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Modeling the Effect of a Road Construction Project on Transportation System Performance

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MTI MINETA TRANSPORTATION INSTITUTE

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MINETA TRANSPORTATION INSTITUTE

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MODELING THE EFFECT OF A ROAD CONSTRUCTION PROJECT ON TRANSPORTATION SYSTEM PERFORMANCE

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16. Abstract

Road construction projects create physical changes on roads that result in capacity reduction and travel time escalation during the construction project period. The reduction in the posted speed limit, the number of lanes, lane width and shoulder width at the construction zone makes it difficult for the road to accommodate high traffic volume. Therefore, the goal of this research is to model the effect of a road construction project on travel time at road link-level and help improve the mobility of people and goods through dissemination or implementation of proactive solutions.

Data for a resurfacing construction project on I-485 in the city of Charlotte, North Carolina (NC) was used evaluation, analysis, and modeling. A statistical t-test was conducted to examine the relationship between the change in travel time before and during the construction project period. Further, travel time models were developed for the freeway links and the connecting arterial street links, both before and during the construction project period. The road network characteristics of each link, such as the volume/ capacity (V/C), the number of lanes, the speed limit, the shoulder width, the lane width, whether the link is divided or undivided, characteristics of neighboring links, the time-of-the-day, the day-of-the-week, and the distance of the link from the road construction project were considered as predictor variables for modeling.

The results obtained indicate that a decrease in travel time was observed during the construction project period on the freeway links when compared to the before construction project period. Contrarily, an increase in travel time was observed during the construction project period on the connecting arterial street links when compared to the before construction project period. Also, the average travel time, the planning time, and the travel time index can better explain the effect of a road construction project on transportation system performance when compared to the planning time index and the buffer time index. The influence of predictor variables seem to vary before and during the construction project period on the freeway links and connecting arterial street links. Practitioners should take the research findings into consideration, in addition to the construction zone characteristics, when planning a road construction project and developing temporary traffic control and detour plans.

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EXECUTIVE SUMMARY

Drivers observe variation in travel time due to congestion and delay on existing transportation facilities. A road construction project has a significant effect on travel time, leading to increased congestion, delay, and driver frustration. The effect on travel time due to the road construction project decreases as the distance from the road construction project location increases. The effect of the road construction project on travel time also extends to other roads that are connected to the road with the construction project. It also depends on the traffic condition and time-of-the-day on these roads. Therefore, one needs to consider spatial dependency, and the influence on links within the proximity of the road construction project, over time, to model the effect of the road construction project on travel time at link-level. The findings from such research will help proactively plan construction activities on roads to mitigate mobility and congestion problems. Therefore, the goal of this research is to model the effect of a road construction project on travel time at link-level and help improve the mobility of people and goods through dissemination or implementation of proactive solutions. The objectives of this research are, for a road construction project which occurred in the city of Charlotte, North Carolina, begun in June 2015 and lasting for six months: 1) to examine travel time and travel time variations, before and during the road construction project period, on the selected road; 2) to examine travel time and travel time variations on roads connected to the selected road; 3) to examine the effect of network characteristics, and develop models to estimate travel time on the selected road and on other connected roads; 4) to examine and develop models to estimate travel time, by the time-of-the-day and by the day-of-the-week, during the road construction project period; and 5) to compare the models for estimating travel time during the construction project period with models for estimating travel time before the construction project period.

Data, from the year 2011 to the year 2016, was gathered from the Traffic Incident Management Systems (TIMS) and local agencies to identify a resurfacing construction project period for modeling the effect of the road construction project on freeways and on connecting arterial street links. The data obtained was processed by the time-of-the-day and the day-of-the-week in order to compute travel time performance measures using the Microsoft SQL 2012 software. A statistical t-test was conducted to examine the relationship between the change in travel time before and during the construction project period.

Generalized Linear Models (GLM) were developed, with the average travel time on a link in the vicinity of the road construction project as the dependent variable. The characteristics of each link, such as the volume/capacity (V/C), the number of lanes, the speed limit, the shoulder width, the lane width, and whether the link is divided or undivided were considered as predictor variables for modeling. Characteristics of neighboring links, such as the upstream and downstream link length, the upstream and downstream V/C, the upstream and downstream number of lanes, and the upstream and downstream speed limit, were also considered as predictor variables for modeling. Furthermore, the time-of-the-day, the day-of-the-week, and the distance of the link from the road construction project were considered as predictor variables for modeling. The goodness-of-fit was assessed using the quasi likelihood under independence model criterion (QIC) and the corrected quasi likelihood under independence model criterion (QICC). The developed models were then validated using randomly selected samples for the same construction project. The samples used for validation were not used for model development.

The travel times before and during the construction project period are significantly different than estimates obtained using the Bureau of Public Roads (BPR) travel time equation. A decrease in travel time was observed during the construction project period on the freeway links when compared to the before construction project period. Contrarily, an increase in travel time was observed during the construction project period on the connecting arterial street links when compared to the before construction project period.

The results obtained indicate that during the before construction project period, predictor variables such as the V/C, the upstream number of lanes, the upstream speed limit, the downstream V/C, and the downstream number of lanes have a significant effect on travel time on freeway links. During the construction project period, the V/C, the upstream link length, the upstream V/C, the downstream link length, the downstream V/C, and the downstream number of lanes have a significant effect on travel time on freeway links. Likewise, during the before construction project period, the V/C, the speed limit, the upstream V/C, and the upstream number of lanes have a significant effect on travel time on the connecting arterial street links. Similarly, during the during the construction project period, the V/C, the speed limit, the upstream V/C, the upstream link length, the upstream number of lanes, and the downstream number of lanes have a significant effect on travel time on the connecting arterial street links.

I. INTRODUCTION

Travel demand has been progressively increasing with the continuous growth of contemporary civilization and the need for more movement of people and goods on the roads. The effect of this increasing travel demand is persisting congestion on limited road networks, an upsurge in air quality problems, and a shortage of intact and reliable transportation infrastructure. Fastest-path to travel from an origin to a destination was adopted, for years, by motorists. These motorists usually plan for some expected delay due to recurring congestion, which is common today in many United States cities and towns. Additionally, motorists are sensitivity to variations and ambiguity in traffic condition. The unexpected, non-recurring congestion on a day-to-day basis concern motorists the most. Situations that may lead to non-recurring congestion include crashes, mechanical failure of vehicles, inclement weather, special events, and freeway or arterial construction zones and activity. Therefore, the reliability of a route is playing a prominent role in motorists' departure and route choice decisions among various other travel time performance measures.[1]

Reliability is defined as the probability that a component or system will perform a required function (without failure) during a time period when used under stated operating conditions.[2] The reliability of a link, corridor or the road network, therefore, could be defined as the ability to consistently provide an acceptable level of service (LOS) to the motorist under-stated environmental and operational conditions during a given period.[3, 4]

Reliability as a performance measure is expected to be widely used in transportation planning, for project prioritization, and for allocation of resources.[5] Travel times are known to vary greatly from day-to-day, and motorists remember those few days they experience through unexpected delays.[5] Figure 1 shows the communication of traffic condition in the past, usually given in terms of averages, and compares this to the ways in which travel times could vary by month.[5]

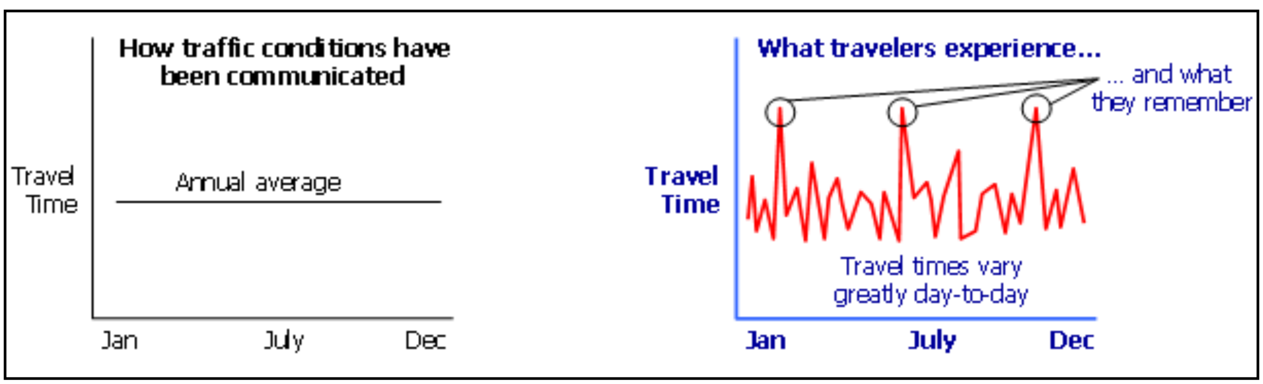

Figure 1. Average Travel Time and Travelers Experience by Month[5]

The reliability of a transportation network varies with situations that lead to non-recurring congestion. It also varies by the type of road construction project. These road construction projects include the construction of new roads or lanes, pavement repair, resurfacing, installation of pavement markers, etc., and often involve one or more lane closures.

Accurate prediction of travel time for a given route or a freeway, however, remains a challenging problem, as it is influenced by many different traffic and road parameters. In addition, traffic can queue up the upstream side of construction due to the staggering, queuing, and delay at the construction zone. Sometimes, vehicular traffic could also migrate from the freeway links to the connecting arterial street links in an effort to avoid congestion and major delays at the construction zone. These effects depend on the time-of-the-day and the day-of-the-week.

CONSTRUCTION ZONES ON FREEWAYS

The number of work zones in the United States has increased in recent years due to efforts to upgrade and expand the life span of highways and roads.[6] These reconstruction and rehabilitation work zones can be found on almost all interstates and freeways. Lane closures are required for various types of work activities, such as pavement repairs, resurfacing, installation of pavement markers, etc. While work zones serve to perform reconstruction and rehabilitation without completely shutting down traffic operations, they nevertheless have significant effects. These effects include reduced freeway capacity, increased crash rates, increased fuel consumption and emissions, increased travel times, increased queue lengths, and additional congestion and delay.[7,8] Delay is one of the most significant problems associated with work zones. In some cases, highway traffic operations can completely fail due to congestion caused by work zones, particularly during the morning and evening peak hours.[7]

In short, road construction projects create physical changes on roads that result in capacity reduction and travel time escalation during the construction project period. Consequently, vehicles go through construction zones at reduced speeds and with fluctuating traffic flow rates.[9] These fluctuations in traffic flow, furthermore, lead to variation in travel times along the route. If the capacity of a road in a construction zone can be predicted, then systematic planning of traffic management can be executed for maintaining certain capacity, for improving travel time, and for reducing delay in the construction zones.[10] Evaluating and predicting the effect of road construction projects on travel time variations, by the time-of-the-day and the day-of-the-week, will aid in better understanding their effect on travel time variations or travel time reliability, and proactively adopt enhanced temporary traffic control practices.

PROBLEM STATEMENT

Network characteristics such as traffic volume, capacity, and speed limit influence travel times. Travel time increases as the traffic volume increases. On the other hand, travel time decreases as the speed limit and the number of lanes increases. In addition, shoulder width and lane width influence travel time either by increasing or decreasing travel times.

During the construction project period, speed limits are lowered from the usual speed limit, which tends to reduce vehicle speed and increase the travel time. Likewise, one or multiple lanes may be closed during the construction project period. The reduction in the number of lanes, lane width and shoulder width at the construction zone makes it difficult for the road to accommodate high traffic volume. It also reduces vehicle speed and increases travel time.

Upstream and downstream links' characteristics, such as link length, traffic volume, capacity, number of lanes, and the speed limit of upstream and downstream links, also influence the travel time on the selected link. If the downstream number of lanes is lower compared to the subject link, then a queue may build up resulting in an increase in congestion and travel time. Similarly, if the upstream and downstream links have entry ramps or exit ramps that connect to arterial streets, they would influence travel time both on the freeway and on the connecting arterial street links. Therefore, the characteristics of downstream and upstream ramps should be considered when modeling travel time of a link.

In addition to network and construction zone factors, parameters such as the time-of-the-day and the day-of-the-week influence travel time. Traffic volumes are higher during the morning and evening peak hours than during off-peak hours. Variation in traffic volume results in variation in travel time. Furthermore, construction activity is scheduled when traffic volume is low (say, nighttime). The variation in travel time due to construction activity at nighttime could be higher than during other times. Likewise, traffic volume is higher during weekdays when compared with the weekend days. Travel patterns and trip purposes are also different over the weekend when compared with the weekday. Therefore, the time-of-the-day and the day-of-the-week should also be considered for studying the effects of construction projects.

As stated previously, construction on a freeway influences the travel time performance on connecting arterial street links. The traffic volume on the connecting arterial street links increases due to the shift in traffic from the freeway links to the connecting arterial street links. The shift in patterns depends on the characteristics of the connecting arterial streets. Therefore, the characteristics of the connecting arterial street links, such as traffic volume, speed limit, number of lanes, and whether the road is divided or undivided, need to be considered for modeling and analysis.

The effect of a construction project is likely to decrease as the distance from the construction project increases. To study the effect of a construction zone, considering spatial structure, the distance of each link from the construction zone should also be considered.

OBJECTIVES OF THIS RESEARCH

The goal of this research is to examine and model the effects of a road construction project on travel time at link-level. The objectives are:

1. to examine travel time and travel time variations, before and during the road construction project period, on a selected road,

2. to examine travel time and travel time variations on roads connected to the selected road with the construction project,

3. to examine the effects of network characteristics and develop models to estimate travel time, on the selected road with the construction project and on other connected roads,

4. to examine and develop models to estimate travel time by the time-of-the-day and the day-of-the-week during the road construction project period, and

5. to compare the models for estimating travel time during the construction project period with models for estimating travel time before the construction project period.

ORGANIZATION OF THE REPORT

The rest of the report consists of 5 chapters. Chapter 2 summarizes past studies on delay and congestion at construction zones, travel time estimations, and predictions on freeways. Also, the limitations of past research are presented in Chapter 2. Chapter 3 summarizes the data collection, data processing, and methodology adopted to examine the effect of a road construction project on travel time at link-level. The relationship between travel time before and during the construction project periods are discussed in Chapter 4. The analysis and results obtained from modeling the effect of a road construction project on travel time are presented in Chapter 5. Chapter 6 summarizes conclusions and discusses recommendations to improve travel time at the construction zone and scope for further research.

II. LITERATURE REVIEW

This chapter presents a review of past studies that have been carried out on congestion, delay, and travel time variations in work zones. It also provides a discussion of methodologies adopted by previous researchers.

CONGESTION, CRASHES AND DELAY DUE TO CONSTRUCTION ZONES

One of the major concerns at work zones is traffic delay. Martinelli (1996) developed a mathematical model to estimate the optimal length of work zones so that the delay can be minimized on freeways.[7] Jiang (1999) predicted traffic flow rate by using the Kalman predictor model; If the predicted traffic flow is similar to or greater than the traffic capacity, then traffic congestion is likely in the coming time period and then the traffic control actions can be taken to prevent the congestion at construction zones.[11]

Kim et al. (2001) developed a regression model to estimate link capacity at work zones. They observed that contributing factors such as the number of closed lanes, the proportion of heavy vehicles, grade, and the intensity of work activity have a significant effect on capacity reduction.[8] Chien et al. (2002) utilized a computer simulation to demonstrate that delays may be underestimated by the use of deterministic queuing theory.[12]

Ghosh-Dastidar and Adeli (2006) developed a neural network-wavelet microsimulation model to track the travel times of individual vehicles, for estimating traffic delay and queue length at freeway work zones. The model developed was observed to be more accurate than other microscopic simulation models.[13] Zheng et al. (2011) compared different traffic capacity predictions models listed in the Highway Capacity Manual (HCM). The comparison showed that the neuro-fuzzy model was more accurate than other linear and multi-linear regression models.[10]

Ramezani and Benekohal (2011) investigated the mechanism of queue propagation and dissipation at two potential bottlenecks at freeway work zones[14]. They showed that when the volume exceeds the capacity of the transition area and the workspace, both locations will be active bottlenecks.[14] Fitzpatrick (2016) explained the operational implications of reduced shoulder and lane widths on freeways; the higher the shoulder width, the higher the speed.[15] Abdelmohsen (2016) developed a novel multi-objective optimization model for generating optimal tradeoffs between minimizing traffic delay and construction cost.[6]

Venugopal and Tarko (2000) developed a regression model to estimate the number of crashes at work zones.[16] For various construction projects, the cost of the project was found to be a good substitute for some of the exposure-to-risk variables, such as the number of on- and off-ramps, the type of work, and the intensity of road work.[16] Garcia et al. (2006) presented possible options such as utilizing Global Positioning System (GPS) technology for improving safety at construction work zones on the freeways.[17] Koilada et al. (2018) identified risk factors influencing the work zone crashes, and recommended implementation of real-time work zone information systems and dynamic lane merging systems to control the safe transmission of vehicles through the work zone area.[18]

TRAVEL TIME RELIABILITY

Unexpected congestion on a day-to-day basis is more inconvenient for travelers than expected congestion. Travelers rely on travel time reliability, as measured from day-to-day or across different times of the day, for decision-making. Several studies focused on the importance of travel time measures; however, not many studies focused on travel time variations at construction zones.

Kwon et al. (2011) proposed an empirical, corridor-level method to divide the travel time unreliability or variability over a freeway section into variability due to incidents, weather, work zones, special events, and inadequate base capacity or bottlenecks.[19] Devarasetty et al. (2012) studied the travel behavior of managed lane users using a Bayesian efficient model.[20]

Carrion (2012) performed a meta-analysis to determine the reasons behind differences among the reliability estimates.[21] Beaud et al. (2012) estimated drivers' willingness to pay for travel time reliability using a mean-dispersion approach and a specific coefficient approach; both the approaches yield quite similar values for the willingness to pay.[22] Li et al. (2013) reviewed empirical measurement paradigms used to obtain willingness to pay for reliability. In addition, they estimated different models to derive values of reliability, scheduling costs, and reliability ratios.[23]

Nicholson (2015) stated that a few methods proposed in the past do not account for the standard deviation of trip times, which is sensitive to the correlation between the travel speeds on the segments of a route.[24] Ignoring such correlations can result in substantial errors when estimating the benefits of projects that are expected to result in an improvement in reliability.[24] Zhang et al. (2016) studied travel time performance of emergency vehicles, and proposed a utility-based model, as opposed to a purely time-based model, to quantify the travel time performance of emergency vehicles.[25]

Several travel time and related reliability performance measures have been proposed and used in the past. A summary of these performance measures is presented in Table 1. Pulugurtha et al. (2016; 2017) evaluated the correlations between selected travel time performance measures. They observed that average travel time is correlated with travel time-based measures, while buffer time index (BTI) is correlated with travel time indices and reliability measures. Buffer time is observed to be correlated with most travel time and travel time reliability measures.[1,3]

Table 1. Summary of Travel Time Reliability Measures [1, 3]

Index	Measure / Equation	Index	Measure / Equation
NCHRP (1998)[26] Definition	Standard deviation of travel time	λSkew[27]	$(TT90-TT50)/(TT50-TT10)$
AASHTO (2008)[28] Definition	On-time performance	λVar[29]	$(TT90-TT10)/TT50$
TranSystems Definition[30]	Probability of on-time performance	Variability[31]	TT85-TT15
Buffer Time (BT)[32]	$TT95-TTAvg$	Variability[31]	TT80-TT20
Buffer Time Index (BTI)[32]	$(TT95-TTAvg)/(TTAvg\times100)$	Variability[31]	TT70-TT30
First worst travel time over a month[33]	$TT95$	Acceptable Travel Time Variation Index[31]	$P(TTavg+ATTV)$
Second worst travel time over a month[33]	$TT90$	Desired Travel Time Reduction Index[31]	$P(TTavg-DTTR)$
Planning Time (PT)[33]	$TT95$	Travel Time Index (TTI)[34]	$TTavg\ /TTfree\ flow$
Planning Time Index (PTI)[35]	$TT95/TTfree\ flow$	Frequency of Congestion[34]	Percent of days/periods that are congested
Travel Time Variability (TTV)[36]	$TT90-TT10$		

Yesantarao and Pulugurtha (2017) and Kukkapalli and Pulugurtha (2018) examined travel time and travel time variations before, during, and after the completion of selected road construction projects, along a selected route, by computing the ratios of travel time performance measures before, during, and after the completion of selected road construction projects.[37, 38]

TRAVEL TIME ESTIMATION OR PREDICTION

Delays increasing travel time lead to an increase in trip cost, vehicular emissions, and energy consumption. Therefore, it is beneficial, though challenging, to use travel time estimation as an effective index to identify measures for reducing traffic congestion and improving reliability.[39]

Accurate travel time prediction is indeed important both for traffic managers and for travelers. Polus (1979) used arterial travel time data and developed regression and statistical model to estimate the travel time.[40] Nam and Drew (1996)[41] estimated travel times directly from flow measurements. The analysis of the flow measurements showed that estimates have good agreement with empirical data measured at 30-second intervals.[41]

Park et al. (1999) predicted link-level travel times by utilizing spectral based artificial neural network (SNN).[42] Their results obtained were compared with different conventional models. SNN was found to be more accurate in predicting travel times.[42]

Uno et al. (2002) analyzed the relationship between traffic information and travel time reliability.[43] They stated that providing additional information to the drivers, such as short-term trends of travel time, might improve travel time reliability.[43] Zwahlen and Russ (2002) investigated the accuracy of real-time travel time prediction systems (TIPS)[44]. Their results showed that real-time TIPS represent a definite improvement over any static non-real-time display system.[44]

Chien and Kuchipudi (2003) developed a link-based / path-based Kalman filtering algorithm model and tested the accuracy of the developed models.[45] The results obtained revealed that during peak hours, the historic path-based data used for travel-time prediction are better than link-based data due to smaller travel-time variance and larger sample size.[45]

Rice and Van-Zwet (2004) predicted travel time using current traffic situations in combination with historical data.[46] They observed a relationship between any future travel time and the current status of travel times.[46] Van-Lint (2004)[27] compared a state space neural network model (SSNN), Kalman filtering model, and Witham and Richards's traffic flow model for predicting the travel times. Among these models, SSNN results in more accurate predictions than the other models.[27]

Van et al. (2005) proposed a freeway travel time prediction framework, which explains the accuracy and robustness with respect to missing input data[29]. Van-Lint and Van-Zuylen (2005) proposed two reliability metrics: width, and skew, based on 10th, 50th, and 90th percentiles for a given route, time-of-the-day, and day-of-the-week.[47] These reliability metrics can be used in developing discrete choice models.[47]

Li et al. (2006) focused on field evaluation of four speed-based travel time estimation models: the instantaneous model; the time slice model; the dynamic time slice model; and the linear model.[48] All four models were observed to underestimate the actual travel times.[48]

Al-Deek and Emam (2006) presented a methodology for multistate system reliability analysis of transportation networks, by considering dependent link failures.[49] Xu and Sun (2007) presented a technique based on macroscopic traffic model, which predicts the future speeds on link segments.[50] Xu et al. (2008) estimated travel times by adopting the Extended Kalman Filtering (EKF) framework.[51] Their results demonstrated acceptable applicability and precision of the method's accuracy.[51]

Steiner and Sick (2008) estimated travel time using time stamps and vehicle length captured at subsequent detector stations.[52] Their proposed approach considerably extends the maximum distance for which travel time estimations can be carried out when compared with the traditional travel time estimation methods.[52]

Liu et al. (2010) predicted travel time on urban networks by proposing granular computing theory based on rough datasets.[53] Chang (2010) developed a logit-based choice model to derive monetary values of travel time variations.[54] Yang et al. (2010) proposed Generalized Autoregressive Conditional Heteroscedasticity (GARCH) for travel time forecasting. Their results predicted that the root-mean-square error, mean absolute error, and mean absolute percent error are all decreasing with an improvement in the transportation system reliability.[55]

Haseman et al. (2010) evaluated quantifiable travel mobility metrics for rural interstates.[56] They suggested that the acquisition of work zone travel time data provides a mechanism for assessing the relationship between crashes and work zone queuing.[56] Thakuriah and Tilahun (2012) proposed a methodology for utilizing real-time weather information for predicting future travel speeds.[57] Their methodology can be used for future weather responsive travel time estimations.[57]

Taylor (2012) developed a Burr statistical model to best represent the travel time reliability by utilizing day-to-day variability in travel times in urban areas.[58] Furthermore, Tu et al. (2012) discussed an empirical example based on a large dataset of freeway traffic flow data from loop detectors, which revealed that the developed travel time reliability measure is, both, intuitively logical and consistent.[59]

Yildirimoglu and Geroliminis (2013) used historic and real-time traffic information to provide travel time predictions.[60] They proposed loop detectors, which result in accurate travel time predictions under varying traffic conditions.[60] Fei et al. (2013)[61] proposed a Bayesian inference based dynamic linear model (DLM) for predicting short-term travel time with license plate recognition data. This method provides accurate and reliable estimates of travel times.[61] Chen et al. (2013) proposed a tendency-based model to estimate link-level travel time.[62] Their results revealed that the long-term and the combined-term tendency-based models have a lower optimal boundary and higher optimization potential than short-term tendency models.[62]

Jenelius and Koutsopoulos (2013) developed statistical models to estimate travel time by using vehicle trajectories obtained from low-frequency GPS-based probes.[63] Li et al. (2013) explored the different ways that travel times are distributed on different types of urban roads.[23] Their predictions showed that the best fitting travel time distribution for different road links, at 15-minute time intervals, differ for different traffic congestion levels.[23]

Wan et al. (2014) predicted travel time by developing a stochastic model.[64] This model utilizes Link-Node Cell Transmission (LN-CTM) to deliver probability travel time distributions.[64] Lei et al. (2014) proposed a path travel time reliability of urban expressways with shock waves, by using a probability-based method.[65] Tak et al. (2014) predicted travel time using a multi-level k nearest neighbor algorithm and a data fusion method; when both the models were combined, rather than used separately, the results are accurate with less than 5% error.[66]

Reza et al. (2015) developed an Autoregressive Integrated Moving Average (ARIMA) model to integrate traffic information from neighboring links in estimating short-term travel time along a corridor due to an incident.[67] Their results revealed that travel times for the successive segments were highly correlated with each other.[67]

Pulugurtha and Mangilipalli (2015) developed different models to estimate average travel speed and travel time for assessing urban arterial street performance.[3] Their results revealed that an increase in the number of signals per mile has a negative effect on arterial street performance.[3] Narayanan et al. (2015) examined travel time estimation techniques that use historical, instantaneous, and predictive data.[68] Their results revealed that dynamic predictive routing using multiple prediction horizons are better estimates than advanced traveler information systems (ATIS).[68]

Kim and Mahmassani (2015) developed a compound probability distribution approach (Gamma-Gamma Model) for collecting both vehicle to vehicle and day-to-day variability in predicting travel time reliability.[69] Their developed model estimates a systematic way of quantifying, comparing, and assessing different types of travel time characteristics.[69]

Wang et al. (2016) integrated spatial and temporal autocorrelations of road traffic network by developing a novel space–time delay neural network (STDNN) model that captures the autocorrelation locally and dynamically.[70] Their results obtained showed that STDNN exceeds the Naïve, ARIMA, and Space Time Autoregressive Integrated Moving Average (STARIMA) models in prediction accuracy.[70]

Hojati et al. (2016) proposed a random parameter Tobit model for quantifying the effects of traffic incidents on freeway travel time reliability.[71] Their results revealed that models with random parameters offer a superior statistical fit for all types of incidents than fixed parameter Tobit model.[71] Woodard et al. (2017) introduced a method called Travel Time Reliability Inference and Prediction (TRIP) to predict the probability distribution of travel times using GPS data from mobile phones.[72] Their proposed method delivers accurate predictions of travel time for large scale road networks.[72]

Marti (2015) estimated travel time directly from electronic toll collection devices.[73] Bahuleyan and Vanajakshi (2016) predicted travel time on urban arterial networks utilizing data from GPS-based probe vehicles.[74] Chen et al. (2016) explored the problem of finding the K reliable shortest paths (KRSP) in stochastic networks under travel time uncertainty, by proposing a deviation path approach; their proposed approach determined KRSP under various travel time reliability values within reasonable computational times.[75]

Ma et al. (2017) developed a Markov chain approach for estimating probability distributions of trip travel times from link travel time distributions.[76] Kou et al. (2017) used a trip scheduling model and a binary logit model to estimate the value of travel time reliability.[77] Their results revealed that the value of travel time reliability differed significantly for different income and time constraint levels, and for different transportation modes.[77]

Xiao (2017) explained the role of scheduling preferences and cost-benefit analysis on travel time reliability.[78] Cost-benefit analyses of travel time reliability improvements yielded consistent results, even if departure time adjustments are not accounted for. Departure time adjustments decrease congestion, which strongly mitigates the cost of travel time variability.[78]

Pulugurtha and Imran (2017) explored a simulation-based approach to develop travel time performance-based thresholds for basic freeway sections.[4] Pulugurtha and Kodupuganti (2017) used real-world travel time data to develop travel time and reliability thresholds for freeway links from a planning perspective.[79]

TRAVEL TIME STUDIES AND IMPACTS OF TRAVEL TIME RELIABILITY

Lomax and Schrank (2002) explained that the use of mobility and reliability measures can provide a framework to analyze the ways in which land use and transportation systems serve the needs of traveler's and businesses.[32] Pesti et al. (2007)[80] identified efficient ways to improve traffic conditions on freeway work zones. They used different control systems at the work zone locations.[80]

Fosgerau and Karlstrom (2010) extracted the value of reliability using the formulation of a scheduling utility model.[81] Their results showed that the mean and standard deviation of trip duration depends on the start time of the trip.[81] Dong et al. (2014) discussed statistical and heuristic models for traffic flow prediction.[82] The combination of both statistical and heuristic models, referred to as a hybrid model, estimated results accurately.[82]

Morrison and Lowell (2016) studied the short-term impacts of employment on travel time reliability.[83] They predicted that travel time increases by 0.71 to 0.24 minutes per one-way commute trip, for each additional 10 workers added per square kilometer.[83] Hajbabaie et al. (2016) presented a decision-making framework incorporating travel time reliability by considering variations in traffic demand levels, inclement weather condition, and incidents that occur on freeways. This framework can help improve the operational performance of freeway facilities.[84] Beaud et al. (2016) analyzed traveler's willingness to pay for travel time reliability, by utilizing a microeconomic model of transport mode choice.[85]

Pulugurtha et al. (2017) surveyed perceptions of motorists to assess the value of travel time, the willingness to pay, and the value of reliability.[1] The computed values were used to illustrate the monetary impact of transportation projects and alternatives (Pulugurtha et al., 2017; Duddu et al., 2018).[1, 86]

LIMITATIONS OF PAST RESEARCH

Past researchers have developed various models for predicting and estimating travel time and travel time reliability on freeways, and for improving the reliability of freeways or work zones. In addition, past researchers have also concentrated on reducing the crash occurrence, delay, and congestion at work zones or construction zones, comparing different prediction models, and comparing the accuracy of travel time reliability models for the freeways.

