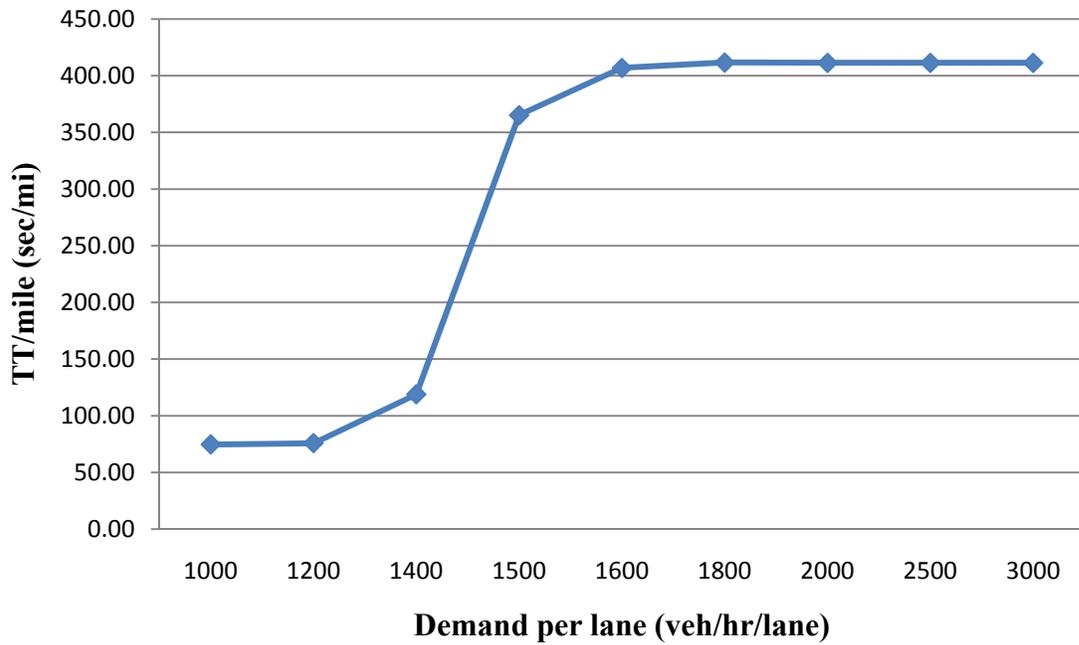


Figure 4-33. Variation of TT per mile with demand (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, ramp Exit % = 5, and downstream capacity = 1515 veh/hr/lane)

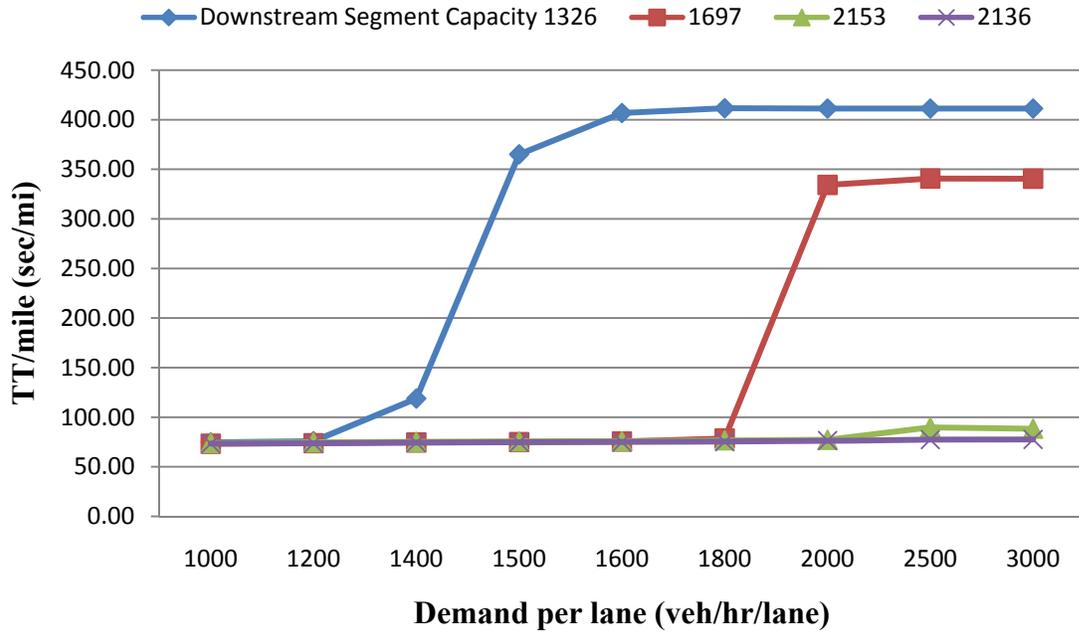


Figure 4-34. Variation of TT per mile with demand for different values of downstream segment capacity (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5)

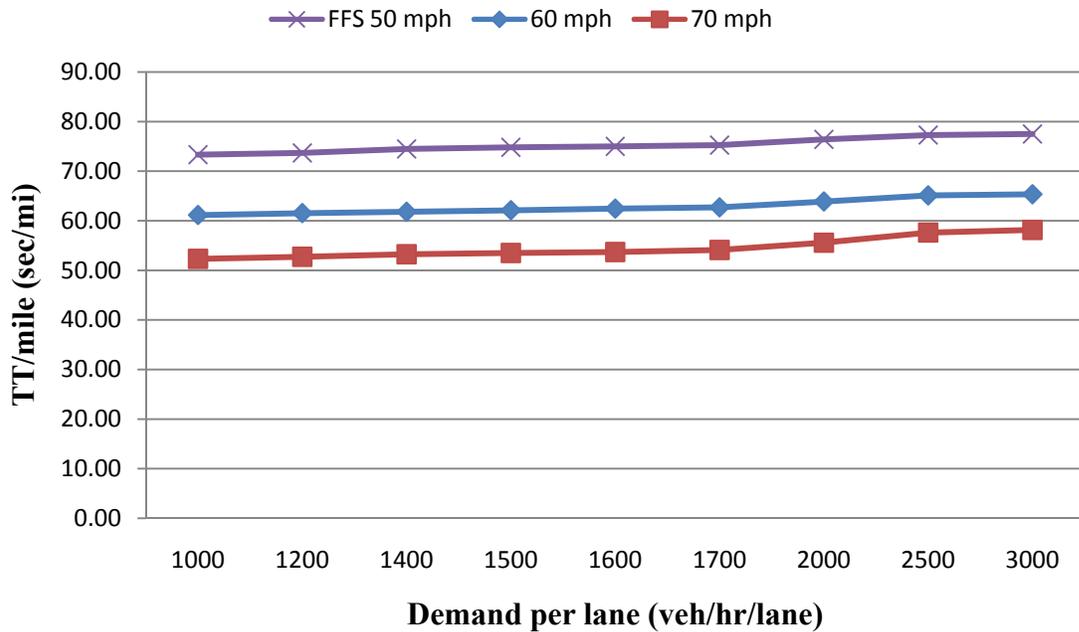


Figure 4-35. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5, and downstream capacity = 2137 veh/hr/lane)

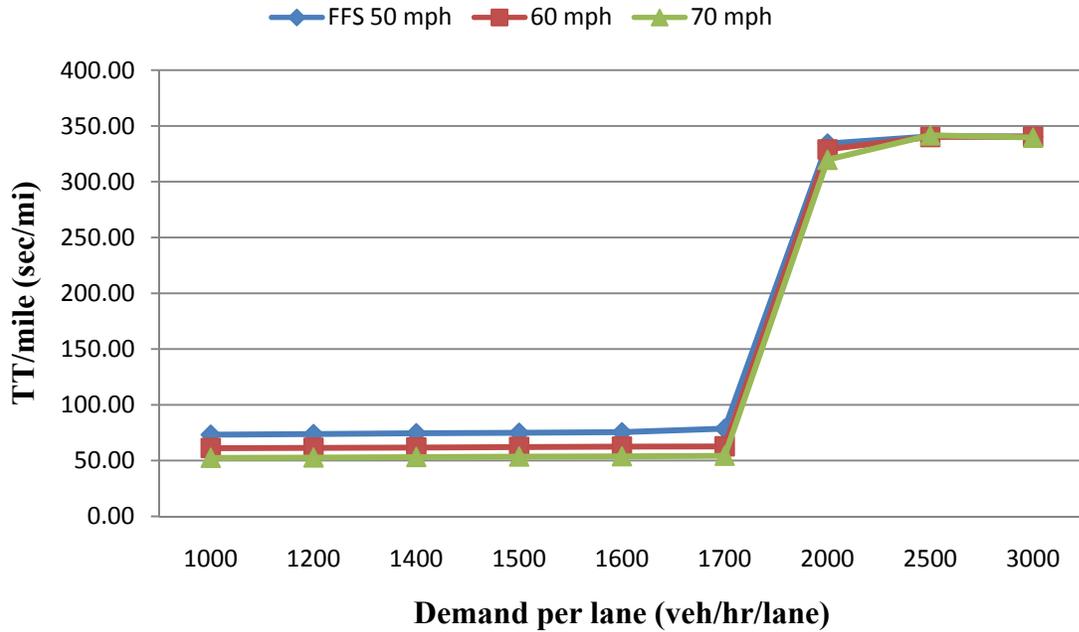


Figure 4-36. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5, and downstream capacity = 1689 veh/hr/lane)

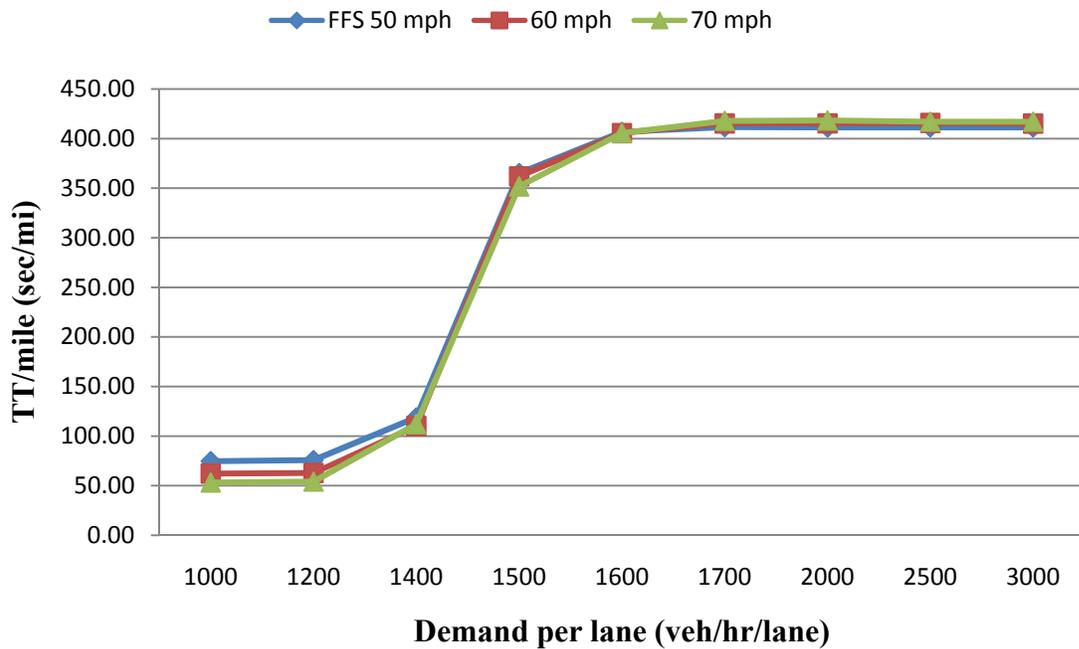


Figure 4-37. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5, and downstream capacity = 1324 veh/hr/lane)

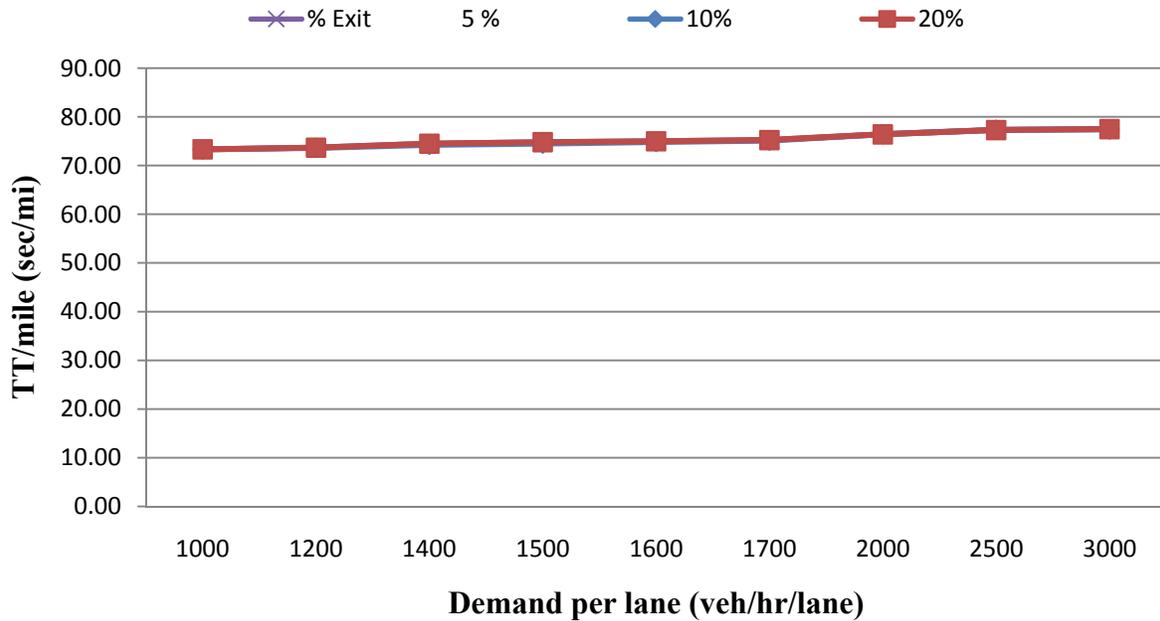


Figure 4-38. Variation of TT per mile with demand for different values of off-ramp exit % (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 2136 veh/hr/ln)

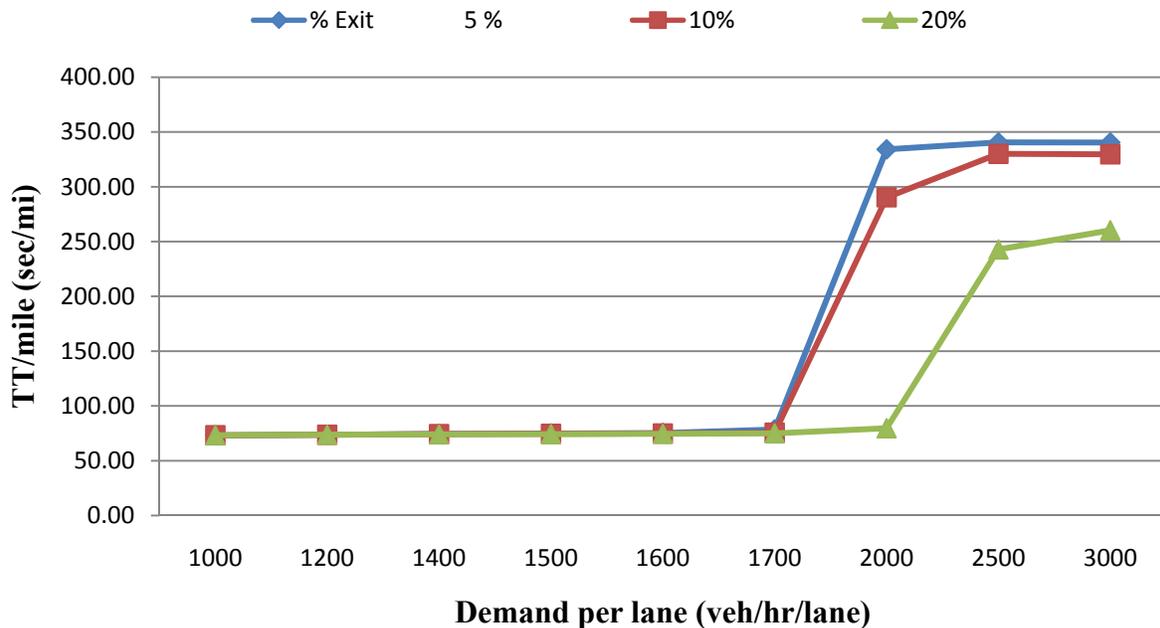


Figure 4-39. Variation of TT per mile with demand for different values of off-ramp exit % (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1689 veh/hr/ln)

