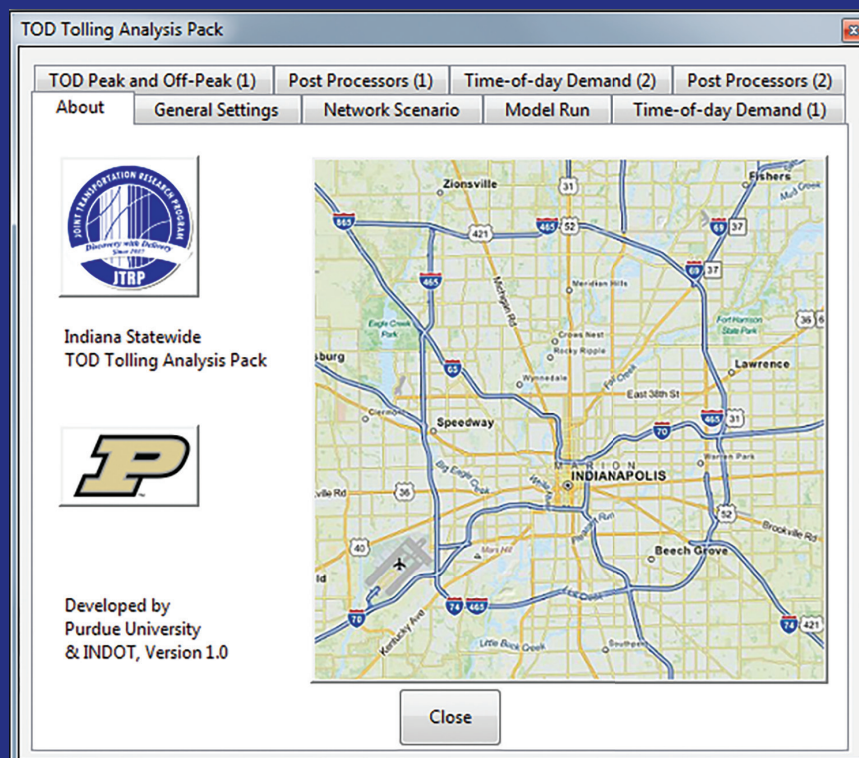


JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY



Evaluating the Impacts of Time-of-Day Tolling on Indiana Roadways



Satish Ukkusuri, Samuel Labi, Feng Zhu, Tho Le, Fasil Sagir

RECOMMENDED CITATION

Ukkusuri, S., Labi, S., Zhu, F., Le, T., & Sagir, F. (2017). *Evaluating the impacts of time-of-day tolling on Indiana roadways* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/08). West Lafayette, IN: Purdue University. <https://doi.org/10.5703/1288284316508>

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ACKNOWLEDGMENTS

The project team is grateful to Roy Nunnally, Samy Nouredin, Korey Chu, Emanuel Nsonwu, and Frank Baukert for their valuable feedback and input.

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The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

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Print ISBN: 978-1-62260-475-3

1. Report No. FHWA/IN/JTRP-2017/08		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Evaluating the Impacts of Time-of-Day Tolling on Indiana Roadways				5. Report Date June 2017	
				6. Performing Organization Code	
6. Author(s) Satish Ukkusuri, Samuel Labi, Feng Zhu, Tho Le, Fasil Sagir				8. Performing Organization Report No. FHWA/IN/JTRP-2017/08	
9. Performing Organization Name and Address Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051				10. Work Unit No.	
				11. Contract or Grant No. SPR-3911	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.					
16. Abstract In recent decades, several agencies have implemented tolls on their highway, bridge, or tunnel infrastructure for purposes that include mitigation and revenue generation. The Indiana Department of Transportation (INDOT) sought to investigate the feasibility of time-of-day tolling at a specific section of Indiana's highways, and therefore commissioned this research study. Recognizing that traditional ex ante methods of tolling evaluation such as surveys and public hearings are time intensive and costly, this project developed a simulation package to measure the expected impacts of TOD tolling in terms of revenue, travel delay, and welfare. The report developed an analytical model and accompanying software tool (a TOD tolling analysis pack) to capture the relationship between the time-of-day toll and route choice, and to evaluate quickly, the impacts of various TOD tolling scenarios. The research products help the analyst to easily visualize traffic flows on roadways and to estimate the revenue, monetary savings, travel times, speeds, vehicle hours of travel, vehicle miles of travel, and welfare in response to different scenarios. The TOD tolling analysis pack reduces drastically, the time and effort in evaluating proposed TOD tolling initiatives for the future. The visualization features illustrate traffic diversions due to tolling implementation and display the most impacted road segments. Further, the TOD tolling analysis pack can be integrated seamlessly with INDOT's existing TransCAD models and with Google Maps to provide users with the capability of acquiring additional pertinent information on the study area.					
17. Key Words time-of-day tolling, road pricing, tolling, user charges, distributional impacts, revenue forecast			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 76	22. Price

EXECUTIVE SUMMARY

EVALUATING THE IMPACTS OF TIME-OF-DAY TOLLING ON INDIANA ROADWAYS

Introduction

Due to increasing shortfalls in road construction and maintenance funding, federal, state, and local governments are seeking new mechanisms of infrastructure financing including tolling. Toll roads have diverse impacts on a region's traffic, land use, economy, and citizens' welfare, and tolling is a useful traffic management strategy. Traffic on state highways varies by the time of day and is sensitive to the toll amount. Time-of-day (TOD) tolling imposes different toll fees at different times of the day, with fees typically lower during off-peak hours.

Time-of-day pricing is an important financing mechanism, but its overall costs and benefits need to be evaluated. Currently, INDOT's planning models are unable to forecast the impact of time-of-day tolls.

This project employed the Indiana Statewide Travel Demand Model (ISTDM) to capture the relationships between time-of-day tolls and route choices based on empirical data. Subsequently, the impacts of time-of-day tolls can be computed for various state roadways based on anticipated changes in route choices. The study used I-465 as the hypothetical toll road and investigated the impacts of toll rates on a nine-county region in the Indianapolis area. Revenue, monetary savings, travel times, speeds, vehicle hours traveled (VHT), vehicle miles traveled (VMT), and welfare were computed based on anticipated changes in route choice. The research product is the TOD Tolling Analysis Pack: time-of-day analysis software that can drastically reduce the time and effort spent analyzing the costs and impacts of any TOD tolling project. This software can also be used to evaluate network-wide impacts of alternating tolling scenarios based on empirical data. Two advantages are that the TOD Tolling Analysis Pack can be integrated with INDOT's existing TransCAD models and can be used by various stakeholders at INDOT.

Findings

The results of this study reveal an increasing trend in revenue from 2015 to 2025 across different scenarios:

- The revenue reaches peaks at 8 AM and during the 4 PM–6 PM block. Relatively low revenues are collected from midnight to 6 AM. The highest revenues result from implementing the most expensive toll option.
- VMT varies during times of day. It is lowest for the 12 AM–6 AM block and highest at 8 AM and for the 4 PM–6 PM block. VMTs generally increase at peak times during any of the three years (i.e., 2010, 2015, and 2025). Additionally, the average travel times have patterns similar to those of the VMTs.

- Average speeds have trends inverse to those of average travel time. Intuitively, speeds reduce during peak hours but they are fairly stable at other times. For higher toll rates, faster travel speeds are observed. Therefore, it can be inferred that toll prices may assure higher speeds and improve the travel time reliability.
- As expected, VHT decreases as tolls are increased. The highest sensitivity of VHT to toll rates is during peak hours.
- Welfare calculations show that the impact of tolling on I-465 does not result in the driver being better off as compared to the no-toll case scenario. This is mainly because the highway capacity for the years analyzed is able to accommodate the traffic volumes for most periods of the day. As a result, the savings in monetary equivalent of travel times is not enough to cover the toll levied. Therefore, it does not generate enough benefit for people who use the toll road.

Implementation

Successful implementation of the study can be facilitated because the research product:

1. Developed a model that captures the relationship between time-of-day toll and route choice.
2. Developed a time-of-day analysis software (the TOD Tolling Analysis Pack) that quickly evaluates the impacts of various time-of-day tolling scenarios.
3. Enables visualization of traffic flows on roadways for the various tolling scenarios. In addition, the TOD Tolling Analysis Pack displays the most impacted roads under any tolling scenario.
4. Has capability to generate intuitive plots of revenue, monetary savings, travel times, speeds, VHT, VMT, and welfare from the results.
5. Incorporates a TOD Tolling Analysis Pack that can be used to compute the impacts of fixed toll rate scenarios by setting fixed values for all times of day. This information can help policymakers and transportation officials determine which scenario to implement and which roads to give management priority (i.e., capacity expansion).

The TOD Tolling Analysis Pack can also be used to analyze the impacts of time-of-day tolling on any highway. An advantage is that this software can be easily compiled to TransCAD software, which is commonly used in transportation agencies. Along with the software, a user's manual, post-analysis tools, and tutorial videos were also developed.

Finally, the TOD Tolling Analysis Pack can drastically reduce the time and effort spent analyzing the impacts of any time-of-day tolling project. It also provides a convenient and flexible tool for testing the impacts of various tolling scenarios for any highway. The visualization features can illustrate the diversion of traffic due to tolling implementation and display the top ten most impacted roads. Moreover, this software can be integrated with Google Maps, which provides the users with additional information on the study area.

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1. INTRODUCTION

Toll roads have diverse impacts on a region's traffic, land use, economy and citizens' welfare. Traffic on state highways varies by the time of day and is sensitive to the toll amount. Time-of-day tolling imposes different levels of tolls at different times of the day, with tolls typically lower during off-peak hours. In addition to generating additional revenue for managing roadways, the goal of this strategy is to allow the highway use by drivers who need to travel and are willing to pay for it. Drivers who are not willing to pay a toll can change their travel time, route, mode, or choose not to travel.

In addition, due to increasing shortfalls in road construction and maintenance funding, federal, state, and local governments now seek new mechanisms of infrastructure financing. Time-of-day pricing is an important mechanism but its overall cost and impacts need to be evaluated. Such evaluation requires reliable assessment of the impacts of the time-of-day tolls on other routes that receive the diverted traffic. Currently, INDOT's planning models are unable to forecast the impact of time-of-day tolls. This information is critical not only for accurate planning forecasts but also for estimating the traffic flow on various roadways, the impacts due to spillover onto adjacent roadways and the additional revenue that can be generated. A tool is needed to understand the variations of the traffic with the time-of-day tolls to make planning decisions and strategic asset management decisions.

This research project developed a software named **"TOD Tolling Analysis Pack"** which seamlessly integrates with the INDOT planning model and computes the costs and impacts of the time-of-day tolling for Indiana's roadways. The TOD Tolling Analysis Pack can be used to evaluate different network-wide impacts of alternative tolling scenarios. The application can be integrated with the existing TransCAD models that already exist at INDOT. The tool developed in this project can help assess the relationships between the time-of-day toll, and route choice, based on empirical data. Based on the anticipated changes in route choice, the impact of the time-of-day toll on various neighboring roadways can be determined.

1.1 Background Information

Tolls are typically collected for highways and bridges in the U.S. as an extra source of income for financing the construction, operation, and maintenance of such infrastructure. Steer Davies Gleave (2013) studied the impact of tolling two Ohio River bridges in the Louisville metropolitan area. These bridges connect southern Indiana with Louisville, downtown with a daily traffic volume that can reach 224,277. They investigated the change of the bridges' traffic volumes if different tolling schemes were introduced. They showed that the annual tolling revenue goes up to \$34 million for the first half year of opening, and over \$210 million 10 years later.

Besides generating considerable revenue, tolling is also shown to be an effective approach in reducing traffic congestion (Akiyama & Okushima, 2006; Lindsey, 2006). Traffic congestion impairs economic development and decreases quality of life. On corridors with high traffic volumes, congestion imposes a burden to economic activities, work and non-work travel, and air quality. On the demand side, many traffic management strategies have been proposed to relieve traffic congestion. Practical implementation of road pricing can be found in big cities around the world. For instance, Singapore launched the Electronic Road Pricing scheme in 1998 and charges road users a congestion fee every time they cross the cordon area (Goh, 2002). London introduced the zonal congestion-pricing scheme in 2003, where a daily fee is charged for every vehicle within the congestion-charging zone.

The Indiana Toll Road, known as "the main street of the Midwest," plays a key role in fueling the economic activities in the region. It is a 156.3-mile-long road that starts at the Indiana/Ohio state line as I-80/90 until it junctions with I-94 near Lake Station. It continues northwest as I-90 while I-94 travels west over I-80. Indiana received \$3.8 billion for leasing the toll road to a private consortium for 75 years in 2006 (Gilroy & Aloyts, 2013). The current tolling scheme of the Indiana Toll Road is not a time-of-day tolling. However, there currently exist technological innovations that can be deployed to vary toll rates within different time periods of the day. It may be noted that the traffic demand typically varies during the day ranging from less-than-saturation to over-saturation, resulting in different levels of impacts and collected revenues. One of the key advantages of time-of-day tolling is that it encourages commuters to shift from peak to off-peak hours, to reduce congested routes, and to promote alternative modes. Time-of-day tolling potentially contributes significantly to congestion mitigation, energy savings, and revenue generation.

1.2 Scope of this Study

Task 1: Literature review

A comprehensive literature review was conducted on previous research on the implementation of time-of-day tolling in the U.S. and other countries. Traffic models were evaluated to determine the effect on driver behavior across different vehicle classes, traffic flow scenarios, and performance measures.

Task 2: Synthesis of available data sources

This task identified and synthesized various data sources. Travel demand modelling and simulation modelling, e.g., GIS files, traffic counts and performance measures. In addition to the above data, network and demand data for I-465 corridor was obtained as input to the assignment model. Different types of intersections have been incorporated within the network.

As the traffic on the network is dynamic, the network was modelled with dynamic demand (AM Peak, AM Off-Peak, PM Peak, and PM Off-Peak). This fine level of data resolution is unprecedented in studies of this kind; however, it is necessary to do so because it is critical to obtain accurate representation of the network-wide impacts and revenue forecasts.

Task 3: Analysis and prediction of traffic shifts under time-of-day tolling system considering multiple vehicle classes

This task developed a TOD Tolling Analysis Pack in TransCAD version 7.0 to estimate the impact of time-of-day tolls. The software considers different vehicle classes and route choices. The tool can be integrated with other TransCAD-compatible planning models at INDOT.

Task 4: Development of a framework to evaluate the impacts of time-of-day tolling

This task developed a framework that used a set of performance measures to evaluate the impacts on revenue, travel time, speed, VHT, VMT, and welfare because of time-of-day tolling. The developed traffic model determines the resulting traffic variations for different vehicle classes. Important inputs for this framework are a time-of-day tolling fee structure, existing traffic counts by vehicle class, and the highway network.

Task 5: Testing different time-of-day tolling fee structures

Various time-of-day tolling fee structure scenarios were developed in this study, and the revenue generated under each tolling fee structure were measured. A manual for assessing the impacts of time-of-day tolling was developed to facilitate time-of-day tolling decision-making at INDOT.

Task 6: Development of a case study to evaluate the impacts of time-of-day tolling

A case study was developed to illustrate the application of the framework. Based on the inputs, the potential impacts on I-465 on revenue, travel time, speed, VHT, VMT, and welfare were analyzed.

1.3 Study Benefits and Deliverables

INDOT is expected to earn significant benefits if the agency decides to implement time-of-day tolls:

1. Reduced congestion and improved mobility
2. Revenue (from toll receipts)
3. Enhanced capability for modeling, planning, decision-making, and benefit to cost analyses on the state highways and local roads
4. Greater reliability of highway travel time

The deliverables from this project are:

1. *A final report.* A comprehensive presentation of all tasks of the projects, methodology of the study, the developed TOD Tolling Analysis Pack, and results from impacts analysis under various time-of-day tolling scenarios.
2. *Suite of software and User's Manual.* This TOD Tolling Analysis Pack has been delivered to INDOT, and was followed by a Q&A session. The User's Manual (available for download at <https://doi.org/10.5703/1288284316508>) guides how to use the TOD Tolling Analysis Pack. The conduction of the impact analysis has been also delivered including two tutorial videos.
3. *Spreadsheet tool for the impact evaluation.* The excel files were prepared as a support tool for post analysis of the revenue, monetary savings, travel times, speeds, VHT, VMT, and welfare. The inputs for those files are the results obtained from TOD Tolling Analysis Pack on TransCAD.
4. *A training program for INDOT staff.* Training was carried out to deliver the items above.

2. A SYNTHESIS OF TOLLING PRACTICE AND RESEARCH

2.1 Introduction

The first task of this project was to conduct a comprehensive literature review on design and implementation of tolling, particularly time-of-day tolling, in the U.S. Documentation on the toll road activities and experience from other states in the U.S. provides useful guidance on the feasibility and impact analysis of the tolling in Indiana. Moreover, the study evaluated suitable travel demand models, toll-rate design methods, and performance measures to assess the impact of tolling on the traffic patterns and welfare.

2.2 Basics of Tolling

2.2.1 Benefits of Roadway Tolling

The benefit of tolling on roadways is two-fold. Firstly, tolling directly generates revenue through money receipts from the facility users, and is therefore considered as an alternative way of financing the construction and maintenance of roads. Further, tolling can be used to manage traffic congestion. For example, the time-of-day tolling varies toll rates to address different levels of traffic demand at different times of the day. The congestion-pricing scheme is intentionally designed to mitigate traffic congestion. In summary, the benefits of tolling on roadways include the following.

Economic benefit. Tolling provides revenue to support the construction and maintenance of roads and bridges (Lauridsen, 2011; Weisbrod & Williams, 2011).

Traffic management. Tolling encourages the use of highways primarily by those who need to travel and are willing to pay for it. Drivers who are not willing to pay can change their travel time, route, mode, or choose not

TABLE 2.1
Characteristics of different types of tolling.

Types	Objectives	Scope	Implementation Complexity
Fixed tolling	Compensation of the facility	Corridor	Low
Time-of-day tolling	Compensation of the facility/traffic demand management	Corridor	Medium
Distance based tolling	Compensation of the facility/traffic demand management	Corridor	Medium
Zone based tolling	Traffic demand management	Area	High
Congestion pricing	Congestion alleviation	Area	High

to travel (Ferrari, 2002; Gupta, Kalmanje, & Kockelman, 2006; Kockelman & Lemp, 2011; Lemp & Kockelman, 2009; Petrella et al., 2014; Ray et al., 2014; Ungemah, 2007; Ungemah, 2010).

Mobility benefit. On the demand side, several traffic-control management strategies have been proposed in the literature to relieve traffic congestion. Tolling has shown to be an effective congestion mitigation strategy (Akiyama & Okushima, 2006; Lindsey, 2006; Peirce et al., 2014; Pessaro & Van Nostrand, 2014).

Environmental benefit. Toll roads change travelers' driving behavior regarding route choice, mode choice, departure time, trip-making decision, etc. Through the alleviation of traffic congestion, tolling helps to lower fuel consumption and vehicular emissions (Ramjerdi, Minken, & Østmo, 2004; Santos & Newbery, 2001; Waersted, 2005).

2.2.2 Types of Tolling

Fixed tolling. This refers to the flat toll rate. Typically, vehicles pay the toll at the facility entrance. The toll rate may vary by vehicle class. This type of tolling is typically implemented for well-defined, special and relatively costly infrastructure (e.g., a bridge, a tunnel, a mountain pass, etc.). It is the most common type of tolling.

Time-of-day tolling. This type of toll imposes various tolls at different times of day and various days of week depending on the demand for the facility. It typically costs more during peak hours and less during off-peak hours. In addition to generating additional revenue for managing roadways, the goal of this strategy is to allow users who need the roadways to use it and are willing to pay for it.