In past studies, there has been little to no research on examining the effect of road construction projects on travel time at link-level. Furthermore, past researchers have not explored the role of construction location characteristics, such as the number of lanes open and closed during the construction, the speed limit, the shoulder width, the lane width, the upstream and downstream link characteristics, the time-of-the-day, the day-of-the-week, or the distance of a link from the study corridor, on travel time. Furthermore, the effect of construction projects on the connecting arterial street links has only been meagerly explored.

This research focuses on the effect a of road construction project on travel time at link-level, using characteristics pertaining to the network, construction zone, upstream and downstream links, and connecting arterial street links.

III. DATA COLLECTION & METHODOLOGY

This chapter presents details pertaining to the study area, data collection, and analytical process adopted in this research.

SELECTING THE STUDY AREA AND A ROAD CONSTRUCTION PROJECT

The city of Charlotte, North Carolina was selected as the study area for modeling the effect a of road construction project. The list of recent road construction projects on the freeways was collected from the Charlotte Department of Transportation (CDoT) and from the Traffic Incident Management System (TIMS) maintained by the North Carolina Department of Transportation (NCDoT). The collected road construction projects were started and completed from the year 2013 to the year 2015. Constructions projects prior to the year 2013 were not considered, as travel time data is not available for most of the links in the study area. The date of completion was set as the year 2015, as research efforts were initiated during the spring of the year 2017.

The aim is to collect real-world and most recent travel time data which lasted for at least six months during the road construction project period, in and around the Charlotte city limits. There could be significant changes within the vicinity of a road construction project, such as new developments that affect the travel time at link-level. It is hard to assess the change in travel times and travel time variations due to a road construction project in such cases. Therefore, multi-year road construction projects were not considered in this research.

From the list of road construction projects, a resurfacing construction project which lasted for six months on I-485 in Charlotte, North Carolina was considered for analysis and modeling. During the construction, one lane was closed in both the directions, while two lanes were open for traffic in both the directions. The resurfacing construction project was started in June 2015. It was completed in six months. The data was collected for a six-month period before (January 2015 to June 2015) the start of the resurfacing construction project and for a six-month period during the resurfacing construction project.

An aerial view of the resurfacing construction project is shown in Figure 2. The red color section in the figure is the actual extent of the construction project. Arterial streets that connect to the freeway are also shown in the figure. Upstream and downstream links were also identified and considered for analysis and modeling and are shown in blue color.

The length of the road construction project is around 8 miles. However, data related to upstream and downstream links, for up to 3 miles from either end of the project, were also collected. Since the effect of the road construction project varies with time and space, the variation in travel times was checked along the upstream and downstream section to capture adequate distance from the study corridor. Similarly, links on the connecting arterial streets were also selected to account for the variations in travel times over space and time.

For this research, 39 freeway links and 60 connecting arterial street links were selected for analysis and modeling purposes. Data related to four time periods, morning peak, morning off-peak, evening peak, and evening off-peak hours, during a weekday and weekend day for each freeway and connecting arterial street link, was gathered. Overall, 312 samples (39 freeway links × 4 time periods × 2 days of the week) on the freeway links and 480 samples (60 freeway links × 4 time periods × 2 days of the week) on the connecting arterial street links were considered. After selecting the samples, outliers, links that are less than 0.3 miles long, and null values were removed. From the final database, 80% of randomly selected samples were used for modeling the travel time and the remaining 20% was used for validating the developed travel time model.

The selected resurfacing construction project corridor (I-485) was operating with a 65 miles/hour speed limit during the study period. Data relevant to the resurfacing construction project was collected and is discussed next.

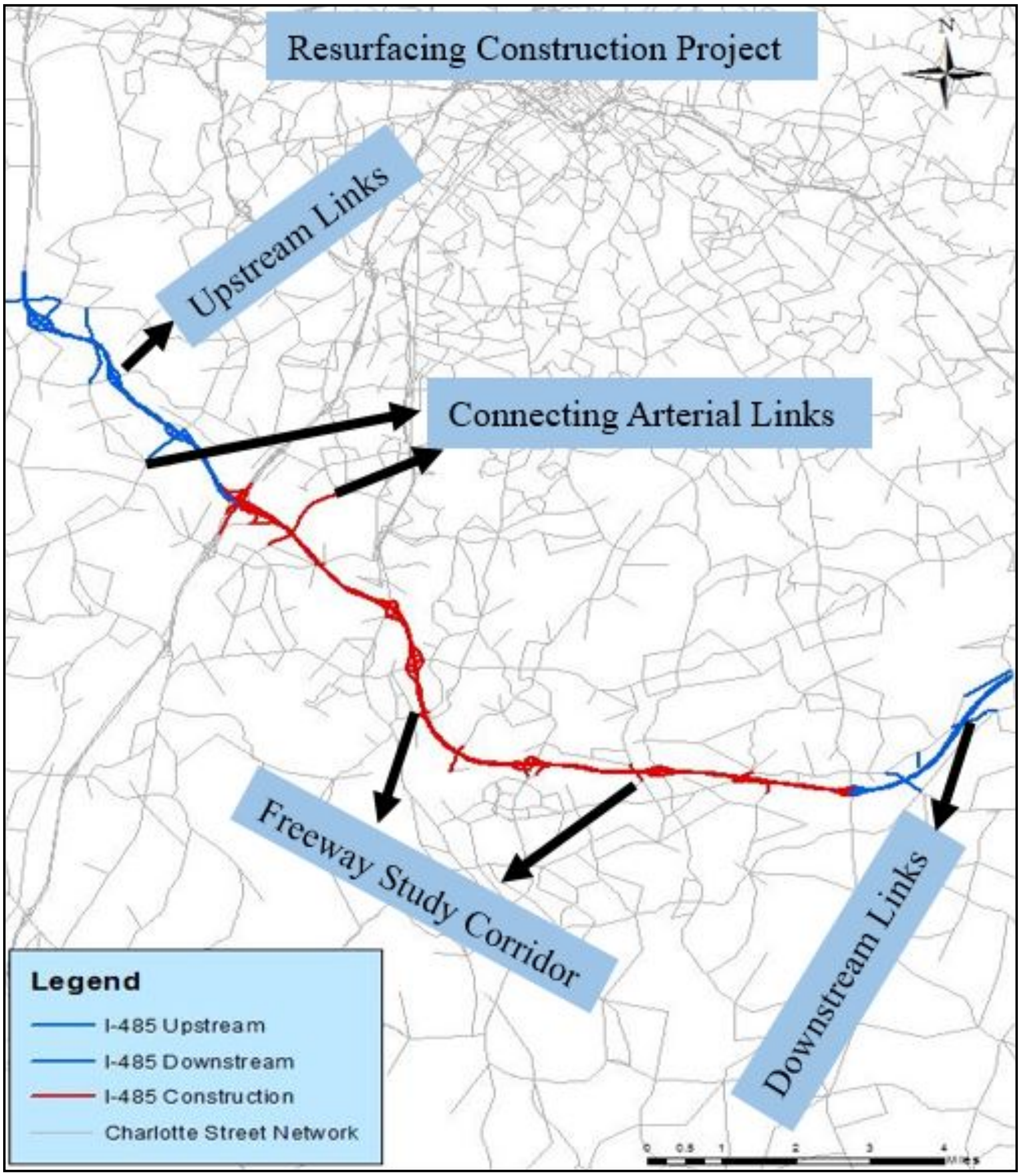

Figure 2. Resurfacing Construction Project Study Corridor

IDENTIFYING DATA ELEMENTS AND DATA COLLECTION

Travel time increases as traffic volume increases. Similarly, a section would attract higher traffic volume if the number of lanes is greater. In addition, travel time increases if the speed limit is lower. Similarly, travel time increases if the lane width and the shoulder width are lower (due to a decrease in motorist comfort level when driving). Therefore, traffic volume, capacity, speed limit, number of lanes, shoulder width, and lane width were considered for analysis and modeling.

One or more lanes may be closed for construction. The speed limit, the lane width, and the shoulder width may be reduced along a construction section, which in turn increases the travel time. Therefore, the number of lanes closed during the construction project period, the reduced work zone speed limit, the shoulder width, and the lane width were collected from TIMS for modeling.

Upstream and downstream traffic volume, speed limit, number of lanes, and link length could also have an influence on the travel time on a link in the construction section. Therefore, the characteristics of upstream and downstream links were identified and considered for modeling.

Furthermore, construction on the freeway links could influence the operational performance of connecting arterial street links. During the construction project period, when one or more lanes are closed on the freeway construction zones, travelers tend to change their paths and migrate to the connecting arterial streets to avoid congested sections and minimize their total travel delay. Therefore, connecting arterial street link characteristics, such as traffic volume, capacity, number of lanes, whether the road is divided or undivided, shoulder width, and lane width was also captured and added to the database for modeling purposes. In addition, the distance of a link from the construction zone was also collected since the effect on travel time is likely to decrease with an increase in the distance from the construction zone.

During morning or evening peak hours, traffic volume is typically higher than when compared with off-peak hours. Traffic volume would also change with respect to the time-of-the-day. Similarly, during the weekdays, traffic volume is higher when compared with the weekend days. Therefore, the time-of-the-day and the day-of-week at which travel time data was collected is also added to the database, for each link. The time-of-the-day categories considered are morning peak (7 AM – 9 AM), morning off-peak (10 AM – 12 PM), evening peak (5 PM – 7 PM), and evening off-peak (10 PM – 12 AM) hours. Monday through Friday was categorized together as the weekday, while Saturday and Sunday were categorized together as the weekend.

A detailed summary of various characteristics considered for modeling the effect of the resurfacing construction project on travel time at link-level is presented in Table 2. Network characteristics such as capacity, speed limit, and the number of lanes, summarized in Table 2, were gathered from the CDoT regional travel demand model and aerial images. Traffic volume before and during the construction project period was collected from the CDoT regional travel demand model. The average width of all lanes, for each freeway and connecting arterial street link, was captured using the Google Earth Pro software and added to the database. A pictorial representation of lane width captured for each link using the Google Earth Pro software is shown in Figure 3. Similarly, the shoulder width was also captured at two random points, using the Google Earth Pro software, for each freeway and connecting arterial street link. The captured shoulder width using the Google Earth Pro software is shown in Figure 4. The average shoulder width is computed and used for analysis and modeling.

Figure 3. Capturing Lane Widths Using Google Earth Pro Software

Figure 4. Capturing Shoulder Widths Using Google Earth Pro

Table 2. Various Characteristics Considered for Modeling the Effect of the Resurfacing Construction Project

Parameters	Characteristics
Freeway Link Parameters	Traffic Volume
	Capacity
	Number of Lanes
	Speed Limit (mph)
	Lane Width (ft)
	Shoulder Width (ft)
Upstream and Downstream Link Parameters	Number of Lanes Closed
	Upstream Link Length (mi)
	Upstream Link Traffic Volume
	Upstream Link Speed Limit (mph)
	Upstream Link Number of Lanes
	Upstream Link Capacity
	Downstream Link Length (mi)
	Downstream Link Traffic Volume
	Downstream Link Speed Limit (mph)
	Downstream Link Number of Lanes
	Downstream Link Capacity
Connecting Arterial Street Link Parameters	Traffic Volume
	Capacity
	Number of Lanes
	Speed Limit (mph)
	Lane Width (ft)
	Shoulder Width (ft)
	Divided/Undivided
	Upstream Link Length (mi)
	Upstream Link Traffic Volume
	Upstream Link Speed Limit (mph)
	Upstream Link Number of Lanes
	Upstream Link Capacity
	Downstream Link Length (mi)
	Downstream Link Traffic Volume
	Downstream Link Speed Limit (mph)
	Downstream Link Number of Lanes
	Downstream Link Capacity
Other Parameters	Time-of-the-day
	Day-of-the-week
	Distance of the Link from the Study Corridor (D) in Miles

TRAVEL TIME DATA AND DATA PROCESSING

Travel time data was downloaded from the Regional Integrated Transportation Information Systems (RITIS) website in a raw unprocessed format. The raw data file usually has a Traffic Message Channel (TMC) code (tmc_code), time-stamp (measurement_tstamp), speed (speed), average speed (average_speed), reference speed (reference_speed), travel time (travel_time_minutes), and score (confidence_score). A snapshot of unprocessed raw travel time data is shown in Table 3. Each field in a typical raw data file is briefly described next (INRIX, 2013).

1. Traffic Message Channel (TMC) defines link identity.

2. Speed is the current estimated space mean speed for the TMC or link in miles per hour.

3. Average speed is the historical average mean speed for the link, for that hour-of-the-day and day-of-the-week in miles per hour.

4. Reference speed is the calculated “free flow” mean speed for the link in miles per hour.

5. Travel time is the current estimated travel time it takes to traverse the link in minutes.

6. Confidence score is an indicator of data type (30 indicates real-time data; 20 indicates real-time data across multiple segments; 10 indicates historical data).

The data requested has average travel time at 1-minute intervals, for different study periods (before and during the construction project). The data processing and mining were performed using Microsoft SQL Server 2012. A data dictionary was developed to explain all data elements in the processed database.

In the database, there are a few missing values and blank cells for some considered links. By using SQL query, the missing and blank cells were removed prior to analysis and modeling. The database consists of real-time data and historical data. Only real-time data (confidence score = 30) was considered for analysis and modeling.

Table 3. Raw Travel Time Data from INRIX, 2013

tmc_code	measurement_tstamp	speed	reference_speed	travel_time_seconds	confidence
125N04663	12/11/2015 10:49	66	70	35.24	0.95
125+04666	12/11/2015 10:49	74	70	34.15	0.98
125N04662	12/11/2015 10:49	68	70	30.94	0.97
125+04665	12/11/2015 10:49	70	70	99.86	0.97
125N04665	12/11/2015 10:49	65	70	68.19	0.95
125+04664	12/11/2015 10:49	65	70	20.2	0.97
125N04664	12/11/2015 10:49	67	70	34.19	0.98
125+04663	12/11/2015 10:49	69	70	102.43	0.97
125N04661	12/11/2015 10:49	68	70	26.56	0.98
125N04660	12/11/2015 10:49	68	70	24.81	0.97
125+04667	12/11/2015 10:49	67	70	41.3	0.97
125N04667	12/11/2015 10:49	73	70	29.99	0.98
125+04662	12/11/2015 10:49	68	70	64.32	0.96
125N04666	12/11/2015 10:49	71	70	31.44	0.97
125+04661	12/11/2015 10:49	67	70	116.23	0.96
125+04660	12/11/2015 10:49	63	70	233.16	0.97
125-04662	12/11/2015 10:49	68	70	102.61	0.97
125-04661	12/11/2015 10:49	68	70	64.6	0.98
125-04664	12/11/2015 10:49	67	70	93.43	0.98
125-04663	12/11/2015 10:49	66	70	19.48	0.95
125-04660	12/11/2015 10:49	68	70	111.04	0.97
125-04666	12/11/2015 10:49	71	70	34.2	0.97
125-04665	12/11/2015 10:49	65	70	35.19	0.95
125+10198	12/11/2015 10:49	65	70	40.89	0.97
125-04667	12/11/2015 10:49	73	70	39.9	0.98
125P04666	12/11/2015 10:49	74	70	30.49	0.98

Overall, travel times were extracted both for the freeway construction project links and for the connecting arterial street links within the vicinity of the resurfacing construction project. Similarly, travel times were extracted for links within three miles upstream and downstream of the actual construction activity zone, to capture the travel times while entering and leaving the construction zone.

The data was used to compute travel time performance measures such as the average travel time (ATT), the 95th percentile travel time (planning time, PT), the buffer time (BT), the buffer time index (BTI), and the travel time index (TTI). Several factors, such as the time-of-the-day, the day-of-the-week, all weekdays of a year, and all weekends of a year are considered when computing and evaluating the travel time performance measures before and during the construction project periods.

EXAMINING THE RELATIONSHIP BETWEEN THE TRAVEL TIME PERFORMANCE MEASURES BEFORE AND DURING THE CONSTRUCTION PROJECT PERIODS

To check the statistical significance of a change in travel times and travel time performance measures, a one-tail paired t-test was performed at a 95% confidence level. The null hypothesis is 'H0: Average travel time remained the same before and during the construction project period (i.e., mean difference between average travel times before and during the construction is zero). The alternative hypothesis is 'H1: Average travel time increased during the construction project period when compared to the before period (i.e., the mean difference between average travel times during and before is greater than zero). The same procedure was adopted to test the difference between PT, BT, BTI, and TTI.

PEARSON CORRELATION ANALYSIS

The correlations between the average travel time and all the predictor variables, pertaining to network characteristics, construction zone characteristics, upstream and downstream characteristics, connecting arterial street link characteristics, the time-of-the-day, the day-of-the-week and the distance of a link from the study corridor, were examined using SPSS. The computed Pearson correlation coefficients lie between -1 and +1. If the P-value is less than or equal to 0.05, at a 95% confidence level, two variables are considered as strongly correlated with each other. The correlation between the dependent variable and each predictor variable was first examined. The correlations between the predictor variables were then examined, in order to select predictor variables that are not correlated to each other, for modeling. This was done to minimize the effect of multicollinearity and improve the accuracy of the travel time estimates. The generalized linear models (GLM) were then developed to model the effect of the road construction project before and during the construction project period.

DEVELOPING GENERALIZED LINEAR MODELS (GLM)

A linear model specifies the relationship between a dependent variable (say, Y) and a group of predictor variables (X1, X2…). The general form of a linear model is shown as Equation 1.

$$Y = C_o + C_1X_1 + C_2X_2 + C_3X_3 + C_4X_4 + \ldots + C_kX_k \quad \text{------------------ Equation 1}$$

In Equation 1, C_o is the intercept, while C_1, C_2…, C_k are regression coefficients for the predictor variables 1, 2, … k. Y is the dependent variable (average travel time).

The structural form of a linear regression model describes the patterns of interactions and associations. In addition, the model parameters also provide measures of strength. However, the data may not always be normally distributed, and the relationship between the predictor variables and the dependent variable may not be linear. A GLM is more appropriate if the dependence is nonlinear (for example, log-link), and the data's distribution is from an exponential family. The general form of a GLM is as shown in Equation 2.

$Y = Exp^{[Co+C1X1+ C2X2+ C3X3+ C4X4+......+CkXk]}$ ------------------Equation 2

The basic assumptions of GLM are listed next (Logistic Regression).

- The data related to 'Y' are independently distributed.
- The dependent variable 'Y' may not be normally distributed. Therefore, it assumes a distribution from an exponential family, such as binomial, Poisson, multinomial, or normal.
- GLM does not assume a linear relationship between the dependent variable and the predictor variables. However, it assumes a linear relationship between the transformed response in terms of the link function and the predictor variables.
- The predictor variables may even be power functions or some other non-linear transformations of the considered original predictor variables.
- The homogeneity of variance is not necessary. Over-dispersion (when the observed variance is greater than the model assumes) may occur in some cases.
- Errors are independent but are not normally distributed.
- GLM uses maximum likelihood estimation (MLE) rather than ordinary least squares (OLS) to estimate the parameters, and, therefore, depends on higher sample size.
- Goodness-of-fit measures rely on sufficiently large samples. The quasi likelihood under independence model criterion (QIC) and corrected quasi likelihood under independence model criterion (QICC) were considered to test the goodness-of-fit in this research. In general, a lower QIC and QICC indicates a good model. In addition, the difference between QIC and QICC should be lower for a valid model estimation.

GLM is sensitive to outliers. Therefore, link lengths which are less than 0.3 miles were removed from the model database. Such links may have uncertain and unexplainable travel times which could affect the model parameters.

Data related to crashes in the construction zone were not known from the TIMS database. The travel time due to the effect of crashes could be outliers and need to be removed to minimize the effect of such incidents on travel time. In addition, outliers could skew the GLM results. Therefore, the average travel times inside the oval-shaped boundary (Figure 5) were considered as outliers and removed prior to conducting the analysis and developing the models.

The data for freeway and connecting arterial street links were checked for outliers, both for the before construction and for during the construction project periods. The outliers were removed prior to conducing the analysis and modeling. The results obtained from the analysis and modeling are presented in chapters 4 and 5.

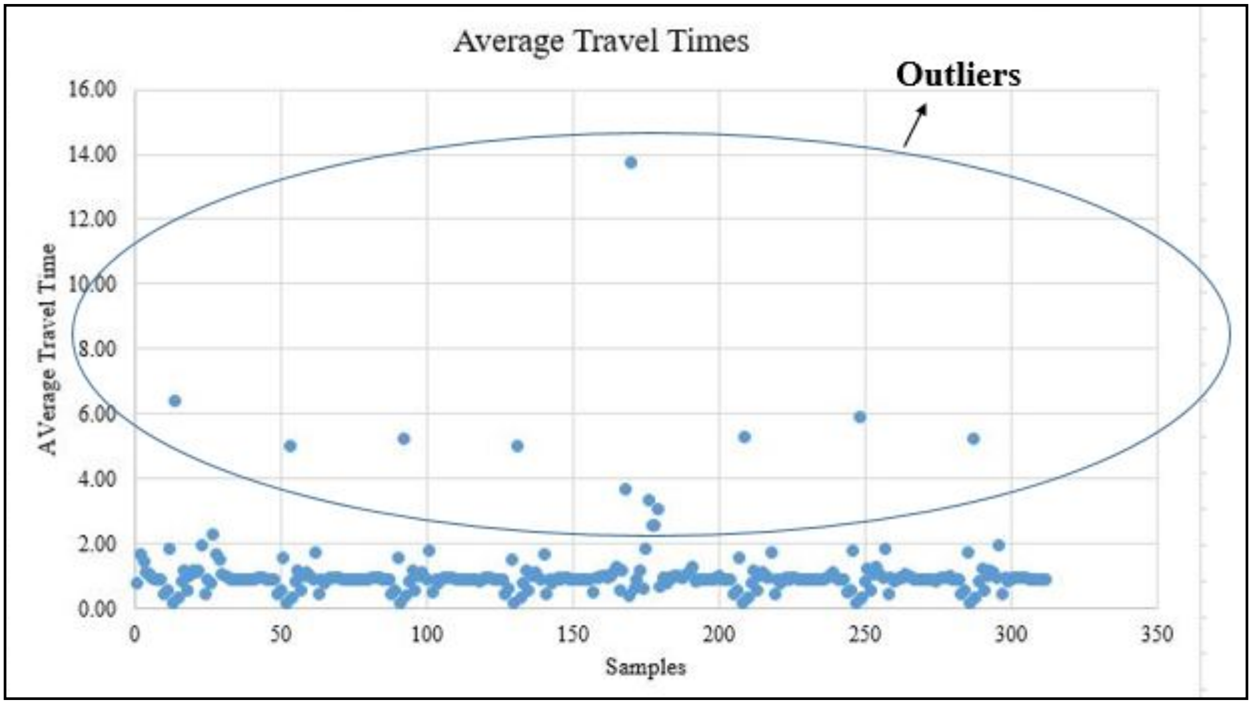

Figure 5. Removing Outliers from the Model Database

MODEL VALIDATION

The Root Mean Square Error (RMSE) and the Mean Absolute Percentage Error (MAPE) were used for validating the model. RMSE measures the differences between values predicted by a developed model and the recorded values.[87] Similarly, MAPE measures the accuracy of the values predicted by the developed model.[87] Values of RMSE and MAPE closer to zero indicates the best-fitted model. Formulas representing RMSE and MAPE are presented as Equation 3 and Equation 4.