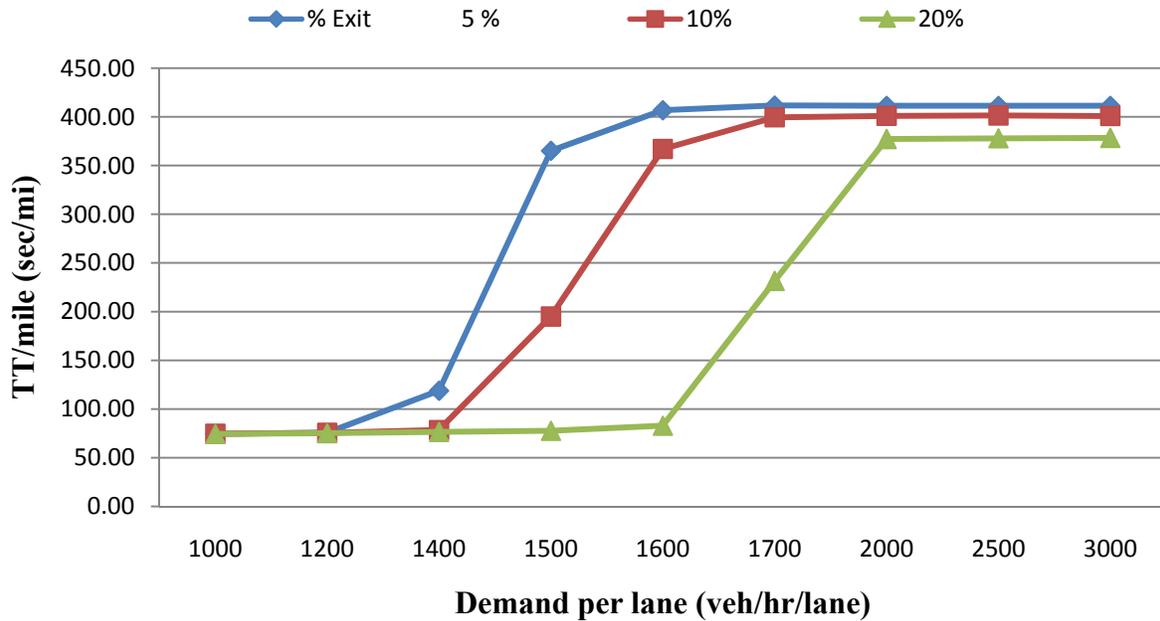


Figure 4-40. Variation of TT per mile with demand for different values of off-ramp exit % (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1324 veh/hr/ln)

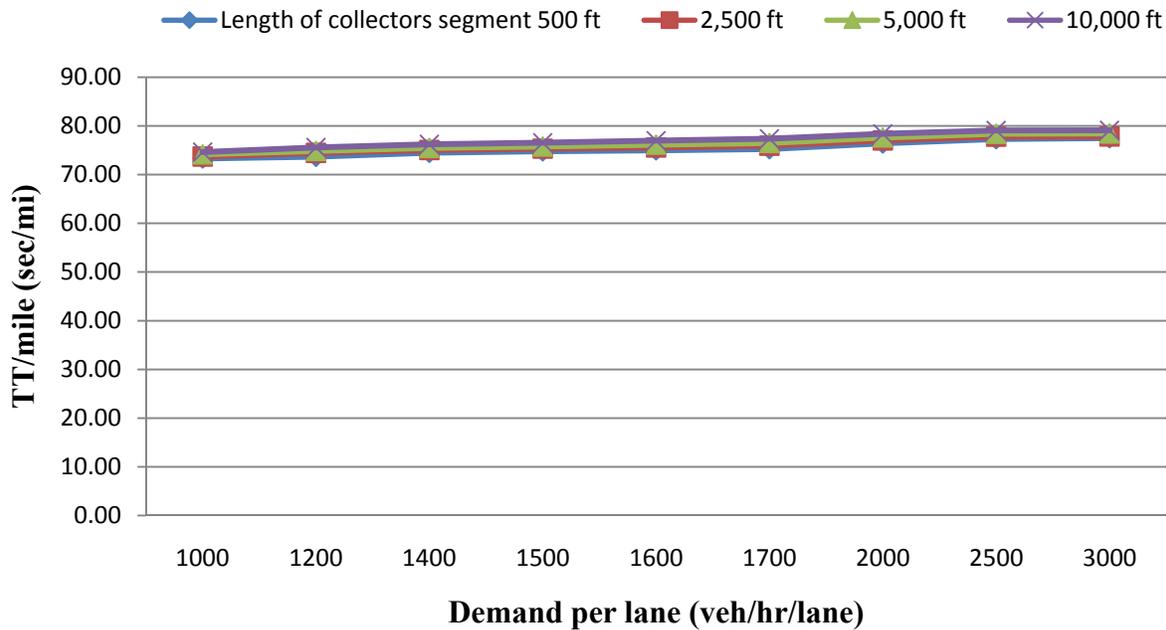


Figure 4-41. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 2136 veh/hr/lane)

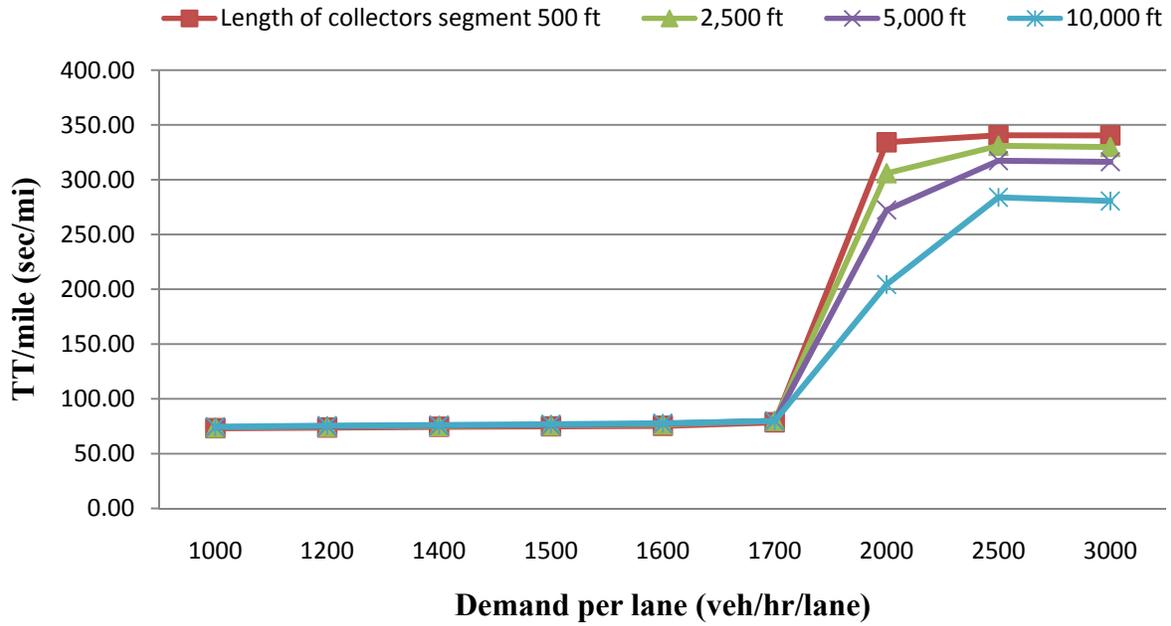


Figure 4-42. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1689 veh/hr/lane)

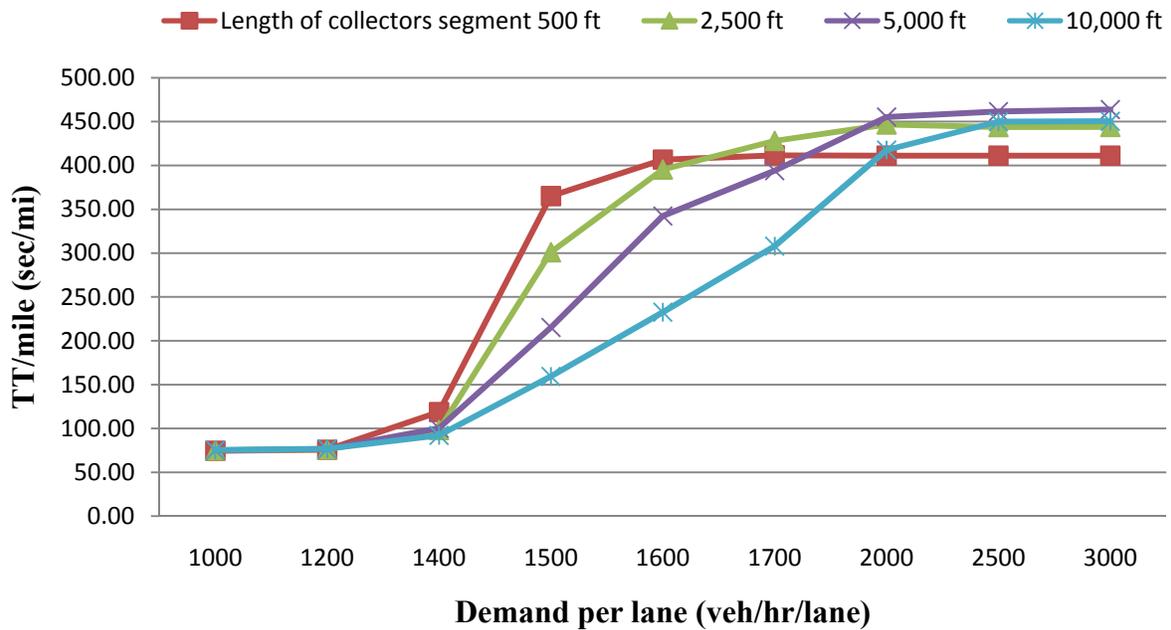


Figure 4-43. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1324 veh/hr/lane)

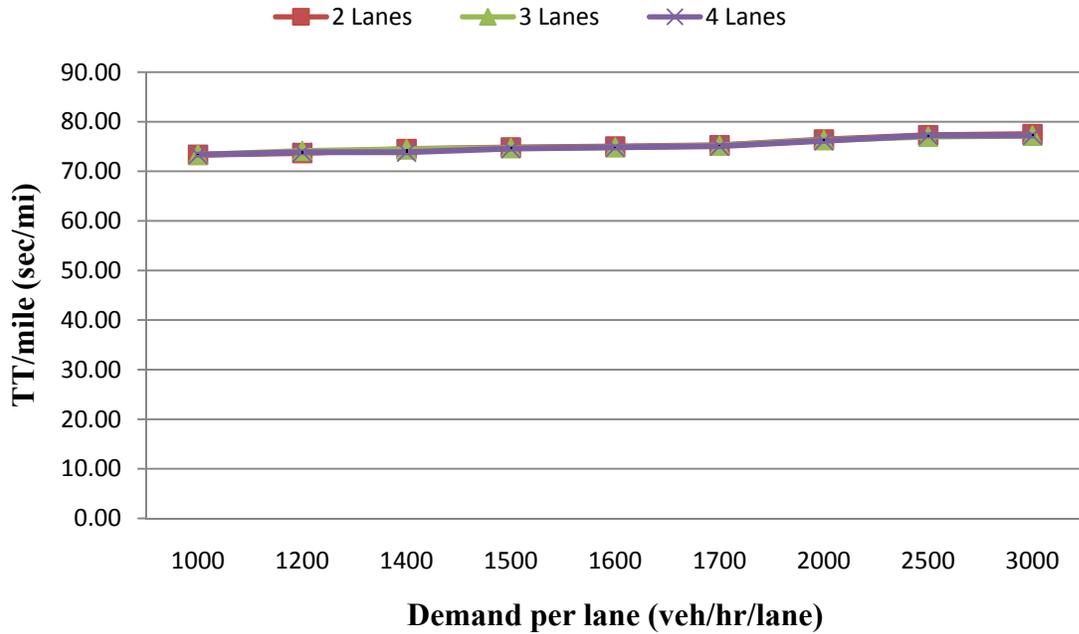


Figure 4-44. Variation of TT per mile with demand for different values of # lanes (length of entry section = 500 ft, and FFS = 50 mi/hr, off-ramp exit % = 5, and downstream capacity = 2136 veh/hr/lane)

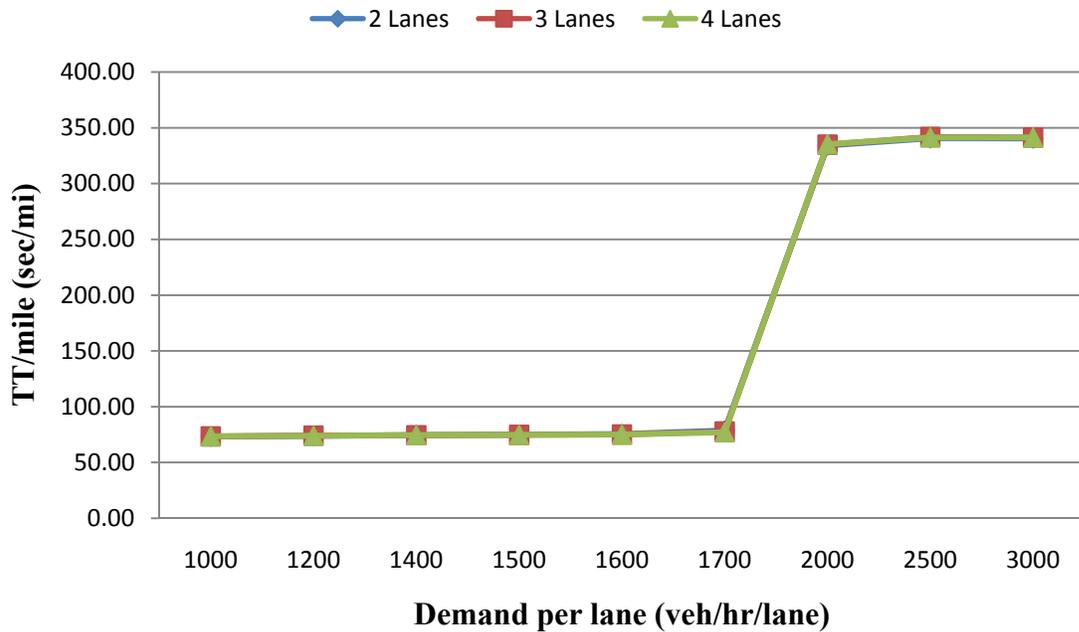


Figure 4-45. Variation of TT per mile with demand for different values of # lanes (length of entry section = 500 ft, and FFS = 50 mi/hr, off-ramp exit % = 5, and downstream capacity = 1689 veh/hr/lane)

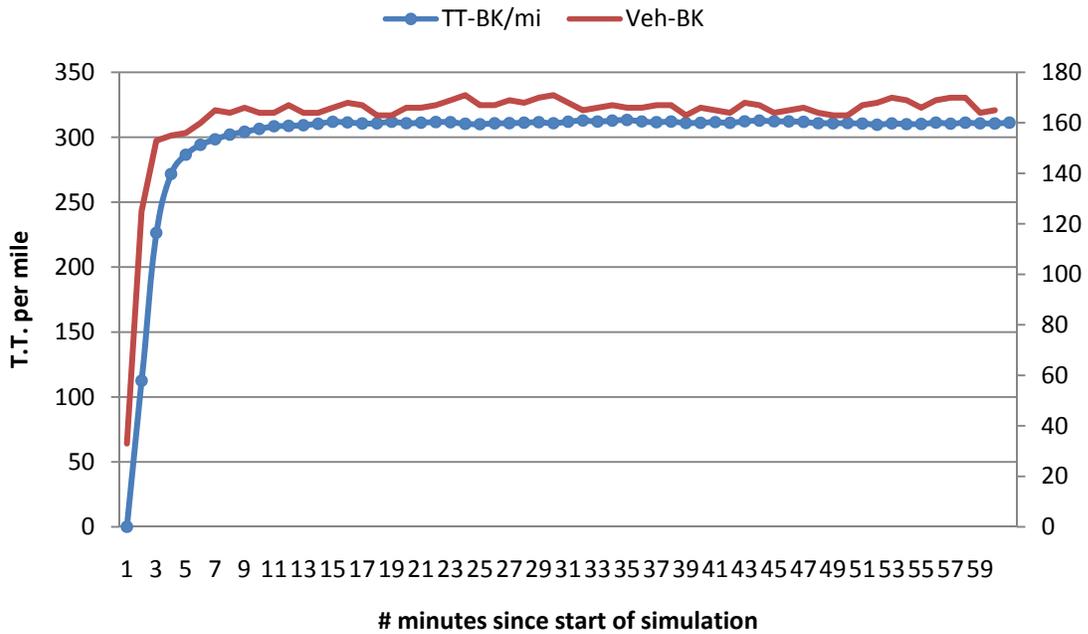


Figure 4-46. Time series plot between TT per mile of the downstream bottleneck and the number of vehicles in the downstream bottleneck