Distance/zone based tolling. In this type of tolling, vehicles are charged based on the total distance driven on the road or specific areas entered. Distance-based tolling is used to reduce the use of the facility, while zone based tolling is used to reduce the number of vehicles entering a specific area. For example, Singapore launched the Electronic Road Pricing (ERP) scheme in 1998, which charges a congestion fee every time a user crosses the cordon area.

TABLE 2.2
Jurisdiction covered by electronic tags from various vendors.

Electronic tag	Covered Jurisdiction
Freedom Pass	Alabama
E-Zpass	Delaware, Illinois, Indiana, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, Virginia, West Virginia
SunPass	Florida
TxTAG	Texas
Fastrak	California
K-Tag	Kansas
MnPass	Minnesota
Pikepass	Oklahoma

Congestion pricing. This type of tolling charges the user according to the congestion levels of the transportation system. The concept of congestion pricing is to charge drivers who use overcrowded facilities to maximize social welfare (Hau, 1998). There have been multiple studies on congestion pricing including those by Nakamura and Kockelman (2002) and Issariyanukula and Labi (2011). It serves to reduce the traffic congestion in the specified area. Thus, it is usually area/zone based and variant over time. For instance, London introduced the zonal congestion-pricing scheme in 2003, where a daily fee is charged for every vehicle within the congestion charge zone. Table 2.1 presents the characteristics of different types of tolling.

2.2.3 Toll Collection Technology

Traditionally, tolls are collected at the tollbooths. In the current era, some tollbooths still exist to allow manual cash payments. However, the emerging technology enables more efficient and low cost toll collection as described below.

Electronic Toll Collection (ETC) system. Drivers equipped with transponders pass through tollbooths without reducing their speed. The Dedicated Short Range Communications (DSRC) technology is used in the Automated Vehicle Identification (AVI) system to collect tolls. ETC system has been widely adopted in the U.S. One major concern regarding ETC is the interoperability of the electronic tags across regions. Table 2.2 presents a number of tag brands and the jurisdictions they cover.

TABLE 2.3
Evolution of the toll road development in the U.S. (Spock, 2008).

Time Period	Major Catalyst	Major Developments
1790 to mid-1800s	Increase in interstate commerce	About 15,000 miles of turnpikes
Mid to late 1800s	Rapid growth of railroads	No-longer-profitable toll operations were abandoned
1890 to 1916	Popularity of bicycles and advent of automobile	Demands for increased Federal role in road improvements produced Federal Aid Road Act of 1916.
1916 to 1956	Rapid economic growth	Interstate highway system envisioned as an interconnected system of toll roads.
1956 to 1987	Federal-Aid Highway Act created Highway Trust Fund for Interstate System	Federal funding was authorized for Interstate highways, with toll charges prohibited.
1987 to 1992	The Interstate System is complete; Federal policy began to recognize tolling as a viable alternative	Beginning with the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), Federal policy allowed greater flexibility and innovation in project delivery methods at the state level.
1992 to the present	New objective of relieving traffic congestion	Between 1992 and 2006, 168 new toll projects moved into various stages of development

Video tolling. Video tolling refers to the use of overhead cameras for vehicle identification. When a vehicle passes through the tolling station, the overhead cameras take pictures of its license plate. Through the Optical Character Recognition (OCR) technology, the license number is extracted from the picture and checked against the database of registered drivers. Video tolling is usually coupled with other types of tolling technology, such as electronic toll collection.

Connected vehicle technology. In the practical implementation of road tolling, wireless communication technology has played a significant role (De Palma & Lindsey, 2011; Ukkusuri et al., 2008). With wireless communication devices installed in the vehicle and the infrastructure, vehicles are able to communicate with the infrastructure (V2I communication) and the tollbooth remotely and automatically bills the driver.

2.3 Tolling Roadways in the U.S.

2.3.1 The Evolution of Tolling in the U.S

The history of toll roads in the U.S. dates to 1792 in Pennsylvania, which had the Philadelphia and Lancaster Turnpikes. Toll collection was considered an efficient way for financing new roads. The first building boom of toll roads emerged at the end of 1920s when the ownership of automobiles increased substantially in the U.S. and there was an obvious need for a nationwide interconnecting highway transportation system. Several roads, bridges, and tunnels were built as toll facilities to generate funds for construction and maintenance (examples include the Holland Tunnel in New York and the Golden Gate Bridge in San Francisco). The Federal-Aid Highway Act authorized the creation of a Highway Trust Fund to generate Federal fuel tax revenues and to finance the construction of the Interstate Highway System on a pay-as-you-go basis. With the implementation of this tax-supported system, proposals for toll roads decreased drastically.

The toll road concept re-emerged in 1980s due to the shortfall of financing support from the government and the emerging of more efficient and low-cost toll collection technologies (e.g., the Electronic Toll Collection system). Moreover, the toll road concept evolved and welcomed investments from the private sectors. Public-private partnerships can be a significant source of financing construction, operation, and maintenance of new highway facilities in the future. Table 2.3 shows the evolution of toll road development in the U.S.

2.3.2 Current Tolling in the U.S.

Indiana's first toll road, the Indiana Toll Road (ITR), opened in 1956. ITR is known as "the main street of Midwest" as it plays a key role in fueling the economic activities in the Midwest area of U.S. This 156.3-mile-long corridor connects the Chicago Skyway and the Ohio Turnpike located in northern Indiana. The fees collected by the Indiana toll road authorities offers a rich source of external financing that covers the construction, operation, and maintenance of this infrastructure. In 2006, Indiana received \$3.8 billion for leasing the toll road to a private consortium for 75 years (Gilroy & Aloyts, 2013).

In Indiana, tolling is not as prevalent as in other states in the U.S. Figure 2.1 presents the share of tolling revenues in total revenues during 1999–2004 in the U.S, and Figure 2.2 presents the mileage of toll roads in the U.S. In both cases, Indiana is ranked in the medium range. Many other states have greater experience with tolling. This provides great opportunity for Indiana to learn from the experience of other states.

2.3.2.1 Texas. In the U.S, the state of Texas is one of the more active states in toll activities in terms of the number of highways tolled. In that state, 38 toll roads have been implemented since the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA, 1991). The Texas DOT is aggressive in maximizing the use of tolls for funding transportation infrastructure

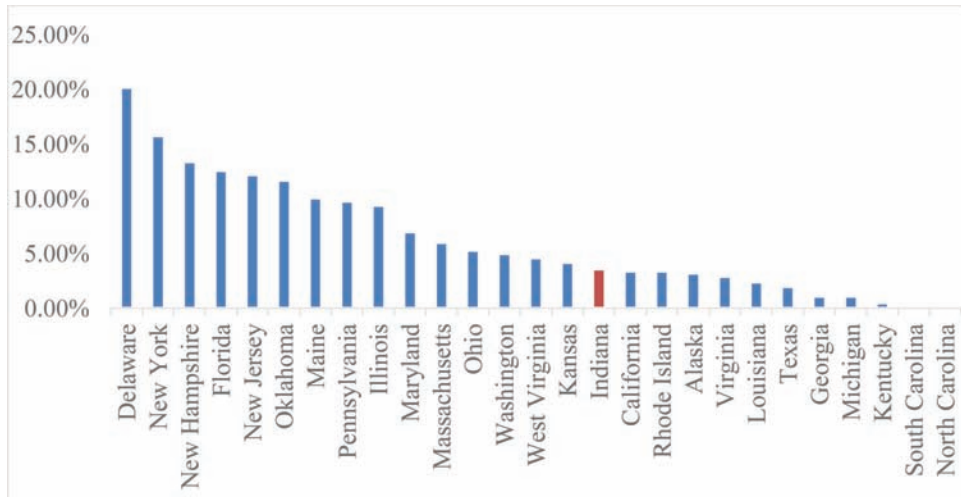


Figure 2.1 Percentage of tolling in total revenues for highways 1999–2004 (NCSL, 2004).

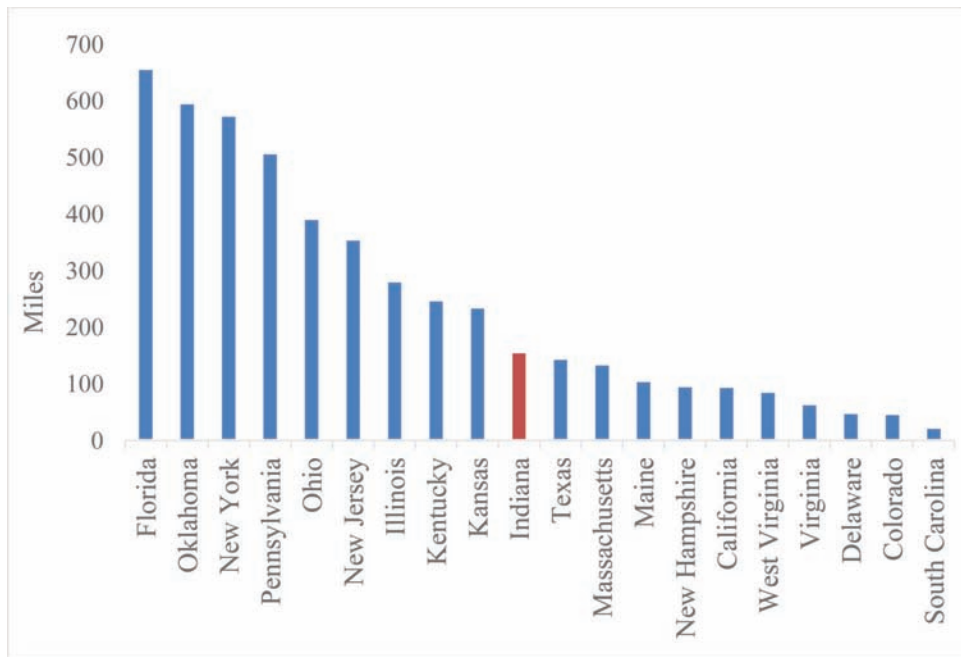


Figure 2.2 Toll road mileage across different states in U.S.

improvements. The agency policy is to prioritize the institutionalization of public-private partnerships as well as the authorization of new regional and metropolitan toll authorities.

The Texas Turnpike Authority Division (TTA), a division of Texas DOT, is responsible for promoting toll road development in Texas. In 2008, the Texas Legislature has enacted the bill HB 3588 that demonstrated Texas DOT’s major commitment to prioritizing tolls as an efficient way to generate revenue for financing the state’s highway construction, operation, and maintenance. Following the passage of HB 3588, TTA developed a toll feasibility analysis process to screen and evaluate candidate toll projects throughout

the state, which includes the following steps (TxDOT, 2007):

1. Screening, of all added-capacity and new location projects in the Unified Transportation Plan (UTP), the state’s 10-year planning document and identification of projects where toll revenue could pay for estimated operations costs.
2. A conceptual analysis which assessed the potential for supporting bonds using a “fatal flaw” analysis, based on ability of toll revenue to pay for estimated operations over 40 years (including estimated operations and maintenance costs), and exhibiting bonding capacity potential.
3. A project-specific evaluation, using refined project cost estimates and conceptual traffic and revenue (T&R) estimates from a certified T&R consultant.

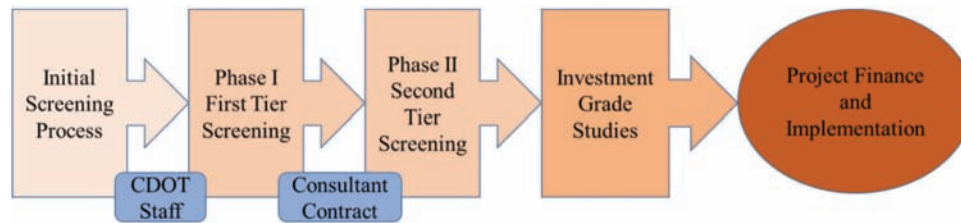


Figure 2.3 Colorado tolling project development process (Wilbur Smith Associates, 2005).

4. A detailed assessment to further refine the project cost and tolling plan, along with an intermediate grade T&R evaluation.
5. An investment grade analysis with extensive and detailed T&R study to determine a toll road project's value in anticipation of proceeding to the bond market.

2.3.2.2 Colorado. The state of Colorado has 12 toll projects at different stages of development. Currently, there are two toll roads in operation including the I-25 HOV Express Lanes and the Northwest Parkway. The Colorado Tolling Enterprise sponsored the remaining nine projects in Colorado, which was a division of the Colorado DOT. CTE was later replaced by High Performance Transportation Enterprise (HPTE), which is more focused on pursuing public-private partnerships and other innovative and efficient means to support infrastructure projects. HPTE carries out systematic feasibility studies for tolling projects. Colorado's tolling project development process is presented in Figure 2.3.

For screening the tolling projects, criteria include: potential safety impacts, viability assessment of toll operations, economic growth considerations, consistency with statewide and regional plan goals, community impact assessment, congestion relief potential network continuity considerations, order-of-magnitude construction cost estimates, general constructability assessment, 20th year traffic and revenue potential, relative financial feasibility index, and other considerations (including public comments) (Wilbur Smith Associates, 2005).

2.3.2.3 Seattle Toll Road SR-520. SR-520, a 4-lane freeway, was constructed in 1979. The Evergreen Point Floating Bridge, an important component of SR-520, connects SR-202 in the East with the I-5 and I-405 in the West. This bridge was forecast to be congested in the future; therefore, the Washington State decided to collect tolls for constructing a new bridge parallel to the existing one. The tolling was implemented in 2011. Washington State Transportation Commission (WSTC)

determined the toll rates. Tolls were collected on both directions and differed from time to time on weekdays and weekends. It is expected to raise \$1.2 billion to help fund the SR-520 Bridge Replacement Program (WSDOT, 2014).

To evaluate the influence of the tolling policy on traveler behavior, a survey was carried out on the same households before and after the tolling to measure a variety of impacts.

The survey showed that the overall corridor trips on SR-520 dropped significantly by 18% after tolling was implemented. Regarding the mode choice, the transit modal share on corridor rose from 15% to 18%. Avoiding tolls was common motivation for switching to transit (45%) but respondents also mentioned reduced stress (44%) and gasoline costs (39%); a few cited improved bus services (8%).

Regarding the route choice, the SR-520's share of corridor trips fell, while those of I-90 and SR-522 both increased. About 86% of those who switched from SR-520 to I-90 or SR-522 cited avoiding the toll as a motivation. There was little net change in trip departure time in the peak vs. off-peak distribution of trips in the corridor. On I-90, the peak share fell from 61% to 56%, while on SR-520, the peak share rose from 53% to 57%.

In all, there was a significant decline in overall travel demand on the Lake Washington corridor, particularly on SR-520. Also, the diversion to toll-free alternative routes and also to transit was observed.

2.4 Summary and Discussion

Tolling implementation initiatives always have project-specific issues and challenges. A recent survey of state transportation officials by the U.S. Government Accountability Office (GAO) identified two broad categories of challenges: those associated with obtaining support and these associated with implementation. Specifically, it is suggested to consider four broad questions (see Table 2.4).

TABLE 2.4
Questions to be considered for new toll road projects (GAO, 2006).

Question	Purpose
How will traffic be diverted and who will be affected?	To analyze how the tolls would affect personal, business and commuting trips and help the decision makers to estimate the extent of traffic diversion. These estimates will help the transportation officials to mitigate the impact of the diversion on affected parties.
To what extent will tolls meet the project's goals?	The extent to which tolls will meet the project's goals will help the sponsors to set the proper toll. If tolls are too low then the project costs may not be covered from the tolling revenues and the congestion may not be relieved to the desired extent.
Who loses and how do we compensate them?	Analyzing the effects a toll project will have on certain groups will help transportation officials address issues related to equity consequences of the project. The data that could be collected include those that capture household and lifestyle characteristics including) income, residential location, commuting patterns, number of vehicles, number of workers, family size, annual travel, and employment type and location. Analysis of the data can help to estimate the extent of shift of drivers to carpool and transit. It would provide insight to transit operators into how they might be able to expand service and how transit service might benefit lower-income users.
How will the project affect business activity and commercial transportation?	Given the importance of transportation to the economy and the impact of congestion on business activity and commercial, transportation officials could consider examining the impact of tolling on business activity and commercial transportation when considering the use of a tolling approach. However, this can be difficult for transportation officials because little is known about the magnitude of congestion costs. Factors affecting this include the logistics patterns of firms; the frequency, origin, and destination of trips; and the ability of firms to adapt to congestion without affecting costs. Research on how a tolling approach would affect commercial carriers operating on those facilities could also provide some insights.

3. METHODOLOGY FOR IMPACT ANALYSIS OF THE TIME-OF-DAY TOLLING

3.1 Introduction

This study developed a tool using static traffic assignment to estimate the impacts of the time-of-day tolling on the network. Figure 3.1 presents the overall framework for the study. The framework contains two parts: (a) statewide network level, and (b) subarea network level.

3.2 Statewide Travel Demand Modeling

The Indiana Statewide Travel Demand Model (ISTDM) Version 6 was used. This model includes state highways, county roads, and local streets in all ninety-two counties (or 4,831 TAZs). ISTDM is the main modeling tool used at INDOT to assess system performance, long-range plans and system-level projects at the statewide level. Some ISTDM features are:

- **Network and traffic analysis zone (TAZ) developments:** INDOT's Road Inventory Data (RID) for each year is attached to the roadways network. The TAZ structure is refined by adding a significant number of TAZs in Indiana. These refinements in the network and TAZ data helped to improve the model's overall reliability and accuracy.
- **Traffic signals:** The locations of traffic signals along with priority of signal approaches and number of upstream signals are coded statewide in the road network. This information is used for estimating realistic link impedance.
- **Trip generation models:** The base-year trip-generation models are updated based on year 2010 census data.
- **Gravity model factors:** ISTDM contains new friction factor curves that are recalibrated to address the refined

transportation network. Friction factors for long trips are developed by a smoothing curve. K-factors are applied by trip purpose and validated to account for factors that are not explained by friction factors.

- **Trip assignment:** The trip assignment process is changed from free-flow based assignment of trucks as a "pre-load" to "simultaneous multi-modal multi-class assignment." Multiple volume-delay functions are specified, based on extensive experimentation with the functions made during model validation.