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{n}(\text{Actual}_{\text{ATT}} - Estimated_{\text{ATT}})^2}{n}} \qquad \text{----------- Equation 3}$$

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{\text{Actual\_ATT} - \text{Estimated\_ATT}}{\text{Actual\_ATT}}\right| \qquad \text{----------- Equation 4}$$

where N = number of the observations, Actual_ATT = Recorded average travel time, and Estimated_ATT= Estimated average travel time from the developed model.

IV. EXAMINING THE RELATIONSHIP BETWEEN TRAVEL TIME PERFORMANCE MEASURES BEFORE AND DURING THE CONSTRUCTION PROJECT PERIOD

It is important to examine whether there exists any significant relationship between the average travel time and other travel time performance measures before and during the construction project period. Data obtained and processed for the resurfacing project was analyzed to examine the relationships between the travel time performance measures before and during the construction project period, for all the considered time periods. As stated in Chapter 3, for each travel time performance measure, a one-tailed paired t-test was used to examine the difference in means, and whether the difference was statistically significant, between travel time performance before and during the construction project period.

AVERAGE TRAVEL TIME (ATT)

Figure 6 shows the average travel time on the selected freeway links and connecting arterial street links, before and during the construction project period, for morning peak and morning off-peak hours during a weekday. The average travel times before and during the construction project periods are the same on almost all the freeway links and connecting arterial street links, in the cases of morning peak and morning off-peak hours on a typical weekday. Figure 7 shows the average travel times before and during the construction project periods, for evening peak and evening off-peak hours on a weekday. The average travel time is almost the same during both the time periods on freeway links. However, the average travel times are greater during the construction project period on the majority of the connecting arterial street links when compared with the before construction project period, in the case of evening peak and evening off-peak hours on a typical weekday.

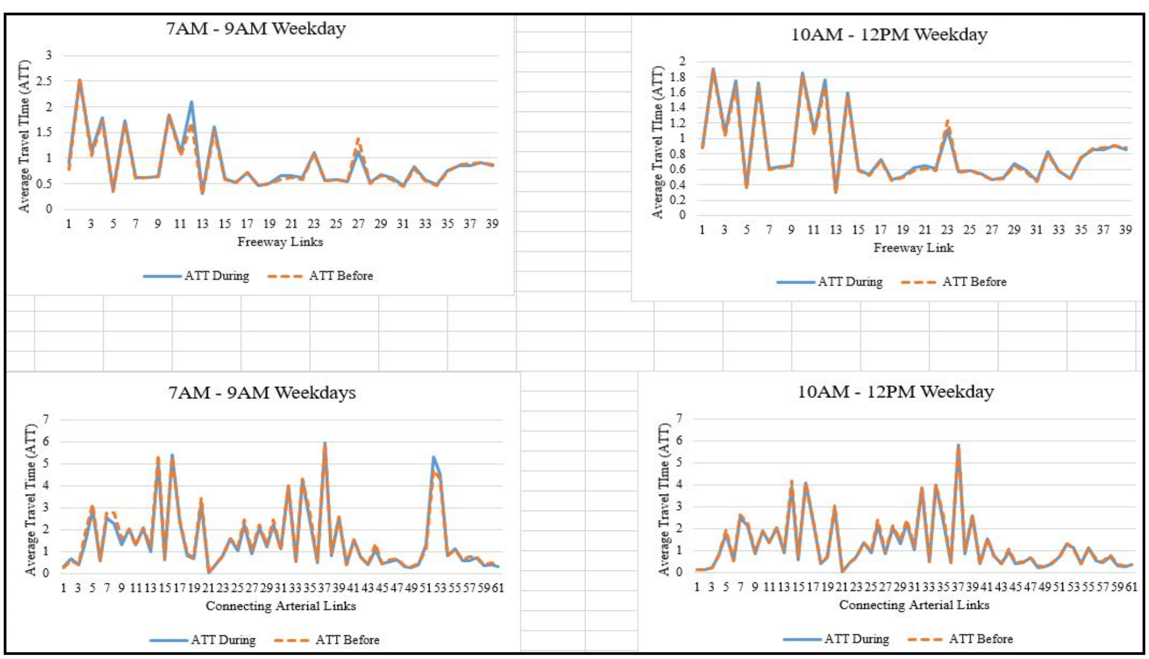

Figure 6. Average Travel Time Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekday

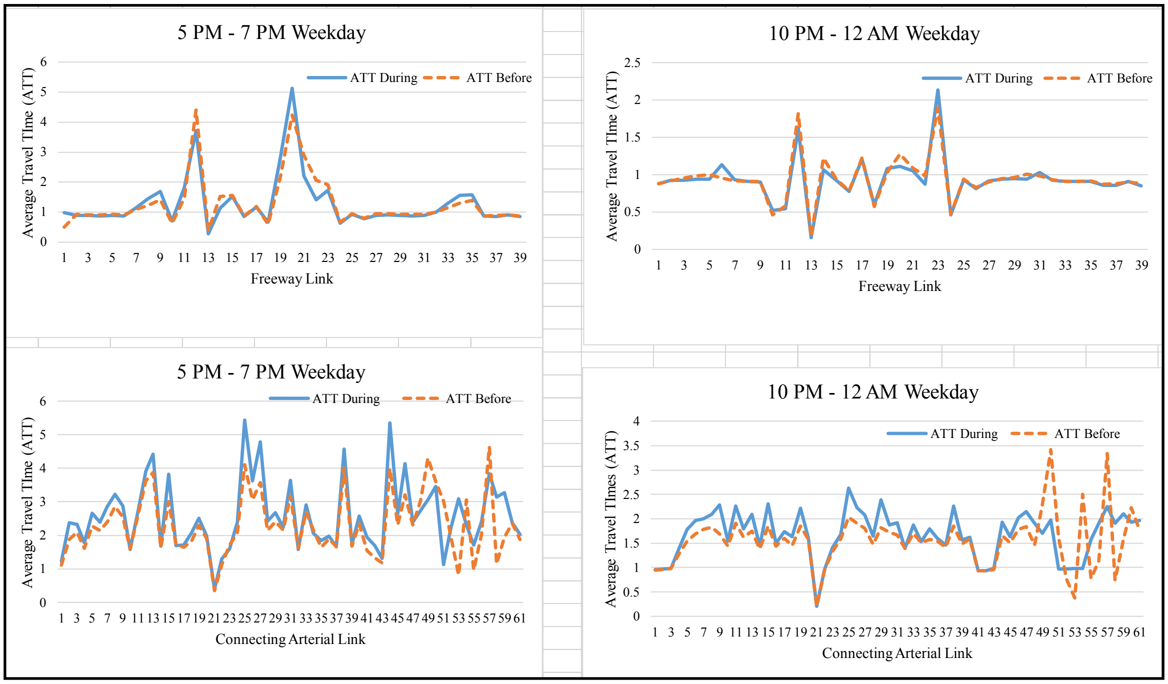

Figure 7. Average Travel Time Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekday

Figure 8 and Figure 9 show the average travel times before and during the construction project period, for morning peak, morning off-peak, evening peak, and evening off-peak hours on a typical weekend day. All the four time periods on a weekend day have similar travel times on most of the freeway and connecting arterial street links for considered time periods on a weekend day.

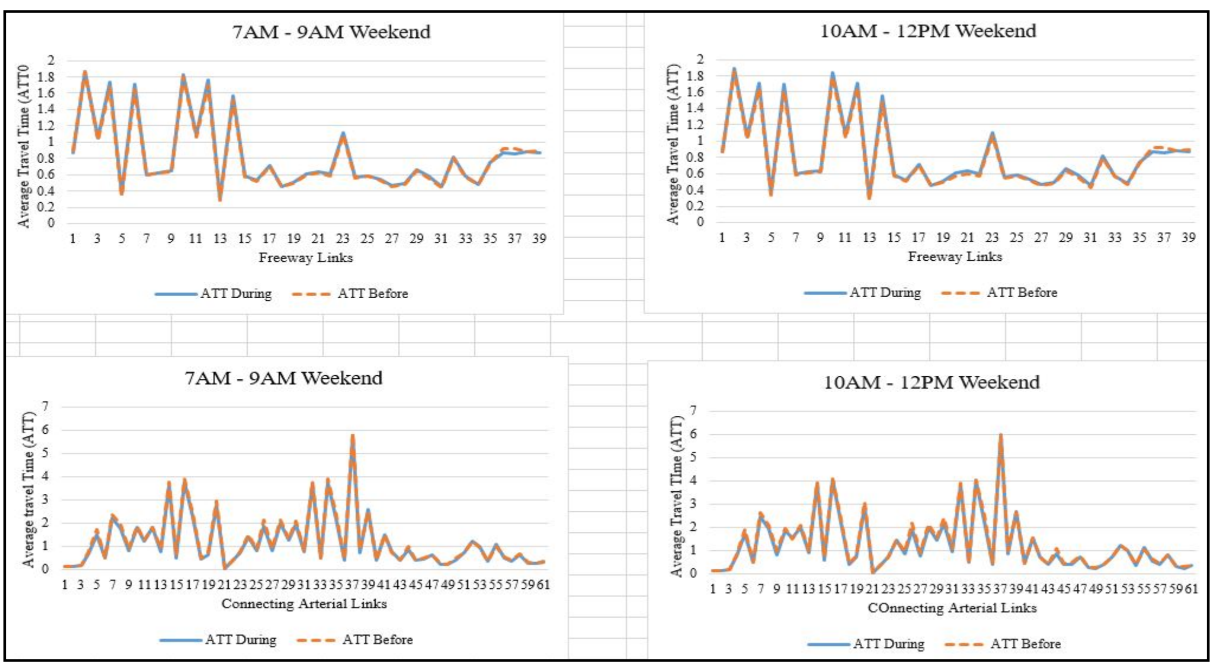

Figure 8. Average Travel Time Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekend Day

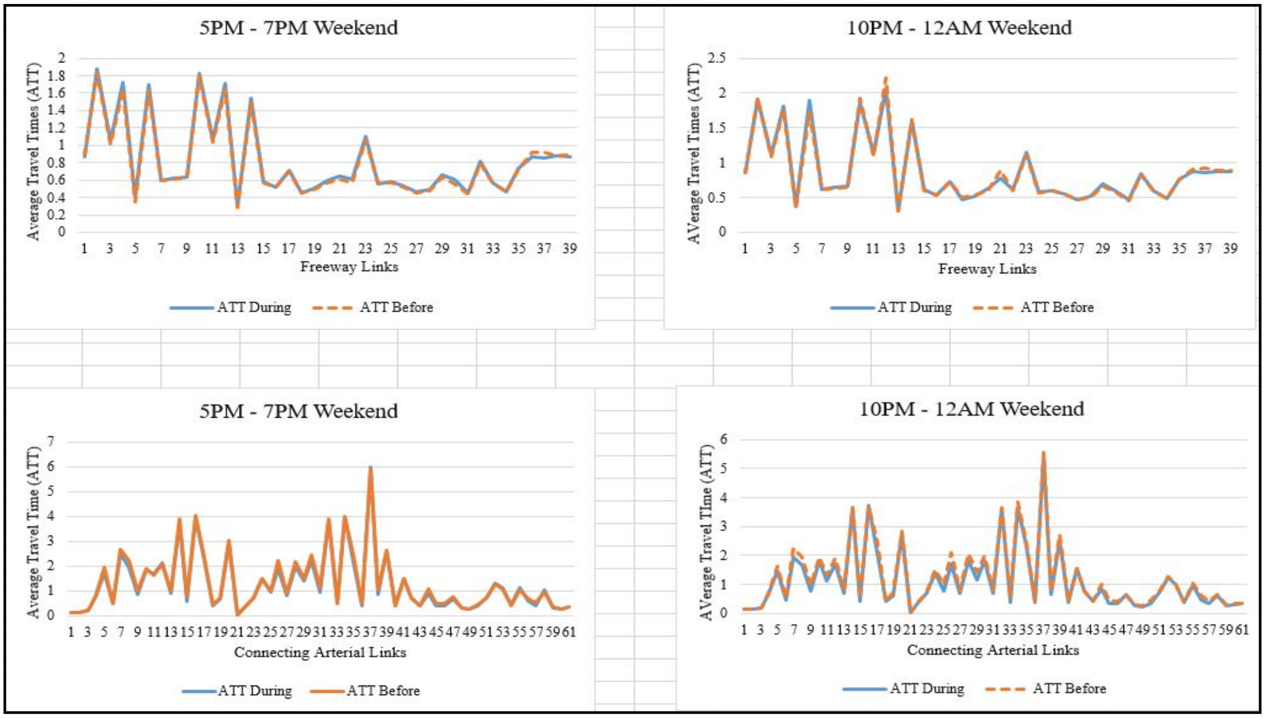

Figure 9. Average Travel Time Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekend Day

The mean differences, t-statistics, and critical t values computed using the average travel times are summarized in Table 4. The means of the average travel time during the construction project period are lower than the means of the average travel time before the construction project period on the freeway links. The t-statistic and critical t value results indicate that there was a statistically significant decrease in the average travel time on freeway links at a 95% confidence level. However, the mean average travel time on the connecting arterial street links increased during the construction project period when compared with before the construction project period. The mean difference is comparatively higher on connecting arterial street links during the construction project period, during the evening peak hours (weekday), when compared with the freeway links, at a 95% confidence level. This could be because the vehicular traffic might have shifted to the connecting arterial street links during the construction project period to avoid major delays on the freeway links.

Table 4. T-test Results: Average Travel Time

		7 AM - 9 AM		10 AM-12 PM		5 PM - 7 PM		10 PM - 12 AM	
		Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end
Freeway Study Links									
Mean	During	1.01	0.95	0.96	0.93	1.40	0.94	1.03	1.00
	Before	1.16	0.98	1.00	0.98	1.54	1.00	1.05	1.02
Diff. between means		-0.15	-0.03	-0.04	-0.05	-0.14	-0.06	-0.02	-0.02
t-Stat		-2.91	-6.50	-4.15	-5.43	-0.64	-3.90	-1.36	-1.16
P(T<=t) one-tail		<0.01	<0.01	<0.01	<0.01	0.26	<0.01	0.09	0.13
t Critical one-tail		1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
P(T<=t) two-tail		0.01	<0.01	<0.01	<0.01	0.53	<0.01	0.18	0.25
t Critical two-tail		2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
Connecting Arterial Street Links									
Mean	During	2.25	1.66	1.81	1.78	2.58	1.83	1.66	1.67
	Before	2.24	1.71	1.71	1.65	2.24	1.71	1.47	1.48
Diff. between means		0.01	-0.05	0.10	0.13	0.34	0.12	0.19	0.19
t-Stat		0.07	-1.91	5.48	5.77	6.75	5.06	8.99	8.27
P(T<=t) one-tail		0.47	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical one-tail		1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
P(T<=t) two-tail		0.94	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical two-tail		2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

PLANNING TIME (PT) OR 95TH PERCENTILE TRAVEL TIME

Figure 10 shows the computed PTs on the selected freeway links and connecting arterial street links, before and during the construction project periods, for morning peak and morning off-peak hours during a weekday. The PTs are same on the majority of the freeway links. However, the PTs during the construction project period are generally higher than before the construction project period on almost all the connecting arterial street links.

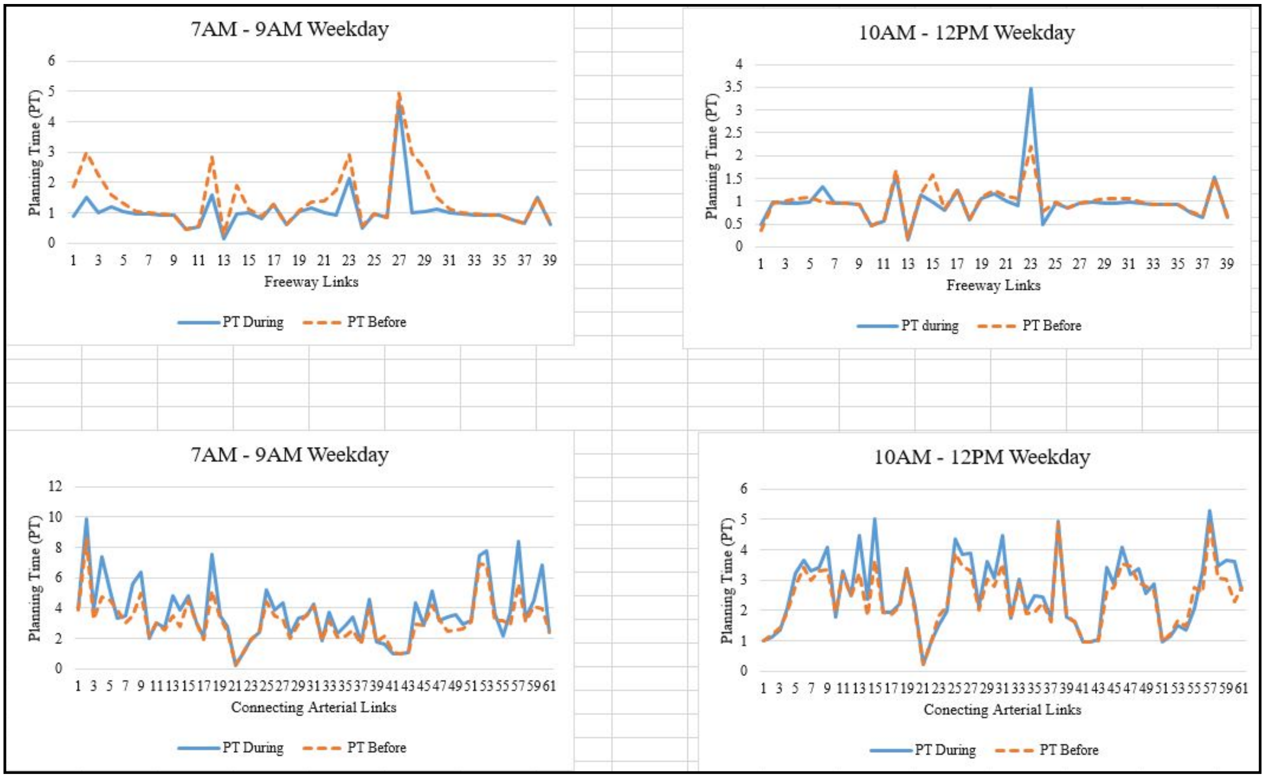

Figure 10. Planning Time Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekday

Figure 11 shows the PTs on the selected freeway links and connecting arterial street links, before and during the construction project periods, for evening peak and evening off-peak hours on a weekday. The PTs are the same on the majority of the freeway links. However, the PTs during the construction project period are generally higher than before the construction project period on almost all the connecting arterial street links, in the case of both time-of-day categories.

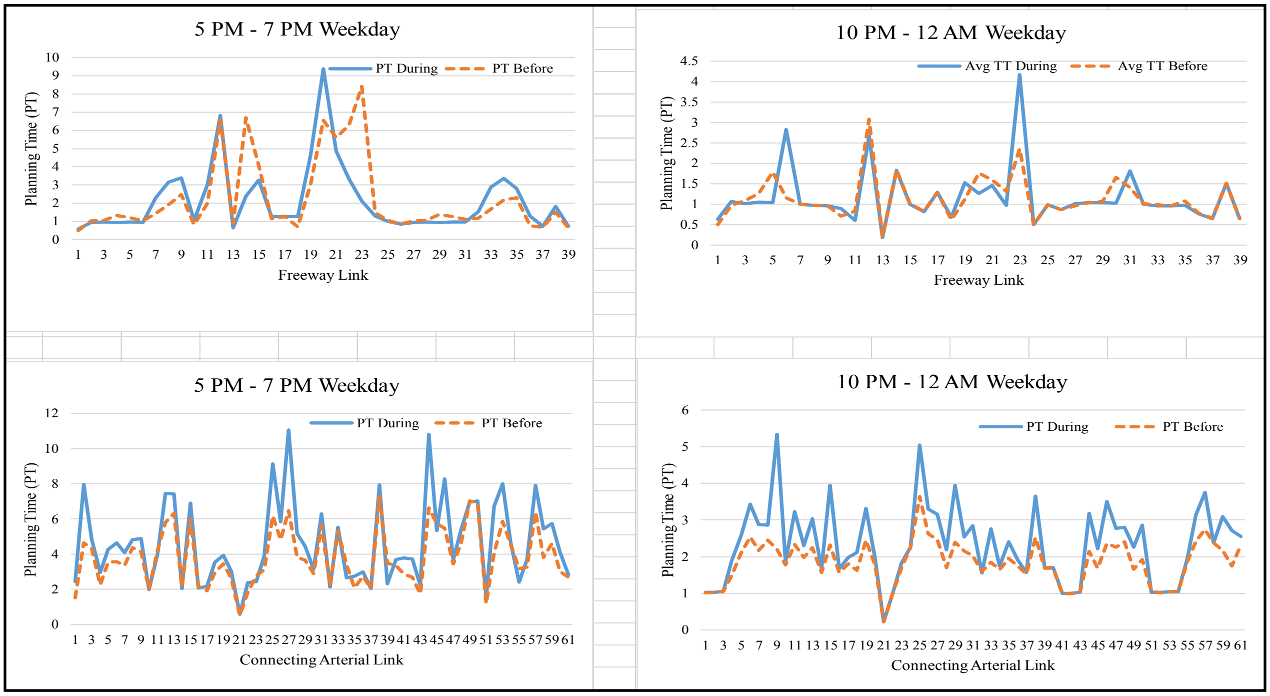

Figure 11. Planning Time Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekday

Figure 12 and Figure 13 shows the computed PTs before and during the construction project period on the selected freeway and connecting arterial street links for morning peak, morning off-peak, evening peak and evening off-peak hours on a typical weekend day. Similar trends were observed on the weekend days where PTs have shown an increase on connecting arterial street links during the construction project period when compared with PTs before the construction project period. The PTs are observed to be similar on the freeway links before and during the construction project period.

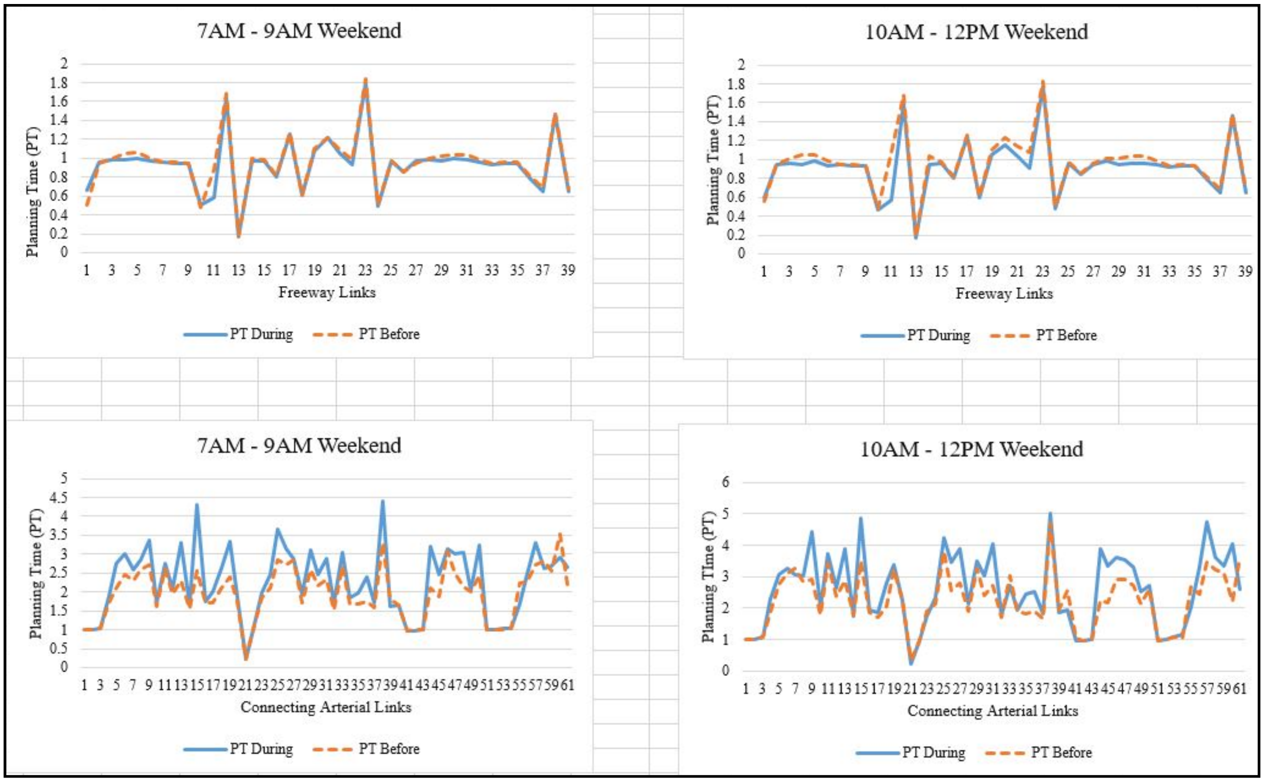

Figure 12. Planning Time Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekend Day

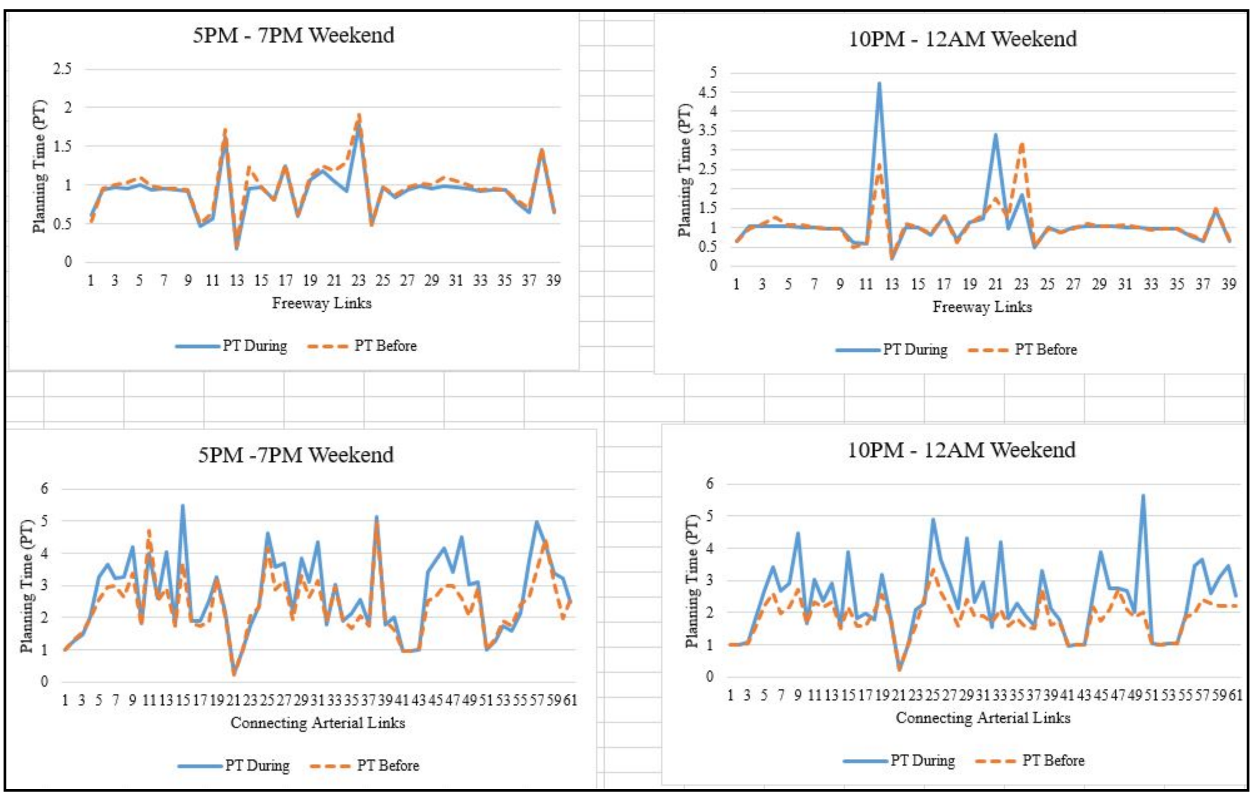

Figure 13. Planning Time Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekend Day

The mean differences, t-statistics, and critical t values computed using the PTs are summarized in Table 5. The mean differences in the PT during and before the construction project period followed a similar trend as the average travel time. The PT is significantly higher before the construction project period when compared with during the construction project period, at a 95% confidence level, during all the considered time periods. In addition, the mean PTs on connecting arterial street links are significantly higher during the construction project period when compared with mean PTs before the construction project period. As stated earlier, vehicular traffic might have shifted from the freeway links to the connecting arterial street links during the construction to avoid the non-enduring delays.