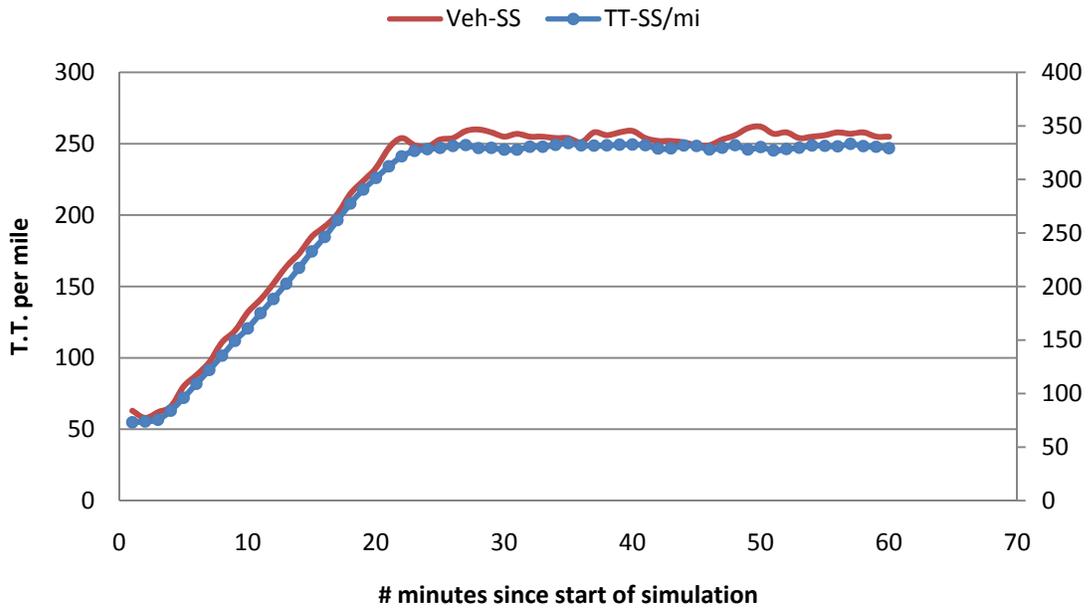


Figure 4-47. Time series plot between TT per mile of the upstream segment and the number of vehicles in the upstream segment

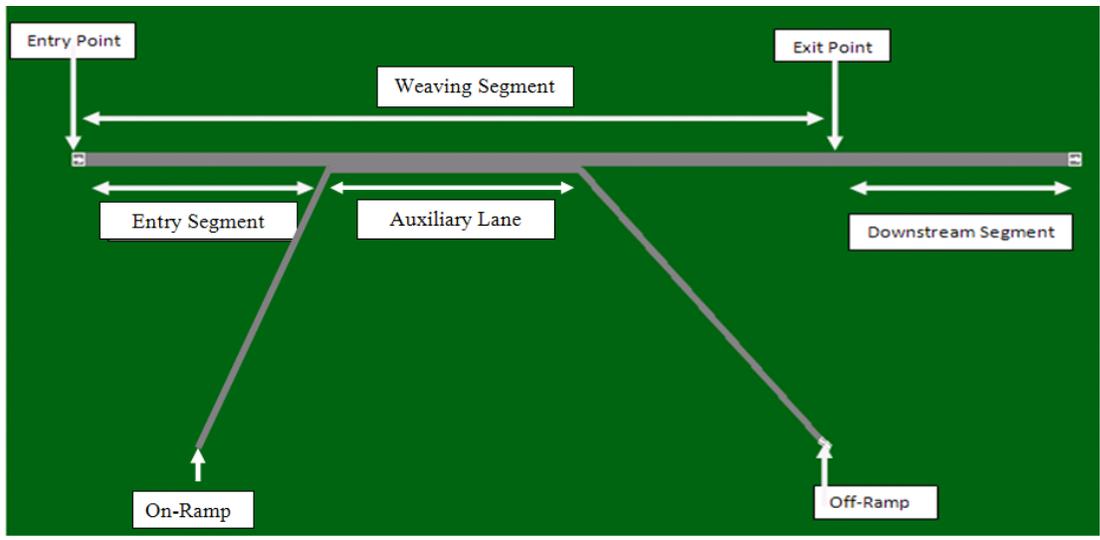


Figure 4-48. Sketch of a weaving freeway segment.

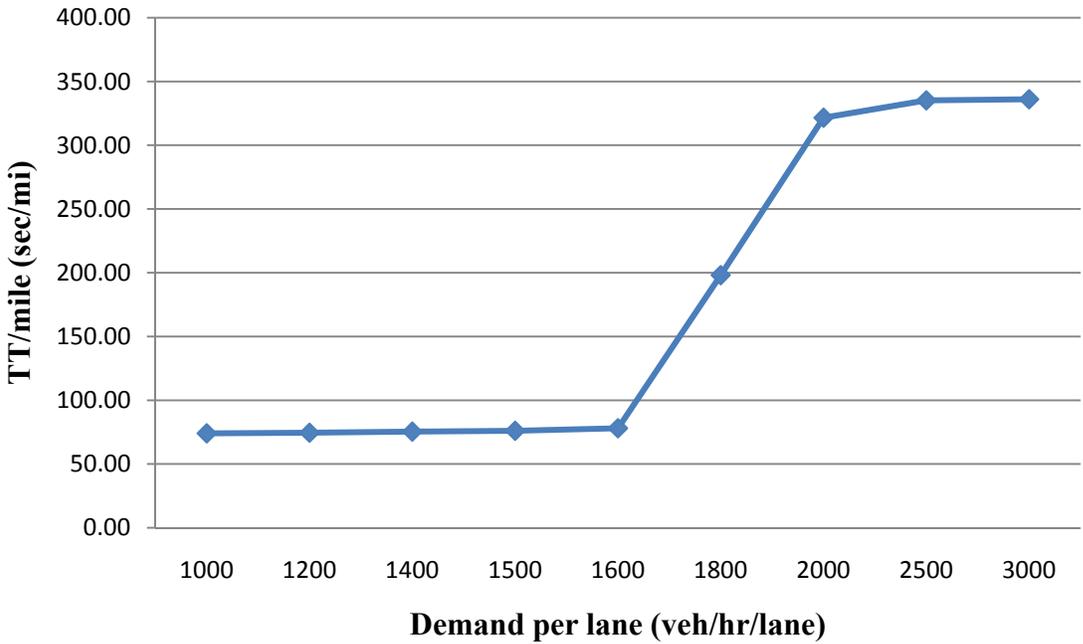


Figure 4-49. Variation of TT per mile with demand (# lanes = 2, FFS = 50 mph, length of entry section = 500 ft, ramp exit % = 5, and downstream capacity = 1696 veh/hr/lane)

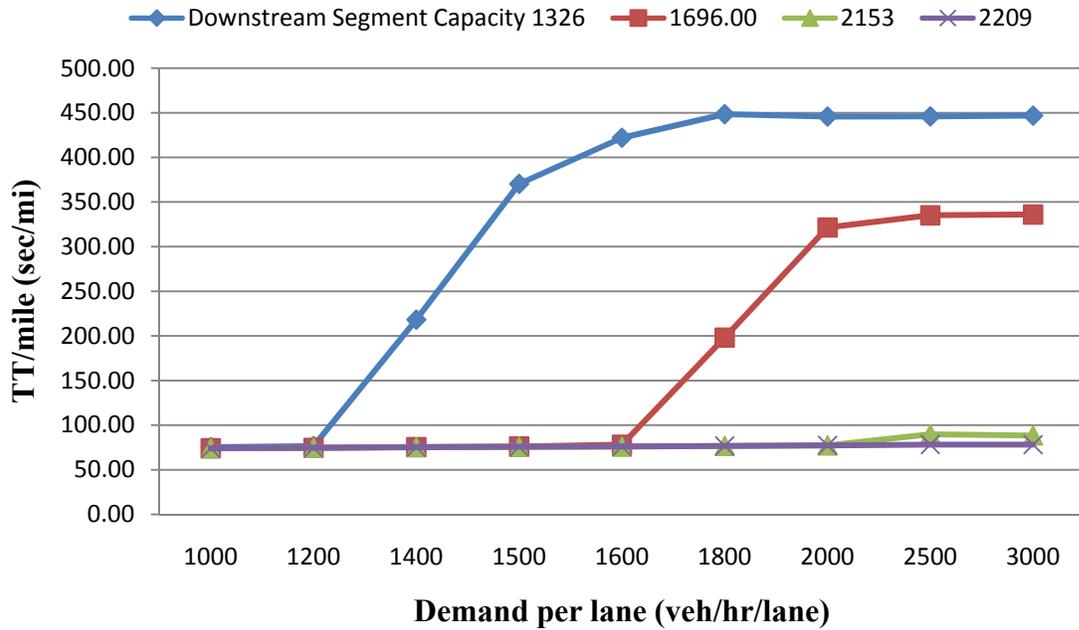


Figure 4-50. Variation of TT per mile with demand for different values of downstream segment capacity (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5)

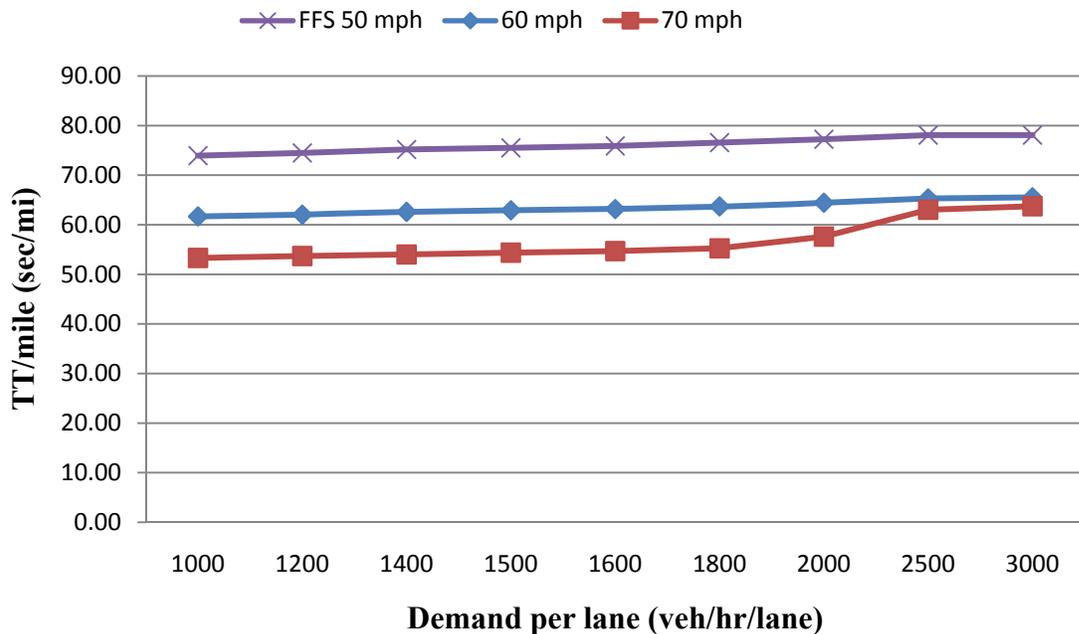


Figure 4-51. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5, and downstream capacity = 2209 veh/hr/lane)

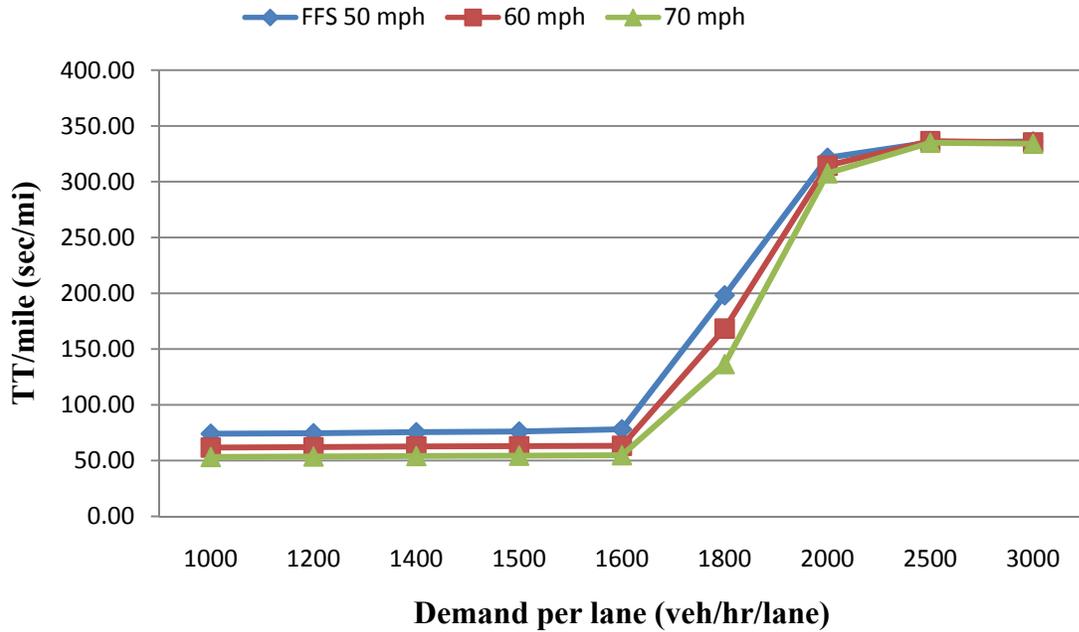


Figure 4-52. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5, and downstream capacity = 1696 veh/hr/lane)

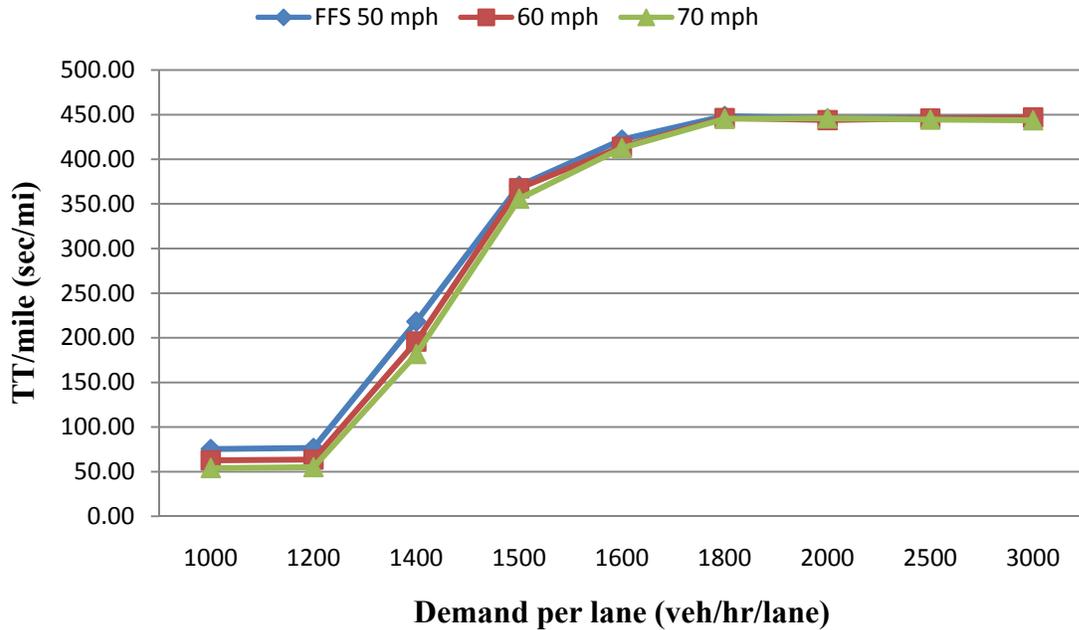


Figure 4-53. Variation of TT per mile with demand for different values of speed (lanes = 2, FFS = 50 mph, length of entry section = 500 ft, and ramp exit % = 5, and downstream capacity = 1326 veh/hr/lane)