3.3 Subarea Time-of-Day Tolling Modeling

The statewide travel demand model is designed to report daily auto and truck volumes assigned to the network. However, to accurately determine the impact (especially the mobility impact and the revenue benefit) from the time-of-day tolling, there is a need for the proposed model to report the time-of-day volumes for each link in the subnetwork during the following periods:

- AM peak period
- AM off-peak period
- PM peak period
- PM off-peak

In addition, the directional traffic volume is estimated from the total traffic volume. To carry out traffic assignment at the desired time period, the following procedures were followed:

- **Time-of-day trip-generation table:** To create an OD trip table that contains the travel demand of different vehicles (i.e., autos and trucks) by time-of-day, a P-A matrix and hourly lookup table are used. The P-A matrix is a

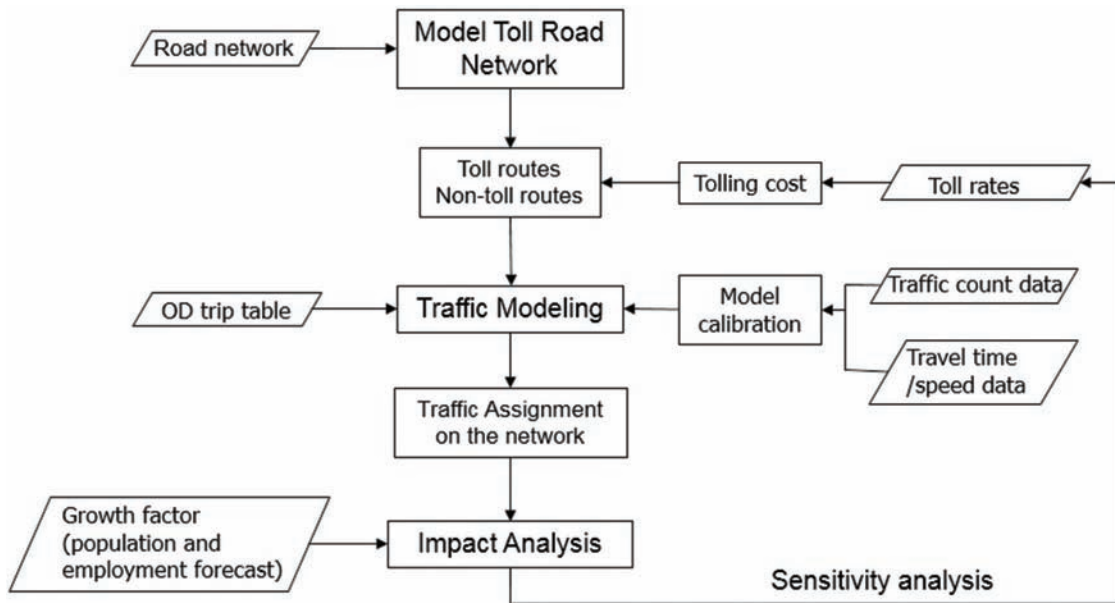


Figure 3.1 Overall framework used in this study for impact analysis of the time-of-day tolling.

24-hour P-A matrix, while the hourly lookup table provides information on travel that occurs in each hour of a day, i.e., the percentage of traffic departs and returns during each hour. Using the tool “Convert P-A matrix to O-D matrix” on TransCad with the input file is P-A matrix, the lookup data view is hourly, and having checked report each hour separately option, the time-of-day trip table can be generated.

- **Traffic assignment:** The directional traffic volume on each link in the subarea network needs to be determined based on the time-of-day trip table.

During each time-of-day period, autos and trucks are assigned simultaneously using the build-in function in TransCAD 7, the Multi-modal Multi-class Assignment (MMA) function. This is a powerful traffic assignment model based on the generalized cost differentiated by individual modes and user classes (e.g., vehicle types). While other assignment models exist in TransCAD 7, MMA was chosen because it can help to avoid the issue of loading all vehicle classes to the network at the same time. Furthermore, to be consistent with the existing model structure, in MMA, the generalized cost is calculated by incorporating the travel time and toll costs in trip distribution and traffic assignment.

The time-of-day tolling is implemented by capturing toll costs based on the specific corridor, trip purpose and vehicle type. As shown in Figure 3.1, the implementation procedure for the time-of-day tolling has the following steps.

1. Skimming the subarea based on free flow time, and skimming the associated toll costs along the links using the Toll Shortest Path functionality in TransCAD7.
2. Convert the toll costs to time units via purpose-specific value-of-time (VOT) that is also used in the assignment.

3. Determine the specific generalized cost impedances based on the travel time plus the converted toll time (Toll cost / VOT).
4. Use the generalized cost impedances in the MMA’s gravity model.

Figure 3.2 presents the user interface of the TOD Tolling Analysis Pack in TransCAD 7 for the impact analysis of time-of-day tolling. The TOD Tolling Analysis Pack was tested with input from INDOT engineers. Users can input the toll rates for different vehicle classes (e.g., autos and trucks) under different periods (specified at one-hour interval). To access the sensitivity of the toll rates, users can change the toll rate inputs and obtain the outcome under different toll rate scenarios.

3.4 Impact Analysis Methods

3.4.1 Revenue

As explained in section 3.3, the MMA traffic assignment procedure was implemented for different tolling scenarios under different time-of-day periods. Using the outcome of the MMA traffic assignment, the revenue of the toll road (i.e., I-465) can be estimated by summing up the tolls collected from automobiles and trucks, as follows:

$$\text{Revenue}(t) = \text{VMT}_{\text{auto}}^t \times \text{Toll}_{\text{auto}}^t + \text{VMT}_{\text{truck}}^t \times \text{Toll}_{\text{truck}}^t \quad (3.1)$$

where

Revenue (t): Aggregated collected toll revenue for the time-of-day period t ,

$\text{VMT}_{\text{auto}}^t$: Vehicle-Miles-Traveled (VMT) by automobiles for the time-of-day period t

$\text{Toll}_{\text{truck}}^t$: Designated toll rate for automobiles for the time-of-day period t

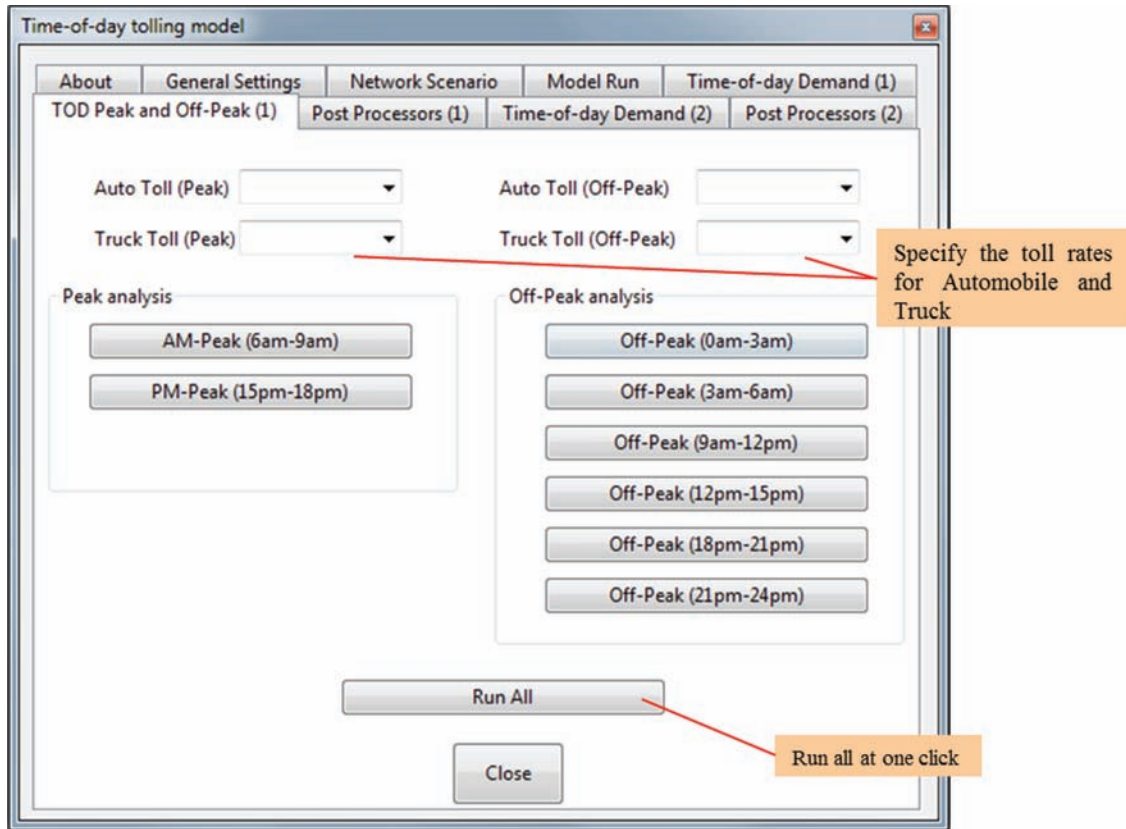


Figure 3.2 User interface of the TOD Tolling Analysis Pack for the impact analysis of time-of-day tolling.

VMT_{truck}^t : Vehicle-Miles-Traveled (VMT) by trucks for the time-of-day period t

$Toll_{truck}^t$: Designated toll rate for trucks for the time-of-day period t

v_a : Traffic volume of link a

α, β : Calibration parameters

3.4.2 Travel Time

The reported link-based travel times are computed as the average of travel time weighted by the hourly traffic volume. The hourly average speed for each link is calculated by using the Bureau of Public Roads (BPR) form of the volume-delay function with link-specific parameters as in the MMA assignment. The volume-delay function is used to adjust the link's free-flow speed based on its hourly volume-to-capacity ratio to account for congestion-related delay. A set of the alpha and beta parameters for the BPR equation are applied. The volume-delay function in the post-analysis section is presented below:

$$S_a(v_a) = t_a \left(1 + \alpha \left(\frac{v_a}{c_a} \right)^\beta \right) \quad (3.2)$$

where

$s_a(v_a)$: Average travel time for link a with traffic volume v_a

c_a : Capacity of link a per hour

t_a : Free-flow travel time on link a

The estimation of the travel time and travel speed in this study is consistent with the procedure presented in ISTDM (CDM Smith, 2014). In ISTDM, the free-flow travel time estimation procedure was developed as part of the survey of the I-69 Tier-1 study. The survey conducted in southwest Indiana, covered 64 locations and recorded vehicle speeds of different road classes, posted speeds, area types, access control types and number of lanes. The facility type was determined for every survey location where the posted speed limits and traffic volumes per hour were recorded. The speed records on highways, which exhibited free-flow condition, as defined by the Highway Capacity Manual, were studied. The selected speed records and the geometric data were analyzed using ANOVA to check if the speeds between two-lane and multi-lane facilities differ significantly. The results confirmed that the speeds at these two facilities differ significantly. Then for each facility type, the relationship between free-flow speed and the posted speed was determined using non-linear regression.

3.4.3 Speed

The travel speeds were estimated using ISTDM. Specifically, the average speed at I-465 corridor was computed

by dividing the total length of I-465 corridor by the sum of travel times of the I-465 segments, as shown below:

$$AVG_SPEED(465) = \frac{\sum_i^N L_i(I465)}{\sum_i^N S_i(I465)} \quad (3.3)$$

where

- $L_i(I465)$: The length of segment i of I-465 corridor
- $S_i(I465)$: The average travel time of segment i of I-465 corridor
- N : Number of segments of I-465 corridor

3.4.4 Monetary Savings

The monetary cost associated with the tolling scenario i is calculated as follows:

$$Cost^i = VHT_{auto} * VOT_{auto} + VHT_{truck} * VOT_{truck} \quad (3.4)$$

where

- $Cost^i$: The total costs associated with a given tolling scenario i
- VHT_{auto} , VHT_{truck} : The vehicle-hours traveled of autos and trucks, respectively
- VOT_{auto} , VOT_{truck} : The auto and truck values of time, respectively

The monetary savings of scenario i with respect to the base scenario is computed using the following formula:

$$Savings^i = Cost^{bc} - Cost^i \quad (3.5)$$

where

- $Savings^i$: The reduction in cost associated with a given tolling scenario i compared to the base case costs, for all i from 1 to 8
- $Cost^{bc}$: The aggregated monetary cost of the base case without tolling
- $Cost^i$: The aggregated monetary cost of scenario i , for all i from 1 to 8

3.4.5 Welfare

Welfare or net user benefit refers to reduction in emissions, crashes, and other externalities that are linked with congestion (AASHTO, 2001). In this project, welfare, defined by Kalmanje and Kockelman (2004) as the increase in consumer surplus after a policy is implemented, is calculated for each scenario for a given area in consideration. It is defined as the aggregate sum of the benefits enjoyed by all the commuters due to the implementation of the TOD in comparison to the base case scenario where there is no toll on I-465. Benefit here is defined as the reduction in monetary or monetary equivalent cost for each commuter for a given scenario as compared to the base case. The cost term for a particular scenario contains the monetary equivalent of travel time plus the toll paid by individuals. The monetary equivalent of travel time is computed using the monetary cost equation (Eq. 3.4).

For example, in the base case scenario, the cost term would include only the monetary equivalent of travel

time though there were no toll. In case of scenario 1, the cost term would include the monetary equivalent of travel time plus the scenario 1 toll paid by individuals. Therefore, if the benefit is positive for a particular scenario, then the total monetary costs as defined for a scenario are lower than that of the base case. On the other hand, if it is negative, then the total monetary costs are higher than that of the base case.

The welfare of this project is computed for each county by the following equation:

$$\begin{aligned} Welfare^i &= Cost^{bc} - (Cost^i + Tolling_Cost^i) \\ &= (VHT_{auto}^{bc} \times VOT_{auto}^{bc} + VHT_{truck}^{bc} \times VOT_{truck}^{bc}) \\ &\quad - (VHT_{auto}^i \times VOT_{auto}^i + VHT_{truck}^i \times VOT_{truck}^i \\ &\quad + Tolling_Cost^i) \text{ for all } i \text{ from 1 to 8} \end{aligned} \quad (3.6)$$

where

- $Welfare^i$: The aggregated welfare of scenario i , for all i from 1 to 8
- $Cost^{bc}$: The aggregated monetary cost of the base case without tolling
- $Cost^i$: The aggregated monetary cost of scenario i , for all i from 1 to 8
- VHT_{auto}^{bc} , VHT_{truck}^{bc} , VHT_{auto}^i , VHT_{truck}^i : The vehicle-hours traveled of autos and trucks, for base case and scenario i , respectively. For all i from 1 to 8
- VOT_{auto}^{bc} , VOT_{truck}^{bc} , VOT_{auto}^i , VOT_{truck}^i : The auto and truck values of time, for base case and scenario i , respectively. For all i from 1 to 8
- $Tolling_costs^i$: The aggregated cost spends on toll in scenario i , for all i from 1 to 8

3.5 Chapter Summary

This chapter described the development of a tool integrated with ISTD in TransCAD to evaluate the impact of hypothetical time-of-day tolling on I-465 corridor in Indiana. The tool is coded in GISDK (the programming language developed by TransCAD) with a user-friendly interface. The overall implementation of the time-of-day tolling analysis consists of two components. The first is the implementation of the Trip Generation, Trip Distribution, and Mode Choice at the statewide level, to obtain the statewide traffic demand. Secondly, the multi-class-multi mode traffic assignment (MMA) was carried out for a small region of Indiana covered by the prospective tolling of I-465, to obtain the link traffic volumes of this sub-area. Using the traffic volume output, a "post analysis" was conducted under different time-of-day tolling scenarios.

Each scenario considered the following performance metrics:

- Toll revenue
- Monetary savings
- Travel time (estimates based on procedures used in the ISTD)
- Average speed (estimates based on procedures used in ISTD)
- VHT

- VMT
- Welfare

The travel times and average speeds were estimated in a manner that is consistent with the procedure used in ISTDM.

4. USER INTERFACE OF THE TOD TOLLING ANALYSIS PACK

The TOD Tolling Analysis Pack has multiple tabs, which are as follows (see Figure 4.1):

- **About:** Provides general information about the analysis, such as the purpose of the TOD Tolling Analysis Pack (TOD tolling analysis), and the developers (Purdue University and INDOT).
- **General settings:** In this tab, the user is requested to provide general inputs for the model.
- **Network scenario:** Selects the network scenario and other inputs for network analysis.
- **Model run:** Run the model.

4.1 Three-Hour Block Components

There are options available for analysis. The first option is the three-hour block option, which includes three tabs, namely, Time-of-Day Demand, TOD Peak and Off-Peak and “Post Analysis” and Visualization. The second option is discussed in detail in section 4.2.

Time-of-day demand. The daily OD is first converted to Hourly OD, then from Hourly OD to Time-of-Day OD. The process of conversion is as follows.

The hour of day factors were used to find the hourly flows for each hour of the day by multiplying the hour of day factor with the Daily OD. Hour of day factor is defined as the fraction of traffic volume that flows through the day in a particular hour. The hourly OD once derived was used to calculate the Time-of-Day OD.

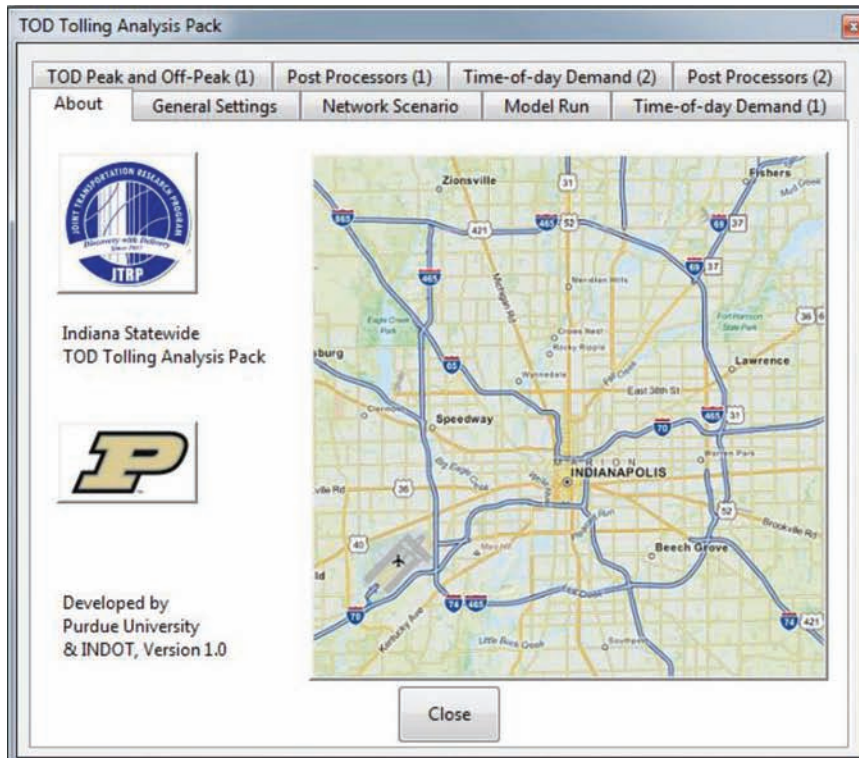
For example, for Option1, one of the Time-of-Day OD was 6 PM–9 PM block and this was calculated by adding up the 3 hourly OD values, i.e., 6 PM–7 PM, 7 PM–8 PM and 8 PM–9 PM OD flows.

TOD peak and off-peak. Input tolls for peak and off-peak hours for auto and truck. The model can be run separately for each time period or run for all time periods together at the same time (see Figure 4.2).

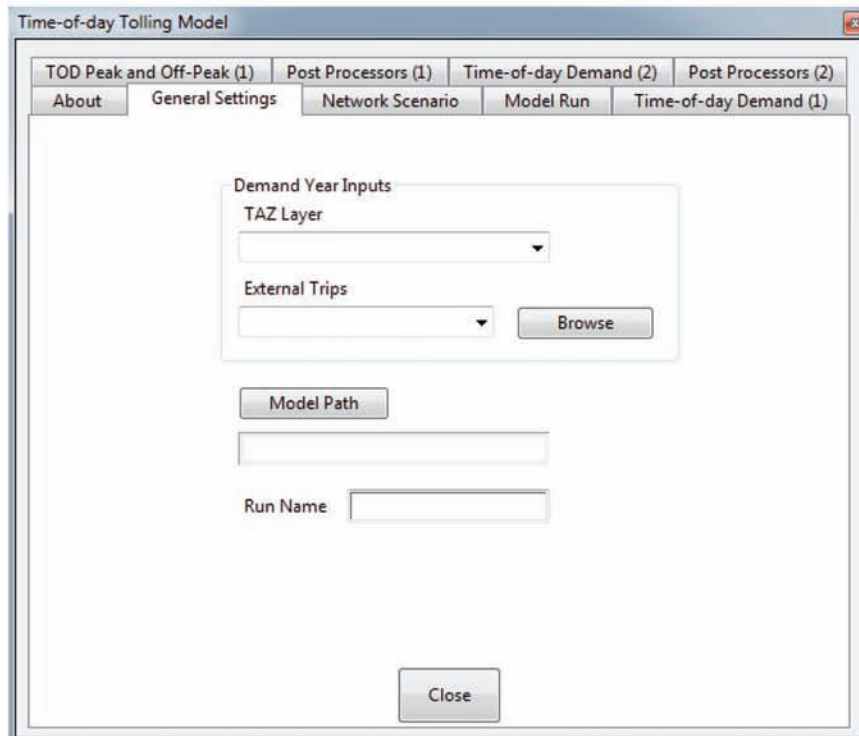
Post processors. This tab carries out the “post analysis,” visualization of Traffic Volumes, and display of the ten most impacted road sections.