Table 5. T-test Results: Planning Time or 95th Percentile Travel Time

		7 AM - 9 AM		10 AM-12 PM		5 PM - 7 PM		10 PM - 12 AM	
		Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end
Freeway Study Links									
Mean	During	1.06	0.93	0.97	0.91	2.11	0.92	1.17	1.10
	Before	1.42	0.95	0.98	0.96	2.21	0.97	1.13	1.06
Diff. between means		-0.36	-0.02	-0.01	-0.05	-0.10	-0.05	0.04	0.04
t-Stat		-4.23	-2.46	-0.28	-3.59	-0.37	-4.25	0.44	0.51
P(T<=t) one-tail		<0.01	<0.01	0.39	<0.01	0.36	<0.01	0.33	0.31
t Critical one-tail		1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
P(T<=t) two-tail		<0.01	0.02	0.78	<0.01	0.71	<0.01	0.66	0.61
t Critical two-tail		2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
Connecting Arterial Street Links									
Mean	During	3.73	2.26	2.63	2.60	4.62	2.72	2.34	2.40
	Before	3.19	1.97	2.41	2.26	3.84	2.36	1.85	1.84
Diff. between means		0.54	0.29	0.22	0.34	0.78	0.36	0.49	0.56
t-Stat		5.32	5.62	4.34	4.75	5.60	5.17	6.78	6.12
P(T<=t) one-tail		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical one-tail		1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
P(T<=t) two-tail		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical two-tail		2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

BUFFER TIME (BT)

Figure 14 shows the BTs on the selected freeway links and connecting arterial street links, before and during the construction project period, for morning peak and morning off-peak hours on a weekday. The BTs on a few freeway links are greater than before the construction project period when compared with during the construction project period. The freeway links on which they were higher varies by the time period. On the other hand, the BTs during the construction project period are generally greater than before the construction project period on almost all the connecting arterial street links, in the case of both the time periods. The trends on connecting arterial street links are similar for BT and for PT based graphs.

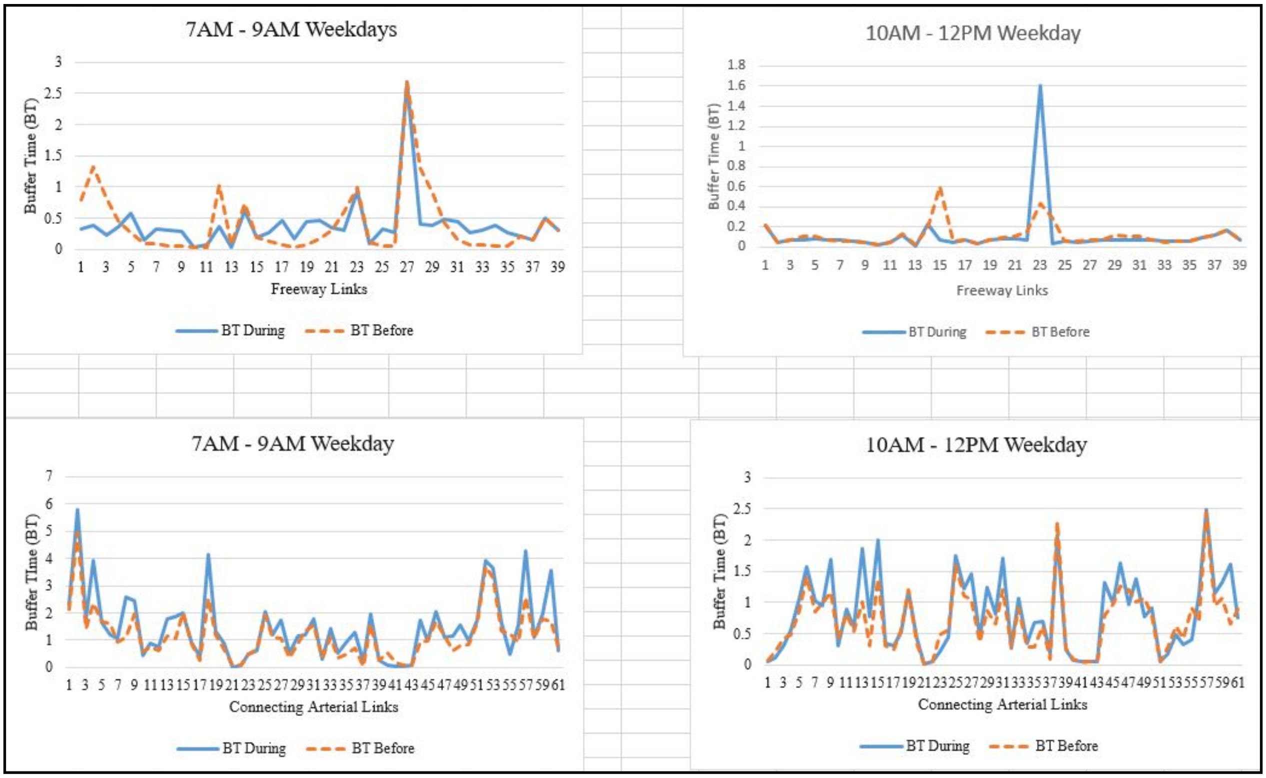

Figure 14. Buffer Time Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekday

Figure 15 shows the BTs on the selected freeway links and connecting arterial street links, before and during the construction project periods, for evening peak and evening off-peak hours on a weekday. The BTs on a few freeway links is greater before the construction project period when compared with during the construction project period. The freeway links on which they were higher varies by the time period. On the other hand, the BTs during the construction project period are generally greater than before the construction project period on almost all the connecting arterial street links, in the case of both the time-of-day categories.

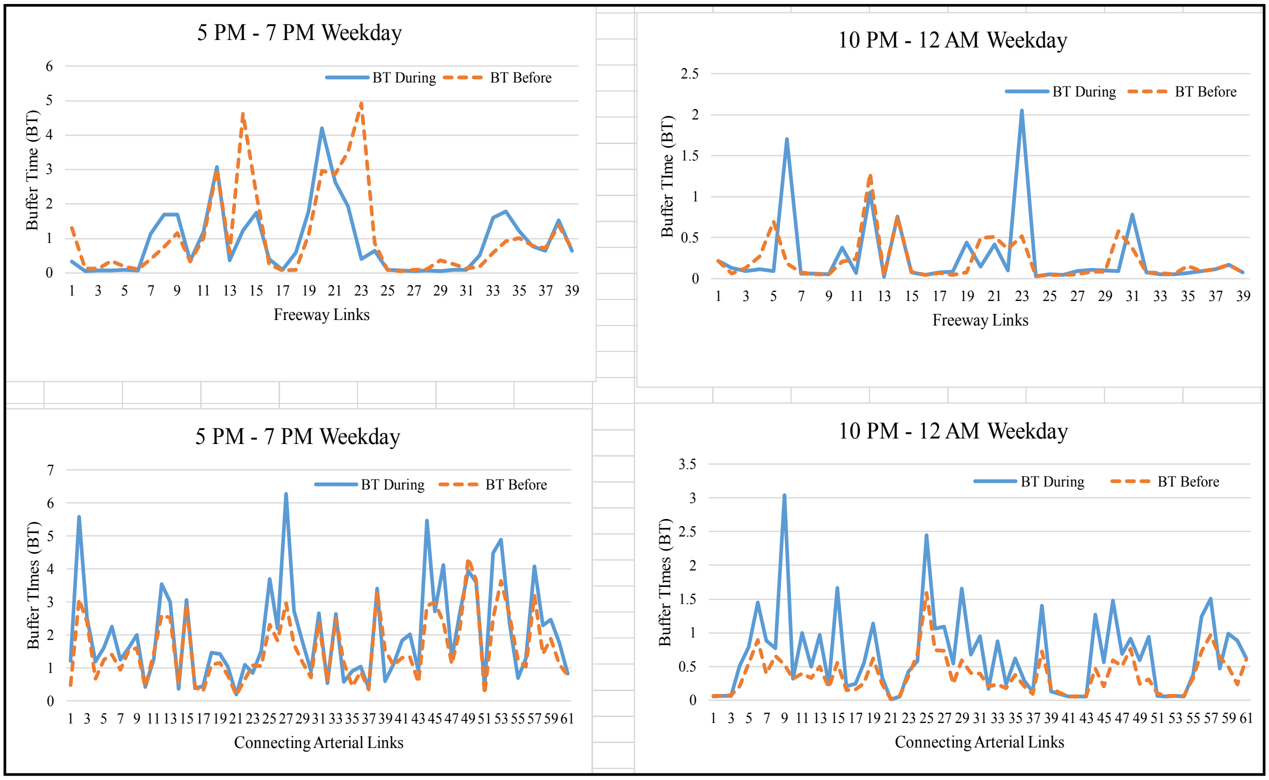

Figure 15. Buffer Time Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekday

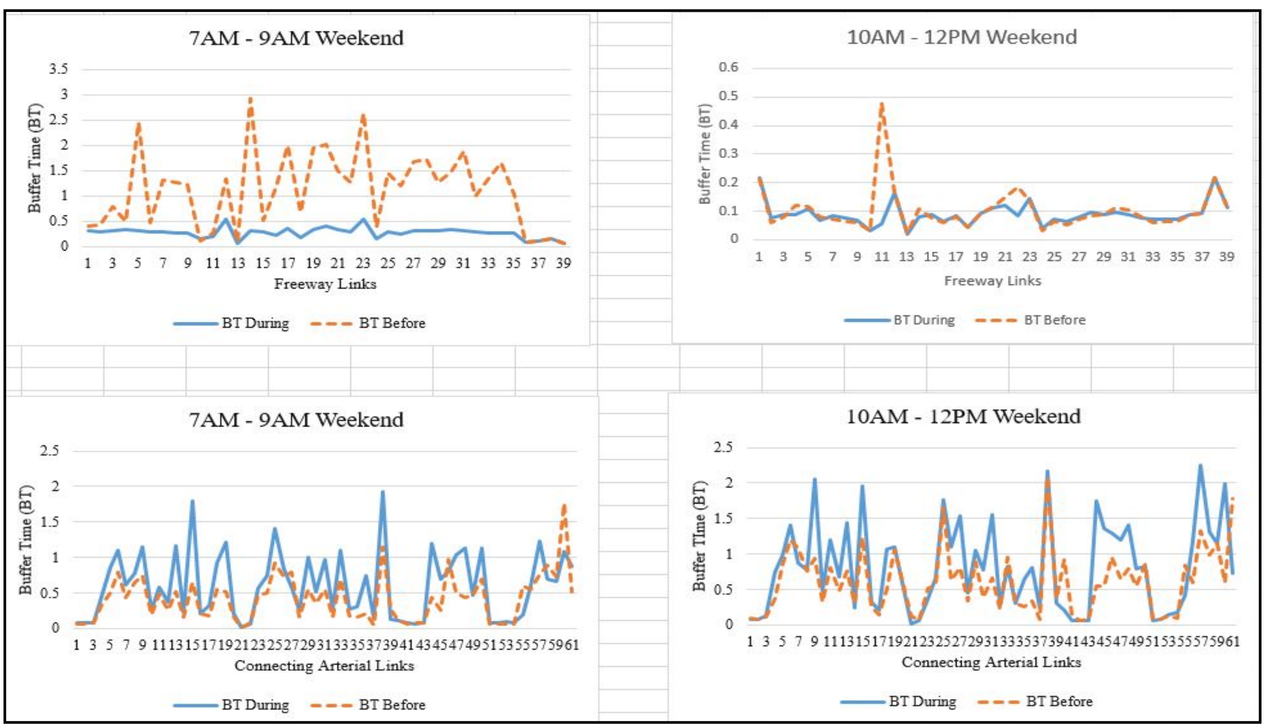

Figure 16. Buffer Time Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekend Day

Figure 16 shows the computed BTs before and during the construction project period on the freeway and connecting arterial street links for morning peak and morning off-peak hours on a weekend day. The BTs before the construction project period were higher on most of the links when compared with the BTs during the construction project period. However, BTs during the construction project period on connecting arterial street links are higher when compared with BTs before the construction project period. BTs during the evening off-peak hours on a weekend day have not shown any changes. On connecting arterial street links, BTs increased during the construction project period when compared with BTs before the construction project period.

Figure 17 shows the computed BTs before and during the construction project period on the freeway and connecting arterial street links for the evening peak and evening off-peak hours on a weekend day. The BTs are similar on the freeway links before and during the construction project period. However, on the connecting arterial street links, BTs were higher during the construction project period when compared with BTs before the construction on the project period.

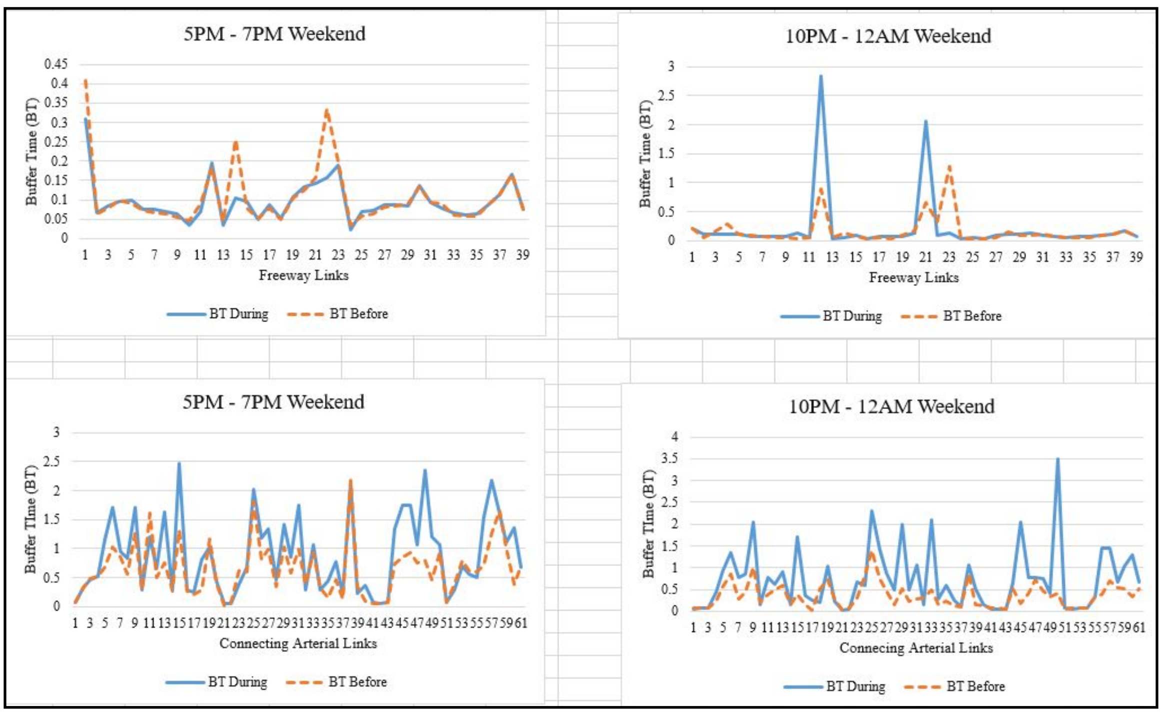

Figure 17. Buffer Time Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekend Day

The mean differences, t-statistics, and critical t values computed using the BTs are summarized in Table 6. The mean BTs during evening off-peak hours are higher during the construction project period when compared with the before construction project period. This could be because most of the construction activities commence during evening off-peak hours when an interruption to vehicular traffic would be minimum. In addition, from the t-statistic and critical t value results, there was a decrease in mean travel times from before to during the construction project period. However, these differences were not statistically significant on the freeway links, with the exception of the morning peak hours on a weekend day.

The mean BTs during the construction project period are significantly higher when compared with the before construction project period on the connecting arterial street links. The BT on the connecting arterial street links showed a statistically significant increase from before to during the construction project period, at a 95% confidence level. The mean difference in BTs is high particularly during the evening peak (weekday) and evening off-peak (weekday and weekend day) hours.

Table 6. T-test Results: Buffer Time (BT)

		7 AM - 9 AM		10 AM-12 PM		5 PM - 7 PM		10 PM - 12 AM	
		Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end
Freeway Study Links									
Mean	During	0.39	0.27	0.11	0.08	0.90	0.09	0.26	0.21
	Before	0.40	1.12	0.11	0.10	1.03	0.10	0.21	0.16
Diff. between means		-0.01	-0.85	0.00	-0.02	-0.13	-0.01	0.05	0.05
t-Stat		-0.17	-7.71	0.05	-1.18	-0.82	-1.47	0.68	0.75
P(T<=t) one-tail		0.43	<0.01	0.48	0.12	0.21	0.07	0.25	0.23
t Critical one-tail		1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
P(T<=t) two-tail		0.87	<0.01	0.96	0.25	0.42	0.15	0.50	0.46
t Critical two-tail		2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
Connecting Arterial Street Links									
Mean	During	1.47	0.60	0.81	0.81	2.04	0.89	0.67	0.73
	Before	1.18	0.42	0.70	0.60	1.60	0.65	0.37	0.36
Diff. between means		0.29	0.18	0.11	0.21	0.44	0.24	0.30	0.37
t-Stat		4.59	4.67	3.21	3.92	4.62	4.89	5.57	5.08
P(T<=t) one-tail		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical one-tail		1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
P(T<=t) two-tail		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical two-tail		2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

BUFFER TIME INDEX (BTI)

Figure 18 shows the computed BTIs on the selected freeway and connecting arterial street links, before and during the construction project periods, for morning peak and morning off-peak hours on a typical weekday. The trends on freeway links and connecting arterial street links seems to be higher before the construction project period when compared with the during construction project period for morning peak hours on freeway links and connecting arterial street links, and for morning off-peak hours on connecting arterial street links. BTIs are similar on the freeway links for morning off-peak hours.

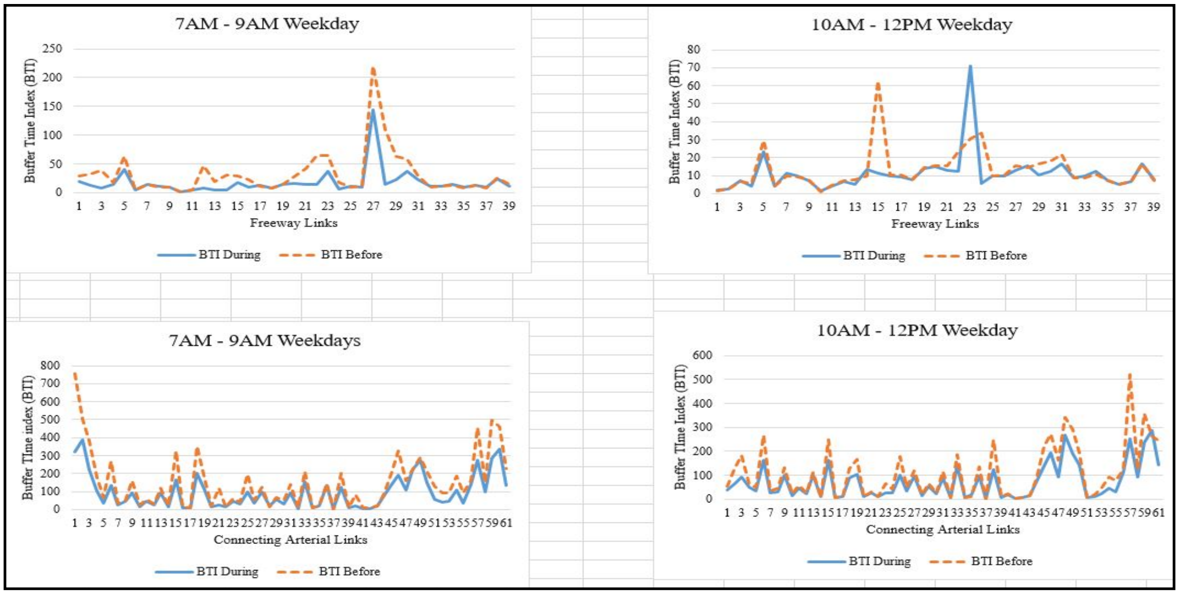

Figure 18. Buffer Time Index Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekday

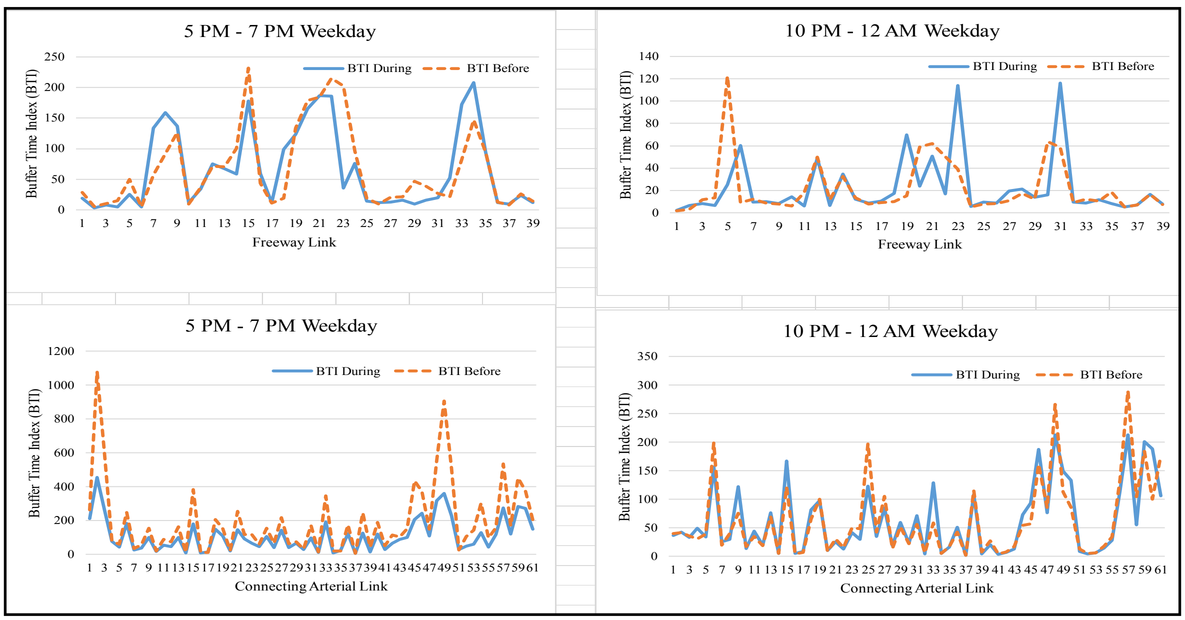

Figure 19. Buffer Time Index Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekday

Figure 19 shows the computed BTIs on the selected freeway and connecting arterial street links, before and during the construction project period, for evening peak and evening off-peak hours on a weekday. BTIs on freeway links during the peak hour is similar before and during the construction project period. However, the differences between the before and during construction project periods are very high on a few freeway links. Except on a couple of connecting arterial street links, the trends in computed BTIs are similar before and during the construction project periods.

Figure 20 shows the computed BTIs before and during the construction project periods on selected freeway links and connecting arterial street links for morning peak and morning off-peak hours on a typical weekend day. BTIs were higher on freeway links and connecting arterial street links for morning peak hours. However, the BTIs were higher before the construction project period when compared with BTIs during the construction project period for morning off-peak hours, on both freeway and connecting arterial street links.