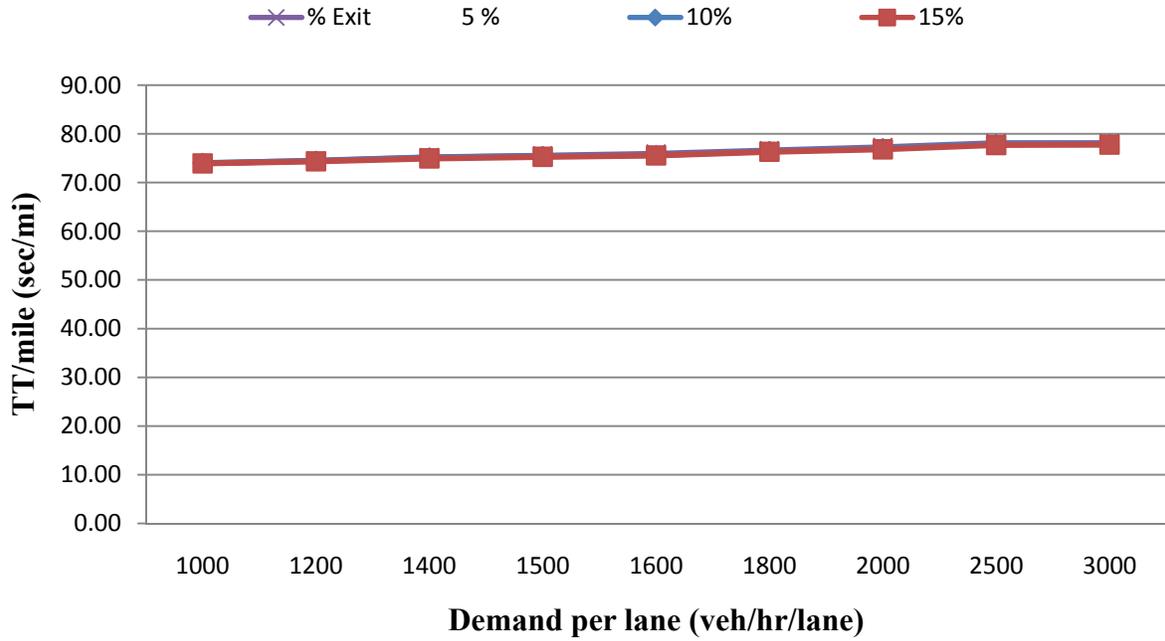


Figure 4-54. Variation of TT per mile with demand for different values of off-ramp exit % (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 2209 veh/hr/ln)

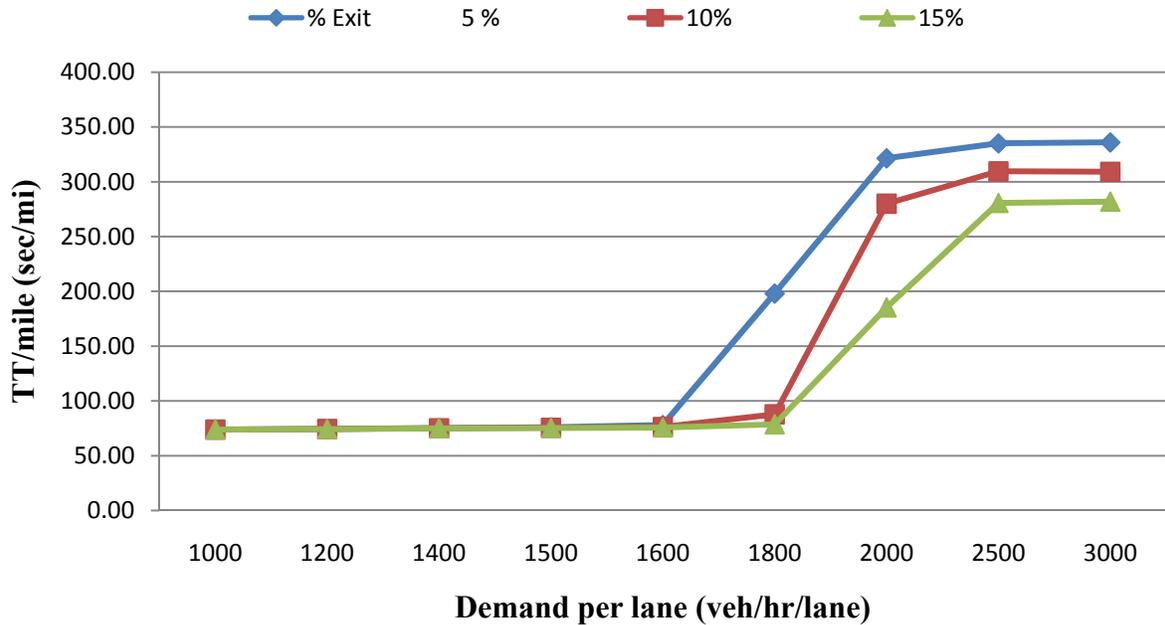


Figure 4-55. Variation of TT per mile with demand for different values of off-ramp exit % (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1696 veh/hr/ln)

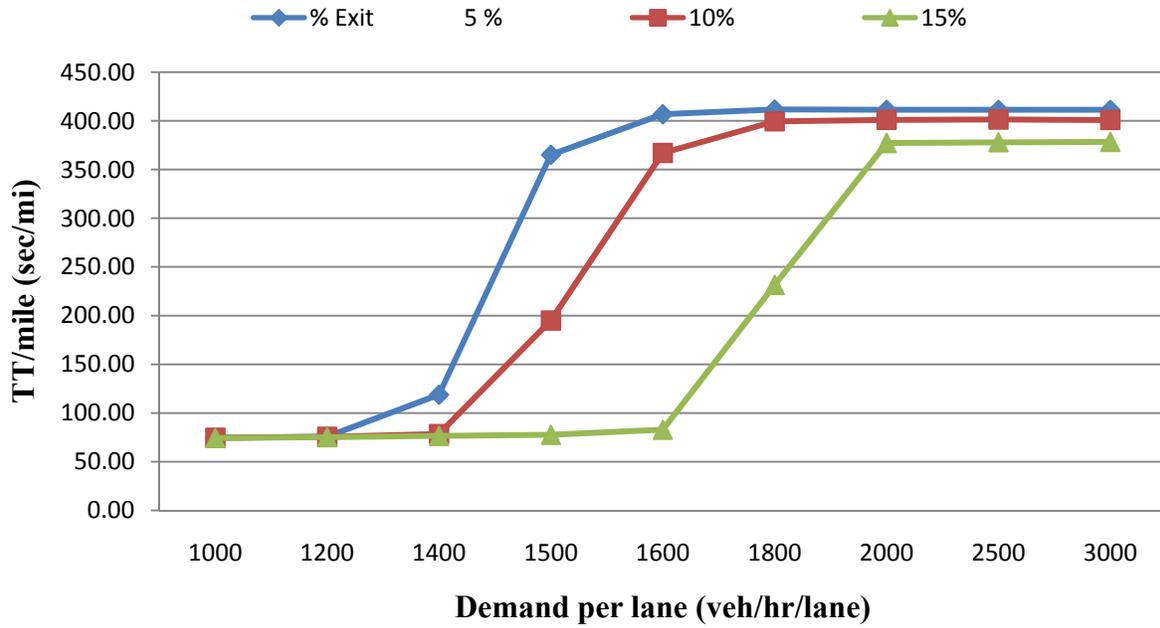


Figure 4-56. Variation of TT per mile with demand for different values of off-ramp exit % (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1326 veh/hr/ln)

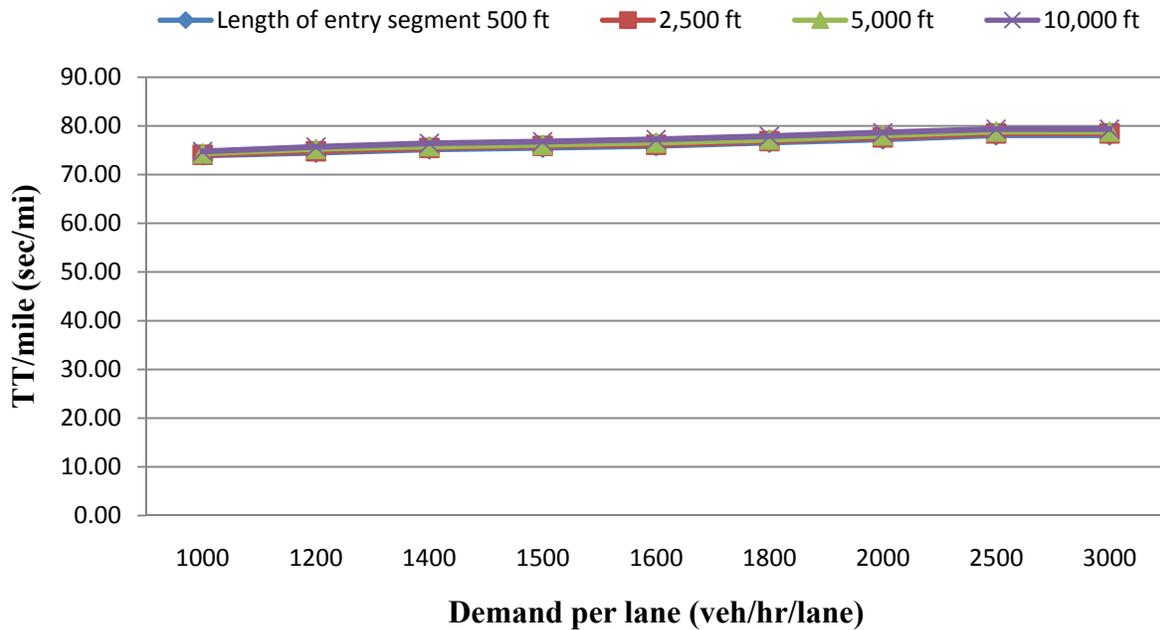


Figure 4-57. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 2209 veh/hr/lane)

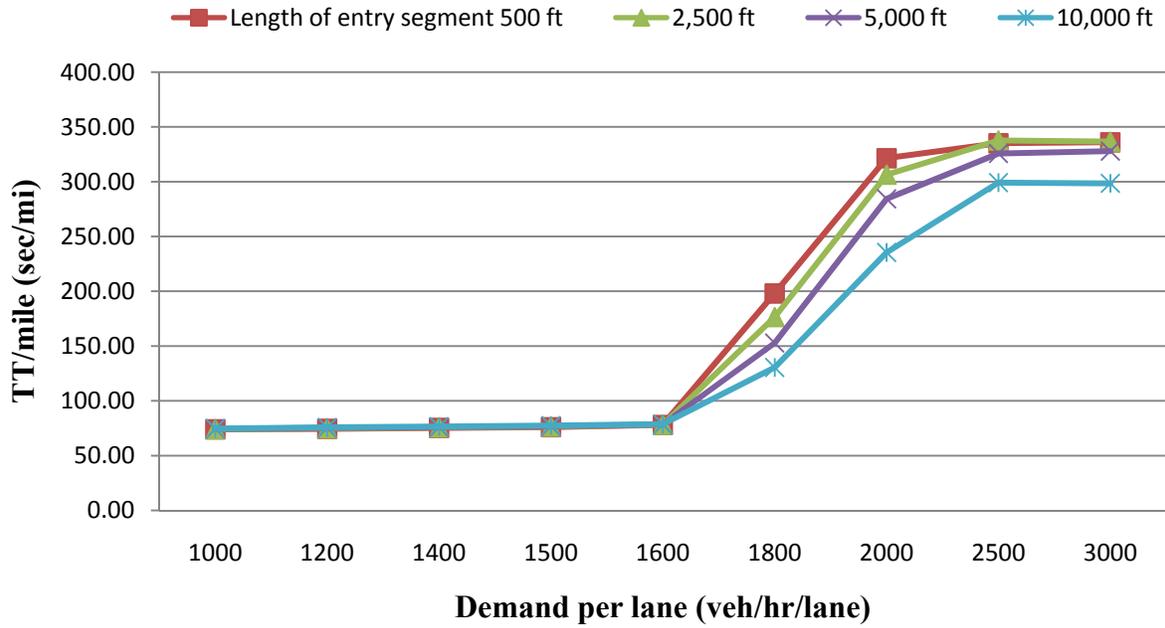


Figure 4-58. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1696 veh/hr/lane)

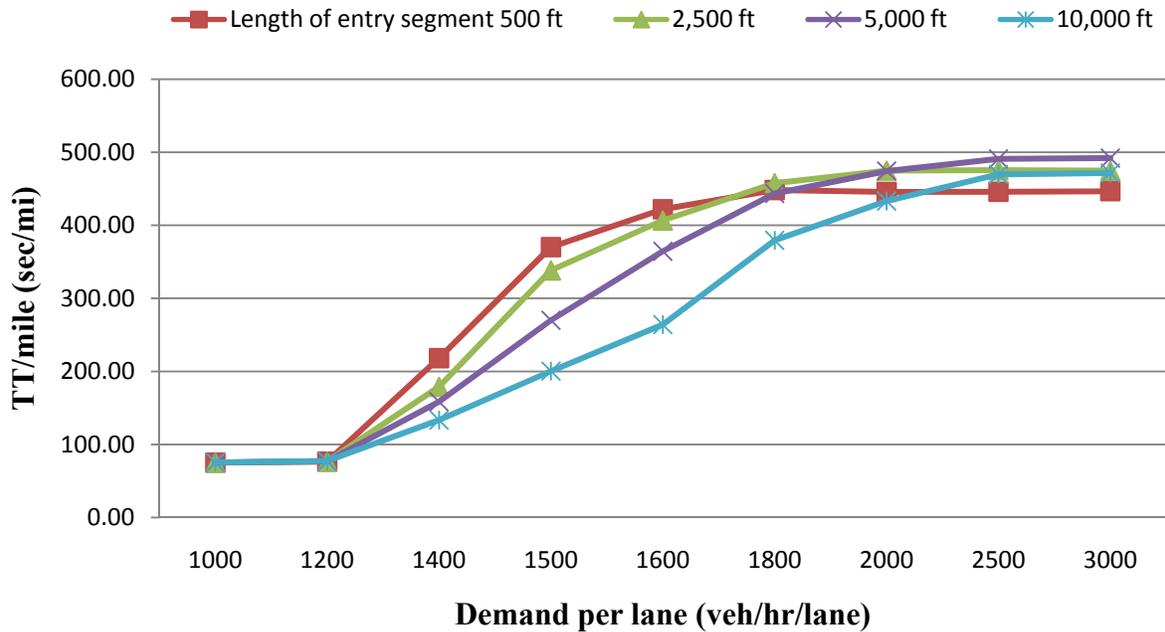


Figure 4-59. Variation of TT per mile with demand for different values of length of entry section (# lanes = 2, FFS = 50 mi/hr, ramp demand = 100 veh/hr/ln, and downstream capacity = 1326 veh/hr/lane)

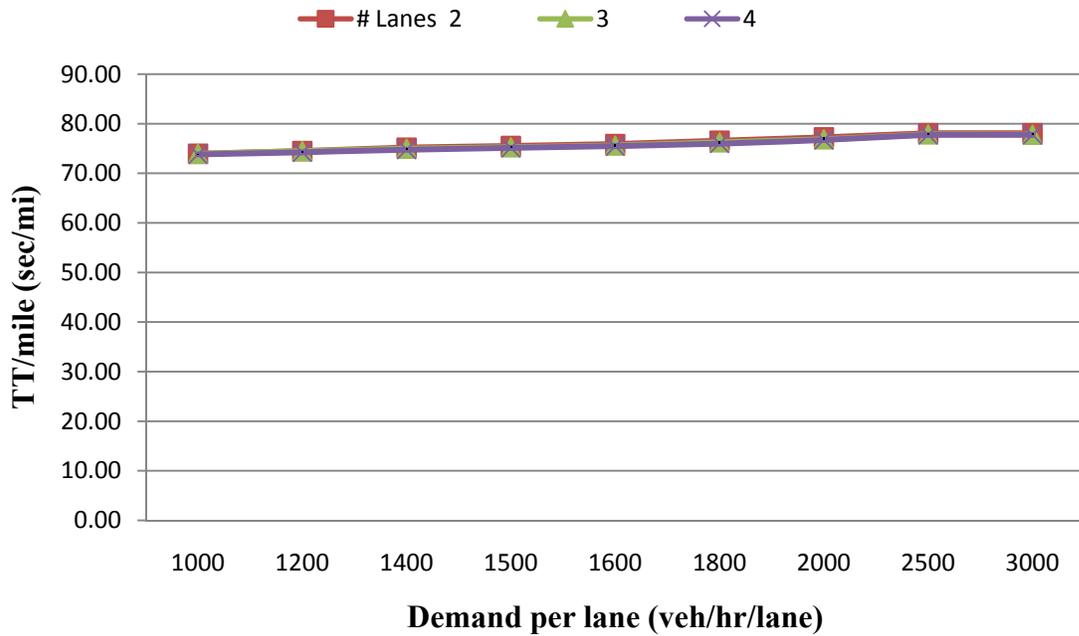


Figure 4-60. Variation of TT per mile with demand for different values of # lanes (length of entry section = 500 ft, and FFS = 50 mi/hr, off-ramp exit % = 5, and downstream capacity = 2209 veh/hr/lane)