4.2 One-Hour Block Components

Similar to the three-hour block option tabs, the developed tool contains an option that presents the results based on one-hour block option with the options shown in Figure 4.3.

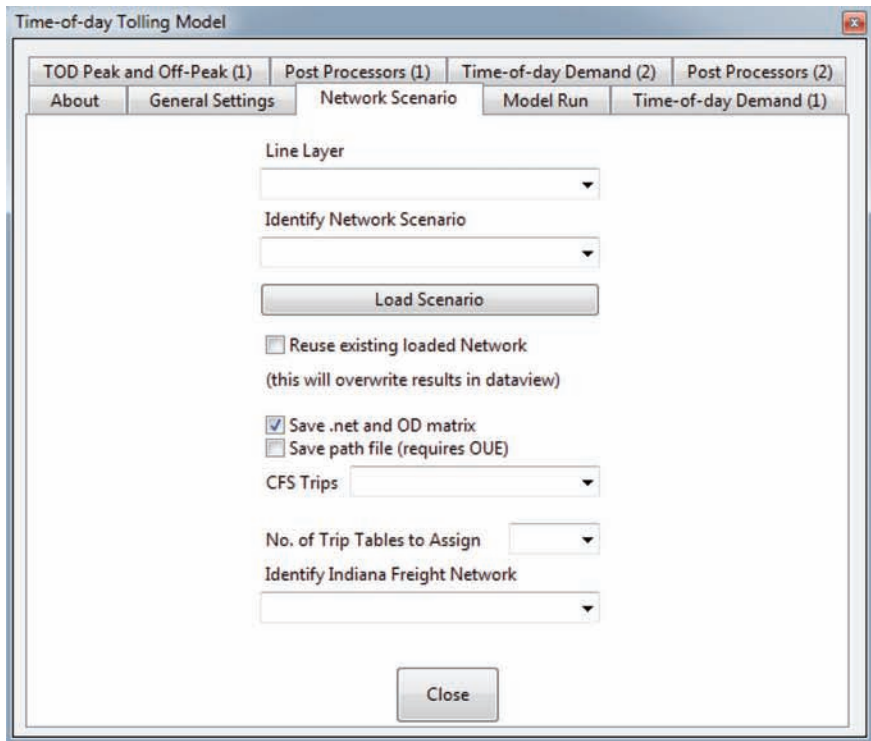


(a) General information related to TOD Tolling Analysis Pack

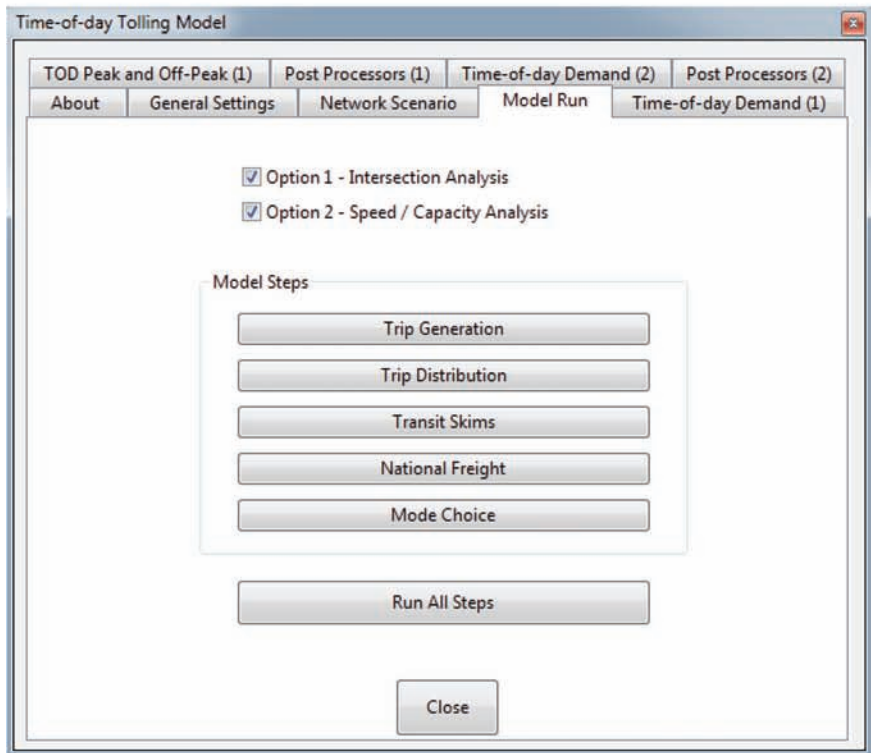


(b) Demand year inputs and model path settings

Figure 4.1 General steps for the analysis. (Figure continued on next page.)

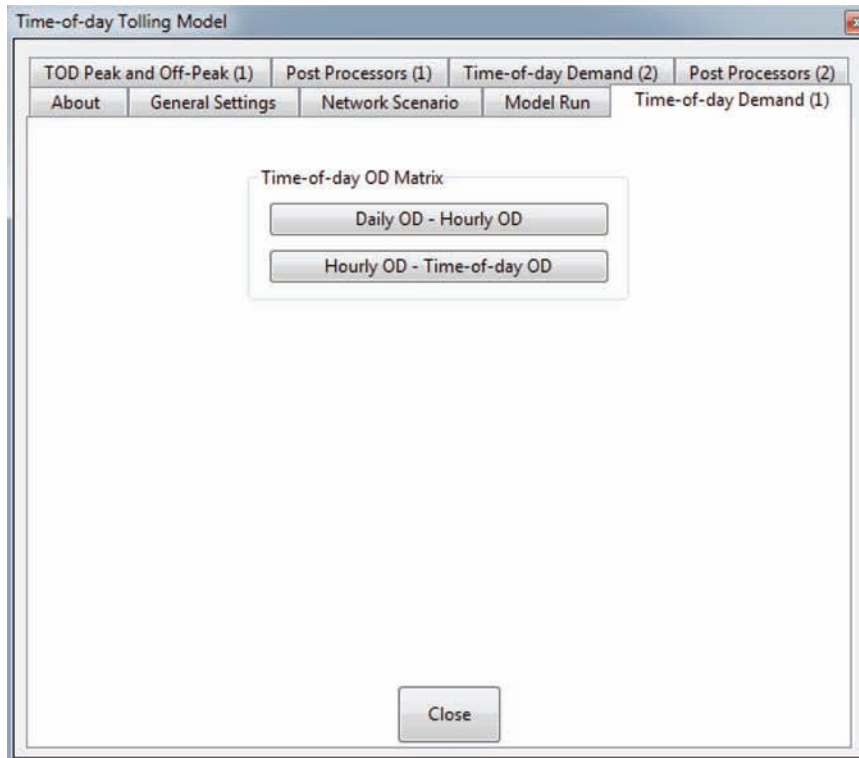


(c) Network settings

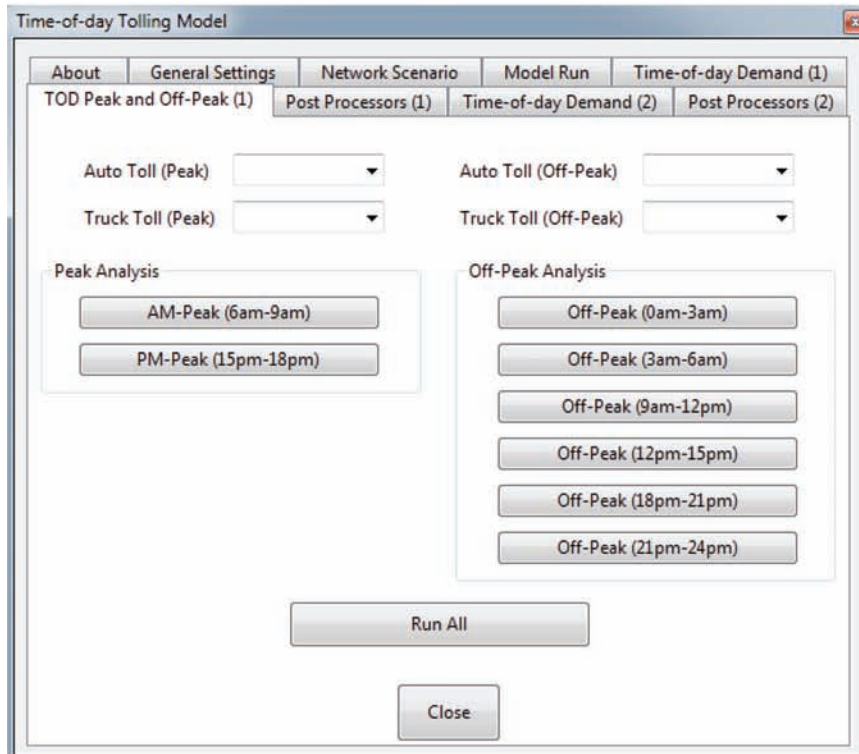


(d) Four-step analysis

Figure 4.1 Continued.

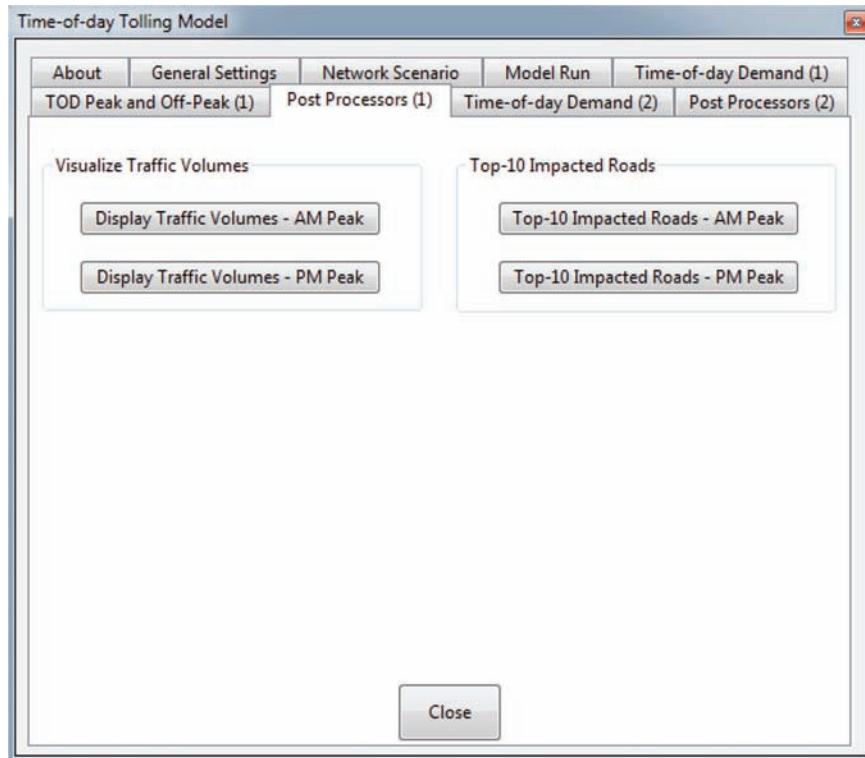


(a) Time-of-day OD matrix calculation



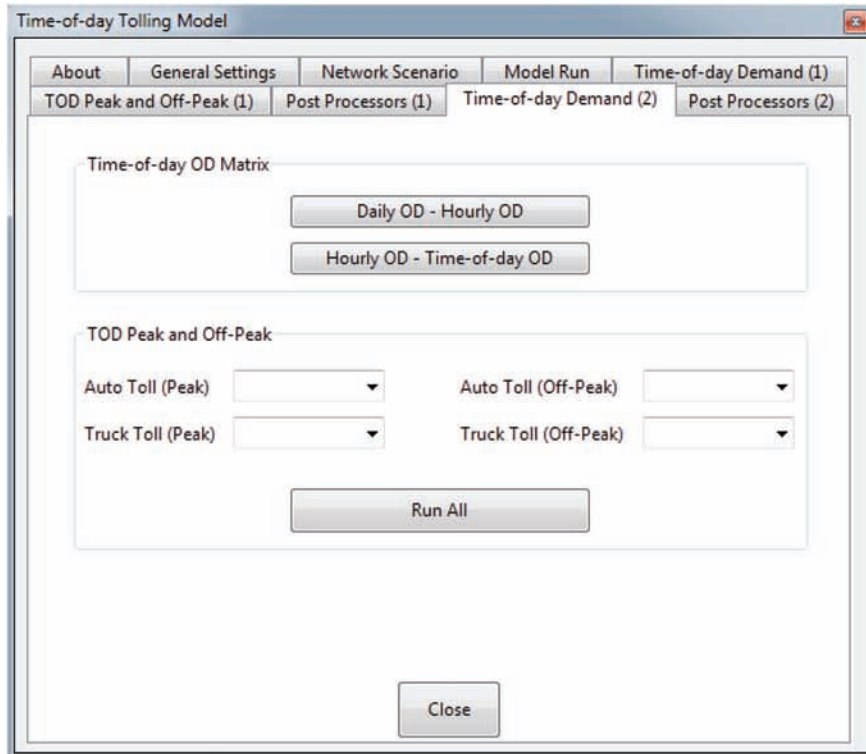
(b) Setting toll levels

Figure 4.2 Steps for implementing a three-hour block analysis. (Figure continued on next page.)

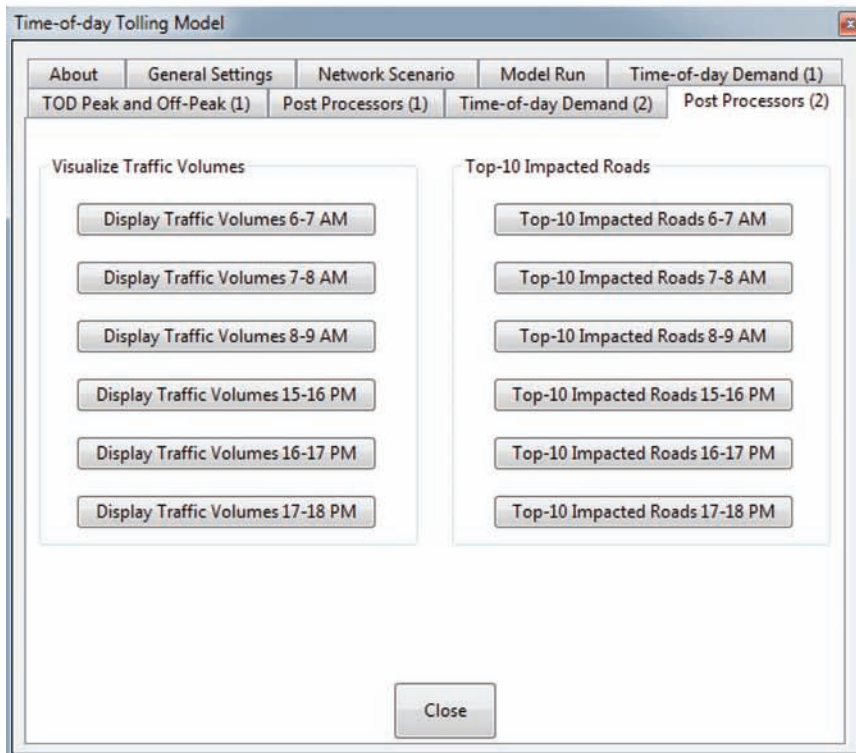


(c) Display traffic volumes and top 10 impacted roads after applying toll

Figure 4.2 Continued.



(a) Time-of-day OD matrix calculation and setting toll levels



(b) Display traffic volumes and top 10 impacted roads after applying toll

Figure 4.3 Steps for implementing a one-hour block analysis.

5. IMPACT ANALYSIS OF TIME-OF-DAY TOLLING

5.1 Study Area

Interstate 465 (I-465) is a beltway around Indianapolis, Indiana. It has a total length of about 57.5 miles (92 km) (FHWA, n.d.). I-465 has several interchanges with other interstate highways, such as I-65, I-69, I-70, I-74 and I-865. Due to increasing travel demand, traffic congestion has been experienced at several road segments that connect to I-465. In addition, INDOT is considering tolling I-465 to generate revenue for highway management as well as to manage traffic congestion on this corridor and other major highway links that are incident to this corridor. Therefore, in this study, I-465 is selected for tolling analysis and nine counties in Indianapolis area (which will experience impacts from the tolling) are chosen to represent the study area (see Figure 5.1). Section 5.3 presents the results of the analysis.

5.2 Toll Scenarios

Multiple scenarios were established for quantifying the impact of toll rates on Indiana roadways. The truck toll rates are assumed to be double that of

autos. In addition, the rates in off-peak hours are half of peak hour rates. The peak hours are 6 AM–9 AM, and 3 PM–6 PM; other hours are off-peak. The base scenario is first created as a reference or the no-toll scenario. Scenarios differ by toll rate. Table 5.1 displays the details of toll scenarios.

5.3 Impact Analysis

All the impact analysis for the nine counties in the following sections include I-465 unless otherwise stated.

TABLE 5.1
Toll scenarios (\$/mile).

Scenario	Peak		Off-Peak	
	Auto	Truck	Auto	Truck
Base	0.000	0.000	0.000	0.000
Scenario_1 (S1)	0.030	0.060	0.015	0.030
Scenario_2 (S2)	0.040	0.080	0.020	0.040
Scenario_3 (S3)	0.050	0.100	0.025	0.050
Scenario_4 (S4)	0.060	0.120	0.030	0.060
Scenario_5 (S5)	0.070	0.140	0.035	0.070
Scenario_6 (S6)	0.080	0.160	0.040	0.080
Scenario_7 (S7)	0.090	0.180	0.045	0.090
Scenario_8 (S8)	0.100	0.200	0.050	0.100

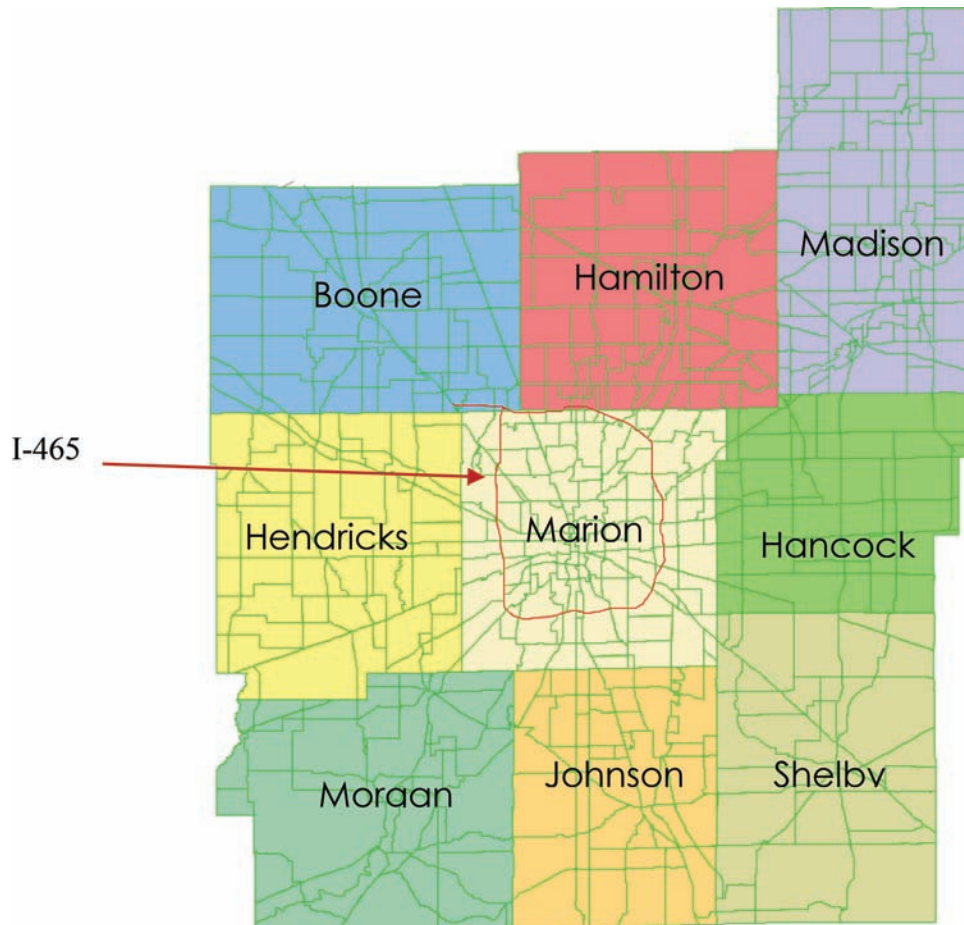


Figure 5.1 Study area (location of I-465 and boundaries of the nine counties).