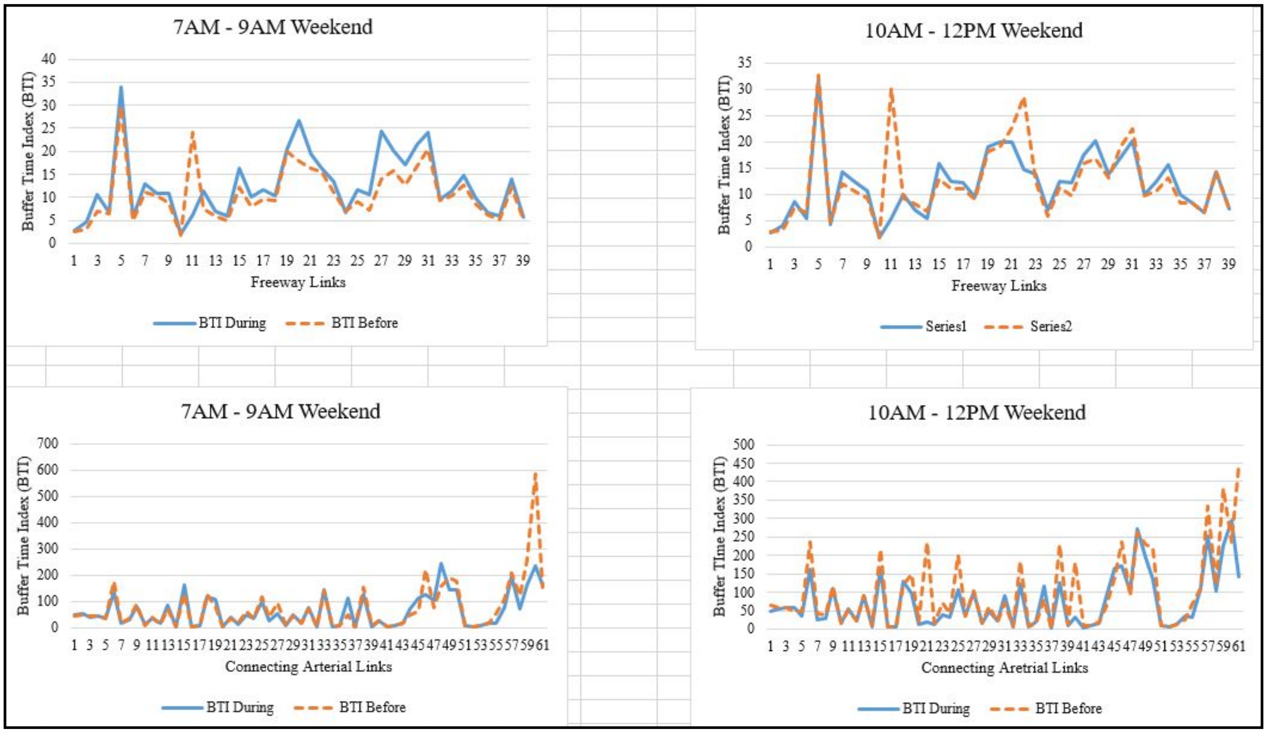

Figure 20. Buffer Time Index Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekend Day

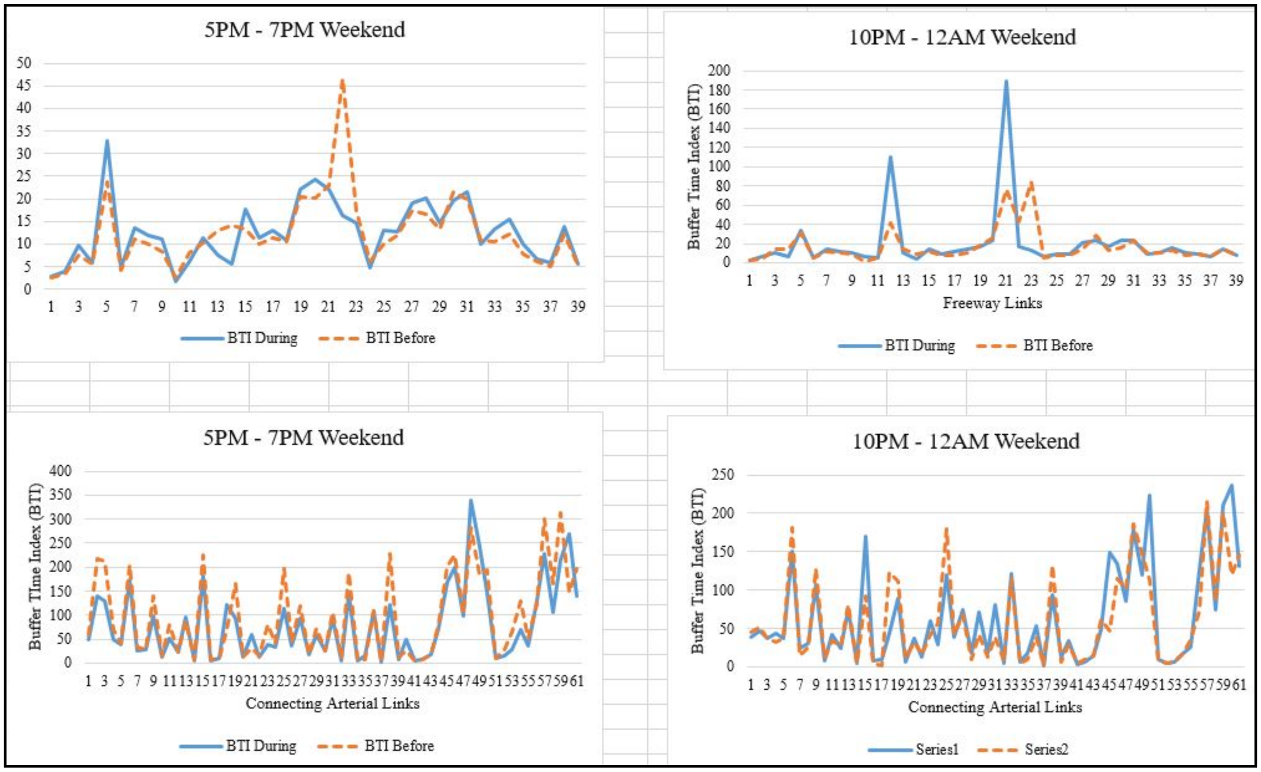

Figure 21. Buffer Time Index Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekend Day

Figure 21 shows the computed BTIs before and during the construction project period on the freeway and connecting arterial street links for evening peak and evening off-peak hours on a weekend day. The trends are similar to the BTIs for morning peak and morning off-peak hours, for both the freeway and connecting arterial street links.

The mean differences, t-statistics, and critical t values computed using the BTIs are summarized in Table 7. The results from the t-test analysis showed that the BTIs are nearly equal during and before the construction project period, on the freeway links, except during the morning peak period on a weekday and weekend day. Therefore, there is no statistically significant change in BTI between the before and during construction project periods on the freeway links.

The mean differences in BTIs are significantly higher on the connecting arterial street links when compared with freeway links. The BTI on these links increased significantly during the construction project period when compared with before the construction project period. The mean difference is higher particularly during the morning peak and evening peak hours on a weekday when compared with other time periods. When the vehicular traffic shifts from the freeway links to the connecting arterial street links during the construction project period, travel times increase significantly, and so does BTI. This seems to be during peak hours. The BTI during night-time off-peak hour on a weekday did not show any increase or decrease when before and during construction project period data were compared.

Table 7. T-test Results: Buffer Time Index (BTI)

		7 AM - 9 AM		10 AM-12 PM		5 PM - 7 PM		10 PM - 12 AM	
		Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end
Freeway Study Links									
Mean	During	17.30	12.57	11.07	11.94	65.19	12.51	21.89	19.40
	Before	31.51	10.79	13.04	12.38	66.23	12.38	21.59	15.54
Diff. between means		-14.21	1.78	-1.97	-0.44	-1.04	0.13	0.30	3.86
t-Stat		-4.06	2.83	-1.05	-0.57	-0.15	0.14	0.07	0.72
P(T<=t) one-tail		<0.01	<0.01	0.15	0.29	0.44	0.44	0.47	0.24
t Critical one-tail		1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
P(T<=t) two-tail		<0.01	<0.01	0.30	0.57	0.88	0.89	0.94	0.47
t Critical two-tail		2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
Connecting Arterial Street Links									
Mean	During	96.16	64.24	73.56	74.32	111.70	80.80	62.23	64.11
	Before	159.78	73.89	108.19	98.72	196.39	96.56	62.14	59.90
Diff. between means		-63.62	-9.65	-34.63	-24.40	-84.69	-15.76	0.09	4.21
t-Stat		-4.80	-1.43	-5.73	-3.22	-5.47	-3.20	0.02	1.00
P(T<=t) one-tail		<0.01	0.08	<0.01	<0.01	<0.01	<0.01	0.49	0.16
t Critical one-tail		1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
P(T<=t) two-tail		<0.01	0.16	<0.01	<0.01	<0.01	<0.01	0.98	0.32

TRAVEL TIME INDEX (TTI)

Figure 22 shows the computed TTIs on the selected freeway links and connecting arterial street links, before and during the construction project periods, for morning peak and morning off-peak hours on a weekday. The TTIs were higher on the freeway links for both the time periods. However, TTIs were lower for most of the links on connecting arterial streets during the construction project period, for both the time-of-day categories.

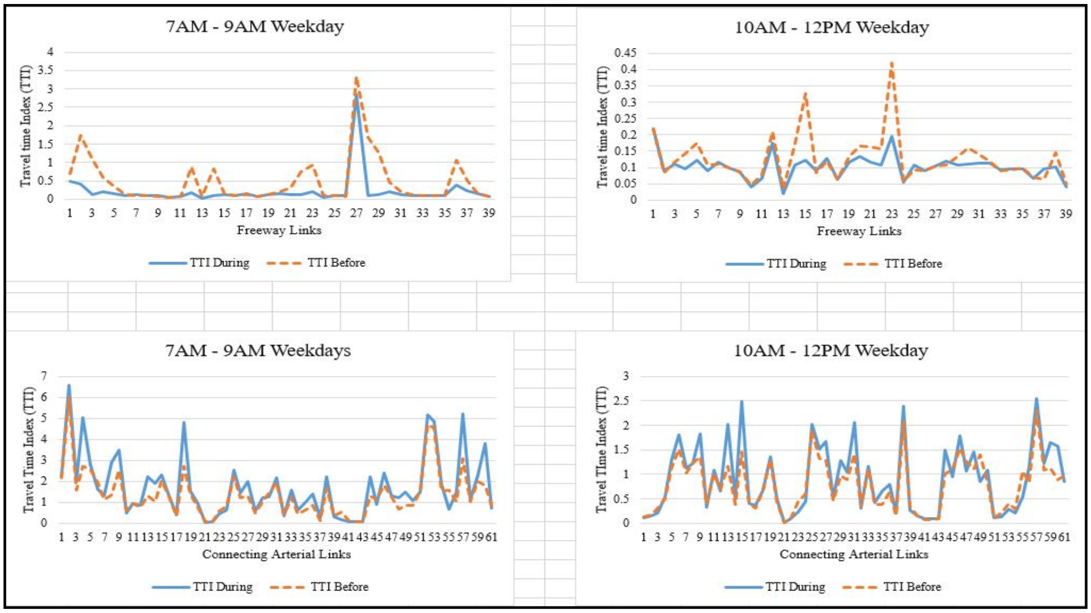

Figure 22. Travel Time Index Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekday

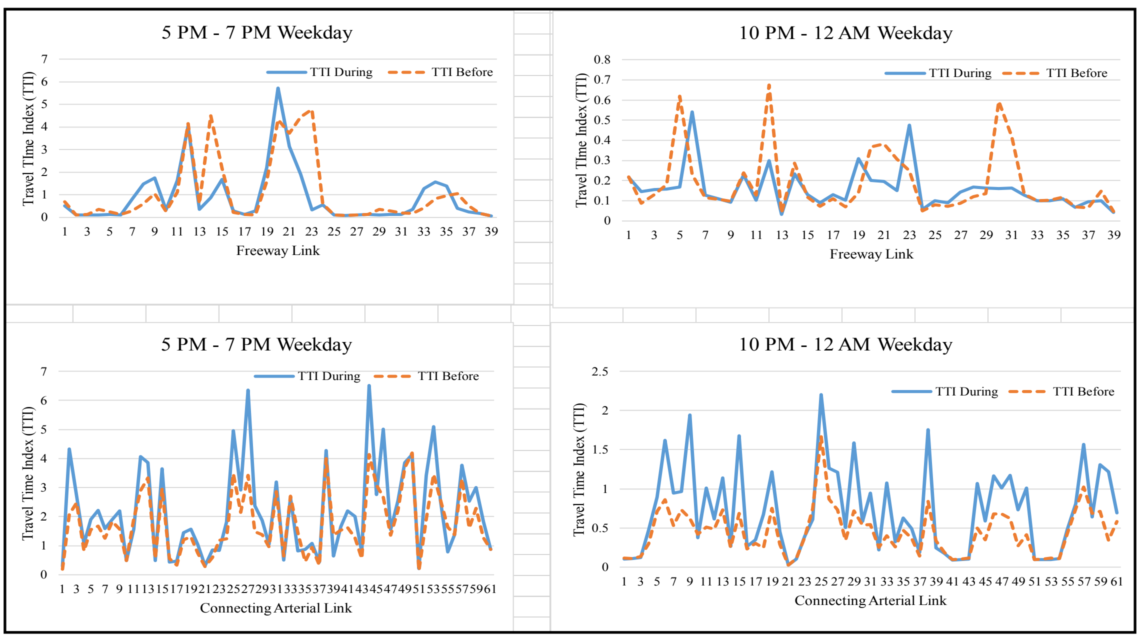

Figure 23. Travel Time Index Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekday

Figure 23 shows the TTIs on the selected freeway links and connecting arterial street links, before and during the construction project periods, for evening peak and evening off-peak hours on a weekday. The TTIs are close to each other, in case of both the study hours, except on a few links. However, the TTIs on the majority of connecting arterial street links are greater during the construction project period than before the construction project period, in case of both the time periods.

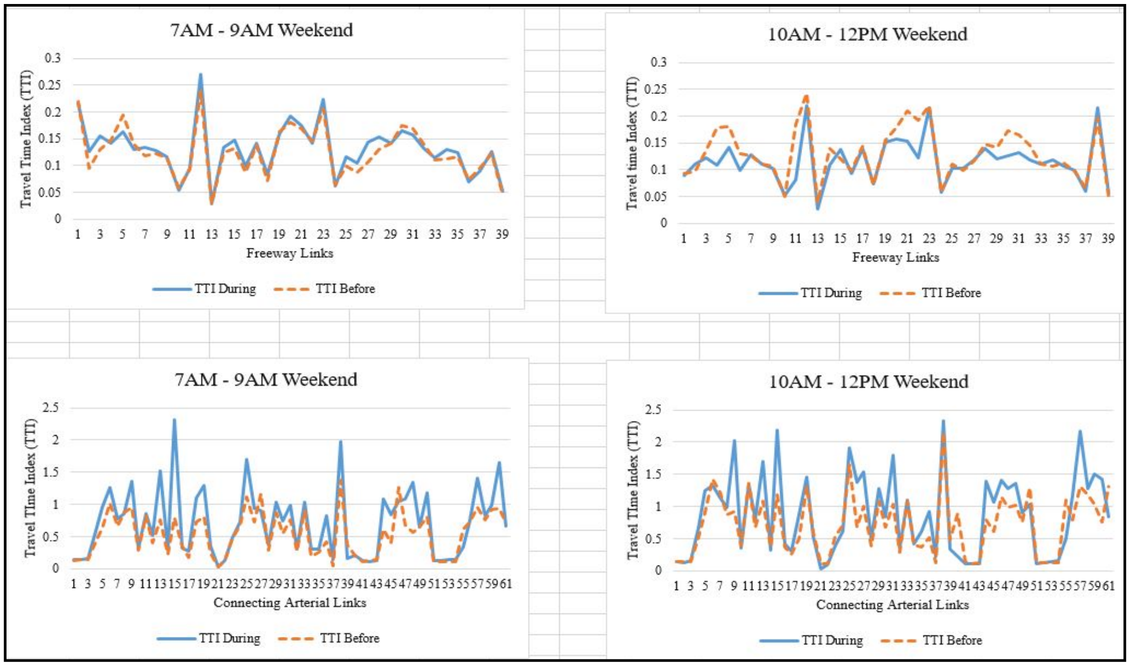

Figure 24. Travel Time Index Before and During the Construction Project Period for Morning Peak and Morning Off-peak Hours on a Weekend Day

Figure 24 shows the TTIs on the selected freeway and connecting arterial street links, before and during the construction project period, for morning peak and morning off-peak hours on a weekend day. TTIs were similar on the freeway links before and during the construction project period for morning peak hours. However, TTIs were higher on freeway links for morning off-peak hours on weekend days. On the other hand, TTIs were higher on the connecting arterial street links during the construction project period when compared with the before construction project period, for both the time-of-day categories.

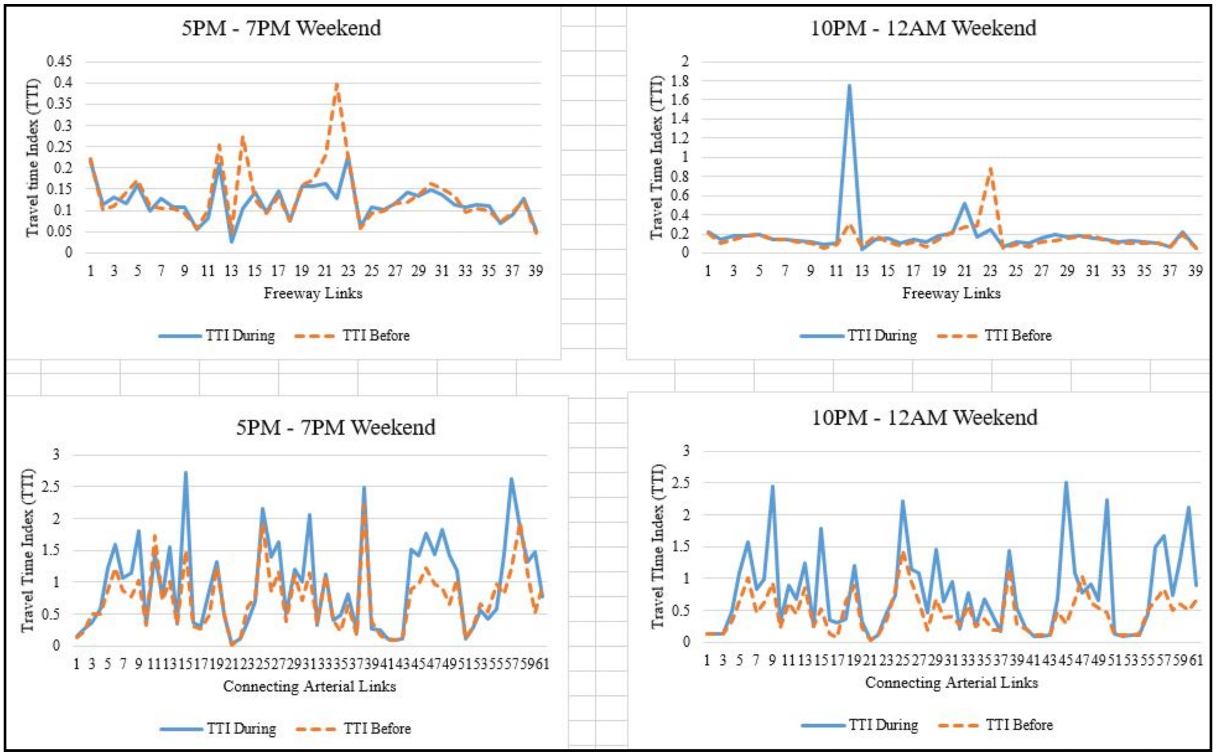

Figure 25. Travel Time Index Before and During the Construction Project Period for Evening Peak and Evening Off-peak Hours on a Weekend Day

Figure 25 shows the TTIs on the selected freeway and connecting arterial street links for evening peak and evening off-peak hours on a weekend day. TTIs before the construction project period were higher when compared with TTIs during the construction project period on freeway links for evening peak hours. However, TTIs are similar before and during the construction project period for evening off-peak hours on freeway links. TTIs were higher during the construction project period on the connecting arterial street links when compared with TTIs before the construction project period for both the time periods.

The mean differences, t-statistics, and critical t values computed using the TTIs are summarized in Table 8. Freeway links and connecting arterial street links showed similar trends. The mean TTIs before the construction project period are higher when compared with during the construction project period on the freeway links. The TTIs during the morning peak period and daytime off-peak hour on a weekday and on a weekend day both decreased from before to during the construction project period on the freeway links. A statistically significant change was not observed on the freeway links during the evening peak and evening off-peak hours.

The mean TTI values are higher during the construction project period, on connecting arterial street link links, when compared with the before construction project period. A significant increase was observed on the connecting arterial street links during all the considered time periods.

Table 8. T-test Results: Travel Time Index (TTI)

		7 AM - 9 AM		10 AM-12 PM		5 PM - 7 PM		10 PM - 12 AM	
		Week-day	Week-end	Week-day	Week-end	Week-day	Week-end	Week-day	Week-end
Freeway Study Links									
Mean	During	0.21	0.13	0.10	0.11	0.89	0.12	0.15	0.19
	Before	0.48	0.12	0.12	0.13	1.07	0.13	0.18	0.15
Diff. between means		-0.27	0.01	-0.02	-0.02	-0.18	-0.01	-0.03	0.04
t-Stat		-4.06	2.76	-2.91	-3.50	-1.05	-1.63	-1.21	0.91
P(T<=t) one-tail		<0.01	<0.01	<0.01	<0.01	0.15	0.06	0.12	0.19
t Critical one-tail		1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
P(T<=t) two-tail		0.00	0.01	0.01	0.00	0.30	0.11	0.23	0.37
t Critical two-tail		2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
Connecting Arterial Street Links									
Mean	During	1.73	0.71	0.90	0.87	2.18	0.96	0.72	0.78
	Before	1.39	0.53	0.79	0.71	1.75	0.74	0.45	0.46
Diff. between means		0.34	0.18	0.11	0.16	0.43	0.22	0.27	0.32
t-Stat		4.37	4.66	3.21	3.62	4.61	4.71	6.43	5.25
P(T<=t) one-tail		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
t Critical one-tail		1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
P(T<=t) two-tail		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

SUMMARY OF RELATIONSHIPS

Table 9 summarizes the travel time performance measures and statistical significance of their changes from the before to during construction project periods (positive, negative, or no statistical significance), categorized by the time-of-the-day and day-of-the-week. A “P” entry indicates an increase in a travel time performance measure during the construction project period when compared with before the construction project period, and an “N” entry indicates a decrease in travel time performance measure during the construction project period when compared with the before construction project period. From Table 9 it can be seen that on freeway links, ATT and PT are the travel time performance measures which are most consistently affected by the road construction project, with both showing a decrease in performance when compared to the before construction project period, for all time-of-day and day-of-the-week categories considered; no consistent trend was observed in the responses of BT, BTI, and TTI on freeway links to the construction project. On arterial street links, except in the case of BTI, significant positive effect on travel time performance was observed when compared with before the construction project period; the positive effect can be consistently observed when ATT, PT, BT, and TTI are used for assessment.

Table 9. Significance of Travel Time Performance Measures

	7 AM - 9 AM		10 AM-12 PM		5 PM - 7 PM		10 PM - 12 AM	
	Weekday	**Weekend**	**Weekday**	**Weekend**	**Weekday**	**Weekend**	**Weekday**	**Weekend**
Freeway Study Links								
ATT	N	N	N	N		N		
PT	N	N		N		N		
BT		N						
BTI	N	N						
TTI	N	P	N	N				
Connecting Arterial Street Links								
ATT			P	P	P	P	P	P
PT	P	P	P	P	P	P	P	P
BT	P	P	P	P	P	P	P	P
BTI	N		N	N	N	N		
TTI	P	P	P	P	P	P	P	P

P = Positive, N = Negative; Blank cell indicate no significant relation.

As the construction project period began, the travel time performance measures decreased on the freeway links and increased on the connecting arterial street links. This may be because, in order to avoid unnecessary delays during the construction, vehicular traffic shifted from the freeway links to the connecting arterial street links. Lower speed limits, reduced capacity, and increased traffic volume on the connecting arterial street links resulted in significantly higher travel times during the construction project period when compared to the freeway links. The performance measures and p values varied by time-of-the-day and day-of-the-week on the freeway and connecting arterial street links. The average travel time (ATT), planning time (PT), and travel time index (TTI) show consistent trends and can better explain the effect of a road construction project on transportation system performance.

Predominantly, the performance on freeway links is expected to be lower during the construction project period, since the actual number of lanes, lane widths, shoulder widths, and speed limits are reduced. However, from the paired t-test analysis, it is observed that the average travel time and travel time performance measures have improved on the freeway links but have worsened on the connecting arterial street links. Therefore, practitioners working on implementing large-scale transportation projects on freeways should forecast the effects both on freeway links, and on connecting arterial street links, due to a construction project period.

The average travel time was selected for modeling, since practitioners and researchers are interested in estimating the expected travel time. It was observed to show consistent trends and can better explain the effect of a road construction project. Therefore, the average travel time was selected as a dependent variable for modeling the effects of a construction project.

The models for estimating the average travel time before and during the construction project period, on the freeway and connecting arterial street links, are presented in the next chapter.

V. MODEL DEVELOPMENT & VALIDATION

Prior to developing the models for estimating the travel time before and during the construction period on freeways and connecting arterial street links, travel times were first estimated by using the formulation suggested by the Bureau of Public Roads (BPR). The BPR travel time equation is represented as follows.

BPR Estimated Travel Time = $TT_{freeflow} \times (1 + \alpha \times (\frac{v}{c})^{\beta})$ --------------- Equation 5

where $TT_{freeflow}$ = Free flow travel time on the selected link.

$\alpha = 0.15$ and $\beta = 4$ were considered as the default values. The V/C is volume over the capacity on the selected link.

The estimated BPR travel time was computed for each selected link and compared with the actual travel time. The RMSE and MAPE were computed to assess the effectiveness of the BPR equation in estimating travel time. Table 10 represents the RMSE and MAPE before and during the construction project period on the freeway and connecting arterial street links.

Table 10. Validation Results from BPR Analysis

	RMSE	MAPE
Freeway Links (BPR)		
Before the Construction Project Period	0.27	19.67%
During the Construction Project Period	0.27	20.93%
Connecting Arterial Street Links (BPR)		
Before the Construction Project Period	0.62	74.23%
During the Construction Project Period	0.70	83.01%

From the results summarized in Table 10, variations were observed between the estimated travel time using the BPR equation and the actual travel time, for freeway and connecting arterial street links before and during the construction project period. This indicates that factors other than V/C influence travel time before and during the road construction project period. Therefore, models were developed in order to better estimate travel times before and during the road construction project.

The average travel times, network characteristics, construction zone characteristics, upstream and downstream characteristics, time-of-the-day, day-of-the-week, and the distance from the construction project, for each link, could influence travel time and were segregated into two different databases; one for before, and one for during, the construction project period.

Descriptive statistics were computed using the freeway link and connecting arterial street link data, for before and during the construction project period. Table 11 summarizes the descriptive statistics for the freeway links. Table 12 summarizes the descriptive statistics for connecting arterial street links.