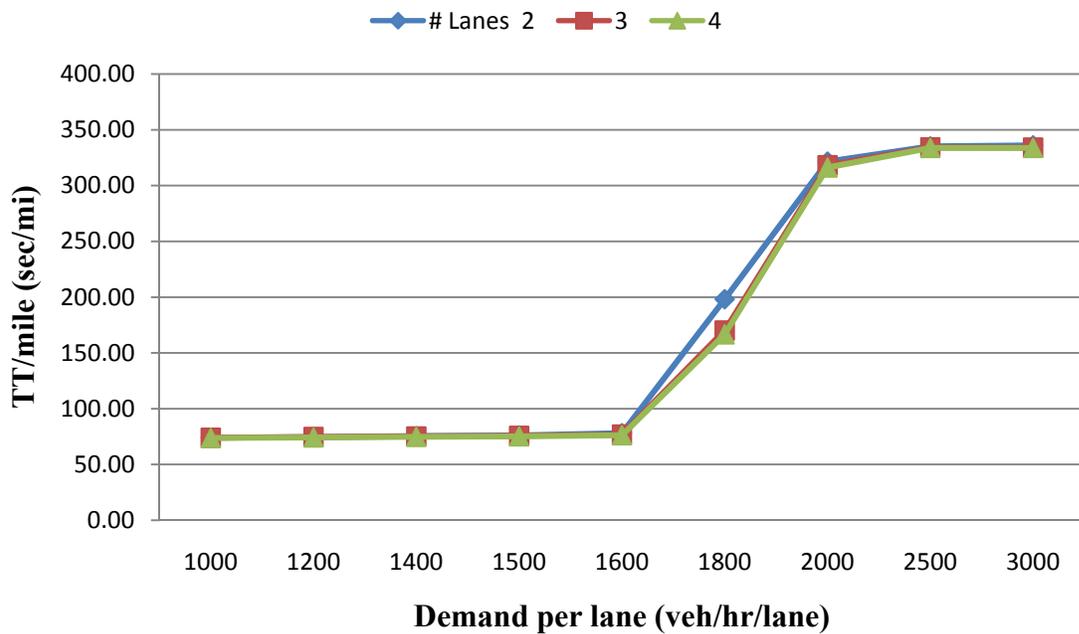


Figure 4-61. Variation of TT per mile with demand for different values of # lanes (length of entry section = 500 ft, and FFS = 50 mi/hr, off-ramp exit % = 5, and downstream capacity = 1696 veh/hr/lane)

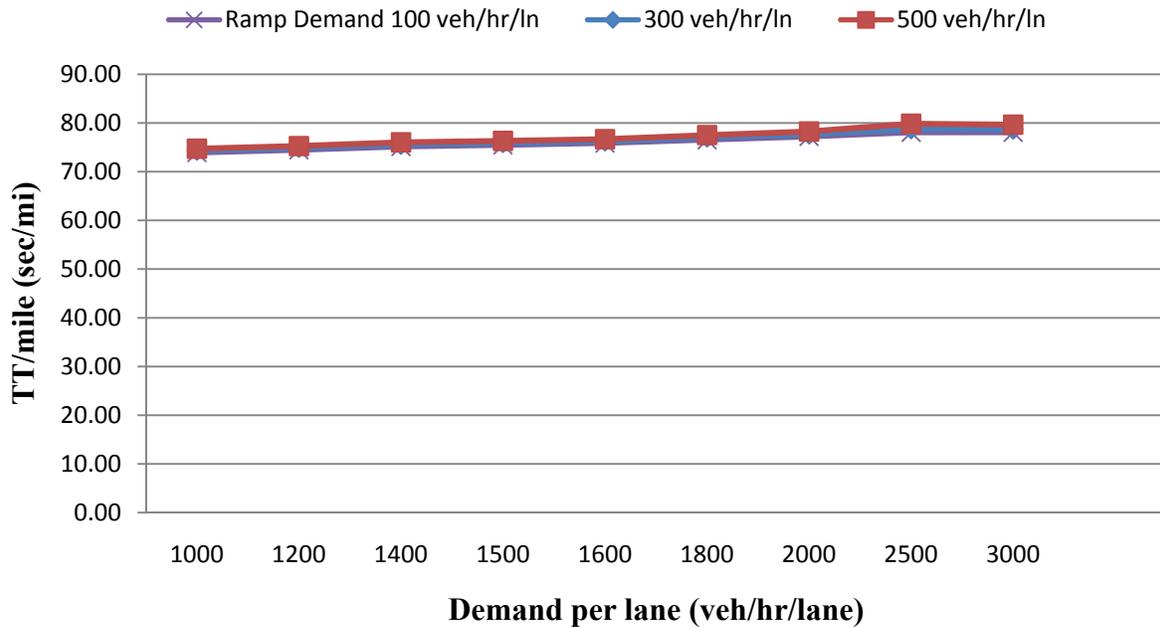


Figure 4-62. Variation of TT per mile with demand for different values of ramp demand (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 2491 veh/hr/lane)

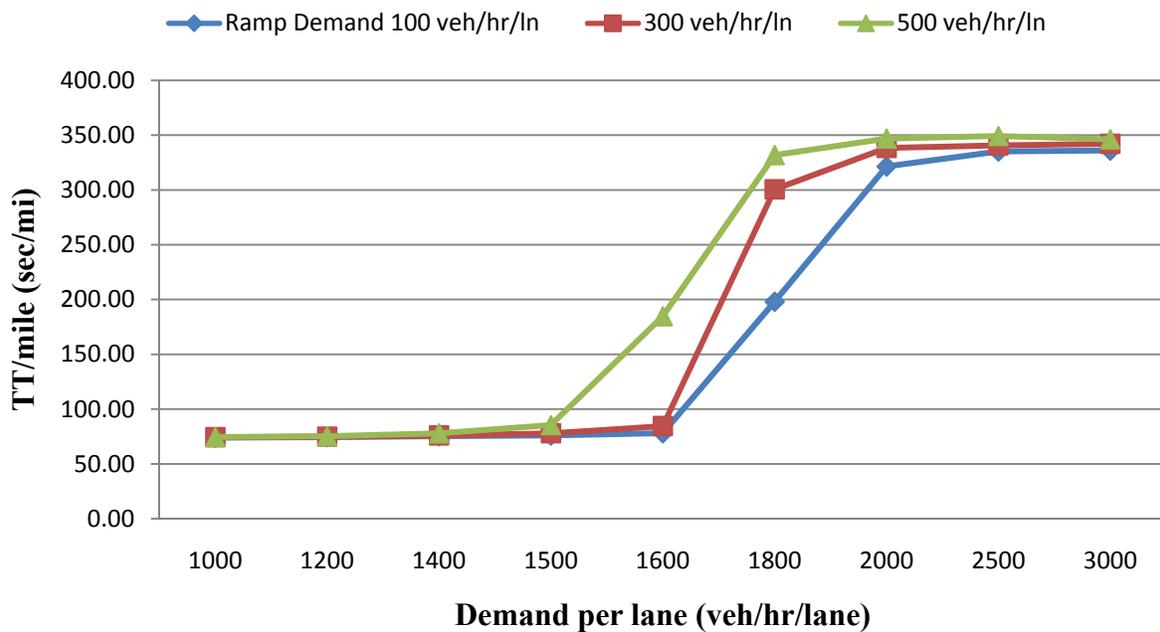


Figure 4-63. Variation of TT per mile with demand for different values of ramp demand (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1689 veh/hr/lane)

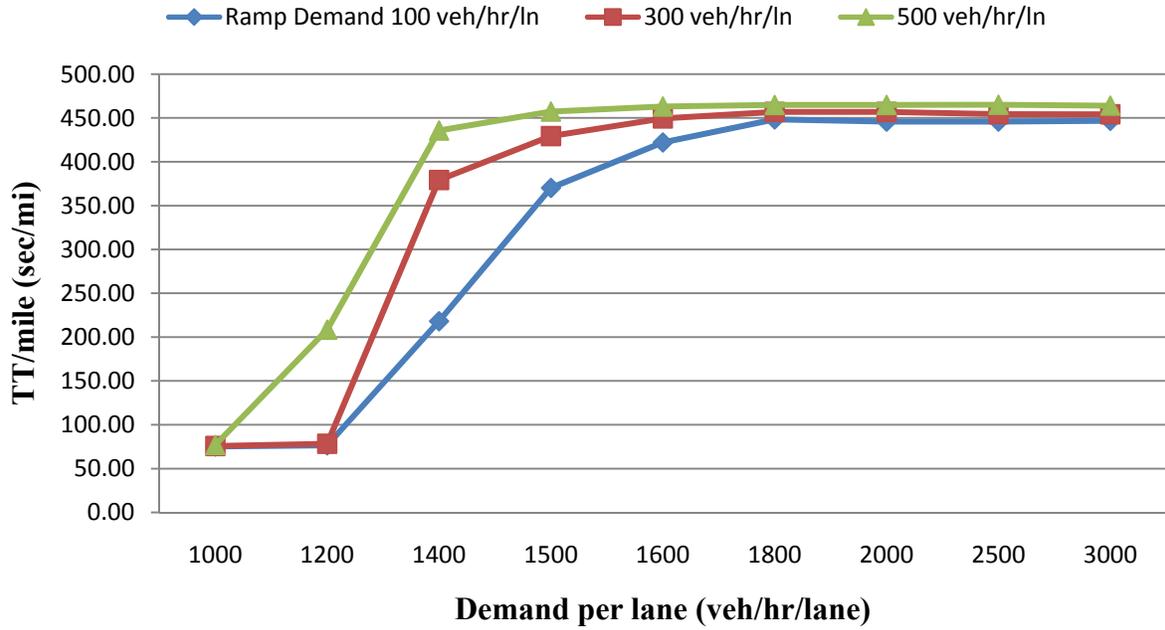


Figure 4-64. Variation of TT per mile with demand for different values of ramp demand (lanes = 2, length of entry section = 500 ft, and FFS = 50 mi/hr, and downstream capacity = 1324 veh/hr/lane)

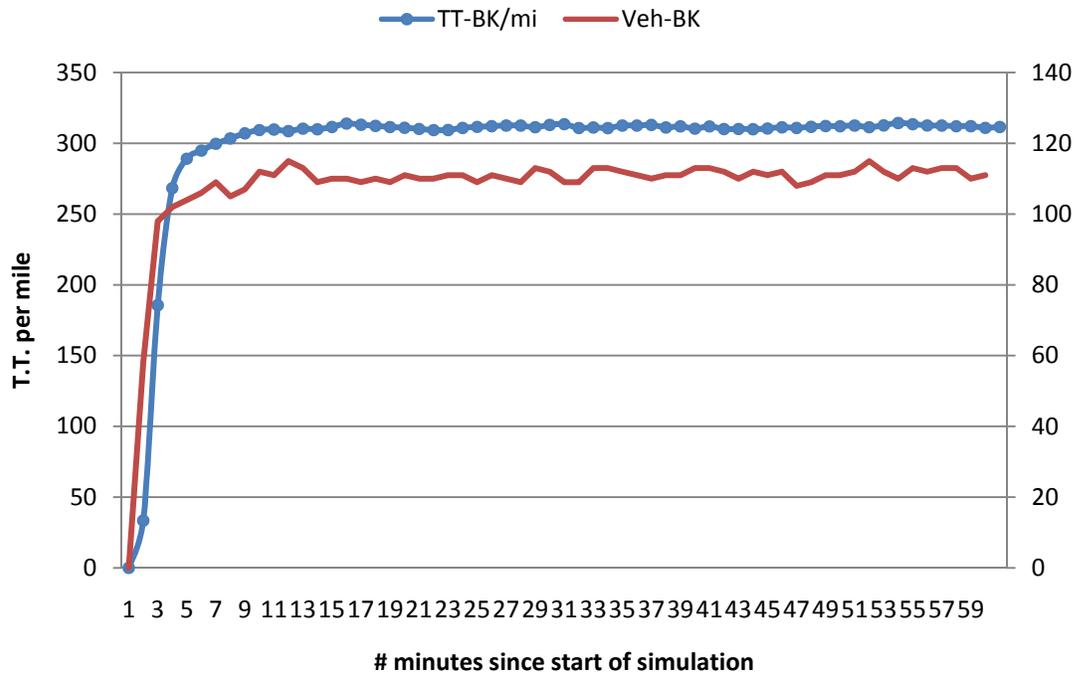


Figure 4-65. Time series plot between TT per mile of the downstream bottleneck and the number of vehicles in the downstream bottleneck

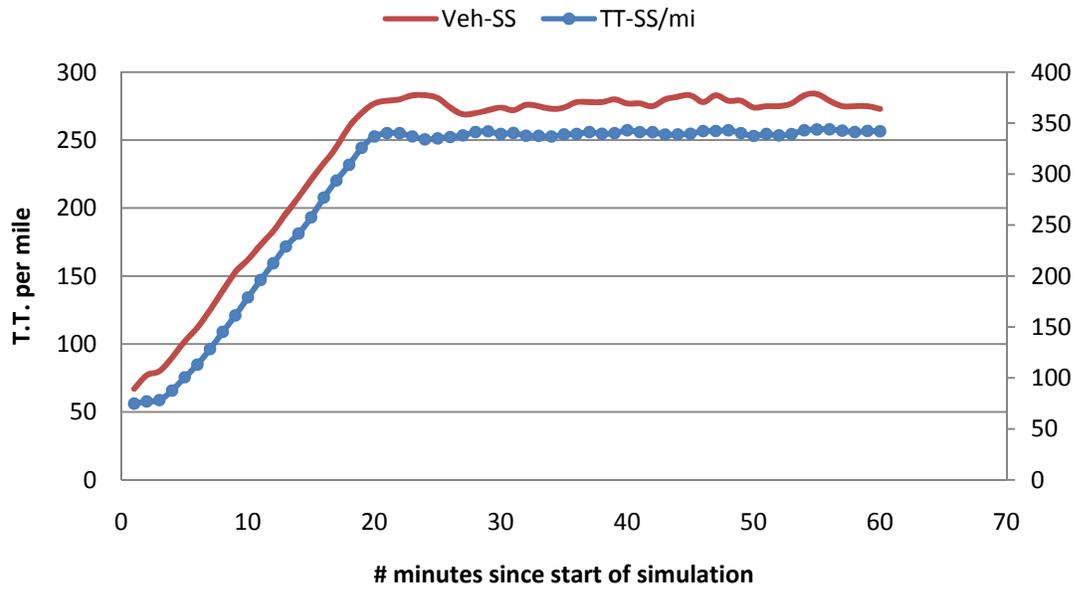


Figure 4-66. Time series plot between TT per mile of the upstream segment and the number of vehicles in the upstream segment

CHAPTER 5 ANALYTICAL MODELS

Based on the simulation results, analytical models are developed to predict T.T. as a function of the selected critical variables. The structure of the analytical models is described in Section 5.1. The analytical models for basic freeway segments are presented in Section 5.2, while the models for merge segments and diverge segments are presented in section 5.3 and Section 5.4. The models for weaving segments are presented in Section 5.5. The models for Bottleneck are presented in Section 5.6.

5.1 Model Structure

T.T. for congested and uncongested conditions is modeled separately and the variables that impact T.T. are also separately considered. The first set of models estimate the T.T. when the demand doesn't exceed downstream segment capacity, while the second set of the models estimates the T.T. when the demand exceeds the downstream segment capacity.