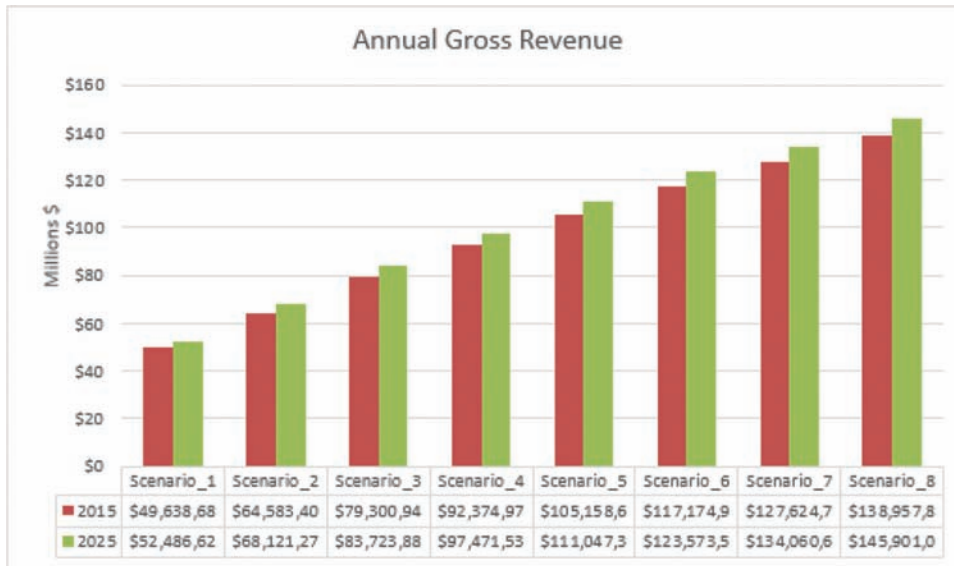


Figure 5.2 Scenarios-wise annual revenues (\$/year).

5.3.1 Revenue Analysis

Figure 5.2 shows an increasing trend of annual revenues for the years 2015 and 2025 (revenues are the same for three-hour block option and one-hour block option). The base case (no toll) and scenario 8 (highest toll) have lowest and highest revenues, respectively, as expected.

The revenue for I-465 increases monotonically for higher levels of toll from scenario 1 to scenario 8. For the given scenarios, the toll revenue continues to grow because the increase of toll per vehicle offsets the drop in revenue due to some vehicles choosing not to use the tolling facility due to a higher toll. The revenue generated via tolls reaches a maximum at approximately \$0.25/mile (toll rate for autos at peak hours). Beyond that rate, the revenues decline due to the higher sensitivity to higher tolls.

In addition, the impact of the toll schedule on travel can be inferred via the summary of VMT and VHT in Table 5.4 and Table 5.5 in section 5.3.7.3.

5.3.2 Monetary Savings Analysis

5.3.2.1 Values of vehicle time. The values of vehicle time used to calculate the monetary costs and monetary savings are given in Table 5.2. For the year 2015, the value of travel time for auto was provided by INDOT (communicated via emails with Mr. Frank Baukert during 2015 and 2016). The value of travel time for trucks was calculated using the 2015 revised value of travel time recommended by USDOT (2016) and the average vehicle occupancy for trucks from the FHWA's (2005) HERS technical report. The 2025 value of time values were estimated by adjusting the corresponding VOT values of 2015 by using the CPI inflation rate of 1.5% for years from 2016 to 2025 (CBO, 2015).

TABLE 5.2
Value of vehicle time (\$/hour).

Year	Auto	Truck
2015	\$ 21.53	\$ 28.39
2025	\$ 25.23	\$ 33.27

TABLE 5.3
The time costs incurred by vehicles using I-465 for the one-hour block option.

Scenario	2015	2025
Base	\$1,319,558	\$1,624,133
Scenario 1 (S1)	\$1,214,926	\$1,497,711
Scenario 2 (S2)	\$1,184,484	\$1,458,484
Scenario 3 (S3)	\$1,165,091	\$1,433,753
Scenario 4 (S4)	\$1,128,645	\$1,391,443
Scenario 5 (S5)	\$1,098,924	\$1,354,314
Scenario 6 (S6)	\$1,073,047	\$1,322,328
Scenario 7 (S7)	\$1,040,385	\$1,276,093
Scenario 8 (S8)	\$1,020,233	\$1,251,676

5.3.2.2 Monetary costs. The monetary costs, which refer to the time costs incurred by vehicles using I-465, can be seen to be gradually decreasing from the base case (no toll) to scenario 8 (highest toll) in Table 5.3. This is due to the reduced VMT, which translates into lower annual monetary costs. This is consistent across all the years of the analysis period.

5.3.2.3 Monetary savings

5.3.2.3.1 I-465. Figure 5.3 presents the annual monetary savings for 2015 and 2025 for each of the 8 scenarios compared to the base case. The monetary savings gradually increase from the base case (no toll)

to scenario 8 (highest toll). The monetary savings accrue due to a reduction in monetary user costs, which is a favorable consequence of lower total travel time. The base case (no toll) and scenario 8 (highest toll) for each of the analysis period have lowest and highest annual monetary savings, respectively.

5.3.2.3.2 *The nine-county region around I-465.*

- For the three-hour block option, Figure 5.4(a) presents the monetary savings for the years 2015 and 2025 and for all eight scenarios in the nine-county region compared to the base case. The monetary savings increase across the scenarios, lowest for the base case (no toll) and highest for scenario 8 (highest toll). The monetary savings are higher for each scenario than the previous year. The increase in monetary savings in percentage terms for scenario 1 is the highest and the lowest for scenario 8.
- Figure 5.4(b) illustrates the monetary savings for the one-hour block option for 2015 and 2025 for the nine-county region. The monetary savings increase from scenario 1 to scenario 6, and decrease from 2015 compared to 2025. However, for the scenarios 7 and 8, the monetary savings of the later years are higher compared to the earlier years.

The values of monetary savings between the three-hour block option and the one-hour block option are different because of the cumulative rounded numbers during computational processes. Compared with the one-hour travel demand data from the one-hour block option, the three-hour block option has a higher average cumulative travel demand (which is an input to the BPR function). Consequently, a higher travel time was computed for the three-hour block option. Therefore, the travel time saving for the three-hour block option is lower than that of the one-hour block option. As a result, the monetary savings associated with that option are lower than those of the one-hour block option.

5.3.3 *Average Travel Time*

5.3.3.1 **I-465.** The average travel time is the lowest from midnight to 6 AM, peaking in the 6 AM–9 AM block.

- The highest travel time is the 3 PM–6 PM period.
- The average travel time gradually tapers down from 6 PM to midnight.
- The evening peak is much higher than the morning peak in all scenarios. The difference in the morning and evening peaks is sensitive to the toll amount. For example, for scenario 8 the evening peak is much lower as compared to the base case. This suggests that the travel time variability can be effectively controlled by tolling.
- The average travel time is highest for the base case (no toll) and lowest for scenario 8 (highest toll). This means the travelers will experience significantly lower travel time by paying higher toll. The illustrations can be seen in Figure 5.5(a).

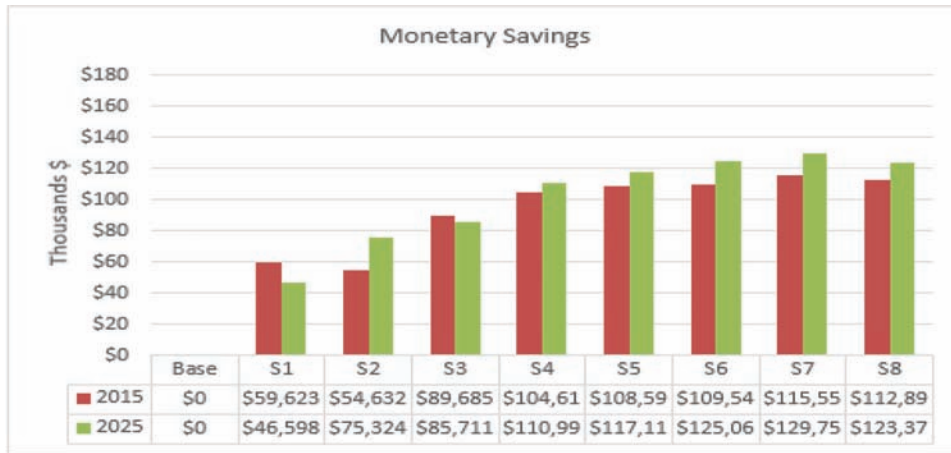
As presented in Figure 5.5(b):

- The time-of-day average travel time is high in the 7 AM–9 AM time block and between 3 PM and 7 PM, followed by a shorter peak from 7 PM to 9 PM. It has peaks at 8 AM and 5 PM. There is also a lower peak at 8 PM.
- The average travel time gradually reduces from the base case (no toll) to scenario 8 (highest toll). That means by paying a higher toll, travelers can save time.
- From midnight to about 6 AM, the travel time is stable for all scenarios. This maybe because during this time the traffic volumes are quite low, and the vehicles can travel at free-flow speeds.

5.3.3.2 **The nine-county region around I-465.** The length of I-465 is only approximately 1.4% of the total length of state highways in the nine-county region (57 miles vs 4,000+ miles), therefore the implementation of tolling on I-465 does not have significant impacts on travel time at nine counties level. From the



Figure 5.3 Annual monetary savings relative to the base case, for the one-hour block option.



(a) Three-hour block option



(b) One-hour block option

Figure 5.4 Monetary savings relative to the base case.

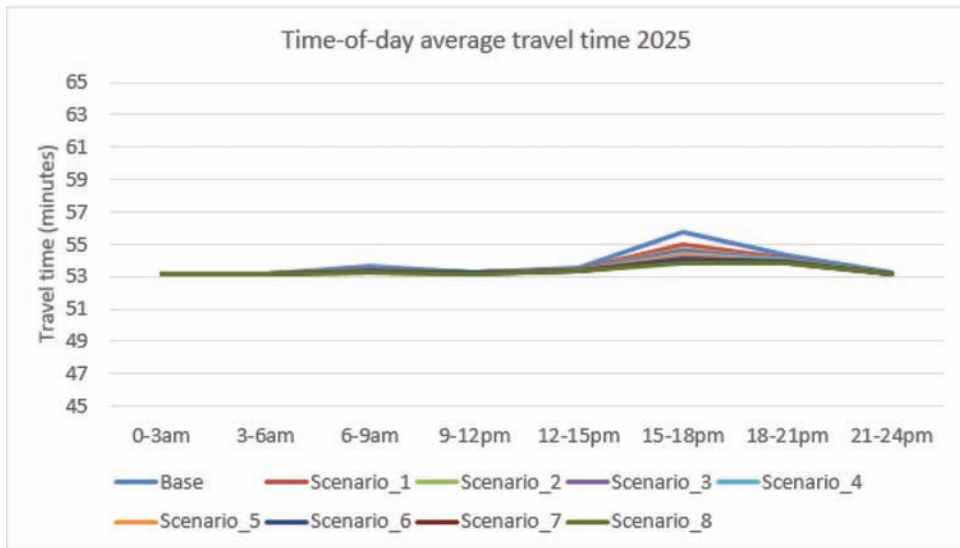
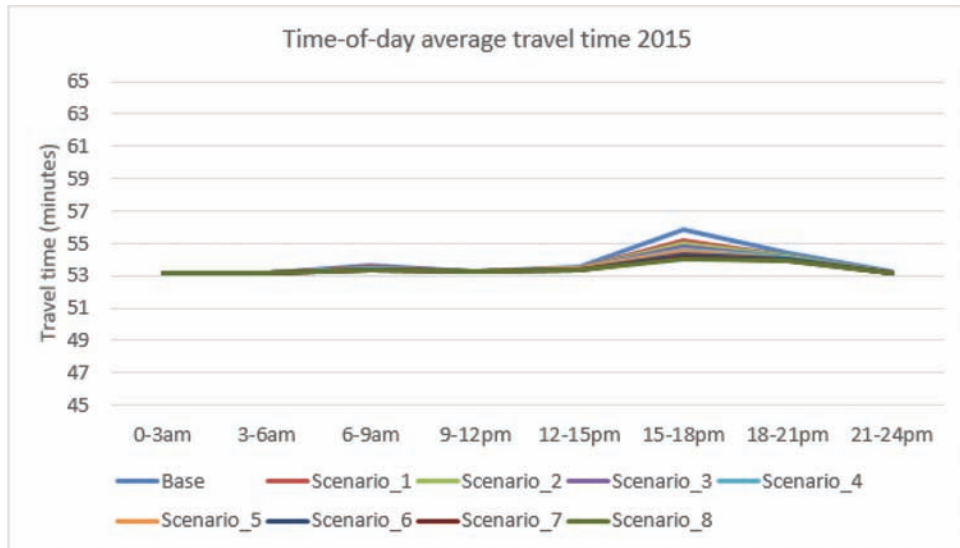
base case to scenario 8, the average of travel time is about the same in both three-hour and one-hour block options as seen in Figure 5.6(a) and Figure 5.6(b), respectively.

5.3.4 Average Speed

5.3.4.1 I-465

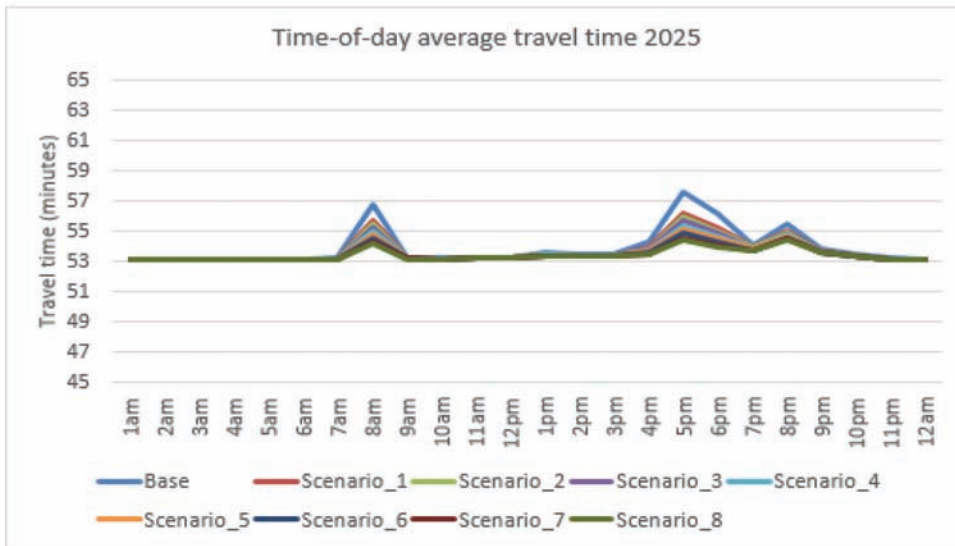
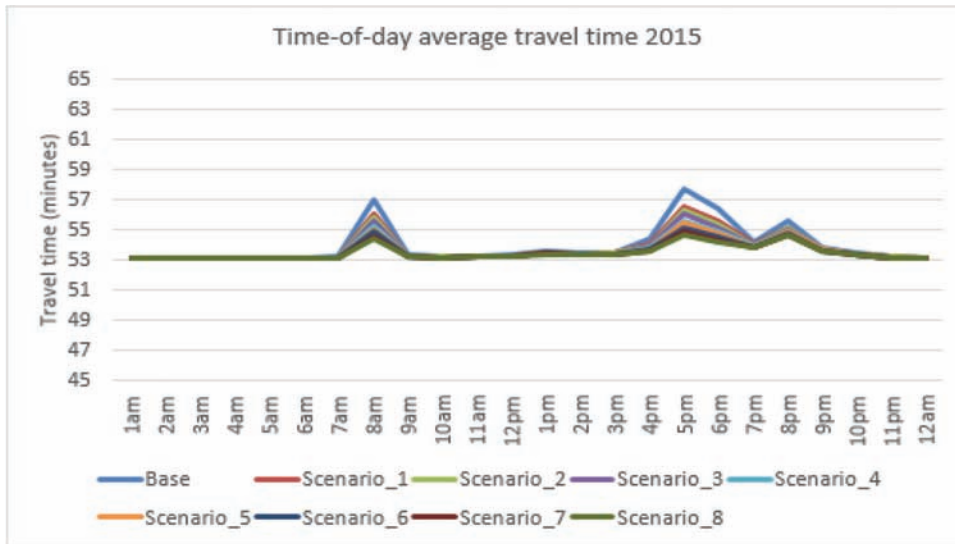
- For the three-hour blocks, the average speed is inversely proportional to the average travel time (Figure 5.7(a)).
 - The average speed is the highest from midnight to 6 AM. It reduces gradually during the 6 AM–9 AM period and then increases in the 9 AM–12 PM period.
 - It reduces in the 12 PM–3 PM block and then increases rapidly in the 3 PM–6 PM block.
 - It increases during the 6 PM–9 PM block and continues to increase until midnight.
 - The average speed is the lowest for the base case (no toll) and highest for scenario 8 (highest toll).

- The average speed is more stable in the scenarios with tolls compared to the base case (no toll), and is the most stable in scenario 8.
- For the one-hour blocks (Figure 5.7(b)), the average speed is low during the 7 AM–9 AM block and through the 3 PM–9 PM block.
 - It sharply decreases to its lowest morning speed at 8 AM, and reaches its absolute minimum speed at 5 PM. A shallower dip compared to the 5 PM low is observed at 8 PM.
 - It gradually increases from base case (no toll) to scenario 8 (highest toll). That means by paying a higher toll, travelers can drive faster.
 - For all scenarios from midnight to around 6 AM, speed is stable because there may be less traffic during this time, which allows the vehicles to travel at free-flow speeds.
 - The speeds at peak hours are similar for both projected years.