Table 11. Descriptive Statistics – Freeway Links

	N	Minimum	Maximum	Mean	Std. Deviation
Before the Construction Project Period					
Average Travel Time	226	0.16	1.97	0.88	0.31
Link Length (mi)	226	0.39	4.10	1.24	0.93
Traffic Volume	226	282	5130	2330	1336
Capacity	226	8800	29333	18985	6277
V/C	226	0.10	0.85	0.16	0.13
No. of Lanes	226	1	4	3	1
Speed Limit (mph)	226	55	65	60	5
Upstream Link Length (mi)	226	0.31	4.10	1.19	0.95
Upstream V/C	226	0.10	0.87	0.47	0.14
Upstream no. of lanes	226	1	4	2	1
Upstream Speed Limit	226	55	65	57	12
Downstream Link Length (mi)	226	0.30	4.10	1.10	0.80
Downstream V/C	226	0.12	0.87	0.46	0.14
Downstream no. of lanes	226	1	4	3	1
Downstream Speed Limit	226	55	65	57	12
D (mi)	226	0.15	4.48	1.32	1.62
During the Construction Project Period					
Average Travel Time	226	0.15	1.92	0.85	0.30
Link Length (mi)	226	0.39	4.10	1.24	0.93
Traffic Volume	226	200	4850	2130	1336
Capacity	226	5867	22000	14907	3971
V/C	226	0.08	0.56	0.19	0.16
No. of Lanes	226	1	3	2	0
Speed Limit (mph)	226	55	65	60	5
Upstream Link Length (mi)	226	0.31	4.10	1.19	0.95
Upstream V/C	226	0.12	0.56	0.47	0.14
Upstream no. of lanes	226	1	3	2	1
Upstream Speed Limit	226	55	65	57	12
Downstream Link Length (mi)	226	0.30	4.10	1.10	0.80
Downstream V/C	226	0.19	0.52	0.46	0.14
Downstream no. of lanes	226	1	3	2	1
Downstream Speed Limit	226	55	65	57	12

Table 12. Descriptive Statistics – Connecting Arterial Street Links

	N	Minimum	Maximum	Mean	Std. Deviation
Before the Construction Project Period					
Average Travel Time	260	0.20	1.99	1.46	0.38
Link Length (mi)	260	0.31	3.75	1.03	0.90
Traffic Volume	260	708	6250	2239	1454
Capacity	260	1106	29333	9500	7871
V/C	260	0.13	1.13	0.30	0.15
No. of Lanes	260	1	3	2	1
Speed Limit (mph)	260	35	55	47	5
Upstream Link Length (mi)	260	0.30	3.75	0.80	0.75
Upstream V/C	260	0.13	1.58	0.42	0.24
Upstream no. of lanes	260	1	3	2	1
Upstream Speed Limit (mph)	260	35	55	46	9
Downstream Link Length (mi)	260	0.31	3.75	0.77	0.78
Downstream V/C	260	0.17	1.13	0.42	0.20
Downstream no. of lanes	260	1	3	2	1
Downstream Speed Limit (mph)	260	35	55	47	5
D (mi)	260	0.21	3.75	1.38	0.97
During the Construction Project Period					
Average Travel Time	221	0.25	1.99	1.74	0.41
Link Length (mi)	221	0.31	3.75	1.03	0.94
Traffic Volume	221	773	6818	3036	1581
Capacity	221	1106	29333	10242	8279
V/C	221	0.14	2.81	0.42	0.34
No. of Lanes	221	1	3	2	1
Speed Limit (mph)	221	35	55	47	6
Upstream Link Length (mi)	221	0.30	2.61	0.79	0.75
Upstream V/C	221	0.14	2.81	0.65	0.55
Upstream no. of lanes	221	1	3	2	1
Upstream Speed Limit (mph)	221	35	55	45	10
Downstream Link Length (mi)	221	0.31	3.75	0.72	0.76
Downstream V/C	221	0.20	1.42	0.58	0.33
Downstream no. of lanes	221	1	3	2	0
Downstream Speed Limit (mph)	221	35	55	47	5
D (mi)	221	0.22	3.75	1.48	0.99

On the freeway links, before and during the construction project period, the speed limit, the shoulder width, and the lane width were observed to be the same throughout the study corridor. Therefore, the speed limit, the shoulder width, and the lane width variables were neglected for the model development for freeway links only. The details of the predictor variables considered for developing the travel time model for freeway links and the connecting arterial street links, before and during the construction project period, are presented in Table 13.

Table 13. Dependent and Predictor Variables

S. No	Dependent Variables	Predictor Variables
1	Average Travel Time (ATT) Before & Average Travel time (ATT) During the Construction Project Period	Volume/Capacity (V/C)
2		Number of Lanes
3		Speed Limit (mph)
4		Shoulder Width (ft)
5		Lane Width (ft)
6		Divided/Undivided (0 or 1)
7		Upstream Link Length (mi)
8		Upstream V/C
9		Upstream Number of Lanes
10		Upstream Speed Limit (mph)
11		Downstream Link Length (mi)
12		Downstream V/C
13		Downstream Number of Lanes
14		Downstream Speed Limit (mph)
15		Link Distance to the Study Corridor (D)
16		Weekday (0 or 1)
17		Weekend Day (0 or 1)
18		Morning Peak (0 or 1)
19		Evening Peak (0 or 1)
20		Morning Off-peak (0 or 1)
21		Evening Off-peak (0 or 1)

TRAVEL TIME BEFORE THE CONSTRUCTION PROJECT PERIOD FOR FREEWAY LINKS

A Pearson correlation analysis was conducted using the before construction project period data for 297 samples on the freeway. From the computed Pearson correlation coefficients, the predictor variables were selected to minimize the effect of multicollinearity between the predictor variables. The results obtained from the Pearson correlation coefficient analysis are presented in Table 14.

From the computed Pearson correlation coefficients, predictor variables such as the number of lanes, the upstream link length, and the downstream number of lanes are positively correlated with the average travel time before the construction project period on the freeway links. Link distance from the study corridor is negatively correlated with the average travel time before the construction project period on the freeway links. As the number of lanes on the link and the number of lanes on the downstream link increases, there could be a possibility to attract a greater number of vehicles on the freeway section, which could, in turn, increase the traffic volume and travel time. In addition, the travel time is expected to decrease as the distance from the study corridor increases.

The predictor variables V/C, upstream V/C, upstream number of lanes, upstream speed limit, downstream V/C, downstream number of lanes, and downstream speed limit were correlated with the remaining predictor variables but were not correlated to each other, at a 95% confidence level.

Generalized linear estimating equation analysis in SPSS software was used for developing the travel time model for freeway links, using the aforementioned predictor variables that are not correlated to each other (V/C, upstream V/C, upstream number of lanes, upstream speed limit, downstream V/C, downstream number of lanes, and downstream speed limit).

Of 297 freeway samples, 226 randomly selected samples were used for modeling the effect of the resurfacing construction project, while the remaining 71 randomly selected samples were used for validating the developed model. The significance level was set at 0.05 (95% confidence). The predictor variables with a significance value greater than 0.05 were eliminated, except V/C, one after another while developing the models. The elimination process was repeated until all other predictor variables in the models have a significance value less than or equal to 0.05.

Linear, gamma log-link distribution, negative binomial log-link distribution, and Poisson log-link distribution based models were developed for the freeway links before the construction project using the selected predictor variables. Table 15 summarizes the regression coefficients for predictor variables, standard errors, p values, QIC, and QICC for the various freeway links models for the before construction project period.

Table 14. Correlation Coefficients for Freeway Links Before the Construction Project Period

	Average TT Before	V/C	(V/C)^ 2	(V/C)^ 3	(V/C)^ 4	(V/C)^ 5	# of Lanes	Upstream Link Length (mi)	Upstream V/C	Upstream # of lanes	Upstream Speed Limit (mph)	Downstream Link Length (mi)	Downstream V/C	Downstream # of lanes	Downstream Speed Limit (mph)	D (mi)	Weekday	Weekend Day	Morning Peak	Evening Peak	Day-Time Off-Peak	Evening Time Off-Peak
Average TT Before	1																					
V/C	0.02	1																				
(V/C)^ 2	<0.01	.964**	1																			
(V/C)^ 3	-0.01	.895**	.980**	1																		
(V/C)^ 4	-0.02	.830**	.943**	.990**	1																	
(V/C)^ 5	-0.02	.777**	.907**	.971**	.995**	1																
# of Lanes	.121*	-.255**	-.263**	-.281**	-.297**	-.308**	1															
Upstream Link Length (mi)	.112*	<0.01	<0.01	<0.01	<0.01	<0.01	-.166**	1														
Upstream V/C	-0.10	0.10	0.08	0.08	0.07	0.07	-.441**	.299**	1													
Upstream # of lanes	0.04	-0.09	-0.10	-.117*	-.131*	-.141*	.601**	-0.09	-.255**	1												
Upstream Speed Limit (mph)	0.04	-0.07	-0.09	-0.10	-.114*	-.122*	.227**	.203**	.561**	.526**	1											
Downstream Link Length (mph)	-0.06	0.03	0.04	0.04	0.04	0.04	0.07	.135*	-.195**	-.118*	-.256**	1										
Downstream V/C	-0.04	0.10	.125*	.144*	.156**	.163**	-0.03	-.207**	-.261**	.249**	-.240**	.210**	1									
Downstream # of lanes	.153**	-.223**	-.214**	-.215**	-.217**	-.218**	.601**	.158**	-.285**	.257**	.190**	<0.01	-.210**	1								
Downstream Speed Limit (mph)	0.03	-0.03	0.00	0.02	0.03	0.03	.227**	0.09	-.227**	.190**	-0.03	.229**	.568**	.526**	1							
D (mi)	-.125*	0.02	0.02	0.02	0.01	0.01	.160**	-.252**	-.199**	.127*	-.276**	-.149**	.193**	-.383**	-.311**	1						
Weekday	0.09	.433**	.447**	.409**	.365**	.328**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1					
Weekend Day	-0.09	-.433**	-.447**	-.409**	-.365**	-.328**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-1.000**	1				
Morning Peak	-0.01	.256**	.250**	.225**	.197**	.172**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1			
Evening Peak	0.10	.394**	.327**	.273**	.237**	.214**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	1		
Day-Time Off-Peak	-0.06	-.144*	-.214**	-.221**	-.205**	-.188**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	1	
Evening Time Off-Peak	-0.03	-.506**	-.363**	-.278**	-.228**	-.197**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	-.333**	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Table 15. Comparison of Model Parameters for freeway Links Before the Construction Project Period

	Linear Model			Gamma Log-Link			Negative Binomial Log-Link			Poisson Log-Link		
Parameter	Coeff.	Std. Error	P-Value	Coeff.	Std. Error	P-Value	Coeff.	Std. Error	P-Value	Coeff.	Std. Error	P-Value
(Intercept)	1.26	0.07	0.01	-0.23	0.07	0.01	3.87	0.07	0.01	3.87	0.07	0.01
V/C	0.07	0.13	0.50	0.01	0.13	0.99	-0.01	0.13	0.99	0.02	0.13	0.85
Upstream V/C	-0.65	0.17	<0.01	-0.76	0.17	<0.01	-0.74	0.17	<0.01	-0.73	0.17	<0.01
Upstream no. of lanes	-0.25	0.04	<0.01	-0.28	0.04	<0.01	-0.28	0.04	<0.01	-0.29	0.04	<0.01
Upstream SL	0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01
Downstream V/C	0.51	0.15	<0.01	0.54	0.15	<0.01	0.53	0.15	<0.01	0.59	0.15	<0.01
Downstream no. of lanes	0.11	0.06	0.05	0.10	0.06	0.07	0.10	0.06	0.07	0.13	0.06	0.02
Downstream SL	-0.01	<0.01	0.04	-0.01	<0.01	0.07	-0.01	<0.01	0.06	-0.01	<0.01	0.01
QIC		30.24			39.87			29.77			1341.6	
QICC		33.97			46.33			44.57			1290.68	

Note: For Negative-Binomial and Poisson Log-link, the Average Travel Time (ATT) was converted into seconds. In case of Linear and Gamma Log-Link distributions, ATT is in minutes.

The linear model has lower QIC and QICC than the other models, and under the linear model, most of the selected predictor variables are statistically significant at a 95% confidence level. The QIC and QICC are also reasonably close to each other for the linear model. Therefore, the linear model was selected for modeling travel times on the freeway links before the construction project period and was validated.

The general form of the final best-fit linear model summarized in Table 15 is as shown in Equation 6.

Average Travel Time = 1.26 +0.07 × (V/C) – 0.65 × (Upstream V/C) – 0.25 × (Upstream number of lanes) + 0.01 × (Upstream Speed Limit) + 0.51 × (Downstream V/C) + 0.11 × (Downstream Number of Lanes) – 0.01 × (Downstream Speed Limit)
-------------- Equation 6

Equation 6 can be used to estimate travel time on a freeway link before the road construction project period. If, the V/C is 0.49, the upstream V/C is 0.58, the upstream number of lanes is 2, the upstream speed limit is 65 mph, the downstream V/C is 0.46, the downstream number of lanes is 2, and, the downstream speed limit is 55 mph for a freeway link; then the average travel time for the freeway link = 1.26 +0.07 × (0.49) – 0.65 × (0.58) – 0.25 × (2) + 0.01 × (65 + 0.51 × (0.46) + 0.11 × (2) – 0.01 × (55) = 0.97 min/mile.

The developed linear model (Equation 6) was then validated using data for 71 samples selected from the same construction project database. The average travel times were computed using the developed model and compared with the actual travel times.

The travel time model before the construction project period on freeway links shows that if upstream V/C and the upstream number of lanes increases, the travel times would reduce. However, if the upstream speed limit increase, link-level travel times would increase. Similarly, if downstream V/C and the downstream number of lanes increases, the travel times would also increase. However, if the downstream speed limit increase, the travel times would reduce before the construction project period on freeway links.

If upstream V/C decreases, travel times increase. While traffic is entering a construction zone from the upstream link, there is a possibility that the traffic would have staggered or queued due to the construction. Similarly, as the upstream number of lanes decreases, the travel times increase. Furthermore, an increase in the upstream speed limit does influence travel times significantly. Vehicle queueing could be building on the upstream links due to the construction, irrespective of the higher speed limit. Similarly, as the downstream V/C increases, travel times are expected to increase. In addition, while the downstream number of lanes increases, more traffic would be attracted to freeway links, which in turn increases travel times significantly. Moreover, if the speed limit decreases on the downstream links, the travel time would also increase significantly.

The RMSE and MAPE were computed and used for validating the model. The computed RMSE is 0.11, while the computed MAPE is 7.75%. A difference of around 6 seconds has been observed between the developed model and the actual recorded average travel times.

TRAVEL TIME BEFORE THE CONSTRUCTION PROJECT PERIOD FOR CONNECTING ARTERIAL STREET LINKS

In order to understand the effect of a road construction project on connecting arterial street links before the construction project period, Pearson correlation coefficients were computed, and the travel time model was developed as well as validated using data captured for the connecting arterial street links.

A Pearson correlation analysis was conducted using data from before the construction project period, for 328 samples, on connecting arterial street links. A few additional predictor variables were included while generating the correlations for the connecting arterial street links. Variables such as link length, whether the link was divided or undivided, shoulder width, lane width, and speed limit were added to the connecting arterial street link characteristics. The results obtained from the Pearson correlation analysis are presented in Table 16.

From the computed Pearson correlation analysis, it was found that nearly all the predictor variables were correlated with the average travel time before the construction project period, at a 95% confidence level. The V/C, the number of lanes, the upstream link length, the upstream number of lanes, the downstream link length, the downstream V/C, the downstream number of lanes, the downstream speed limit, and morning and evening peak hours are positively correlated with the average travel time before the construction project period. As the V/C increases, the travel times would increase significantly; increase in the number of lanes would attract more vehicular traffic, which in turn increases travel times.

Similarly, other predictor variables such as upstream link length, upstream number of lanes, downstream link length, and downstream number of lanes does eventually increase travel times by attracting traffic volume on the network. Furthermore, travel time is expected to increase as the speed limit decreases. Similarly, travel time is expected to increase as the lane and the shoulder width decreases.

The travel times are expected to increase as the downstream speed limit decreases. It is expected that travel times would decrease as the distance from the study corridor increase. During the weekday, traffic volume will be higher which would increase the travel time. However, during the weekend the traffic volume is likely to be lower when compared to weekday, and so travel times are lower as well.

Table 16. Correlation Coefficients for Connecting Arterial Street Links Before the Construction Project Period

	ATT Before	Link Length (mi)	V/C	Divided/ Undivided	# of Lanes	Speed Limit (mph)	Shoulder Width (ft)	Lane Width (ft)	Upstream Link Length (mi)	Upstream V/C	Upstream #of lanes	Upstream Speed Limit (mph)	Downstream Link Length (mi)	Downstream V/C	Downstream # of lanes	Downstream Speed Limit (mph)	D (mi)	Weekday	Weekend Day	Morning Peak	Evening Peak	Day-Time Off-Peak	Evening Time Off-Peak
ATT Before	1																						
Link Length (mi)	-.162**	1																					
V/C	.392**	.092*	1																				
Divided/ Undivided	-.233**	-0.07	-0.01	1																			
# of Lanes	.132**	.132**	.160**	.113*	1																		
Speed Limit (mph)	-.413**	-.288**	-.176**	.206**	-.199**	1																	
Upstream Link Length (mi)	.132**	-.130**	0.06	-.148**	-.225**	-0.06	-.111*	-.203**	1														
Upstream V/C	0.07	.211**	.188**	-0.03	0.06	0.00	-.121**	-.290**	.161**	1													
Upstream # of lanes	.325**	-.363**	0.08	-.117**	0.07	-.235**	-.271**	-.170**	.177**	.220**	1												
Upstream Speed Limit (mph)	-0.03	-0.02	0.04	.092*	-0.07	.175**	.166**	-.268**	-0.07	.096*	.207**	1											
Downstream Link Length (mi)	.195**	-.131**	.195**	-.327**	-.444**	-.180**	-.151**	-.147**	.427**	0.08	.263**	-0.03	1										
Downstream V/C	.138**	0.02	.245**	0.08	0.01	-0.09	-.121**	-.169**	.222**	.156**	-0.03	.118**	.148**	1									
Downstream # of lanes	.177**	-.163**	<0.01	-0.02	0.07	-0.04	-0.06	.089*	-.147**	0.09	.134**	0.01	.178**	.229**	1								
Downstream Speed Limit (mph)	-.222**	0.07	-0.02	.170**	-.124**	.421**	.297**	.209**	0.03	.185**	-.152**	-0.02	-0.05	.119**	.201**	1							
D (mi)	-.218**	.770**	0.03	-0.05	-.108*	-0.04	0.03	-0.03	-0.07	.136**	-.435**	0.04	<0.01	-0.01	-0.02	.111*	1						
Weekday	.224**	<0.01	.227**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1					
Weekend Day	-.224**	<0.01	-.227**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-1.000**	1				
Morning Peak	.185**	<0.01	.131**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1			
Evening Peak	.185**	<0.01	.131**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	1		
Day-Time Off-Peak	-.091*	<0.01	-.131**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	1	
Evening Time Off-Peak	-.279**	<0.01	-.131**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	-.333**	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

The predictor variables V/C, whether the link is divided or undivided, speed limit, upstream V/C, upstream number of lanes, and link distance from the construction corridor, were selected for modeling as they were correlated with all other predictor variables but are not correlated to each other, at a 95% confidence level. For example, the speed limit and the number of lanes on a selected link are correlated with each other, and so only one of those two variables were used for model development. Similar logic was applied with the upstream and downstream predictor variables.

Generalized linear estimating equation analysis, conducted in SPSS, was used for developing the travel time model, for connecting arterial street links before the construction project period, using the predictor variables that are not correlated to each other (V/C, whether the link is divided or undivided, speed limit, upstream V/C, upstream number of lanes, and link distance from the construction corridor).

For the connecting arterial street links, before the construction project period, 260 randomly chosen samples were used for the developing models while 68 samples were used for validating the developed models. The significance level was set at 0.07 (93% confidence). The predictor variables with a significance value greater than 0.07 were eliminated, excluding V/C, one after another while developing the models. A few variables that are significant in estimating the travel times have a confidence level close to 93%. Therefore, the variables which are less than a 93% confidence level were eliminated from the models.

The elimination process was repeated until all the remaining predictor variables in the model have a p-value less than or equal to 0.07. The QIC and QICC were used to evaluate the model's goodness-of-fit.

Similarly, to the case of freeway links before the construction project period, linear, gamma log-link, negative binomial log-link, and Poisson log-link distribution based models were developed for the connecting arterial street links before the construction project period. Table 17 summarizes the regression coefficients, standard errors, p values, QIC, and QICC for the various connecting arterial street links models for the before construction project period.

Table 17. Comparison of Model Parameters for Connecting Arterial Street Links Before the Construction Project Period.

	Linear Model			Gamma Log-Link			Negative Binomial Log-Link			Poisson Log-Link		
Parameter	Coeff.	Std. Error	P-value	Coeff.	Std. Error	P-value	Coeff.	Std. Error	P-value	Coeff.	Std. Error	P-value
(Intercept)	2.80	0.20	<0.01	1.97	0.20	<0.01	6.05	0.20	<0.01	5.85	0.20	<0.01
Divided/ Undivided	0.15	0.05	<0.01	0.10	0.05	0.04	0.10	0.05	0.05	0.09	0.05	0.10
V/C	0.60	0.10	<0.01	0.41	0.10	0.03	0.41	0.10	0.39	0.41	0.10	0.01
Speed Limit	-0.04	<0.01	<0.01	-0.03	<0.01	<0.01	-0.04	<0.01	<0.01	-0.03	<0.01	<0.01
Upstream V/C	-0.24	0.13	0.06	-0.25	0.13	0.40	-0.24	0.13	0.50	-0.16	0.13	0.58
Upstream No. of Lanes	0.04	0.03	0.07	0.04	0.03	0.27	0.04	0.03	0.32	0.03	0.03	0.49
D (mi)	-0.04	0.02	0.02	-0.02	0.02	0.60	-0.02	0.02	0.66	-0.02	0.02	0.46
QIC		34.66			86.25			23.41			1336.42	
QICC		30.3			31.94			31.18			985.21	

Note: For negative binomial and Poisson log-link, the Average Travel Time (ATT) was converted into seconds. In case of linear and gamma log-Link distributions, ATT is in minutes.

The linear model has lower QIC and QICC than the gamma log-link, negative binomial log-link, and Poisson log-link distribution based models. The linear model's QIC and QICC are also reasonably close to each other. Therefore, the linear model was used as a best-fit model for estimating travel times before the construction project period for connecting arterial street links.

The general form of the final best-fit model summarized in Table 17 is as shown in Equation 7.

Average Travel Time = 2.80 + 0.15 × (Divided/Undivided) + 0.60 × (V/C) – 0.04 × (speed Limit) – 0.24 × (Upstream V/C) + 0.04 × (Upstream Number of Lanes) – 0.04 × (D)
-------------- Equation 7

Equation 7 can be used to estimate travel time on a connecting arterial street link before the road construction project period. For example if the V/C is 0.43, the speed limit is 45 mph, the upstream V/C is 0.47, the upstream number of lanes is 2, the road is divided (divided/undivided is 1), and the distance from the project location is 0.35 miles for a connecting arterial street link; then the average travel time for the connecting arterial street link = 2.80 + 0.15 × (1) + 0.60 × (0.43) – 0.04 × (45) – 0.24 × (0.47) + 0.04 × (2) – 0.04 × (0.35) = 1.38 min/mile.

The developed linear model (Equation 7) was then validated using data for 68 samples selected from the same construction project database.

The developed travel time model for before the construction project period on the connecting arterial street links shows that V/C, and whether the link is divided or undivided, both would increase link-level travel time at a 95% confidence level. If the upstream number of lanes increases, travel times at link-level would also increase. In addition, predictor variables such as speed limit, upstream V/C, and the distance of a link from the study corridor increase, link-level travel times would reduce at a 95% confidence level.

As traffic volume increases and capacity decreases, travel times would increase significantly. Before the construction project period, if the speed limit is reduced, the travel time is expected to increase. As the upstream V/C is reduced, the travel times would increase following similar trends as freeway links. An increase in the upstream number of lanes attracts high traffic volume and increases travel time predominantly. The downstream link characteristics do not have a significant effect on travel times before the construction project period on connecting arterial street links.

The estimated average travel times were computed using the developed model and compared with the actual travel times. The computed RMSE is 0.45 and MAPE is 24.28%. A difference of around 20 seconds has been observed between the developed model's estimated travel times and the actual recorded average travel times.

TRAVEL TIME DURING THE CONSTRUCTION PROJECT PERIOD FOR FREEWAY LINKS

The travel time during the road construction project period could be related to the travel time before the road construction project period. Therefore, a linear model, a linear model with no intercept, and gamma log-link, negative binomial log-link, and Poisson log-link distribution models were developed with the average travel time during the road construction project period as the dependent variable and the actual average travel time before the road construction project period as the predictor variable. Data for 226 randomly selected samples were used for developing the model and 71 samples were used for validation. A linear model with no intercept was selected since the QIC and QICC are lower and close to each other. The computed RMSE and MAPE are 0.05 and 3.53%. The results obtained show that travel time during the construction project period is lower than the travel time before the construction project period on a freeway link. Table 18 summarizes the regression coefficients, standard errors, p values, QIC, and QICC for the various freeway link models for the during the construction project period.

Table 18. Comparison of Model Parameters for Freeway Links During the Construction Project Period Related to During and Before Average Travel Time

	Linear Model			Gamma Log-Link			Negative Binomial Log-Link			Poisson Log-Link			Linear Model (No Intercept)		
Parameters	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**
(Intercept)	0.12	0.04	<0.01	-1.07	0.08	<0.01	3.13	0.05	<0.01	3.02	0.08	<0.01	-	-	-
ATT Before	0.86	0.04	<0.01	1.02	0.08	<0.01	0.01	>0.01	<0.01	0.01	<0.01	<0.01	0.98	<0.01	<0.01
QIC		10.32			19.96			394.77			11.3			6.14	
QICC		8.07			15.51			387.34			14.9			6.4	

Note: For Negative-Binomial and Poisson Log-link, the Average Travel Time (ATT) was converted into seconds. In case of Linear and Gamma Log-Link distributions, ATT is in minutes.

The general form of the final best-fit model summarized in Table 18 is as shown in Equation 8.

Average Travel Time During = 0.98 × (Average Travel Time Before) ---------- Equation 8

The travel time during the construction project period will depend on the V/C during the construction project period on freeway links. However, it is not possible to collect the volume and capacity of the freeway links during a future construction project period, prior to the beginning of the construction project. Therefore, a model was developed for estimating the V/C during a construction project period, using the V/C before the construction project period as the predictor variable.

The sample size used for estimating the V/C during the construction project period was 226 randomly selected samples. Data for the remaining 71 samples were used for validating the developed model. Three models, a linear model, a linear model with no intercept and a gamma log-link distribution model, were developed. Table 19 presents the regression coefficients, standard errors, p values, QIC, and QICC for the freeway link V/C model, for during the construction project period.

Table 19. Model During the Construction Project Period for Estimating V/C – Freeway Links

	Linear Model			Linear Model (No Intercept)			Gamma Log-Link		
Parameters	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**
(Intercept)	-0.01	<0.01	<0.01	-	-	-	-2.91	0.08	<0.01
V/C Before	1.19	0.05	<0.01	1.16	0.03	<0.01	5.95	0.10	<0.01
QIC		8.69			6.78			30.42	
QICC		4.75			2.76			29.58	

The QIC and QICC were lower and closer to each other for the linear model with no intercept than for the other developed models. Therefore, in order to avoid having a negative intercept, the linear model with no intercept was selected for estimating the V/C during the construction project period on freeway links. The general form of the V/C model summarized in Table 19 is as shown in Equation 9.

Estimated (V/C) = 1.16 × (V/C Before) ---------- Equation 9

The QIC and QICC values are lower for this model than for the other models and close to each other. The developed model was then validated with data for 71 links. From the developed model, V/C before the construction project period positively influences V/C during the construction project period on freeway links, at a 95% confidence level.

The computed RMSE and MAPE are 0.04 and 15.04%, respectively. The estimated V/C during the construction project period was then used as one of the predictor variables while developing the Pearson correlations and travel time model for during the construction project period on the freeway links.

During the construction project period, 297 randomly selected samples were used for computing Pearson correlation coefficients. The results obtained from the correlation analysis are presented in Table 20. From the correlation analysis, it was found that the downstream number of lanes is positively correlated with the average travel time on the freeway links, during the construction project period. As the downstream number of lanes increases, the traffic volume, and hence the travel time, increases.