When the demand doesn't exceed downstream segment capacity, it is concluded that the relation between T.T., demand, and other variables is linear. Thus, these set of conditions are modeled using simple multivariate regression models. On the other hand when the demand exceeds downstream segment capacity, it is found that the relation between T.T., demand, and other variables takes the shape of an "S" curve, as shown in Figure 5-1. As shown in Figure 5-1, the T.T. remains relatively constant until demand reaches downstream segment capacity. Once demand reaches downstream segment capacity, T.T. starts to linearly increase with demand and then the relationship flattens out to a maximum value of T.T.

The "S" curve can be characterized by two points; (1) when demand equals downstream segment, until this point the T.T. remains relatively constant and after this point the T.T. starts to increase at an exponential rate (2) when the exponentially increasing T.T. starts to flatten and

reaches a maximum value of T.T. This “S” curve can be modeled using either (a) three separate linear models (b) using a single logistic function (c) estimate only the maximum T.T. using simulated data and use a theoretically derived parameter that defines the location on the “S” curve. The first approach requires identification of the points where the T.T. starts to increase at an exponential rate and where the exponentially increasing T.T. starts to flatten and reaches a maximum value of T.T. This task, of identifying the two characteristic points, is implicitly taken care while estimating the logistic model. Moreover, the logistic curve, as shown in Figure 5-2, is smoother at the characteristic points. However, use of logistic function either forces the relation between T.T. and other variable also to be logistic or made the function very complicated and hard to read. The third approach; where the maximum T.T. is first estimated using simple multivariate regression models and then a parameter, which defines the location on the “S” curve, is theoretically derived as a function demand, capacity, and length of the segment alone. Thus, the third approach is used to model T.T. under congested conditions.

The structure of the multivariate regression models used for uncongested conditions is described in section 5.1.1, similar regression functions are used for congested conditions and are described in section 5.1.2. The two sets of models developed and their applications are presented in Section 5.1.3.

5.1.1 Models for Uncongested Conditions

This section describes the structure of models used to estimate T.T. when the demand does not exceed downstream segment capacity. The structure of simple multivariate regression model is as follows:

$$Y_{i1} = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_k X_{ki} + \epsilon_i \quad \text{for } i = 1, 2 \dots n. \quad (5-1)$$

Where,

Y_i = Dependent variable (in this case travel time per mile)

$X_{1i}, X_{2i}, \dots, X_{ki}$ = Explanatory factors or independent variables.

$$X_{ki} = \frac{D}{C_d}$$

β_0 = Constant term.

$\beta_1, \beta_2, \dots, \beta_k$ = Coefficients on the explanatory variables. These coefficients capture the marginal impact of the corresponding explanatory variable.

ϵ_i = Error term, which captures the impact of unobserved factors (not accounted for by $X_{1i}, X_{2i}, \dots, X_{ki}$)

It should be noted that the above regression equation is very similar to that of the speed-flow curve in HCM 2000. However, in HCM, the variation between speed and flow is studied and in this study, the variation between T.T. and demand is studied. Moreover, in HCM the analysis is done for only basic freeway segment. However, in this study, the analysis is done for all the four freeway segments.

5.1.2 Models for Congested Conditions

This section describes the structure of models used to estimate T.T. when the demand exceeds downstream capacity. Models for congested conditions are developed in two stages; first the maximum T.T. is estimated, and then a parameter alpha is estimated. Alpha parameter describes the location on the “S” curve.

$$Y_{2i} = \alpha * T^{\text{range}} \tag{5-2}$$

Where,

Y_i = Dependent variable (Travel time)

α = Parameter describing the location on the “S” curve. This parameter is derived theoretically.

$$\mathbf{T}^{\text{range}} = \mathbf{g}(\beta_i \mathbf{X}_i)$$

$\mathbf{g}(\beta_i \mathbf{X}_i)$ = A simple multivariate regression model.

$\mathbf{X}_i = \{X_{1i}, X_{2i}, \dots, X_{ki}\}$ = Explanatory factors or independent variables.

$\beta_i = \{\beta_1, \beta_2, \dots, \beta_k\}$ = Coefficients on the explanatory variables. These coefficients capture the marginal impact of the corresponding explanatory variable.

The above two models can be combined into a single model which can be applied in all situations irrespective of the relative values of demand and downstream capacity.

5.1.3 Application

This section presents the combined model, which combines models from both the parts described above. The following construct is used to achieve this combination, which is described below:

$$\mathbf{Y}_i = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \dots + \beta_k \lambda + \alpha * \mathbf{T}^{\text{range}} \quad (5-3)$$

Where,

\mathbf{Y}_i = Dependent variable (Travel time)

$\mathbf{X}_i = \{X_{1,i}, X_{2,i}, \dots, X_{k-1,i}\}$ = Explanatory factors or independent variables.

$\beta_i = \{\beta_1, \beta_2, \dots, \beta_k\}$ = Coefficients on the explanatory variables. These coefficients capture the marginal impact of the corresponding explanatory variable.

β_0 , = Constant.

$\mathbf{g}(\beta_i \mathbf{X}_i)$ = A simple multivariate regression model.

$\lambda = \min\left(1, \frac{D}{C_d}\right)$; yields 1 if demand exceeds downstream capacity. Thus, when demand exceeds downstream capacity, the first part of the model produces max T.T. for uncongested conditions.

D = Demand.

C_d = Capacity of downstream segment.

A special case of this combination, when the demand is less than the downstream segment capacity, yields us the model from the first part. Another special case, when the demand exceeds the downstream capacity, yields the model from part two.

Using the model structure shown above in Equation-3, five separate models are estimated one each for basic freeway segment, merge segment, diverge segment, and weaving segment and the fifth for bottleneck.

5.2. Travel Time Models for BFS

When demand is less than the downstream segment capacity, “free flow speed” is found to be the only variable that impacts travel time. T.T. model for uncongested conditions is presented below:

$$TT^1 = 120.87 - 1.006 * V + 4.6547 * \left(\frac{D}{C_d}\right)$$

V = Free flow speed

D = Demand

C_d = Capacity of downstream segment.

The regression statistics for BFS is presented in Table 5-1

It should be noted that the above regression equation presented is very similar to that of the speed-flow curve in HCM 2000. However, in HCM, the variation between speed and flow is studied and in this study, the variation between T.T. and demand is studied. Moreover, in HCM the analysis is done for only basic freeway segment. However, in this study, the analysis is done

for all the four freeway segments. The T.T. predicted by the uncongested model is compared with the HCM speed flow graph and presented in Figure 5-3.

In order to tie up the uncongested model with congested model, the uncongested model is modified such that when demand exceeds downstream segment capacity, the T.T. predicted by uncongested model becomes a constant T.T. This new structure is presented below:

$$TT^1 = 120.87 - 1.006 * V + 4.6547 * \text{MIN} \left(1, \frac{D}{C_d} \right) \quad (5-4)$$

It can be observed from equation-4 that the T.T. varies with demand until demand is less than downstream segment capacity. Once the demand reaches downstream segment capacity, T.T. does not vary with increase in demand, and it becomes a constant. Thus, the estimated model behaves consistently with the objective of the first part of the model.

The second part of the model corresponds to those scenarios where demand is greater than the downstream segment capacity. In this part of the model, demand, downstream capacity, and length of the basic freeway segment variables impact T.T. Thus, for this part of the models, demand, downstream segment capacity, and length of the basic freeway segment are considered as explanatory variable. The model for second part is estimated in two stages, first the range of the T.T. is modeled and then the shape of the sigmoid curve is estimated.

In order to estimate the range of T.T., a few plots were created between the range of T.T. and demand for a series of length of basic freeway segment. One of the plots is presented in Figure 5-4. As shown, for a given length of basic freeway segment, the range of T.T. varies similar to a parabolic curve with demand. It is also observed that as the length of the basic freeway segment increases, the range of the T.T. decreases.

As the final objective of this model estimation is to develop a combined model that will be used for all values of demand, the second model is modified such that it smoothly connects the model from first part at demand equals downstream capacity. This modification involves

modeling range of T.T. minus T.T. from part one when demand equals capacity. The model for estimating range of T.T. minus T.T. from part one when demand equals capacity is shown below:

$$T^{range} = 4.561 * ((C_d - 2400)/100)^2 - 0.524 * (L^{bfs}/5200) * ((C_d - 2400)/100)^2 \quad (5-5)$$

Where,

T^{range} = Range of travel time minus travel time from part one when demand equals capacity

L^{bfs} = Length of basic freeway segment

C_d = Capacity of downstream segment

The congested T.T. range model statistics are presented in Table 5-2.

It can be observed from equation-5 that as the length of the basic freeway segment increases, the range of the T.T. decreases. Further it can also be observed that as the downstream segment capacity increases the maximum T.T. exponentially decreases. Thus, it is found that the estimated model follows the observed logic in the model.

The parameter “ α ” is theoretically derived using simple queuing system. Consider a section of road, such as BFS shown in Figure 4-1, with a bottleneck of capacity “ C_d ” at the downstream end of the section. When demand exceeds the downstream capacity, a moving queue starts forming inside the segment. As the queue length increases the T.T. per mile increases as shown in Figure 4-15. Once the moving queue completely occupies the entire segment, the T.T. per mile reaches a maximum value. The parameter “ α ” tries to capture the ratio of the average T.T. to the maximum T.T..

The parameter “ α ” is calculated using the equation shown below.

$$\alpha = T.T. \text{ avg} / T.T. \text{ max} = \frac{\min(1, \Delta t)}{2 * \max(1, \Delta t)} + (1 - \min(1, \Delta t)) \quad (5-6)$$

$$\text{Where } \Delta t = \frac{L * J}{D - C_d}$$

L = Length of the section

J = Jam density

D = Freeway demand

C_d = Downstream capacity

The combined model for basic freeway segment (BFS) is presented below:

$$TT = 120.87 - 1.006 * V + 4.6547 * \text{MIN} \left(1, \frac{D}{C_d} \right) + \alpha * (4.561 * ((C_d - 2400)/100)^2 - 0.524 * (L^{bfs}/5200) * ((C_d - 2400)/100)^2) \quad (5-7)$$

5.3 Travel Time Models for Merge Segment

When demand is less than the downstream segment capacity, “free flow speed” is found to be the only variable (besides demand and downstream capacity) that impacts travel time. T.T.

model for uncongested conditions is presented below:

$$TT^1 = 126.83 - 1.09 * V + 5.678 * \left(\frac{D + D_r}{C_d} \right) - 0.001 * C_d \quad (5-8)$$

V = Free flow speed

D = Freeway demand

D_r = On-ramp demand

C_d = Capacity of downstream segment

The summary of uncongested model for merge segment is presented in Table 5-2.

In order to tie up this model with model from second part,

$$TT^1 = 126.83 - 1.09 * V + 5.678 * \text{MIN} \left\{ 1, \left(\frac{D + D_r}{C_d} \right) \right\} - 0.001 * C_d \quad (5-9)$$

It can be observed from equation-6 that the T.T. varies with demand until demand is less than downstream segment capacity. Once the demand reaches downstream segment capacity, T.T. does not vary with increase in demand, and it becomes a constant. Thus, the estimated model behaves consistently with the objective of the first part of the model.

The second part of the model corresponds to those scenarios where demand exceeds the downstream segment capacity. Under these conditions, demand, downstream capacity, and

length of the basic freeway segment variables were found to impact T.T. and are used as explanatory variable. The congested model is estimated in two stages: first the range of the T.T. is modeled and then the shape of the sigmoid curve is estimated.

As the final objective of this model estimation is to develop a combined model that will be used for all values of demand, the second model is modified such that it smoothly connects the model from first part at demand equals downstream capacity. This modification involves modeling range of T.T. minus T.T. from part one when demand equals capacity. The model for estimating range of T.T. minus T.T. from part one when demand equals capacity is shown below:

$$T^{range} = 14.76 + (3.35 - 0.1 * (L^e/5200)) * ((C_d - 2400)/100)^2 + 192.1 * Dr/C_d \quad (5-10)$$

Where,

T^{range} = Range of travel time minus travel time from part one when demand equals capacity

L^e = Length of basic freeway segment

C_d = Capacity of downstream segment

The congested T.T. range model statistics are presented in Table 5-4.

It can be observed from equation-5 that as the length of the basic freeway segment increases, the range of the T.T. decreases. Further it can also be observed that as the downstream segment capacity increases the maximum T.T. exponentially decreases. Thus, it is found that the estimated model follows the observed logic in the model.

The combined model for basic freeway segment (BFS) is presented below:

$$TT = 120.4 - 0.981 * V + 1.401 * \text{MIN} \left(1, \frac{D}{C_d} \right) + \alpha * (14.76 + 3.35 * ((C_d - 2400)/100)^2 - 0.1 * (L^e/5200) * ((C_d - 2400)/100)^2 + 192.1 * Dr/C_d) \quad (5-11)$$

Where C_d , is derived similarly to the way it is derived for basic freeway segment, but the demand now includes freeway demand and the on-ramp demand.

5.4 Travel Time Models for Diverge Segment

When demand is less than the downstream segment capacity, “free flow speed” was found to be the only variable that impacts travel time. T.T. for uncongested conditions is presented below:

$$TT^1 = 132.81 - 1.038 * V + 8.634 * \left(\frac{D}{C_d}\right) - 0.006 * C_d \quad (5-12)$$

Where,

V = Free flow speed

D = Demand

C_d = Capacity of downstream segment.

The summary of uncongested model for BFS is presented in Table 5-5.

In order to tie up this model with model from second part,

$$TT^1 = 132.81 - 1.038 * V + 8.634 * \text{MIN}\left(1, \frac{D}{C_d}\right) - 0.006 * C_d \quad (5-13)$$

It can be observed from equation-4 that the T.T. varies with demand until demand is less than downstream segment capacity. Once the demand reaches downstream segment capacity, T.T. does not vary with increase in demand, and it becomes a constant. Thus, the estimated model behaves consistently with the objective of the first part of the model.

The second part of the model corresponds to those scenarios where demand exceeds the downstream segment capacity. Under these conditions, demand, downstream capacity, and length of the entry segment variables were found to impact T.T. and are used as explanatory variable. The congested model is estimated in two stages: first the range of the T.T. is modeled and then the shape of the sigmoid curve is estimated.

As the final objective of this model estimation is to develop a combined model that will be used for all values of demand, the second model is modified such that it smoothly connects the

model from first part at demand equals downstream capacity. This modification involves modeling range of T.T. minus T.T. from part one when demand equals capacity. The model for estimating range of T.T. minus T.T. from part one when demand equals capacity is shown below:

$$T^{range} = 4.868 * \left(\frac{C_d - 2400}{100}\right)^2 + 0.24 * (L^e / 5200) * ((C_d - 2400) / 100)^2 - 10.412 * D^{off} \quad (5-13)$$

Where,

T^{range} = Range of travel time minus travel time from part one when demand equals capacity

L^e = Length of entry segment

C_d = Capacity of downstream segment

D^{off} = Off-ramp demand/exit percentage

The congested T.T. range model statistics are presented in Table 5-6.

It can be observed from equation-5 that as the length of the basic freeway segment increases, the range of the T.T. decreases. Further it can also be observed that as the downstream segment capacity increases the maximum T.T. exponentially decreases. Thus, it is found that the estimated model follows the observed logic in the model.

The combined model for basic freeway segment (BFS) is presented below:

$$T.T. = 132.81 - 1.038 * V + 8.634 * \text{MIN} \left(1, \frac{D}{C_d}\right) - 0.006 * C_d + \alpha * \left((4.868 + 0.24 * (L^e / 5200)) * \left(\frac{C_d - 2400}{100}\right)^2 - 10.412 * D^{off} \right) \quad (5-14)$$

Where α , is derived similarly to the way it was derived for basic freeway segment, but the demand now includes freeway demand and the off-ramp demand.

5.5 Travel Time Models for Weaving Segment

When demand is less than the downstream segment capacity, “free flow speed” was found to be the only variable that impacts travel time. T.T. model for uncongested conditions is presented below:

$$TT^1 = 115.18 - 1.05 * V + 12.835 * \left(\frac{D^f + D^r}{C_d} \right) + 0.0012 * C_d \quad (5-15)$$

Where,

V = Free flow speed

D = Demand

C_d = Capacity of downstream segment

The summary of uncongested model for weaving segment is presented in Table 5-7.

In order to tie up this model with model from second part,

$$TT^1 = \mathbf{115.18} - \mathbf{1.05} * V + \mathbf{12.835} * \text{MIN} \left(1, \frac{D^f + D^r}{C_d} \right) + \mathbf{0.0012} * C_d \quad (5-16)$$

It can be observed from equation-4 that the T.T. varies with demand (sum of freeway demand and ramp demand) until demand equals downstream segment capacity. Once the demand reaches downstream segment capacity, T.T. does not vary with increase in demand, and it becomes a constant. Thus, the estimated model behaves consistently with the objective of the first part of the model.