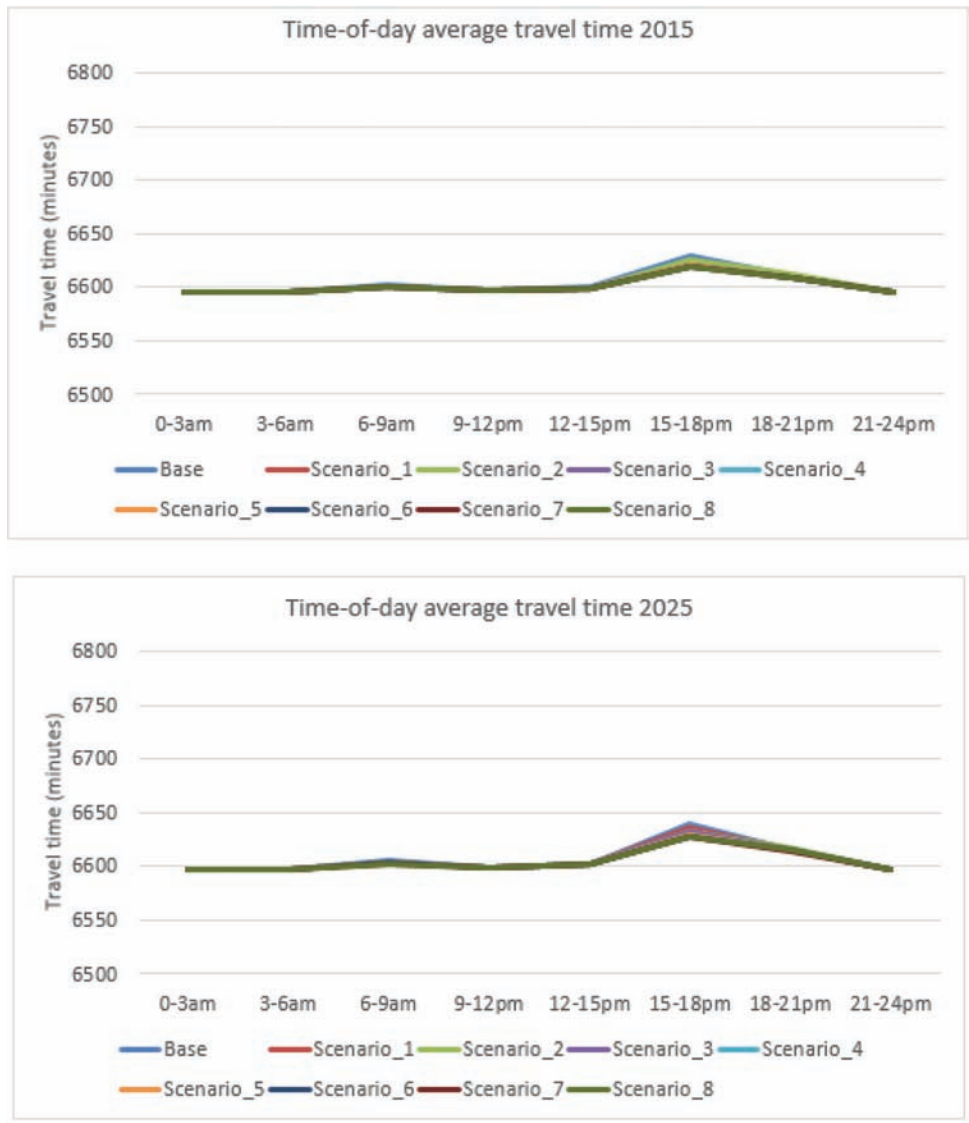
(a) Three-hour block option (2015 and 2025)

Figure 5.5 Time-of-day average travel time. (Figure continued on next page.)



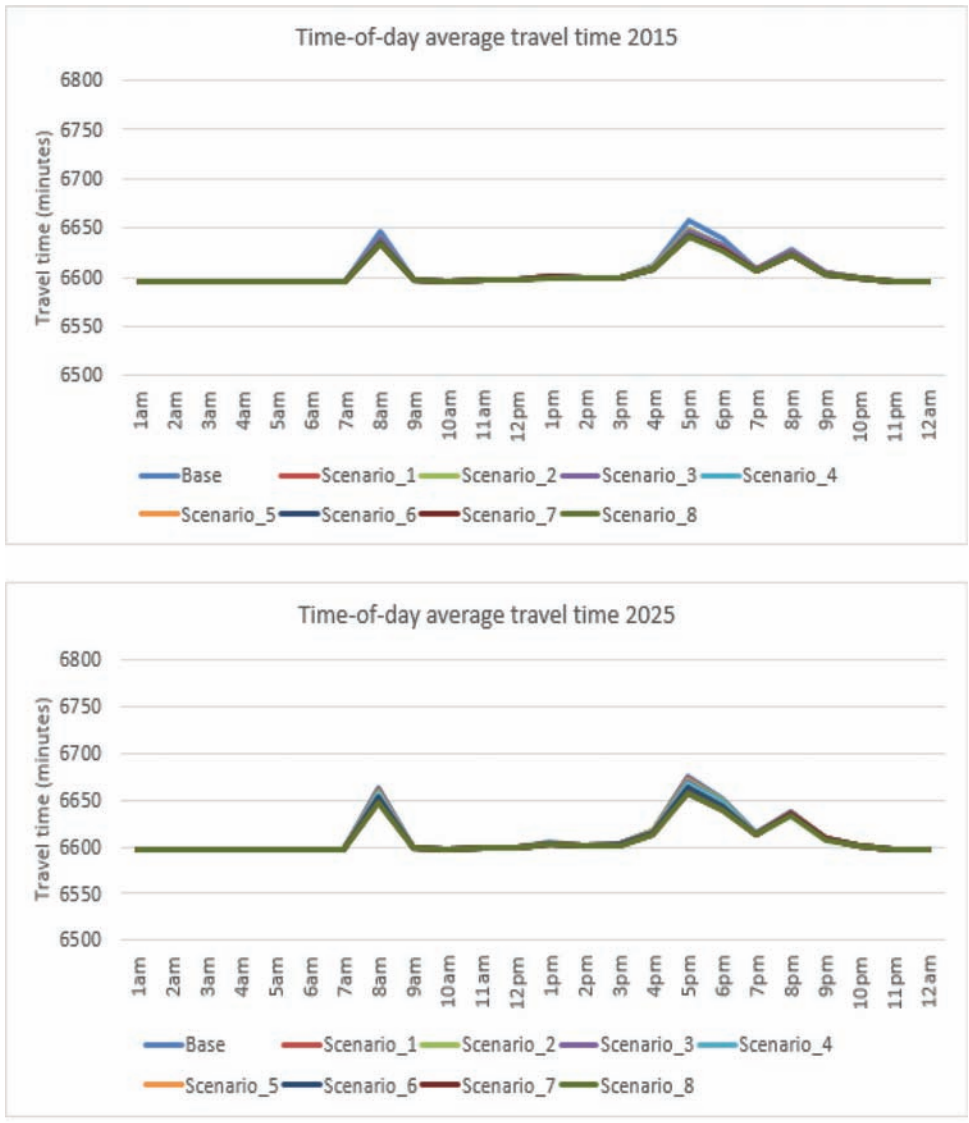
(b) One-hour block option (2015 and 2025)

Figure 5.5 Continued.



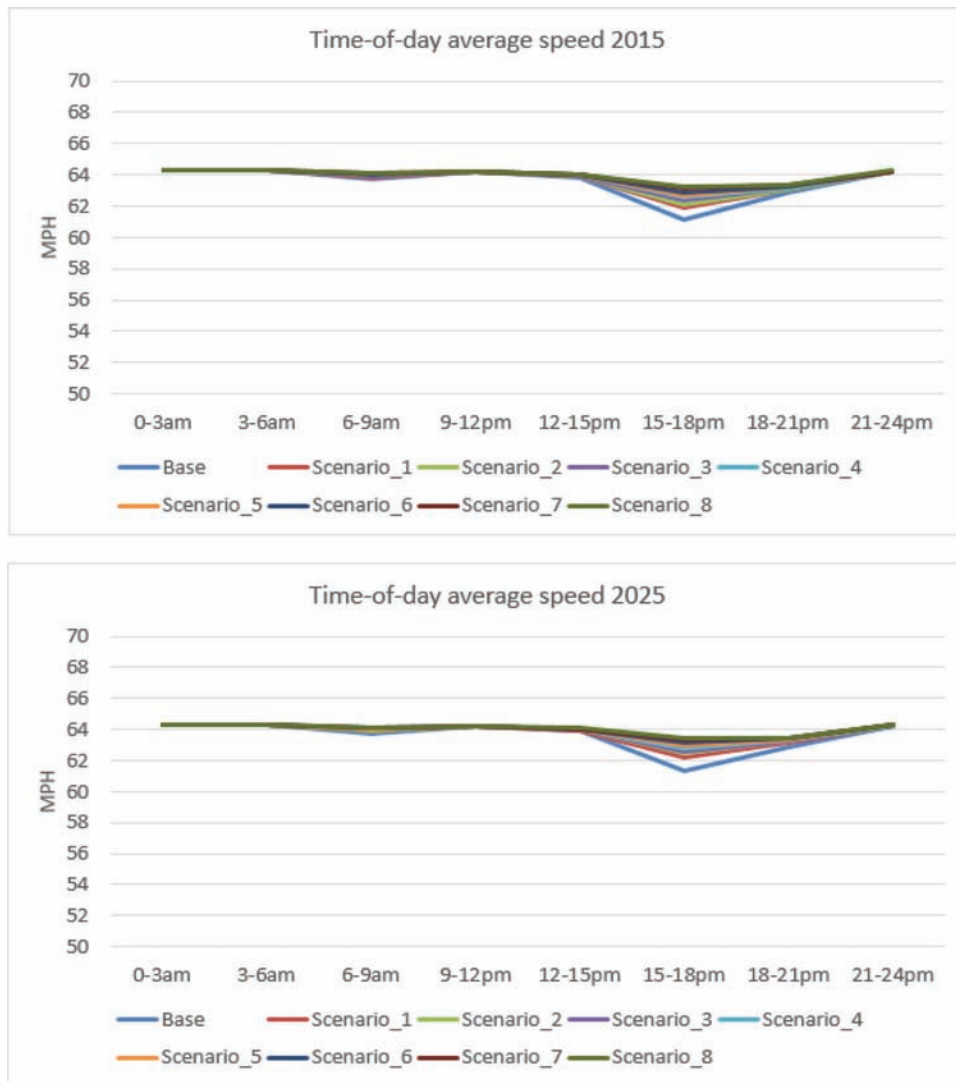
(a) Three-hour block option (2015 and 2025)

Figure 5.6 Scenario-wise average travel times across different times of day, nine-county region around I-465. (Figure continued on next page.)



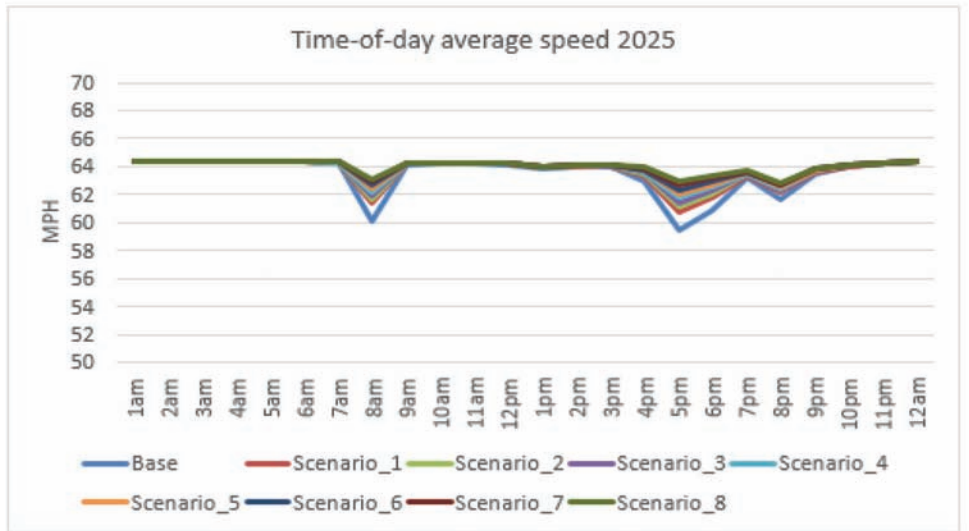
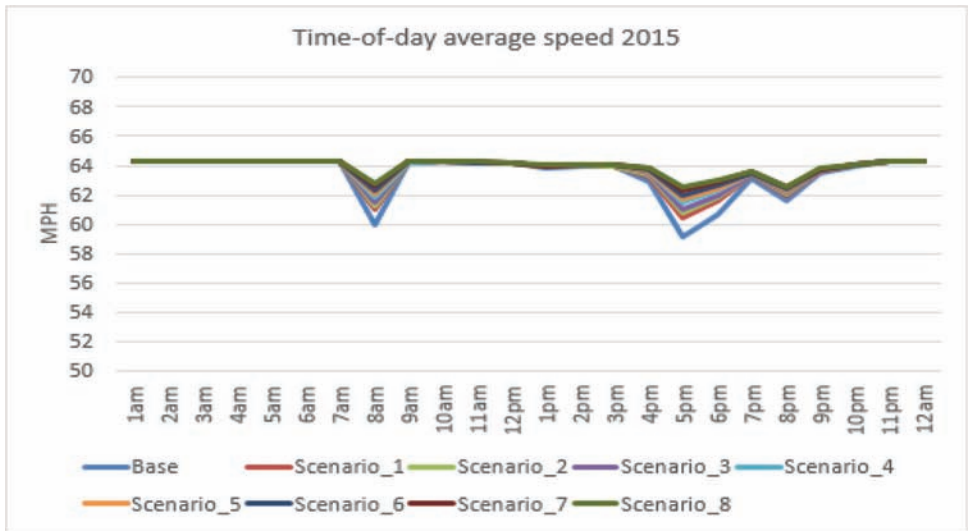
(b) One-hour block option (2015 and 2025)

Figure 5.6 Continued.



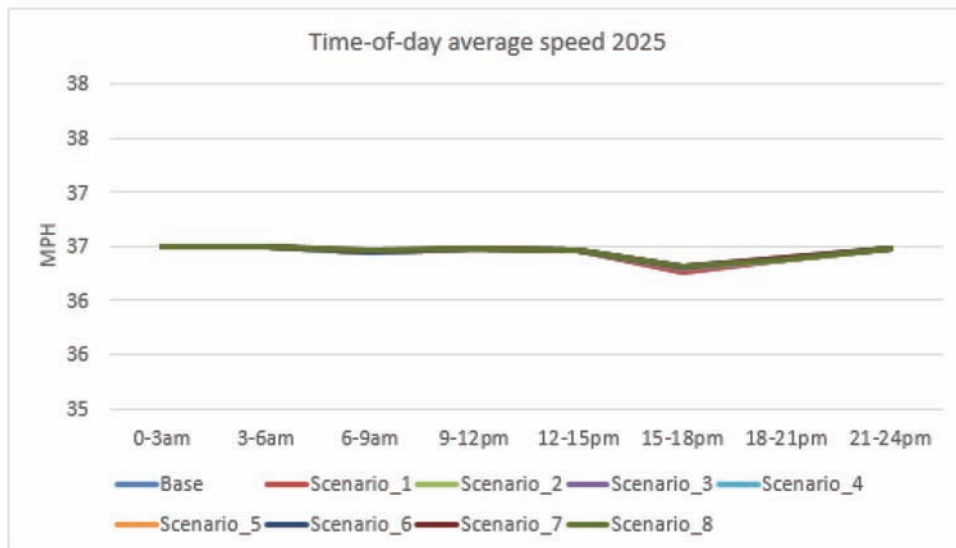
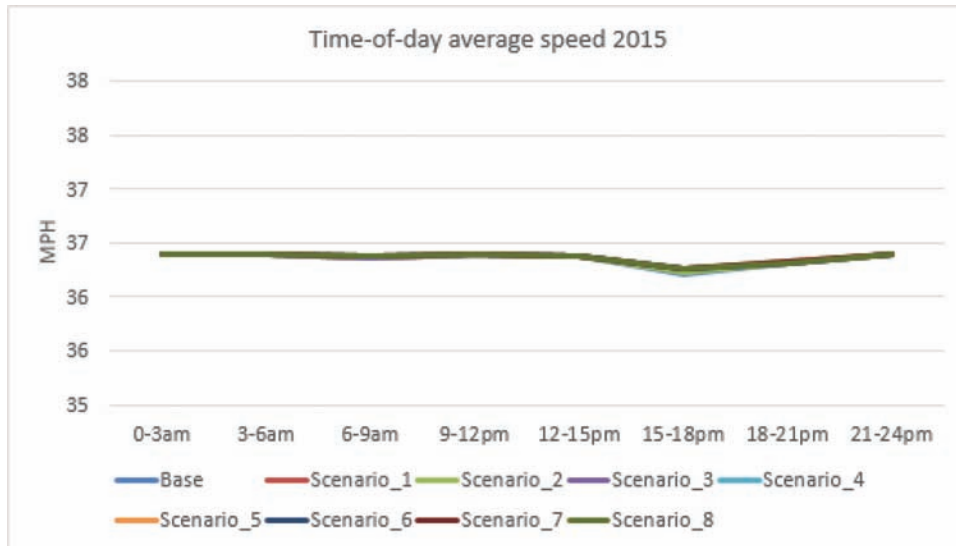
(a) Three-hour block option (2015 and 2025)

Figure 5.7 Scenario-wise average travel speeds across different times of day, I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

Figure 5.7 Continued.



(a) Three-hour block option (2015 and 2025)

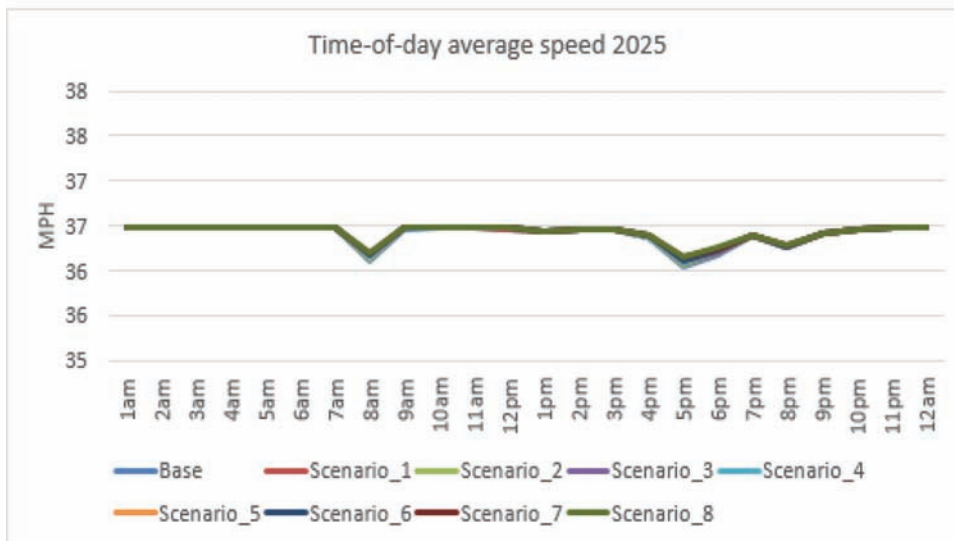
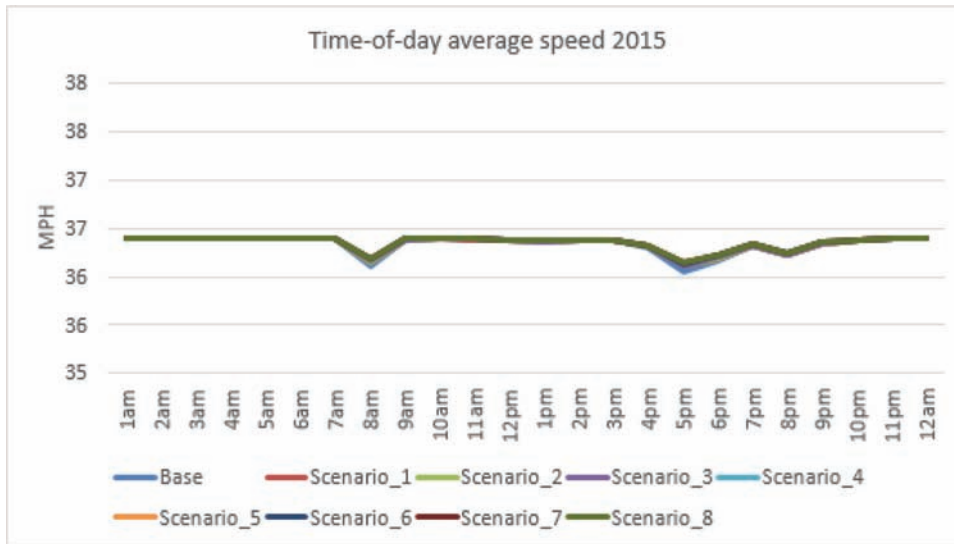
Figure 5.8 Scenario-wise average travel speeds across different times of day, nine-county region around I-465. (Figure continued on next page.)