Table 20. Correlation Coefficients for Freeway Links During the Construction Project Period

	Avg TT During	V/C	# of Lanes	Speed Limit (mph)	Upstream Link Length (mi)	Upstream V/C	Upstream # of lanes	Upstream Speed Limit (mph)	Downstream Link Length (mi)	Downstream V/C	Downstream # of lanes	Downstream Speed Limit (mph)	D (mi)	Weekday	Weekend Day	Morning Peak	Evening Peak	Day-Time Off-Peak	Evening Time Off-Peak
Avg TT During	1																		
V/C	0.03	1																	
# of Lanes	0.09	-.124*	1																
Speed Limit (mph)	-0.09	-0.01	.273**	1															
Upstream Link Length (mi)	0.10	-0.03	-0.11	-.173**	1														
Upstream V/C	-0.09	-0.01	-.198**	-.243**	.298**	1													
Upstream # of lanes	0.05	0.01	.541**	.202**	-0.05	0.10	1												
Upstream Speed Limit (mph)	-0.04	-0.01	.177**	-0.02	.112*	.533**	.664**	1											
Downstream Link Length (mi)	-0.06	0.04	0.05	-.204**	.135*	-.264**	-.148**	-.239**	1										
Downstream V/C	0.10	<0.01	.200**	-.155**	-0.03	.186**	.246**	0.08	.353**	1									
Downstream # of lanes	.122*	-0.09	.541**	-0.05	0.05	-.143*	.223**	-0.07	<0.01	0.11	1								
Downstream Speed Limit (mph)	0.07	-0.02	.324**	-0.02	0.04	-0.04	.276**	-0.04	0.06	.520**	.664**	1							
D (mi)	-0.11	-0.02	.333**	.774**	-.252**	-.283**	.170**	-0.03	-.149**	-.136*	-.216**	-.122*	1						
Weekday	0.09	.483**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1					
Weekend Day	-0.09	-.483**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-1.000**	1				
Morning Peak	-0.04	.345**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1			
Evening Peak	0.10	.310**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	1		
Day-Time Off-Peak	-0.06	-.152**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	1	
Evening Time Off-Peak	-0.01	-.504**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	-.333**	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

The generalized linear estimating equations analysis in SPSS software was used for developing the travel time during the construction project period on the freeway links.

The predictor variables V/C, upstream link length, upstream V/C, downstream link length, downstream V/C, downstream number of lanes, and downstream speed limit were considered for model development. The upstream speed limit and the upstream number of lanes are correlated to each other; therefore, either the upstream number of lanes or the upstream speed limit could be used for model development; however, the upstream number of lanes were eliminated since the p-value is greater than 0.05. The downstream link characteristics were not correlated to each other and are significant at a 95% confidence level.

Of 297 freeway samples, data for 226 randomly selected samples were used for modeling while data for the remaining 71 randomly selected samples were used for validating the model. The significance level was set at 0.05 (95% confidence). The predictor variables with a significance value greater than 0.05 were eliminated, except the V/C, one after another, while developing the models. The elimination process was repeated until all the predictor variables in the models have a significance value less than or equal to 0.05.

Table 21 summarizes the regression coefficients, standard errors, p values, QIC, and QICC for the various freeway links models for the during the construction project period. The linear model has lower QIC and QICC than the other models; QIC and QICC are also reasonably close to each other for the linear model. In addition, most of the predictor variables are significant at a 95% confidence level for the linear model when compared with other distributions.

Table 21. Comparison of Model Parameters for Freeway Links During the Construction Project Period

	Linear Model			Gamma Log-Link			Negative Binomial Log-Link			Poisson Log-Link		
Parameters	Coeff.	Std. Error	P-Value	Coeff.	Std. Error	P-Value	Coeff.	Std. Error	P-Value	Coeff.	Std. Error	P-Value
(Intercept)	1.14	0.08	<0.01	0.21	0.08	0.03	4.30	0.08	<0.01	4.26	0.08	<0.01
V/C	0.04	0.10	0.35	0.20	0.10	0.88	0.02	0.10	0.87	0.04	0.10	0.74
Upstream Link Length	0.04	0.02	0.05	0.06	0.02	0.02	0.06	0.02	0.02	0.05	0.02	0.02
Upstream V/C	-0.63	0.17	<0.01	-0.83	0.17	0.01	-0.81	0.17	<0.01	-0.69	0.17	<0.01
Downstream Link Length	-0.06	0.03	<0.01	-0.09	0.03	0.01	-0.09	0.03	0.01	-0.07	0.03	0.04
Downstream V/C	0.78	0.19	<0.01	0.93	0.19	0.01	0.93	0.19	<0.01	0.90	0.19	<0.01
Downstream no. of lanes	0.09	0.04	<0.01	0.08	0.04	0.18	0.08	0.04	0.17	0.10	0.04	0.06
Downstream SL	-0.01	0.00	<0.01	-0.01	0.00	0.01	-0.01	0.00	<0.01	-0.01	0.00	<0.01
QIC		33.45			42.48			29.68			1349.28	
QICC		33.92			45.46			44.08			1282.77	

Note: For Negative-Binomial and Poisson Log-link, the Average Travel Time (ATT) was converted into seconds. In case of Linear and Gamma Log-Link distributions, ATT is in minutes.

The general form of the final best-fit linear model summarized in Table 21 is as shown in Equation 10.

Average Travel Time = 1.14 + 0.04 × (V/C) + 0.04 × (Upstream Link Length) – 0.63 × (Upstream V/C) – 0.06 × (Downstream Link Length) + 0.78 × (Downstream V/C) + 0.09 × (Downstream Number of Lanes) – 0.01 × (Downstream Speed Limit)
------------ Equation 10

Equation 10 can be used to estimate travel time on a freeway link during the road construction project period. If the V/C is 0.46, the upstream V/C is 0.58, the upstream link length is 0.53 miles, the downstream link length is 0.74 miles, the downstream V/C is 0.46, the downstream number of lanes is 2, and the downstream speed limit is 55 mph for a freeway link; then the average travel time for the freeway link = 1.14 + 0.04 × (0.46) + 0.04 × (0.53) – 0.63 × (0.58) – 0.06 × (0.74) + 0.78 × (0.46) + 0.09 × (2) – 0.01 × (55) = 0.76 min/mile.

The developed linear model (Equation 10) during the construction project period on freeway links showed that, if the upstream link length increase, the link-level travel times would also increase. However, if the upstream V/C increase, link-level travel times would decrease at a 95% confidence level. In addition, downstream characteristics such as downstream link length and downstream speed limit increase, travel times would decrease during the construction project period. However, the downstream V/C and the downstream number lanes increase, travel times would increase at a 95% confidence level.

An increase in the upstream link length increases the travel time. When the upstream V/C and the downstream link length decrease, the travel time would increase significantly. Also, an increase in the downstream V/C has a significant effect on the travel time. Furthermore, an increase in traffic volume on the downstream links would ultimately increase the travel time. Similarly, as the downstream number of lanes increases, travel times would also increase. An increase in lane capacity would attract more traffic on the downstream links. Furthermore, if the speed limit is reduced on the downstream links, the travel time is expected to increase. Overall, from before to during the construction project period on the freeway links, upstream and downstream link lengths have a significant effect on link-level travel time. The upstream number of lanes and the upstream speed limit do not have a significant effect during the construction project period when compared with before the construction project period on the freeway links.

The developed model was validated using data for the 71 randomly selected freeway samples. The RMSE and MAPE are 0.15 and 8.67%, respectively. From the quantification results, the model was observed to be accurately estimating travel times during the construction project period.

TRAVEL TIME DURING THE CONSTRUCTION PROJECT PERIOD FOR CONNECTING ARTERIAL STREET LINKS

The travel time during the construction project period could be related to the travel time before the construction project period. Therefore, a linear model, a linear model with no intercept, and gamma log-link, negative binomial log-link, and Poisson log-link distribution models were developed with the average travel time during the road construction project period as the dependent variable and the average travel time before the road construction project period as the predictor variable. Data for 221 randomly chosen samples were used for developing the model and 59 samples were used for validation. A linear model with no intercept was selected since the QIC and QICC are lower for this model than for the others and are close to each other. The computed RMSE and MAPE are 0.34 and 18.04%. The results obtained show that travel time during the construction project period is higher than the travel time before the construction project period on a connecting arterial street link. Table 22 summarizes the regression coefficients, standard errors, p values, QIC, and QICC for the various connecting arterial street link models for during the construction project period.

Table 22. Comparison of Model Parameters for Connecting Arterial Street Links During the Construction Project Period Related to During and Before Average Travel Time

	Linear Model			Gamma Log-Link			Negative Binomial Log-Link			Poisson Log-Link			Linear Model (No Intercept)		
Parameters	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**
(Intercept)	0.05	0.05	0.30	-0.98	0.10	<0.01	3.27	0.06	<0.01	3.12	0.10	<0.01	-	-	-
ATT Before	1.01	0.03	<0.01	0.93	0.07	<0.01	0.01	<0.01	<0.01	0.01	0.01	<0.01	1.05	<0.01	<0.01
QIC		11.37			17.91			404.23			8.2			8.5	
QICC		9.77			12.12			397.65			11.86			7.81	

Note: For Negative-Binomial and Poisson Log-link, the Average Travel Time (ATT) was converted into seconds. In case of Linear and Gamma Log-Link distributions, ATT is in minutes.

The general form of the final best-fit model summarized in Table 22 is as shown in Equation 11.

Average Travel Time During = 1.05 × (Average Travel Time Before) --------- Equation 11

The Pearson correlation coefficients were computed, and a travel time model was developed for connecting arterial street links during the construction project period. The predictor variable V/C during the construction on connecting arterial street links, for a future construction project, is not known before the construction is commenced; however, the V/C during construction can be estimated using the V/C before the construction project period on the connecting arterial street links as the predictor variable.

Data for 221 random selected samples was used for developing the model, while data for the remaining 59 samples were used for validating the developed model. Three models, a linear model, a linear model with no intercept and gamma log-link distribution model, were developed. The developed V/C model was validated with the V/C from during the construction project period data for connecting arterial street links. The regression coefficients, standard errors, p values, QIC, and QICC are shown in Table 23.

Table 23. Model During the Construction Project Period for Estimating V/C – Connecting Arterial Street Links

	Linear Model			Linear Model (No Intercept)			Gamma Log-Link		
Parameters	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**	**Coeff.**	**Std. Error**	**P-Value**
(Intercept)	-0.16	0.04	<0.01	-	-	-	-0.15	0.08	0.03
V/C Before	2.06	0.18	<0.01	1.59	0.12	<0.01	0.87	0.10	0.21
QIC		20.93			21.15			42.48	
QICC		9.12			8.41			45.46	

For the linear model with no intercept, the QIC and QICC are lower than they are for the other models. In addition, to avoid the negative intercept, a linear model with no intercept was selected for estimating the V/C during the construction project period on a connecting arterial street link.

The general form of the final V/C model summarized in Table 23 is as shown in Equation 12.

Estimated (V/C) = 1.59 × (V/C Before) ---------- Equation 12

For the developed V/C model, the QIC and QICC values are lower and close to each other. From the developed model, V/C before the construction project period influences V/C during the construction project period on the connecting arterial street links.

The V/C model was validated by comparing with the V/C during the construction project period on the connecting arterial street links. The RMSE and MAPE are 0.08 and 3.06%, respectively. The developed V/C model during the construction project period was then used as one of the predictor variables while developing the Pearson correlations and the travel time model for the connecting arterial street links during the construction project period.

Similarly, to the case of the freeway links, a Pearson correlation analysis was conducted for connecting arterial street links. Data for 280 samples were used to compute the Pearson correlation coefficients. The correlation results showed that the majority of the variables are correlated to the average travel time on the connecting arterial street links during the construction project period.

The V/C, the number of lanes, the upstream link length, the upstream number of lanes, the downstream link length, the downstream V/C, the downstream number of lanes, and weekday evening peak are positively correlated with the average travel time during the construction project period. As the V/C increases, the average travel time would increase since the volume would increase while capacity is less. As the number of lanes increases, arterial streets would attract more traffic volume, which in turn increases the travel time. Similarly, the average travel time would increase if the downstream V/C, upstream V/C, and the number of lanes increases.

On the other hand, speed limit, whether a link is divided or undivided, upstream V/C, downstream speed limit, distance from the study corridor, weekend day, and evening off-peak hours are negatively correlated with the average travel time during the construction project period. As the speed limit decreases, the travel time would increase. If the link is not a divided section, the travel time could increase due to the reduced comfort level from close oncoming traffic. A similar trend applies for the upstream V/C and the downstream speed limit. In addition, as vehicles move away from the study corridor, travel time would reduce. The Pearson correlation coefficients and the p values are presented in Table 24.

Table 24. Correlation Coefficients for Connecting Arterial Street Links During the Construction Project Period

	Avg TT During	Link Length (mi)	V/C	# of Lanes	Divided/ Undivided	Speed Limit (mph)	Upstream Link Length (mi)	Upstream V/C	Upstream # of lanes	Upstream Speed Limit (mph)	Downstream Link Length (mi)	Downstream V/C	Downstream # of lanes	Downstream Speed Limit (mph)	D (mi)	Weekday	Weekend Day	Morning Peak	Evening Peak	Day-Time Off-Peak	Evening Time Off-Peak
Avg TT During	1																				
Link Length (mi)	-.202**	1																			
V/C	.250**	.185**	1																		
# of Lanes	.090*	.132**	.186**	1																	
Divided/ Undivided	-.172**	-0.07	0.01	.113*	1																
Speed Limit (mph)	-.395**	-.288**	-.238**	-.199**	.206**	1															
Upstream Link Length (mi)	.122**	-.130**	0.08	-.225**	-.148**	-0.06	1														
Upstream V/C	-.101*	.156**	.261**	0.07	-0.09	.102*	.237**	1													
Upstream # of lanes	.327**	-.363**	.157**	0.07	-.117**	-.235**	.177**	.219**	1												
Upstream Speed Limit (mph)	-0.04	-0.02	0.02	-0.07	.092*	.175**	-0.07	0.00	.207**	1											
Downstream Link Length (mi)	.177**	-.131**	.160**	-.444**	-.327**	-.180**	.427**	0.08	.263**	-0.03	1										
Downstream V/C	.105*	0.05	.322**	.105*	0.09	-.099*	.150**	-0.01	-0.06	.115*	.230**	1									
Downstream # of lanes	.186**	-.163**	0.04	0.07	-0.02	-0.04	-.147**	<0.01	.134**	<0.01	.178**	.224**	1								
Downstream Speed Limit (mph)	-.203**	0.07	0.07	-.124**	.170**	.421**	0.03	.244**	-.152**	-0.02	-0.05	0.02	.201**	1							
D (mi)	-.245**	.770**	.103*	-.108*	-0.05	-0.04	-0.07	.133**	-.435**	0.04	<0.01	<0.01	-0.02	.111*	1						
Weekday	.234**	<0.01	.172**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1					
Weekend Day	-.234**	<0.01	-.172**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-1.000**	1				
Morning Peak	0.04	<0.01	.099*	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1			
Evening Peak	.235**	<0.01	.099*	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	1		
Day-Time Off-Peak	-0.09	<0.01	-.099*	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	1	
Evening Time Off-Peak	-.189**	<0.01	-.099*	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-.333**	-.333**	-.333**	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

The predictor variables speed limit, whether the link is divided or undivided, V/C, upstream link length, upstream V/C, upstream number of lanes, downstream number of lanes, and distance of a link from the construction project were considered for model development. All the predictor variables considered are correlated to other predictor variables and are not correlated to each other. The logic applied for previous models while selecting the predictor variables was again applied for selecting the predictor variables in developing the models for during the construction project period.

Data for 221 randomly selected samples were used for developing the model, while data for the remaining 59 samples were used for validating the developed model. The significance level was set at 0.05 (95% confidence). The predictor variables with a significance value greater than 0.05 were eliminated, except V/C, one after another, while developing models. The elimination process was repeated until all the predictor variables remaining in the models had a significance value less than or equal to 0.05.

Table 25 summarizes the coefficients, standard errors, p values, QIC, and QICC for the various connecting arterial street links models for the during the construction project period. The linear model was selected as the best-fit model for estimating the travel time. For the linear model when compared with the other models, the QIC and QICC are lower; additionally, in the linear model the QIC and QIC were close to each other, and most of the predictor variables were significant at a 95% confidence level.

The general form of the final linear model summarized in Table 25 is as shown in Equation 13.

Average Travel Time = 2.99 + 0.29 × (Divided/Undivided) + 0.33 × (V/C) – 0.04 × (Speed Limit) + 0.11 × (Upstream Link Length) – 0.25 × (Upstream V/C) + 0.04 × (Upstream Number of Lanes) – 0.07 × (Downstream Number of Lanes) – 0.03 × (D) ----- Equation 13

Equation 13 can be used to estimate travel time on a connecting arterial street link during the road construction project period. If the V/C is 0.47, the speed limit is 45 mph, the road is divided (divided/undivided is 1), the upstream link length is 0.39 miles, the upstream V/C is 0.39, the upstream number of lanes is 1, the downstream number of lanes is 2, and the distance of the link from the construction project location is 0.66 miles for a connecting arterial street link; then the average travel time for the connecting arterial street link = 2.99 +0.29× (1) + 0.33 × (0.47) – 0.04 × (45) +0.11× (0.39) – 0.25 × (0.39) + 0.04 × (1) – 0.07 × (2) – 0.03 × (0.66) = 1.54 min/mile.

Table 25. Comparison of Model Parameters for Connecting Arterial Street Links During the Construction Project Period

	Linear Model			Gamma Log-Link			Negative Binomial Log-Link			Poisson Log-Link		
Parameter	Coeff.	Std. Error	P-value	Coeff.	Std. Error	P-value	Coeff.	Std. Error	P-value	Coeff.	Std. Error	P-value
(Intercept)	2.99	0.23	<0.01	2.10	0.23	<0.01	6.19	0.23	<0.01	5.89	0.23	<0.01
Divided/ Undivided	0.29	0.04	<0.01	0.22	0.04	<0.01	0.21	0.04	<0.01	0.20	0.04	<0.01
V/C During	0.33	0.05	<0.01	0.29	0.05	<0.01	0.28	0.05	<0.01	0.23	0.05	<0.01
Speed Limit (mph)	-0.04	0.00	<0.01	-0.03	0.00	<0.01	-0.03	0.00	<0.01	-0.03	0.00	<0.01
Upstream Link Length	0.11	0.02	<0.01	0.06	0.02	0.05	0.06	0.02	0.05	0.07	0.02	<0.01
Upstream V/C	-0.25	0.06	<0.01	-0.35	0.06	0.01	-0.34	0.06	0.02	-0.20	0.06	0.19
Upstream no. of lanes	0.04	0.04	<0.01	0.08	0.04	0.23	0.07	0.04	0.23	0.04	0.04	0.42
Down-stream no. of lanes	-0.07	0.05	<0.01	-0.11	0.05	0.22	-0.11	0.05	0.22	-0.06	0.05	0.31
D (mi)	-0.03	0.02	<0.01	0.01	0.02	0.93	0.01	0.02	0.95	-0.01	0.02	0.65
QIC		32.88			106.6			19.57			1186.67	
QICC		32.21			32.51			31.86			875.88	

Note: For the negative binomial and Poisson log-link models, the Average Travel Time (ATT) was converted into seconds. In case of the linear and gamma log-link models, ATT is in minutes.

The developed linear model (Equation 13) during the construction project period on the connecting arterial street links shows that the V/C, and whether the link is divided/undivided increases, travel time at link-level would increase. However, as the speed limit increase, travel times would decrease at link-level. Furthermore, as the upstream link length and the upstream number of lanes increase, travel times at link-level would increase at a 95% confidence level. As the upstream V/C increase, travel times would decrease during the construction project period. In addition, the downstream number of lanes and the distance of a link from the study corridor increase, the travel times would decrease at a 95% confidence level.

On the connecting arterial street links, most of the predictor variables that are observed to have statistically significant effects on travel times before the construction project period are also observed to have statistically significant correlations with travel times during the construction project period. As the V/C increases, the travel time would increase on the connecting arterial street links. During the construction project period, if the speed limit is reduced, the travel time would increase. In addition, the upstream link length and the upstream number of lanes has a significant effect on link-level travel time. As the length of the link increases, travel time would increase. Similarly, upstream V/C and the downstream number of lanes have a significant effect on link-level travel time. Since reduced V/C on the upstream links fails to accommodate incoming traffic, entering the construction zone would ultimately increase the travel time. From before to during the construction project period, the upstream link length and the downstream number of lanes have a significant effect in increasing or decreasing the travel time. The effect of other predictor variables remained the same from before to during the construction project period on connecting arterial street links.

The developed travel time model was then validated using data for 59 randomly selected samples. The computed RMSE and MAPE are 0.44 and 33.42%, respectively. The developed travel time model accurately estimates travel times during the construction project period on the connecting arterial street links. The validation results from the freeway and connecting arterial street link models show that the developed models estimate travel times more accurately than the conventional BPR equation (Table 10).

COMPARISON OF V/C AND LINK-LEVEL TRAVEL TIMES

The V/Cs from the regional travel demand model was compared with the estimated V/Cs for the freeways links and the connecting arterial street links (equations 9 & 12) during the construction project period. Likewise, the actual travel times were compared with the estimated travel times for the freeway links and the connecting arterial street links, before and during the construction project period. The ratio of the actual travel time to the estimated travel time, for the freeway links and for the connecting arterial street links, before and during the construction project period, were also computed and compared in this section.

Comparison of the V/C for the freeway links and the connecting arterial street links during the construction project period

Figure 26 compares, for the freeway links during the construction project period, the actual V/C, calculated from the regional travel demand model to the estimated V/C calculated from the developed model according to Equation 9.

From Figure 26, it can be seen that for off-peak hours, actual V/C during the construction project period, calculated from the regional travel demand model, is close to the estimated V/C calculated from Equation 9, for the majority of the freeway links, when V/C is less than 0.2. Similarly, Figure 27 compares the actual V/C during the construction project period, calculated from the regional travel demand model to the estimated V/C calculated from Equation 12, for the connecting arterial street links, for off-peak hours: the developed model for connecting arterial street links underestimates or overestimates for most of the link links; however, the differences between actual V/C and estimated V/C are small when V/C is less than 0.2.

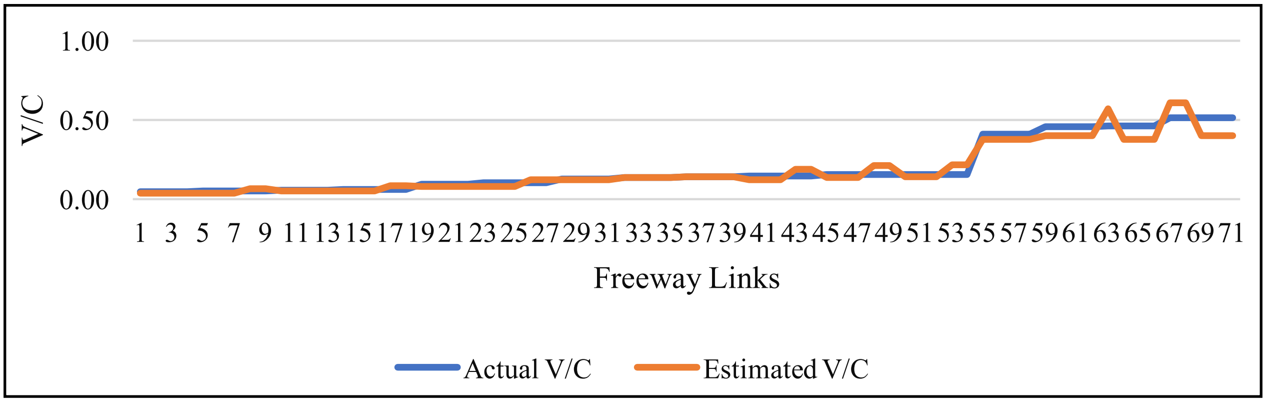

Figure 26. Comparison of V/C for the Freeway Links During the Construction Project Period

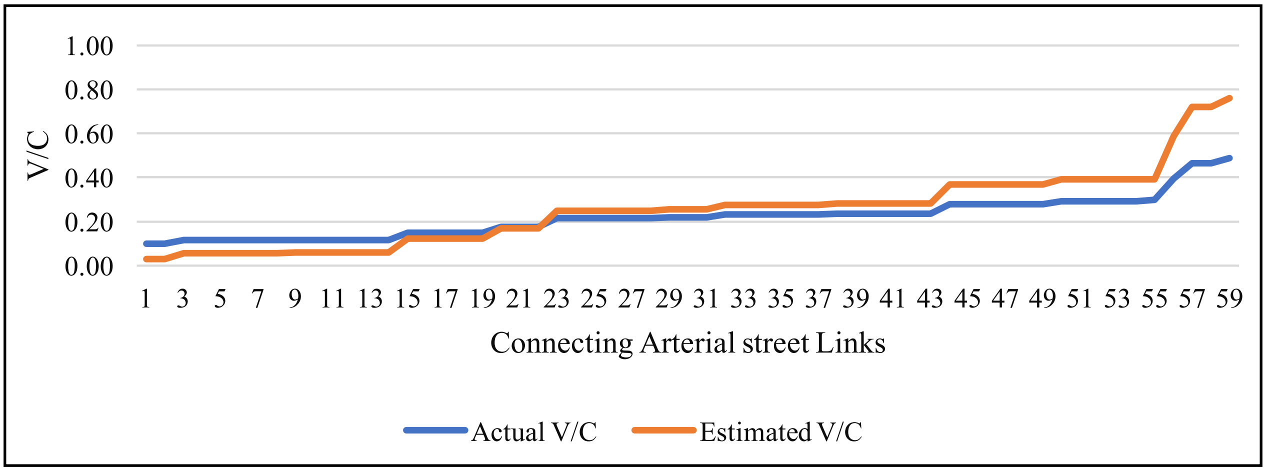

Figure 27. Comparison of V/C for the Connecting Arterial Street Links During the Construction Project Period

Figure 28 shows the ratios of actual V/C, calculated from the regional travel demand model to the estimated V/C, calculated from Equation 9, for the freeway links during the construction project period. Assuming a ±10% allowable error for estimating the V/C, the trend is that the developed model for freeway links underestimates for 20%, and overestimates for 50%, of the freeway links.

Figure 29 shows the ratios of V/C from the regional travel demand model over the estimated V/C for the connecting arterial street links during the construction project period. Assuming a ±10% allowable error for estimating the V/C, the trend is that the developed model for the connecting arterial street links underestimates for 20%, and overestimates for 50%, of the connecting arterial street links.