The second part of the model corresponds to those scenarios where demand exceeds the downstream segment capacity. Under these conditions, demand, downstream capacity, and the length of the entry segment variables were found to impact T.T. and are used as explanatory variable. The congested model is estimated in two stages: first the range of the T.T. is modeled and then the shape of the sigmoid curve is estimated.

As the final objective of this model estimation is to develop a combined model that will be used for all values of demand, the second model is modified such that it smoothly connects the

model from first part at demand equals downstream capacity. This modification involves modeling range of T.T. minus T.T. from part one when demand equals capacity. The model for estimating range of T.T. minus T.T. from part one when demand equals capacity is shown below:

$$T^{\text{range}} = 34.8396 + 3.4097 * ((C_d - 2400)/100)^2 - 0.0568 * (L^e/5200) * ((C_d - 2400)/100)^2 - 4.4184 * D^{\text{off}} \quad (5-17)$$

Where,

T^{range} = Range of travel time minus travel time from part one when demand equals capacity

L^e = Length of entry segment

C_d = Capacity of downstream segment

D^{off} = Off-ramp demand/exit percentage

The congested T.T. range model statistics are presented in Table 5-8.

It can be observed from equation-5 that as the length of the basic freeway segment increases, the range of the T.T. decreases. Further it can also be observed that as the downstream segment capacity increases the maximum T.T. exponentially decreases. Thus, it is found that the estimated model follows the observed logic in the model.

The combined model for weaving segment is presented below:

$$T.T. = 115.18 - 1.05 * V + 12.835 * \text{MIN} \left(1, \left(\frac{D^f + D^r}{C_d} \right) \right) + 0.0012 * C_d + \alpha * (34.8396 + (3.4097 - 0.0568 * (L^e/5200)) * ((C_d - 2400)/100)^2 - 4.4184 * D^{\text{off}}) \quad (5-18)$$

Where α , is derived similarly to the way it was derived for basic freeway segment, but the demand now includes freeway demand, on-ramp demand, and off-ramp demand.

5.6 Travel Time Models for Bottleneck

In this study a bottleneck is always assumed to be a basic freeway segment. T.T. models for a bottleneck are developed only under congested conditions. When the bottleneck is

uncongested, the T.T. models developed for basic freeway segment are used assuming the downstream segment of the bottleneck has unrestricted capacity. This section presents the T.T. models for bottleneck under congested conditions.

It was found that demand and capacity are the only variables that impacts T.T. for congested conditions. The impact of demand on T.T. for various capacity values is shown in Figure 5-6. As shown in Figure 5-6, for a given capacity the impact of demand on T.T. is insignificant.

The impact of capacity on T.T. for various values of demand is shown in Figure 5-7. As shown in Figure 5-7, for a given demand the impact of capacity on T.T. is significant and the impact of demand on T.T. is insignificant.

As shown in Figure 5-7, the variation of T.T. with capacity is in the shape of a parabola with the transition point near 2400. Thus, a parabolic function is used to model the relationship between T.T. and capacity.

The model for estimating T.T. of the bottleneck is shown below:

$$T^{\text{range}} = 114.05 + 1.723 * ((C_d - 2400)/100)^2 \quad (5-19)$$

Where,

T^{range} = Range of travel time minus travel time from part one when demand equals capacity

C_d = Capacity of downstream segment

The congested travel time range model statistics are presented in Table 5-9.

Table 5-1. BFS uncongested model statistics

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	120.8686	0.634767	190.4141	0
V	-1.00632	0.009373	-107.361	0
$\frac{D}{C_d}$	4.654677	0.333106	13.97355	0
Goodness of fit measures				
R2	0.975288			
Adjusted R2	0.975122			
Number of cases	300			

Table 5-2. BFS congested T.T. range model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	0	N/A	N/A	N/A
$((C_d - 2400)/100)^2$	4.561	0.130	35.040	0.000
$(L^{bfs}/5200) * ((C_d - 2400)/100)^2$	-0.524	0.041	-12.827	0.000
Goodness of fit measures				
R2	0.889			
Adjusted R2	0.886			
Number of cases	400			

Table 5-3. Merge uncongested model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	126.831	1.128	112.409	0.000
Speed	-1.090	0.011	-95.440	0.000
$((D+Dr)/C_d)$	5.678	0.636	8.923	0.000
DS Capacity	-0.001	0.000	-2.087	0.037
Goodness of fit measures				
R2	0.92			
Adjusted R2	0.92			
Number of cases	844			

Table 5-4. Merge congested T.T. range model statistics and estimates

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	14.76	3.27	4.52	0.00
$((C_d - 2400)/100)^2$	3.35	0.06	54.42	0.00
$(L^{bfs}/5200) * ((C_d - 2400)/100)^2$	0.10	0.05	2.08	0.04
Dr/C_d	192.10	17.91	10.73	0.00

Table 5-5. Diverge uncongested model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	132.810	1.40	94.71	0.00
Speed	-1.038	0.01	-69.41	0.00
D/C	8.634	0.70	12.41	0.00
DS-Capacity	-0.006	0.00	-13.71	0.00
Goodness of fit measures				
R2		0.82		
Adjusted R2		0.82		
Number of cases		1152		

Table 5-6. Diverge congested T.T. range model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	0	N/A	N/A	N/A
$((C_d - 2400)/100)^2$	4.868	0.081	59.818	0.000
$(L^{bfs}/5200) * ((C_d - 2400)/100)^2$	0.240	0.069	3.458	0.001
% Exit	-10.412	0.553	-18.845	0.000
Goodness of fit measures				
R2		0.93		
Adjusted R2		0.93		
Number of cases		720		

Table 5-7. Weaving segment uncongested model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	115.18	1.38	83.51	0.00
Speed	-1.0496	0.01	-79.19	0.00
$D^f + D^r$				
C_d	12.8346	0.58	22.03	0.00
DS-Capacity	0.0012	0.00	2.72	0.01
Goodness of fit measures				
R2		0.65		
Adjusted R2		0.65		
Number of cases		3615		

Table 5-8. Weaving segment congested T.T. range model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	34.8396	2.1193	16.4392	0.0000
$((C_d - 2400)/100)^2$	3.4097	0.0282	120.8524	0.0000
$(L^{bfs}/5200) * ((C_d - 2400)/100)^2$	-0.0568	0.0218	-2.6077	0.0092
% Exit	-4.4184	0.1836	-24.0636	0.0000
Goodness of fit measures				
R2		0.94		
Adjusted R2		0.94		
Number of cases		1728		

Table 5-9. Bottleneck T.T. model summary

Explanatory variables	Coefficients	Standard Error	t Stat	P-value
Intercept	114.049	4.316	26.427	0.000
$((C_d - 2400)/100)^2$	1.723	0.037	46.221	0.000
Goodness of fit measures				
R2		0.49		
Adjusted R2		0.49		
Number of cases		2232		

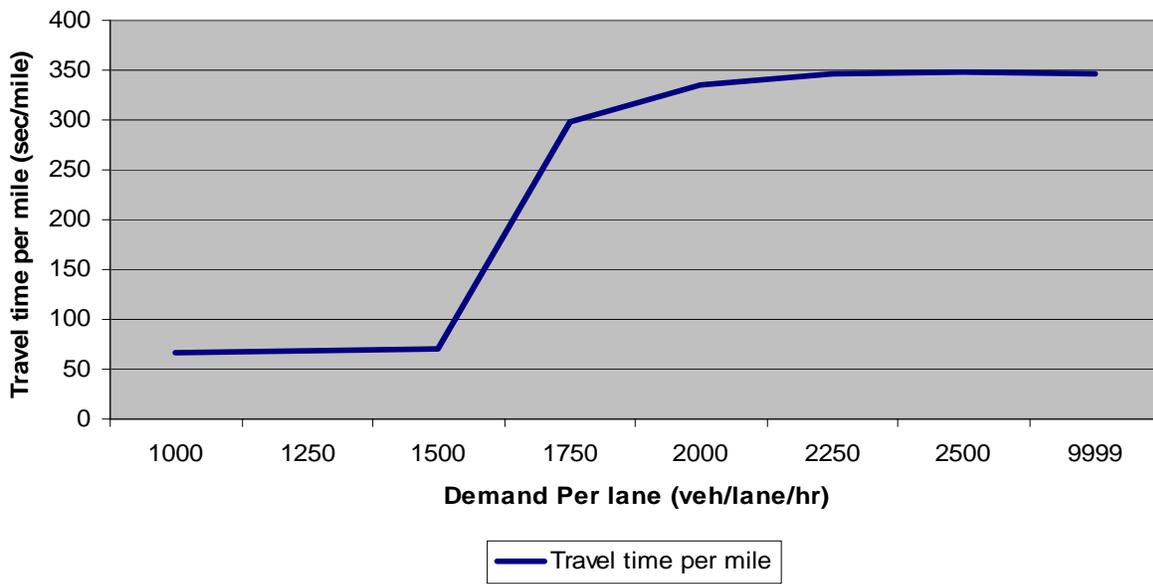


Figure 5-1. Variation of TT per mile with demand (lanes = 2, FFS = 50 mph, length of basic freeway segment = 5000 ft, and downstream capacity = 1515 veh/hr/lane)

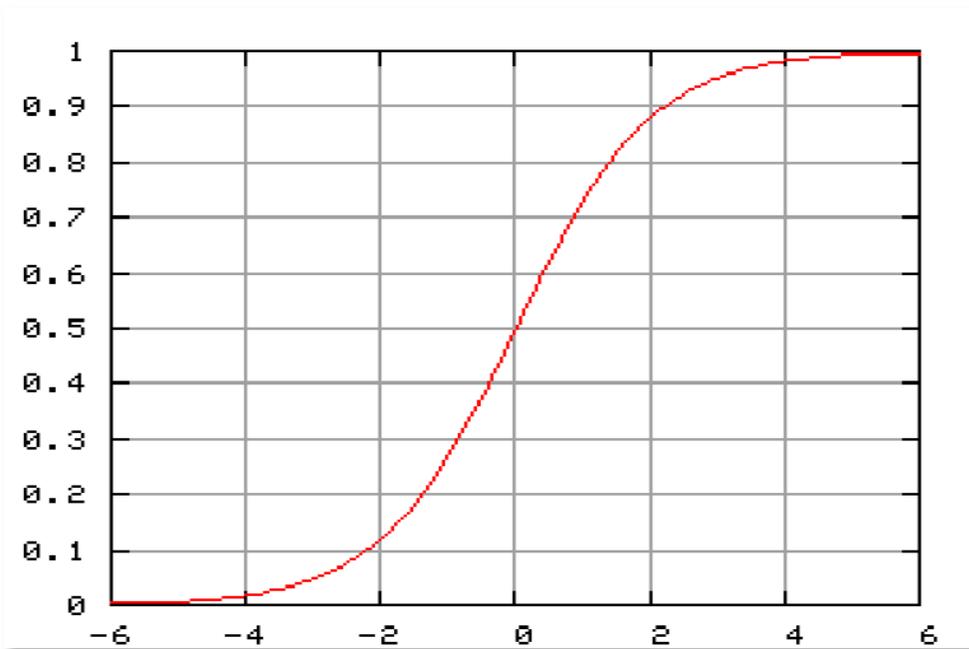


Figure 5-2. Sigmoid curve

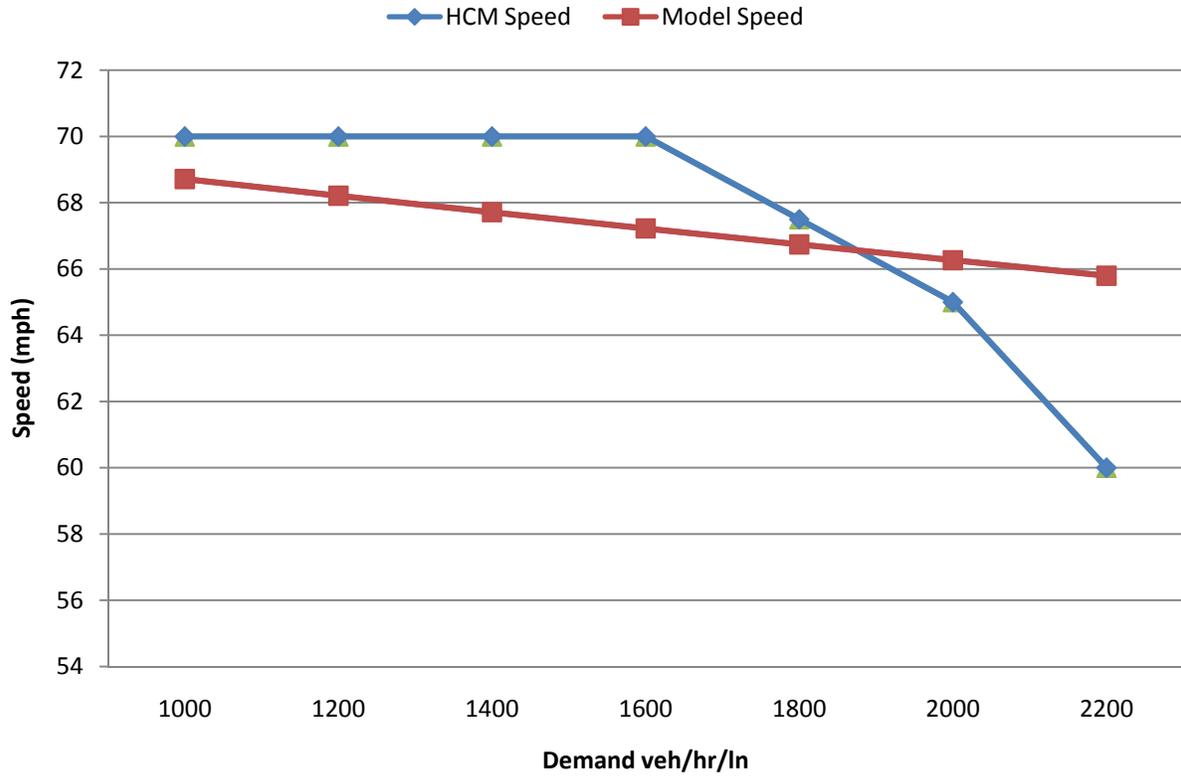


Figure 5-3. Comparison of average HCM speed and model speed

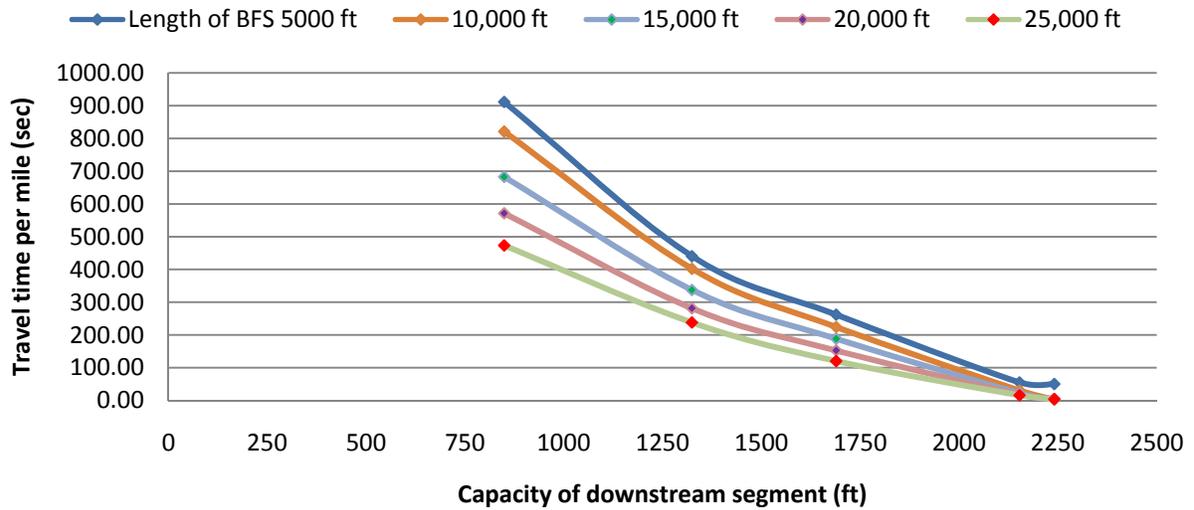


Figure 5-4. Variation of maximum T.T. with demand for a series of length of basic freeway segment