5.3.4.2 The nine-county region around I-465. Many road sections in the nine-county region have a speed limit of 25 mph and do not experience high traffic volumes. This results in the traffic moving at free-flow speeds for a significant portion of the day. Therefore, the average speed for the nine-county region is fairly stable and close to 37 MPH across different times of the day. The speed is slightly lower during AM peak and PM peak hours. Again, the increase in speed on I-465 (which is only small fraction of the road length in the region) does not significantly affect the average speed of vehicles in the region with regard to either three-hour block option or the one-hour block option (Figure 5.8(a) and Figure 5.8(b), respectively).

5.3.5 Vehicle Hours Traveled (VHT)

5.3.5.1 I-465

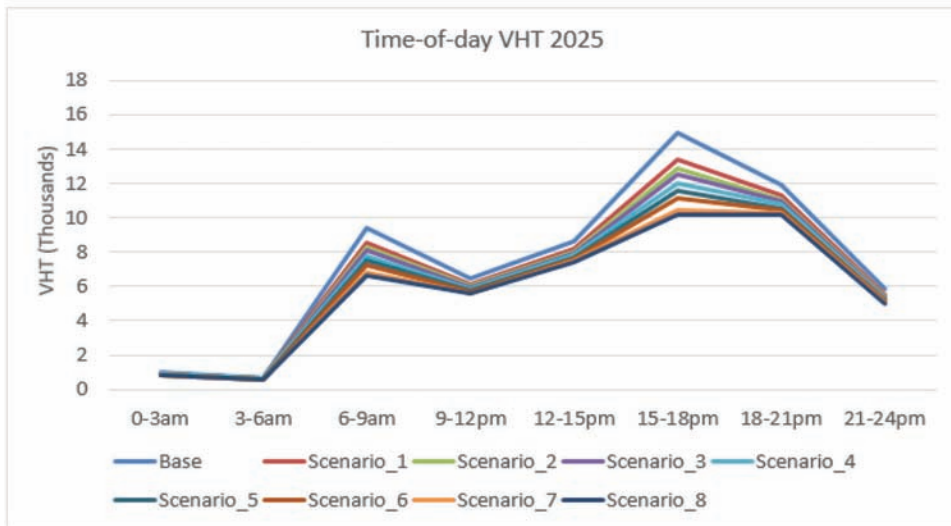
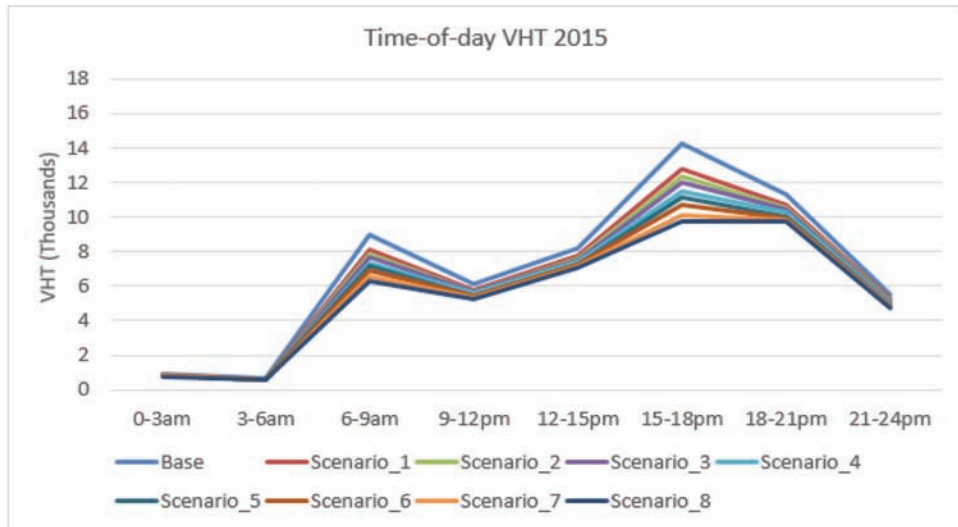
- For the three-hour block option, it can be observed that the VHT is lowest in 12 AM–6 AM block (Figure 5.9(a)).
 - It increases to reach a maximum at the AM peak in the 6 AM–9 AM block, then decreases to about 6,000 VHTs in the 9 AM–12 PM period.
 - It gradually increases in the next time block, and then sharply increases to the highest peak in the 3 PM–6 PM block.
 - It gradually reduces in the next two time blocks to about 5,000 VHT.



(b) One-hour block option (2015 and 2025)

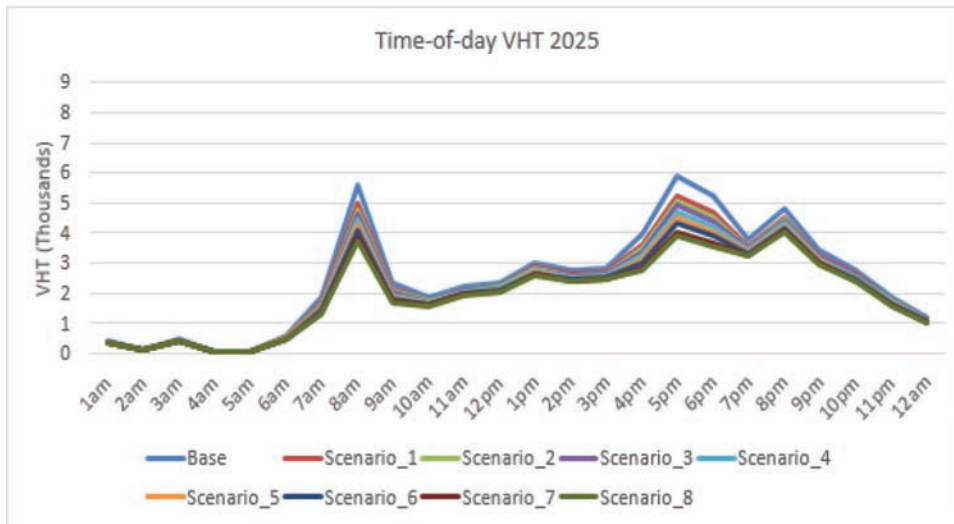
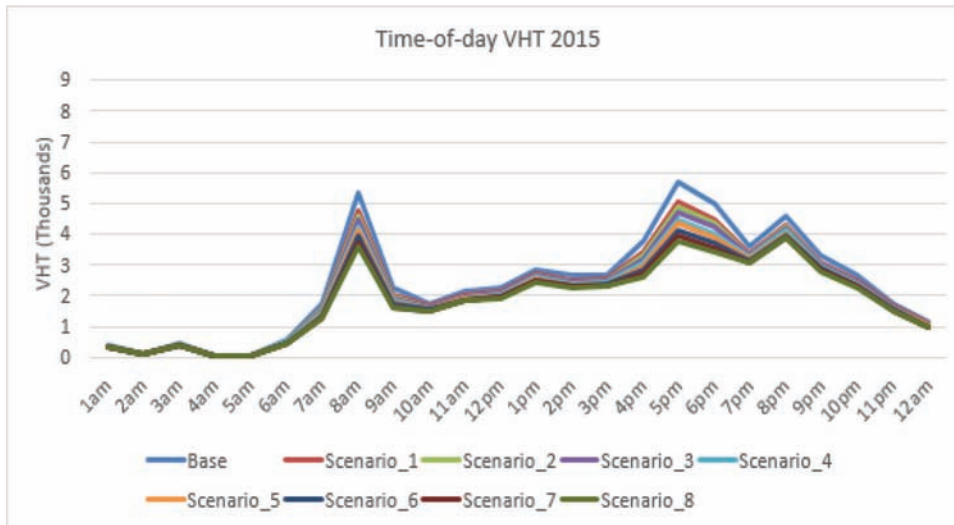
Figure 5.8 Continued.

- It can be observed that the VHT of the scenarios with lower toll are higher than that of the scenarios with higher toll. This is reasonable because the travel demand is lower, and the speeds are higher on I-465 in the higher toll scenarios compared to lower toll scenarios.
- The VHT in one-hour block option follows similar trends as in the three-hour block (Figure 5.9(b)).
- In this option, the times of day are split into granular blocks so the trends are clearer at corresponding hours.
- From midnight to 6 AM, the VHT is lowest for the day, slightly increases at 7 AM and rapidly reaches the morning peak at 8 AM.
- The VHT decreases at 9 AM and reaches the lowest VHT in daytime at 10 AM.
- The VHT gradually rises until 4 PM, and then climbs to the highest daily peak at 5 PM, which is slightly higher than that at the morning peak.
- The VHT falls in the next two hours and then reaches a lower peak at 8 PM. It then steadily decreases to reach a nadir at midnight.



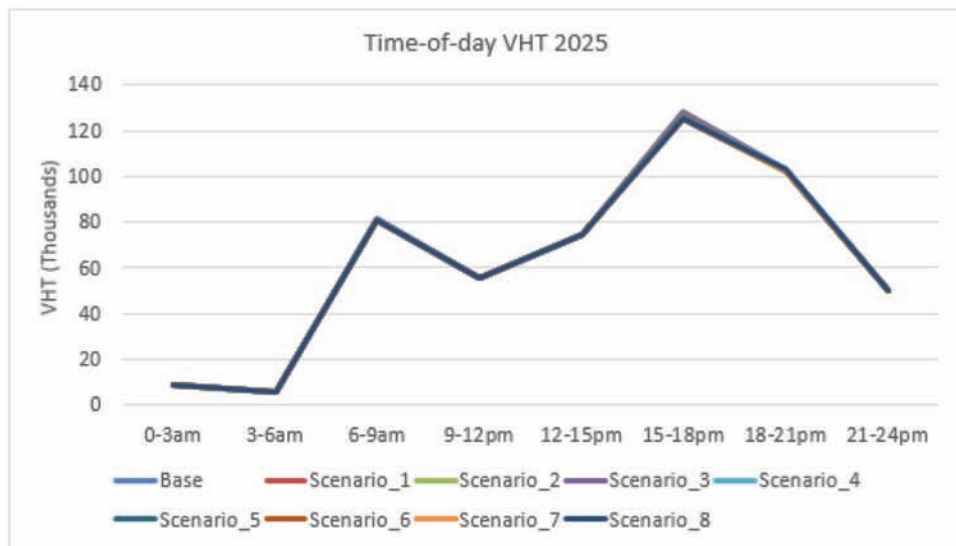
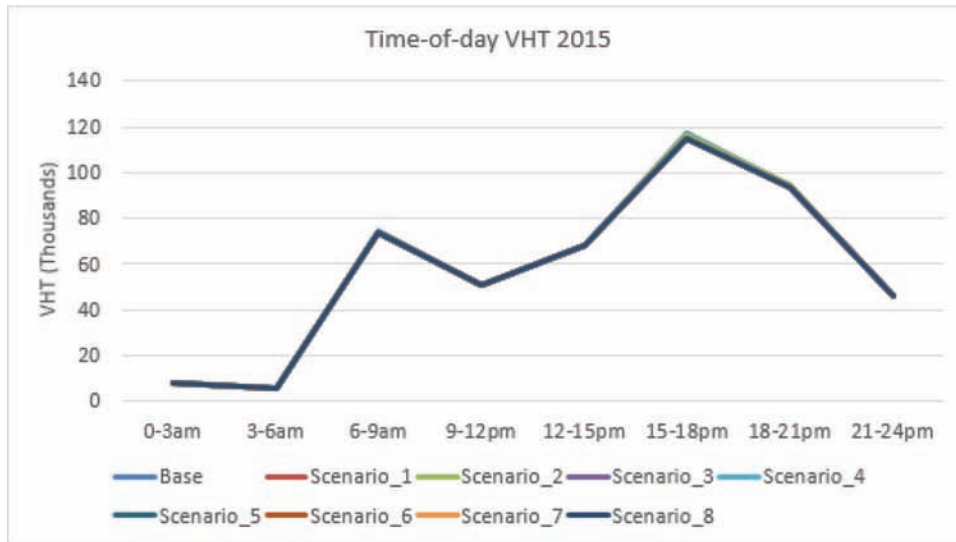
(a) Three-hour block option (2015 and 2025)

Figure 5.9 Scenario-wise VHT across different times of day, I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

Figure 5.9 Continued.



(a) Three-hour block option (2015 and 2025)

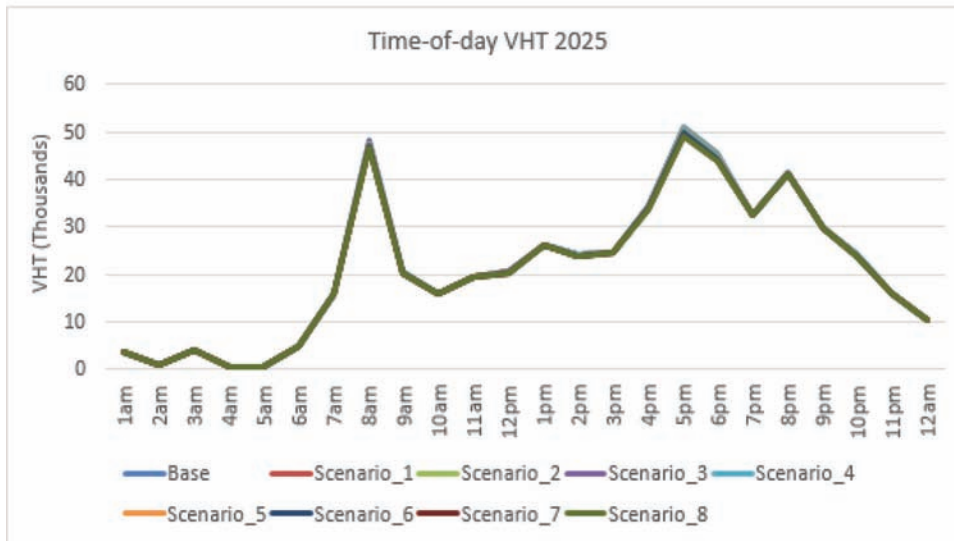
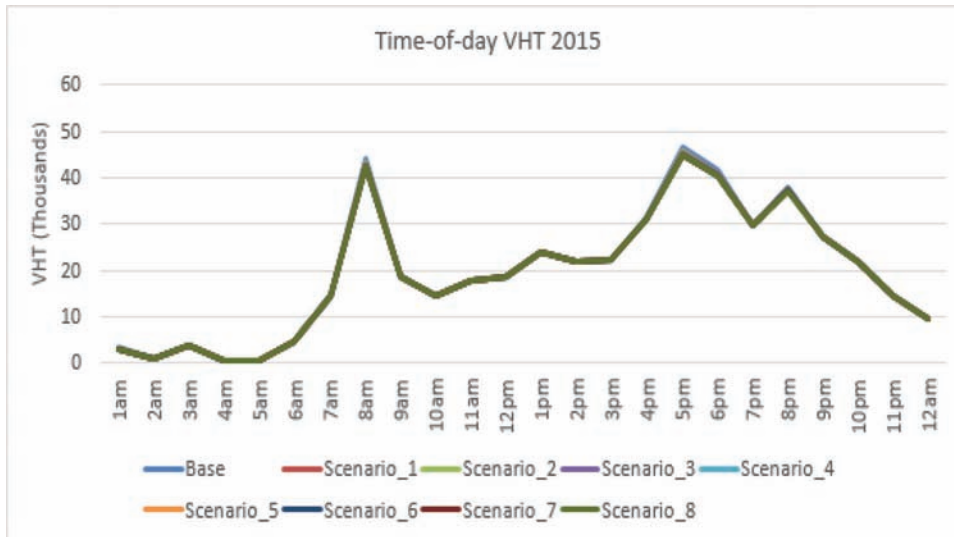
Figure 5.10 Scenario-wise VHT across different times of day, nine-county region around I-465. (Figure continued on next page.)

5.3.5.2 The nine-county region around I-465. The VHT in nine counties follows the same trends as discussed for I-465. As mentioned before, I-465 corridor comprises of 1.4% share of the total length of roads in nine-county region, therefore, toll implementation on I-465 significantly alter the VHT of nine counties. As a result, the VHT of each of the three-hour block option and the one-hour block option across scenarios are generally consistent across the eight scenarios. The total VHT increases from 2015 to 2025 (Figure 5.10(a) and Figure 5.10(b), respectively). This may be due to growth in the travel demand through those years.

5.3.6 Vehicle Miles Traveled (VMT)

5.3.6.1 I-465

- In the three-hour block option, the lowest VMT occurs during the 12 AM–6 AM block.
- The VMT increases significantly during the 6 AM–9 AM block which is likely to be due to the increase in traffic related to office trips.
- It reduces during the 9AM–12PM block but then starts increasing again in the 12 PM–6 PM block, peaks in the 3 PM–6 PM block.