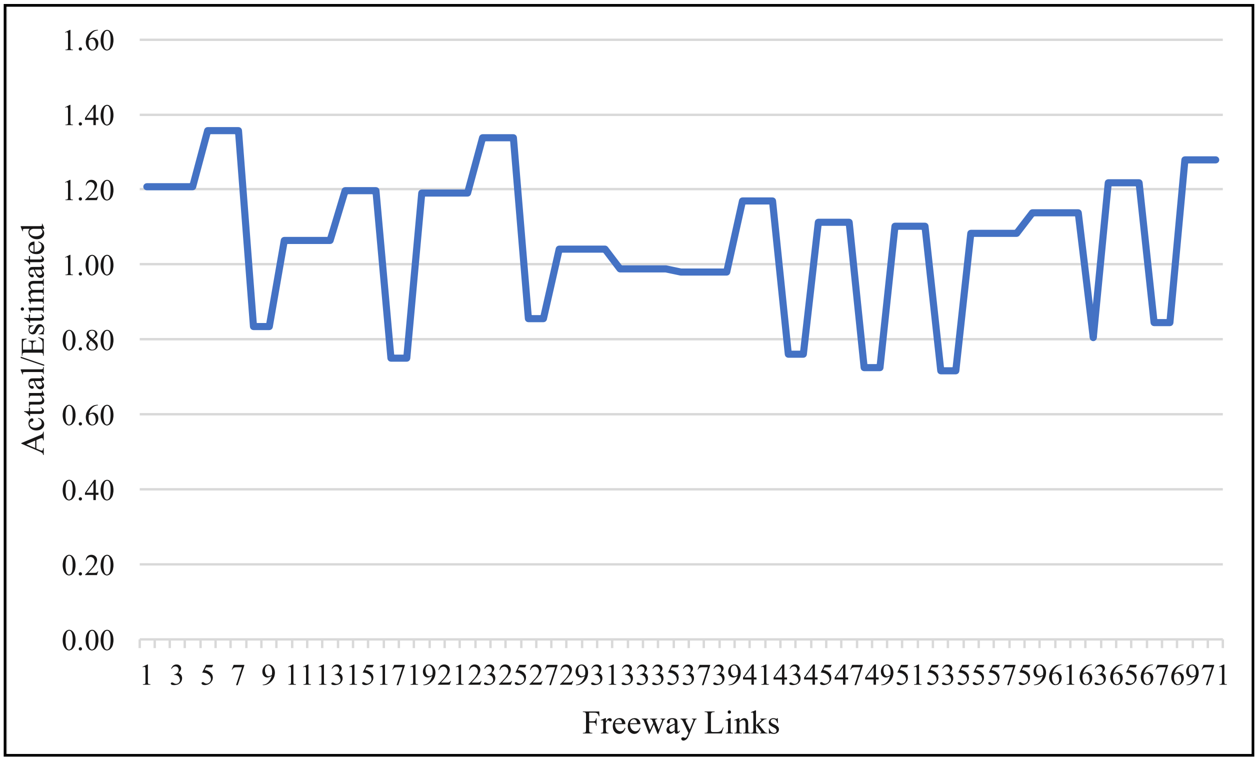

Figure 28. Comparison of V/C Ratios for the Freeway Links During the Construction Project Period

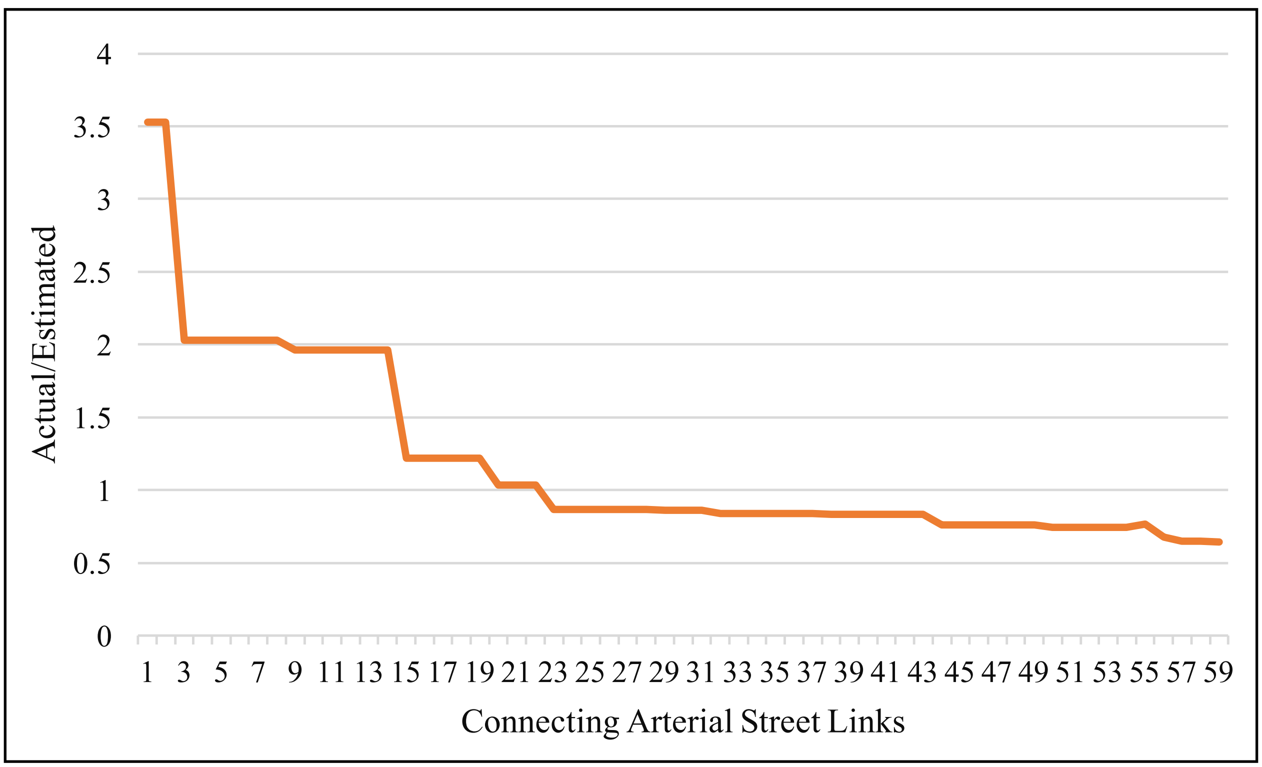

Figure 29. Comparison of V/C Ratios for Connecting Arterial Street Links During the Construction Project Period

Comparison of travel time before and during the construction project period, for the freeway links and the connecting arterial street links

Figure 30 compares, for the freeway links before the construction project period, the actual travel time with the estimated travel time calculated from Equation 6. The actual travel times are projected on the graph in ascending order for both freeway and connecting arterial street links, to show how the estimated travel times are differing from actual travel times. The actual and the estimated travel times are close to each other for the majority of freeway links before the construction project period.

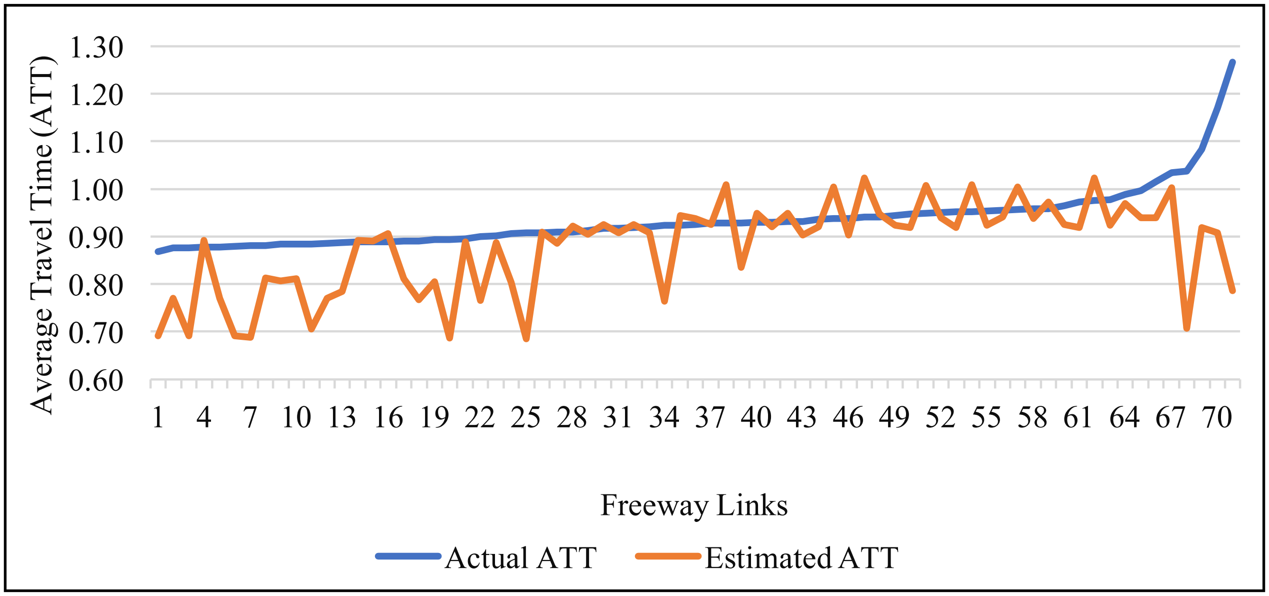

Figure 30. Comparison of Travel Time for Freeway Links Before the Construction Project Period

Figure 31 compares, for the freeway links during the construction project period, the actual travel time with the estimated travel time calculated from Equation 8. Again, the actual travel times are close to the estimated travel times for the majority of freeway links during the construction project period.

One particular link has a higher variation in travel time during the evening peak hours when compared with the actual travel time recorded before and during the construction project period. This link is located near the entry and exit ramps to the Charlotte-Douglas International airport. Higher traffic volume during the evening peak hour could be influencing the travel time and error.

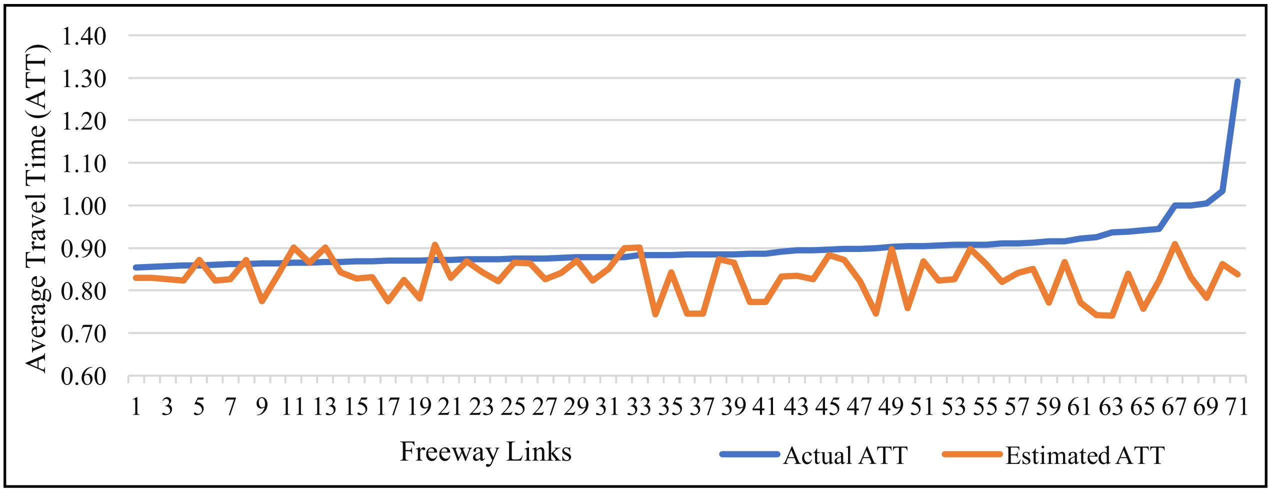

Figure 31. Comparison of Travel Time for the Freeway Links During the Construction Project Period

Figure 32 compares the ratios of the actual travel times to the estimated travel times, for freeway links, before and during the construction project period. Assuming a ±10% allowable error for estimating the travel time ratios, the trend is that the estimates calculated from the developed models, both, for before and for during the construction project period fall within the allowable error for 70% of the links. Both the developed models for the freeway links overestimate travel time for 30% of the links. Neither model underestimated, beyond the allowable error, for any of the links.

Figure 33 compares, for the connecting arterial street links before the construction project period, the actual travel times with the estimated travel times calculated from Equation 7. The trend is that the developed model underestimates or overestimates travel time for a majority of the connecting arterial street links.

Similarly, Figure 34 compares, for connecting arterial street links during the construction project period, the actual travel times with the estimated travel times calculated from Equation 11. The trend is that the estimated travel time is close to the actual travel time for the majority of the connecting arterial street links.

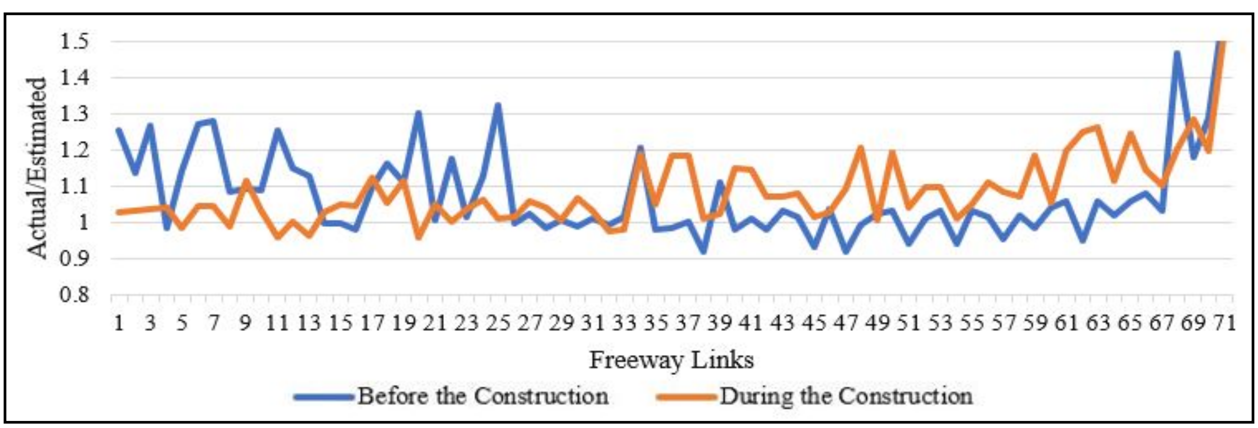

Figure 32. Comparison of Travel Time Ratios for the Freeway Links Before and During the Construction Project Period

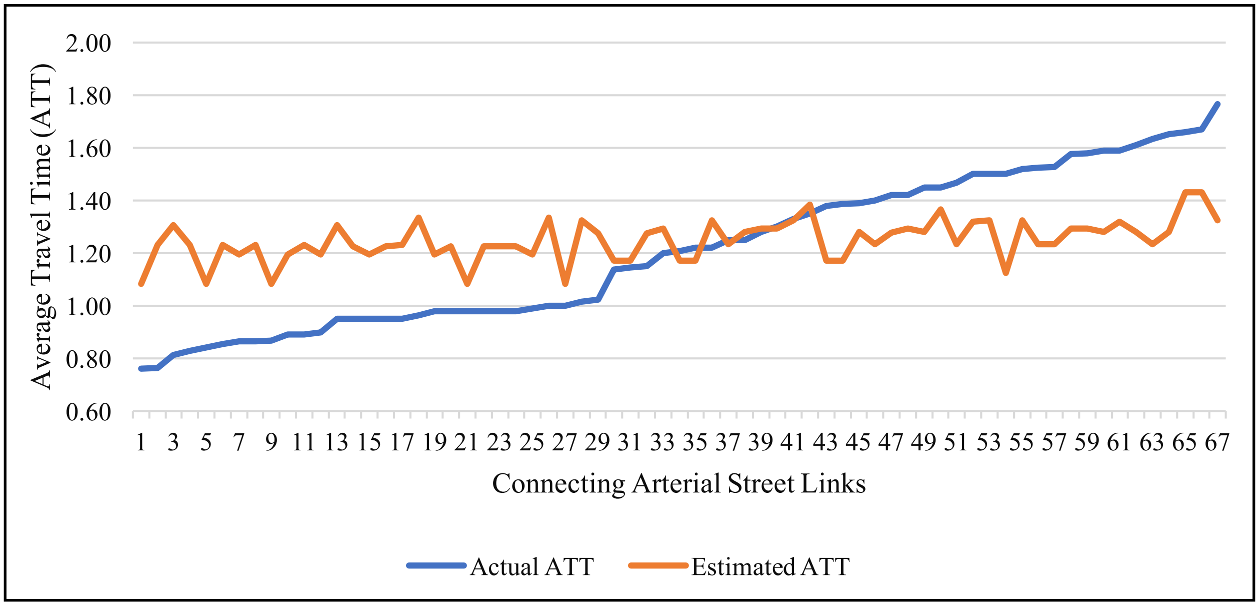

Figure 33. Comparison of Travel Times for Connecting Arterial Street Links Before the Construction Project Period

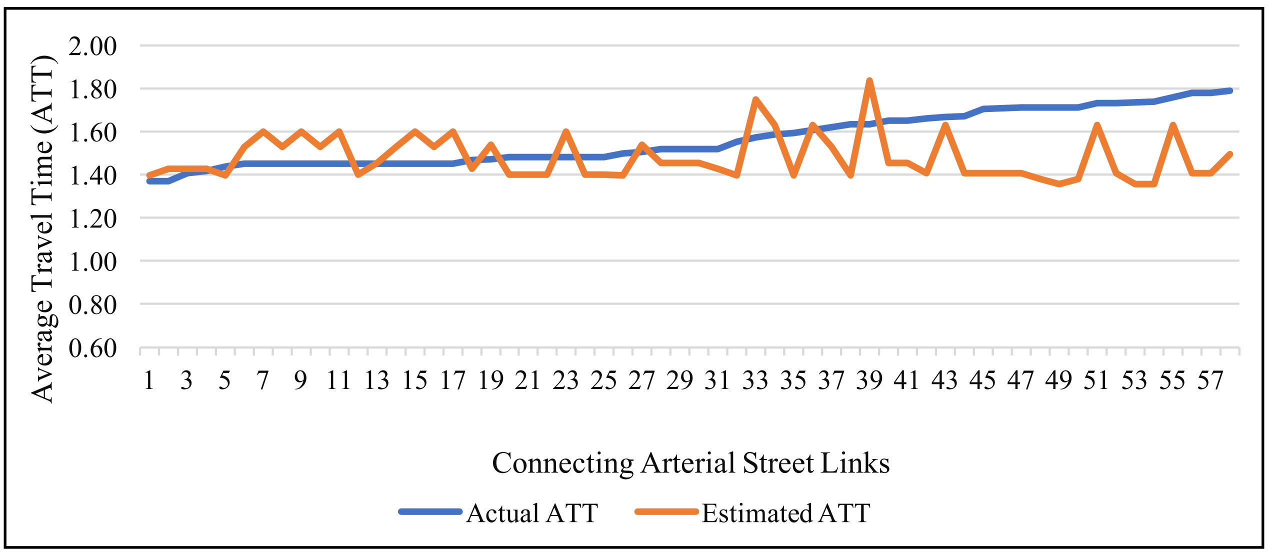

Figure 34. Comparison of Travel Times for Connecting Arterial Street Links During the Construction Project Period

Figure 35 compares the ratios of the actual travel times to the estimated travel times, for the connecting arterial street links, before and during the construction project period. Assuming a ±10% allowable error for estimating the travel time on the connecting arterial street links before the construction project period, the trend is that before the construction project period, the developed model underestimates travel time for 40% of the links, while the developed model overestimates travel time for 30% of the links.

On the other hand, the trend is that during the construction project period, the estimated and actual travel times are close to each other for 60% of the links, while the actual travel times are greater than the estimated travel times for 30% of the links. The actual travel times are lesser than the estimated travel times for 10% of the links. Note that in Figure 35, since some outliers were removed from the dataset, there was a difference in the number of links before and during the construction project period.

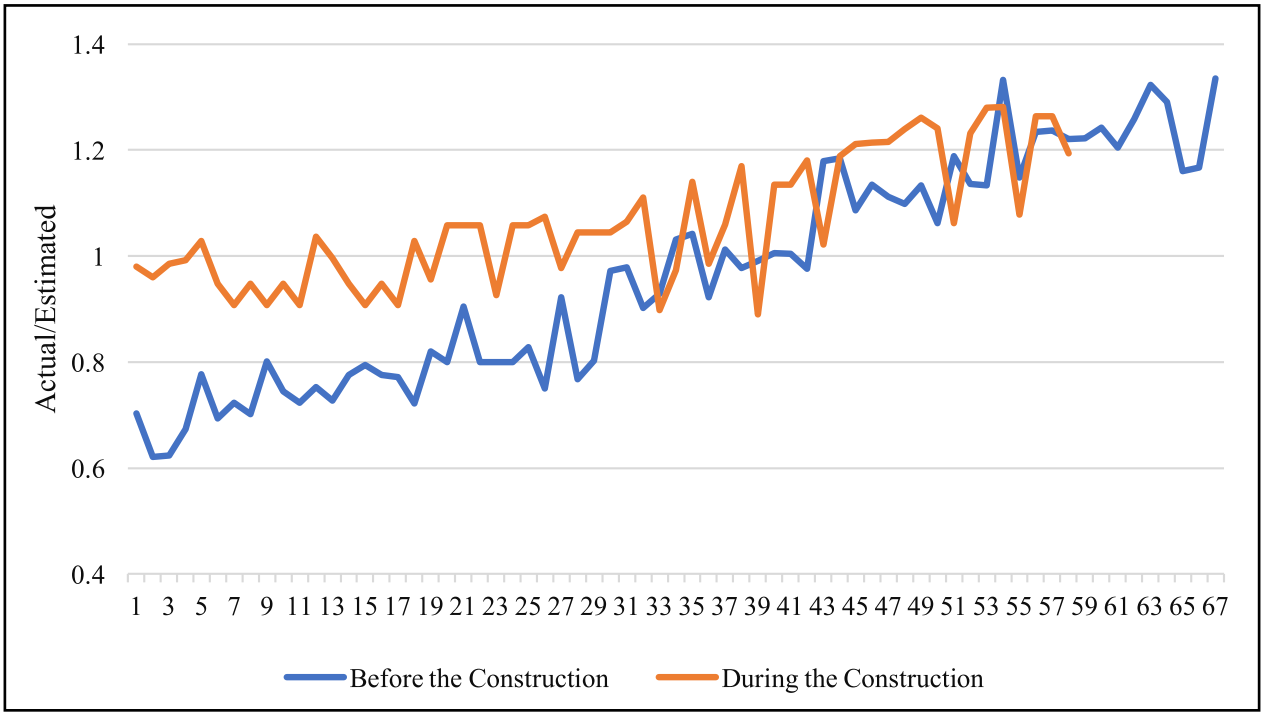

Figure 35. Comparison of Travel Time Ratios for Connecting Arterial Street Links Before and During the Construction Project Period

VI. CONCLUSIONS

A road construction project increases delay and congestion and lowers travel time performance on freeway links and on connecting arterial street links. By modeling the effect of a road construction project in Charlotte, NC, on travel times at link-level, this research provides insights pertaining to factors that influence travel times on the freeway and on the connecting arterial street links, before and during the construction of a resurfacing project period.

The travel times estimated by the models developed in this research are significantly different from estimates obtained using the BPR travel time equation. The actual travel times during the construction project period decreased significantly on the freeway links and increased significantly on the connecting arterial street links. To avoid unnecessary delay during the construction, vehicular traffic could have shifted from the freeway links to the connecting arterial street links, potentially explaining this result Lower speed limit, reduced capacity, and increased traffic volume on the connecting arterial street links resulted in significantly higher travel times during the construction project period when compared to the freeway links. The performance measures, and the effects of the road construction project on these measures, varied by the time-of-the-day and the day-of-the-week on the freeway and on the connecting arterial street links. The aforementioned findings were observed during all times of the day, except during the evening off-peak hours. The increase in the average travel time during the evening off-peak hour could be attributed to the planned construction activity under low traffic condition. Overall, the average travel time, the planning time, and the travel time index can better explain the effect of a road construction project on transportation system performance, when compared to the planning time index and the buffer time index.

Travel time models were developed for the freeway links and the connecting arterial street links, both before and during the construction project period. The upstream V/C and the downstream speed limit increase would increase travel time at link-level on freeway link travel time before and during the construction project periods. On the other, the downstream V/C and the downstream number of lanes increase travel time on the freeway link travel time before and during the construction project period. While the increase in upstream link length increases travel time, the increase in downstream link length would reduce the travel times on the freeway links during the construction project period. However, before the construction project period, both upstream and downstream link length have an insignificant effect on the freeway link travel time. If the distance of a link from the construction project section increase, travel times would decrease for both before and during the construction project periods on the connecting arterial street links.

The V/C varies with the time-of-the-day and the day-of-the-week and was observed to have a higher correlation with the time-of-the-day and the day-of-the-week. Therefore, in order to avoid the effects of multicollinearity, V/C was forced into the models (i.e., V/C was included in the models whether or not its correlation with the average travel time was statistically significant), while the time-of-the-day and the day-of-the-week were not considered when developing the models. From the developed travel time model results for the connecting arterial street links, the findings indicate that an increase in the V/C will result in an increase in the average travel time. This could be attributed to an increase in the traffic volume, with no compensating change in the capacity, on the connecting arterial street links. If the V/C, whether the link is divided or undivided, and the upstream number of lanes increases, travel times would also increase on the connecting arterial street links before and during the construction project period. If the speed limit and the upstream V/C increase, travel times would decrease at link-level travel time before and during the construction project periods. However, if the downstream number of lanes increases, travel times would decrease during the construction project period on the connecting arterial streets links. Its effect is not statistically significant before the construction project period.

Overall, predictor variables such as the V/C, the speed limit, and the upstream and downstream link characteristics, have a significant effect on travel time on the freeway and the connecting arterial street links. Practitioners should take these factors into consideration, in addition to construction zone characteristics, when planning resurfacing construction projects on freeways. The construction project also influenced travel times on the connecting arterial street links. The effects on these links should be considered when developing temporary traffic control and detour plans.

LIMITATIONS AND SCOPE FOR FUTURE WORK

The data for the entire construction project period was considered for this research. However, the data related to construction activity or actual construction work times were not available. Collecting the actual start and end times of the construction activity and considering these details for analysis and modeling would improve the accuracy of estimates. The development and validation of the travel time models were based on the characteristics of a resurfacing construction project on the freeway links. Travel times may vary by the type of construction project on the freeway. Therefore, analyzing and modeling the effects of other construction projects merits an investigation. Furthermore, the effect of a construction project on arterial streets could also be different on arterial streets. Data should be collected in order to analyze and model the effect of construction projects on the arterial street links.

Socioeconomic, demographic, and land use characteristics surrounding the construction project could have a significant effect on travel time performance. These, along with data for other cities and towns, should be explored in order to better understand and quantify the effects of construction projects on travel time performance measures.

ABBREVIATIONS AND ACRONYMS

ATT	Average Travel Time
BT	Buffer Time
BTI	Buffer Time Index
BPR	Bureau of Public Roads
GLM	Generalized Linear Models
MAPE	Mean Absolute Percentage Error
PT	Planning Time (95th Percentile)
RMSE	Root Mean Square Error
RITIS	Regional Integrated Transportation Information Systems
TTI	Travel Time Index

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