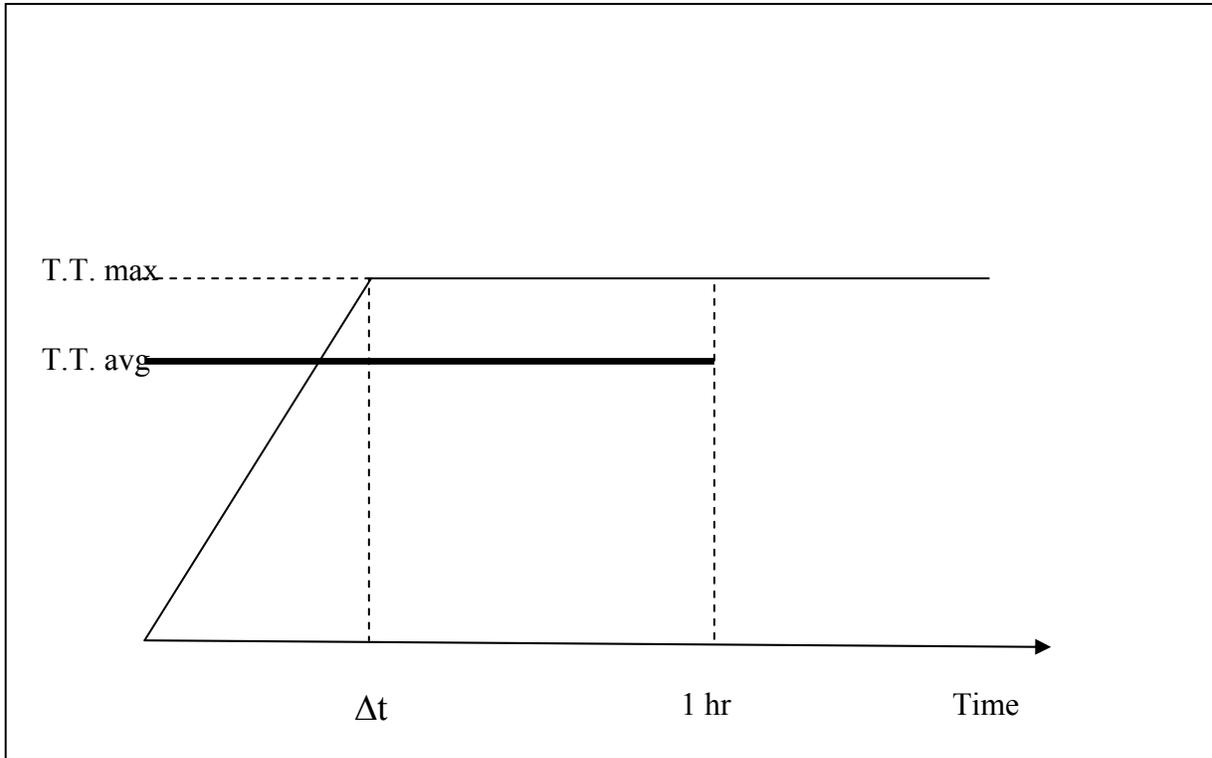


Figure 5-5. Variation of travel time with time interval

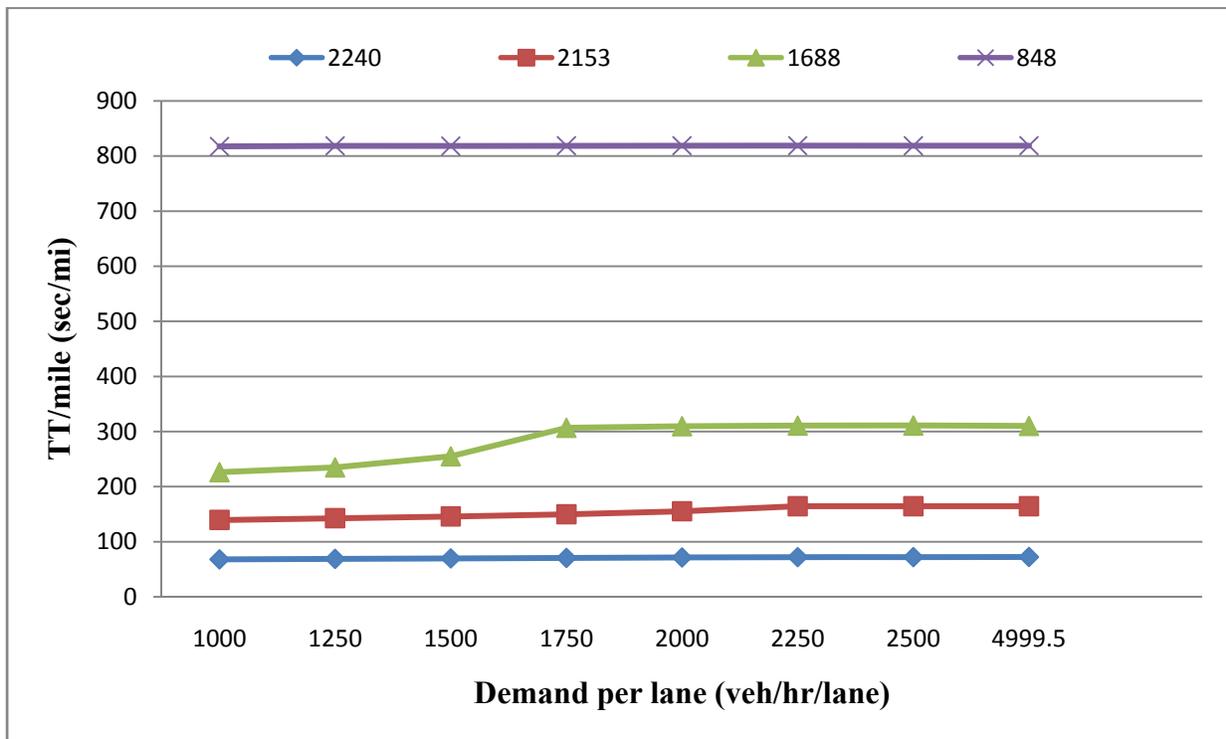


Figure 5-6. Variation of TT per mile with demand for various values of downstream capacity (lanes = 2, length of basic freeway segment = 5000 ft and FFS is 55 mph)

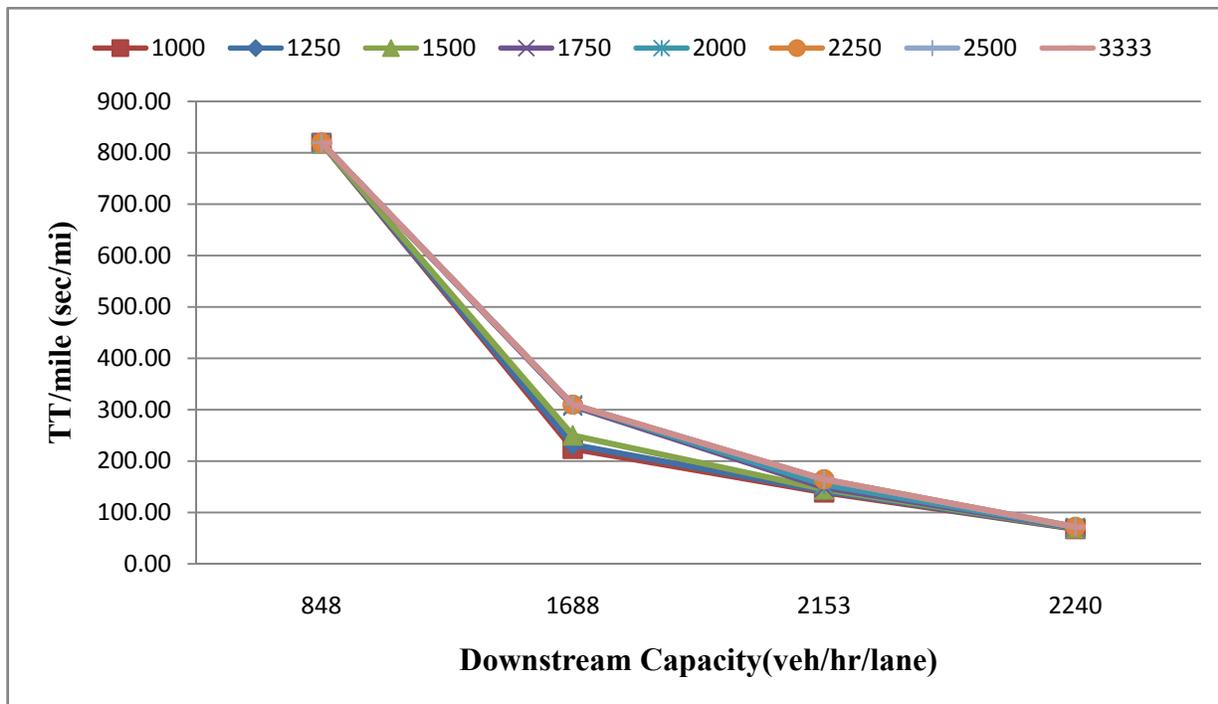


Figure 5-7. Variation of TT per mile with capacity for various values of demand (lanes = 2, length of basic freeway segment = 5000 ft and FFS is 55 mph)

CHAPTER 6 COMPARISON WITH OTHER ANALYTICAL MODELS

This section compares the estimated T.T. from analytical models and other existing planning T.T. models. As the BPR and MTC models are macroscopic and focus mainly on the planning applications, reasonable comparisons cannot be made between them and Akceliks model nor with the analytical models developed in this study. The analytical models developed in this study are comparable with Akceliks model only, and these comparisons are presented below.

The analytical T.T. models are compared with the existing models such as: BPR, MTC, and Akcelik. Based on these comparisons, the methodology of using simulation for estimating T.T. can be compared against existing models.

It can be observed that both Akceliks model and analytical models developed in this study make similar predictions under uncongested conditions i.e., when demand is less than the downstream capacity. However, when demand exceeds downstream segment capacity, the analytical models Akceliks model and developed in this study do not make similar predictions. While the Akceliks model shows linear change in travel time between congested and un-congested conditions. The analytical model however predicts that the travel time increases exponentially and then flattens out after the study segment is saturated.

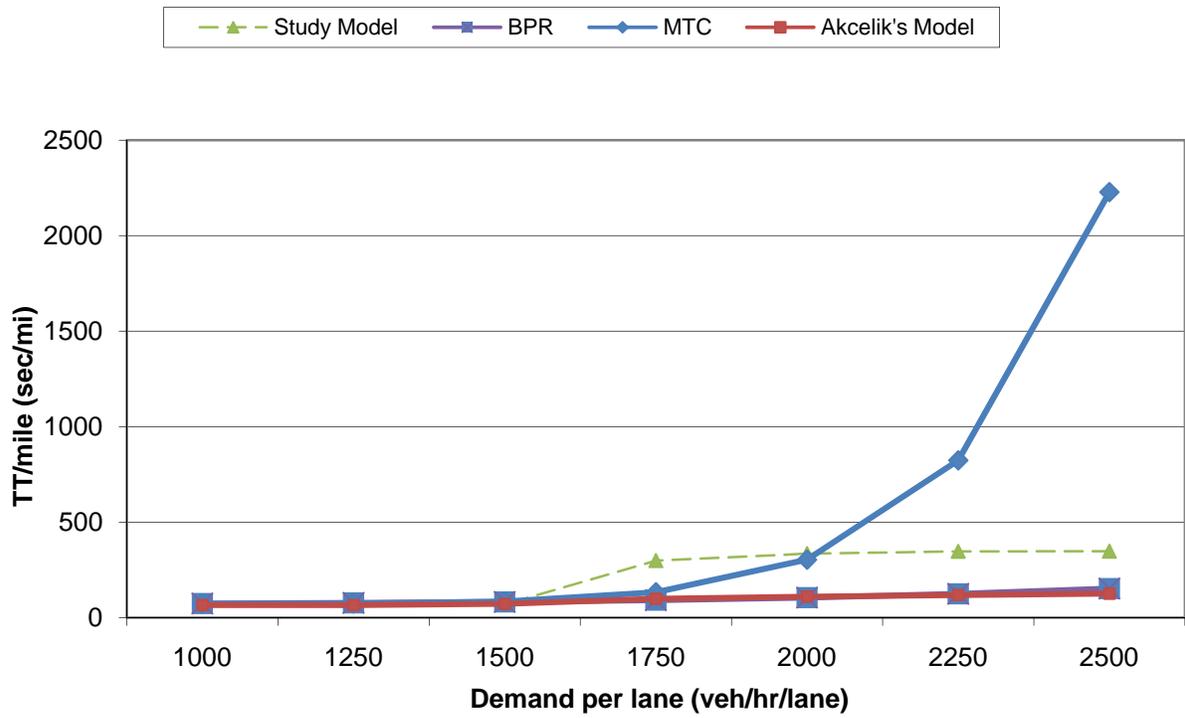


Figure 6-1. Variation of upstream segment T.T. with demand for several analytical models with capacity at 1515 veh/hr/ln

CHAPTER 7 CONCLUSIONS & RECOMMENDATIONS

This chapter summarizes the main findings from the research work carried out as part of this thesis. Based on these findings, further research recommendations are made.

7.1 Summary

Literature was reviewed to identify variables that might impact T.T.. Using these variables, scenarios were developed and simulated to identify the most important variables that may affect T.T. in the simulator. Using these important variables, a set of scenarios were developed and simulated to obtain a database for analytical model development. Analytical models were developed using this database. The analytical models developed in this thesis were compared to other T.T. estimation models.

7.2 Conclusions

Analytical T.T. models using demand have been developed, and are applicable for both under-saturated and oversaturated conditions. At high levels of demand or congestion these models are not consistent with each other and have not been compared with field data. Further, some of the existing models, such as BPR, consider flows greater than capacity, which is unrealistic. Thus there is a need for further advancement in the T.T. estimation models which make accurate predictions at both saturated and unsaturated congestion levels. Moreover most of the existing models (BPR and MTC) do not consider the queuing phenomenon explicitly. Thus analytical models which consider formation and dissipation of queues and also consider the delay associated with these queues in estimation of T.T. is required. Towards this end, the present study developed analytical models for estimating T.T., using simulation data.

A preliminary list of variables that may affect the T.T. are considered. These variables are used for simulation, and significant variables are selected for further consideration. Not all of the

freeway segments require the same set of inputs to estimate T.T., therefore each segment type is considered separately. The models developed in this study can be used in various freeway applications, listed in Section 7.3 to estimate freeway corridor T.T.

These models can be used to estimate freeway T.T. easily and quickly compared to a full-scale simulation of the corridor. Further, the models developed in this study are much more accurate and represent field conditions better than the BPR and MTC models, which do not consider capacity restrictions on links i.e. allow more vehicles to be loaded onto the link than the capacity of the link. Moreover, the models developed in this study are applicable to all the freeway segment types are thus more versatile than the BPR and MTC models which don't distinguish the different freeway segments.

7.3 Model Applications

The models developed as part of this thesis can be applied to study freeway corridors under several situations as listed below:

- Freeway Work Zones
 - When there is a freeway work-zone, some of the lanes might be closed. This lane closure creates bottleneck, which affects the T.T. of all the upstream segments. The T.T. of the work-zone bottleneck and the upstream segments can be obtained from the models developed in this thesis.
- Freeway corridors with lane drops
 - When there is a lane drop, bottleneck is created. This bottleneck affects the T.T. of all the upstream segments. The T.T. of the lane drop bottleneck and the upstream segments can be obtained from the models developed in this thesis.
- Freeway Incidents
 - When there is a freeway incident, a bottleneck is created. This bottleneck affects the T.T. of all the upstream segments. The T.T. of the lane drop

bottleneck and the upstream segments can be obtained from the models developed in this thesis.

7.4 Further Research

This study used CORSIM micro-simulation software package for simulating scenarios, which are later used for development of the analytical models. Several other micro-simulation software packages are available, including AIMSUN, PARAMICS, and VISSIM that suit the general requirements of this study. The algorithms used in these micro-simulation software packages are different. The impact of other micro-simulation software packages on the analysis conducted in this study can be carried out.

Driver population factor and percentage of trucks were not considered in this study, to contain the number of scenarios within a reasonable range. Future research might consider these variables in addition to the variable already considered in this study.

Instead of using simulation to generate the data for estimating models, the possibility of using flow-density curves to estimate uncongested and congested T.T.s should be explored.

Instead of using a queuing system to model the transition from uncongested conditions to congested conditions, the possibility of using shockwave analysis should be explored.

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BIOGRAPHICAL SKETCH

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