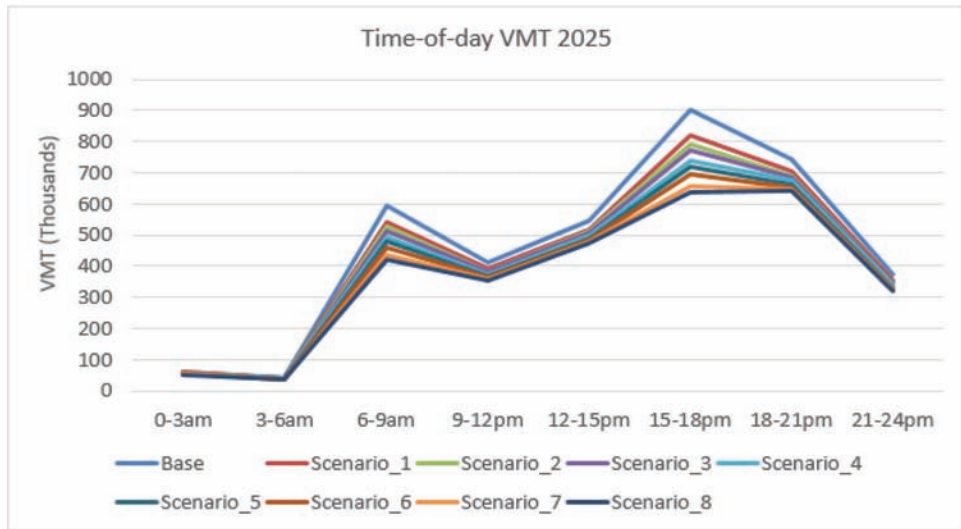
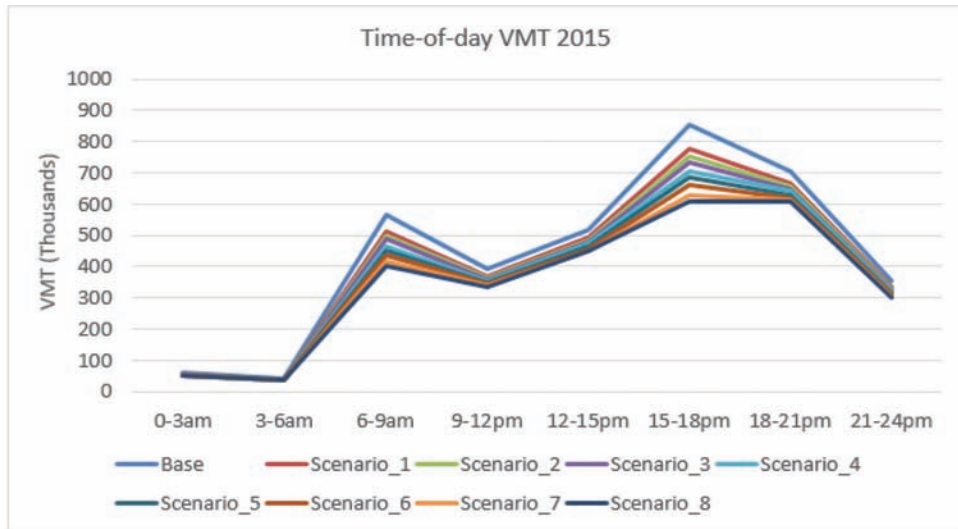


(b) One-hour block option (2015 and 2025)

Figure 5.10 Continued.

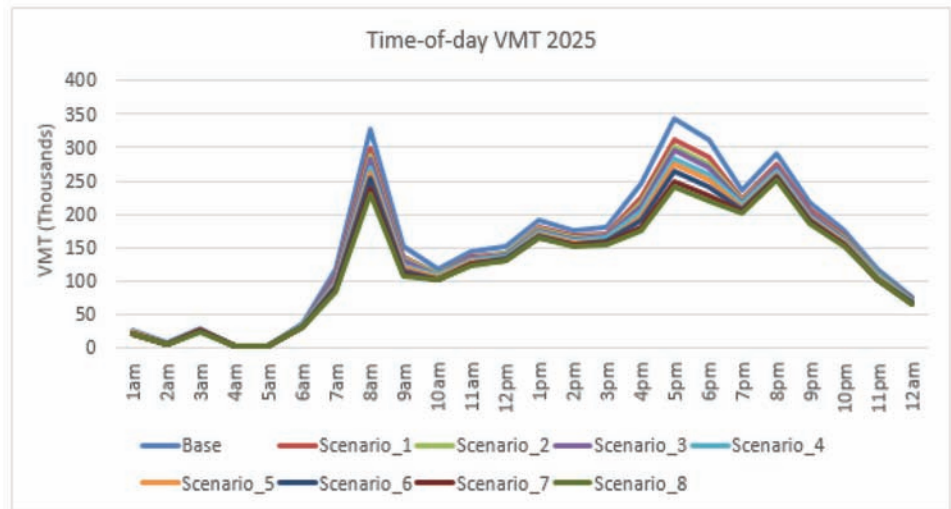
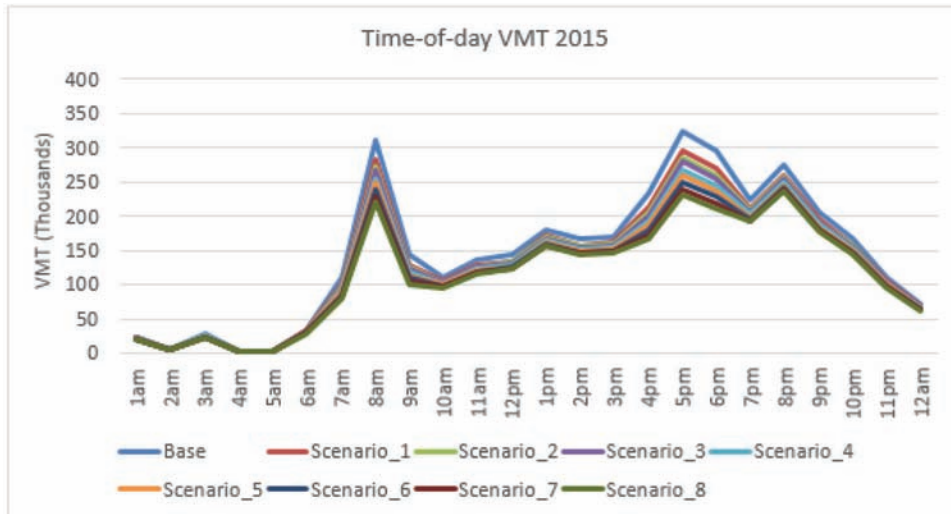
- The VMT gradually reduces during the 6 PM–12 AM block. The highest VMT is for the base case (no toll) and lowest for scenario 8 (highest toll).
- The peak VMT is the highest for the base case scenario (no toll) increasing from 852,000 vehicle-miles in 2015 to 901,000 vehicle-miles in 2025.
- The peak VHT increases only marginally for scenario 8; increasing from 14,260,660 vehicle-hours in 2015 to 14,935,000 vehicle-hours in 2025.
- With regard to the one-hour block option, VMT is lowest in the 12 AM–6 AM block, and then spikes to its morning peak at 8 AM, falls at 9 AM, and reaches its lowest daytime point at 10 AM.
 - VMT gradually increases and sharply rises to its maximum at 5 PM, falls at 7 PM, and increases to an evening peak at 8 PM.
 - The evening peak may be due to recreational activity. For example, people may go to restaurants in the downtown area after work (during the first evening peak period), then drive back home (during the second evening peak period).
 - The VMT then gradually decreases to its lowest by midnight. VMT in the base scenario is always higher than the VMT of other scenarios, whereas scenario 8 has lowest VMT.
 - VMTs at peak hours are higher in 2015 compared to 2025 (Figure 5.11).

5.3.6.2 The nine-county region around I-465. As expected, the VMT profile by time of day for nine-county region exhibits trends similar to those of I-465. The different levels of tolling on I-465 do not yield significantly different impacts on VMT at level of nine-county region. The details can be seen in Figure 5.12.



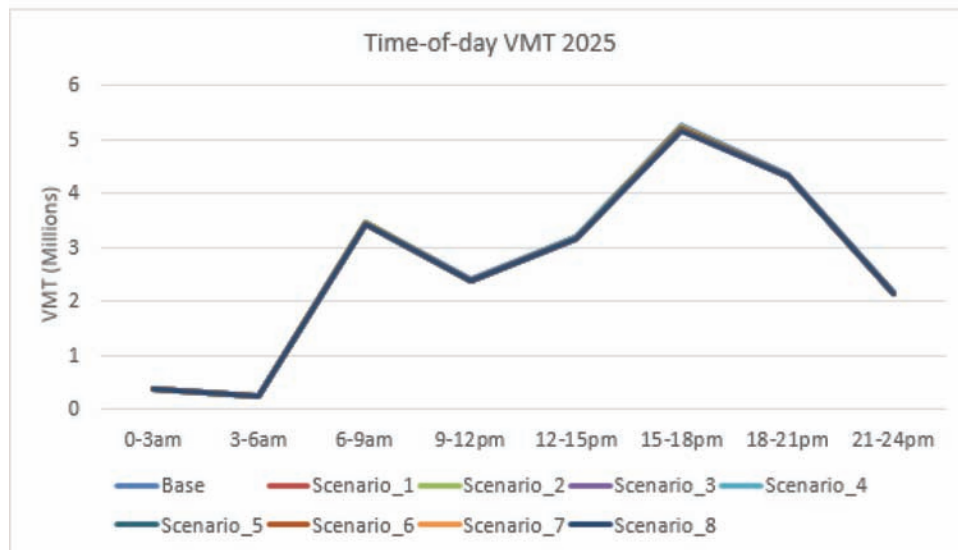
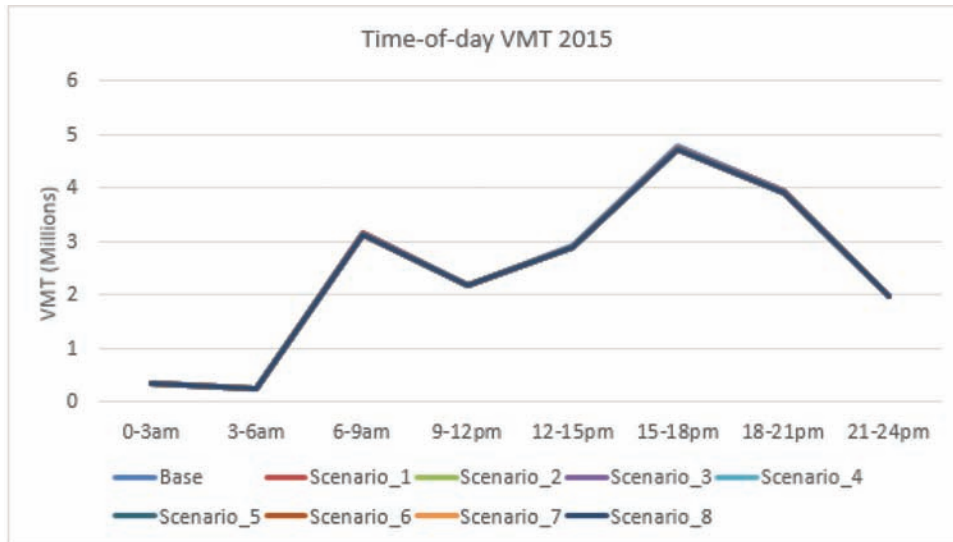
(a) Three-hour block option (2015 and 2025)

Figure 5.11 Scenario-wise VMT across different times of day, I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

Figure 5.11 Continued.



(a) Three-hour block option (2015 and 2025)

Figure 5.12 Scenario-wise VMT across different times of day, nine-county region around I-465. (Figure continued on next page.)

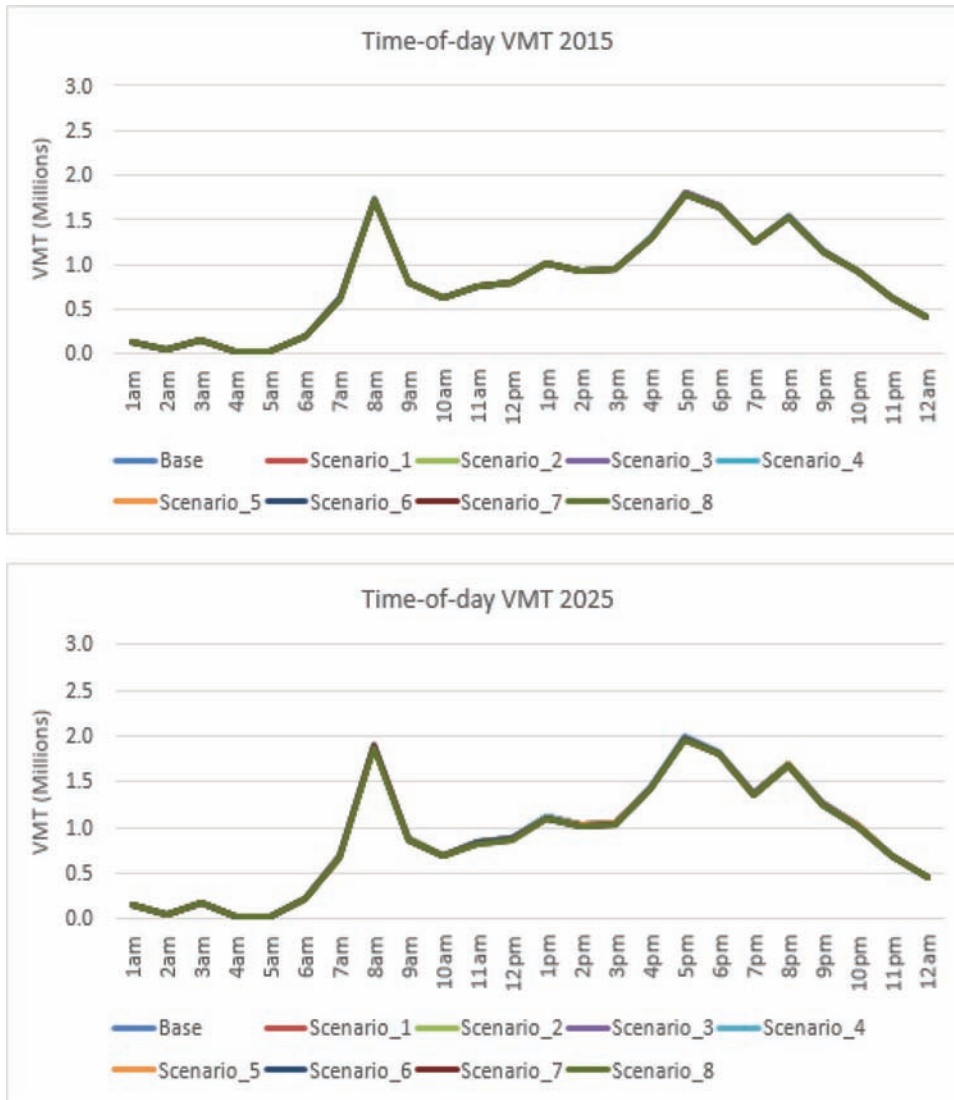
5.3.7 Summary of Post Analysis

5.3.7.1 I-465

- Figure 5.13 shows an increase in averages of all the outcomes: average travel time saving, average speed, VHT saving, and VMT saving from 2015 and 2025.
- The average of the average speed shows an increase from the base case to scenario 8, with the highest savings in the scenario 8 wherein the toll is the highest. This means by paying higher toll the travelers can travel faster. It is observed that the increase in average speed in 2015 is only slightly higher than in 2025.
- The average of the VHT and VMT saved, presented in Figure 5.13, gradually increases from the base case (no toll) to scenario 8 (highest toll). This means by paying higher toll the travelers save more time and distance. The base case (no toll) and scenario 8 (highest toll) for two

projected years have lowest and highest savings, respectively. The average VHT and VMT saved is lowest for scenario 1 and the highest for scenario 8, for each of the years considered for the analysis.

- The difference in the values of mean of average speed increasing, average of VHT saving, and average of VMT saving between the one-hour block and three-hour block is due to the difference in rounding of values done by TranCAD for different time periods. In fact, the difference in values for the two options is not significantly different when the values are compared against each other for any two scenarios. However, when the base case values of average travel time saving, mean of average speed increasing, average of VHT saving, and average of VMT saving are deducted from the corresponding values in scenarios 1 to 8, the resultant values can be quite different for the three-hour block option and one-hour block option.



(b) One-hour block option (2015 and 2025)

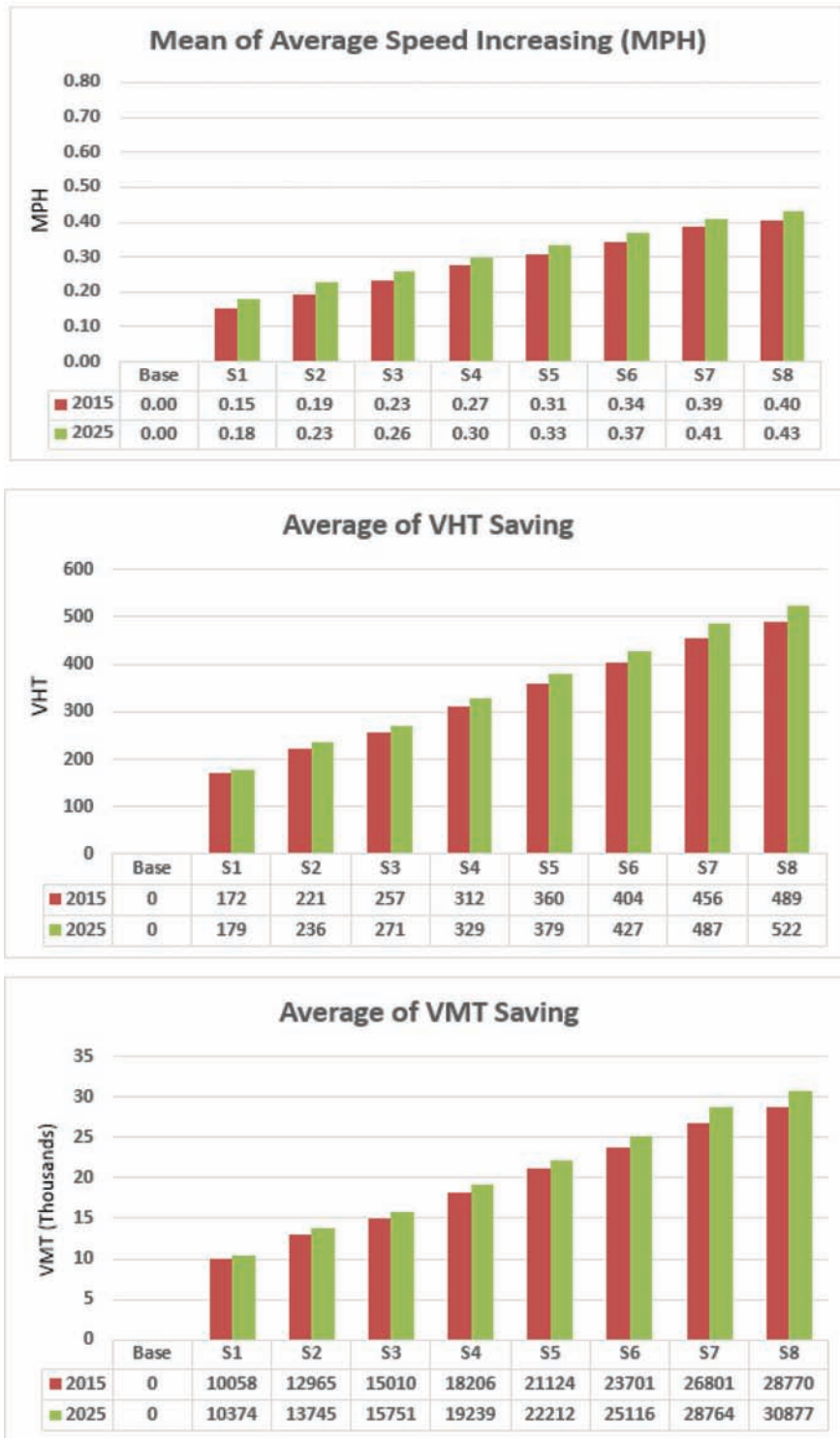
Figure 5.12 Continued.

5.3.7.2 The nine-county region around I-465. The summary results of the three-hour block option and the one-hour block option on average travel speed, VHT saving, and VMT saving are presented in Figure 5.14.

5.3.7.3 Comparison of VMT and VHT for I-465 and other roads in the nine counties. Table 5.4 shows the VMTs for I-465 and other roads in the nine counties (excluding I-465). The daily VMTs calculated for I-465 are decreasing for the higher values of tolls as expected. On the other hand, the VMTs for other roads in the nine counties (excluding I-465) grow

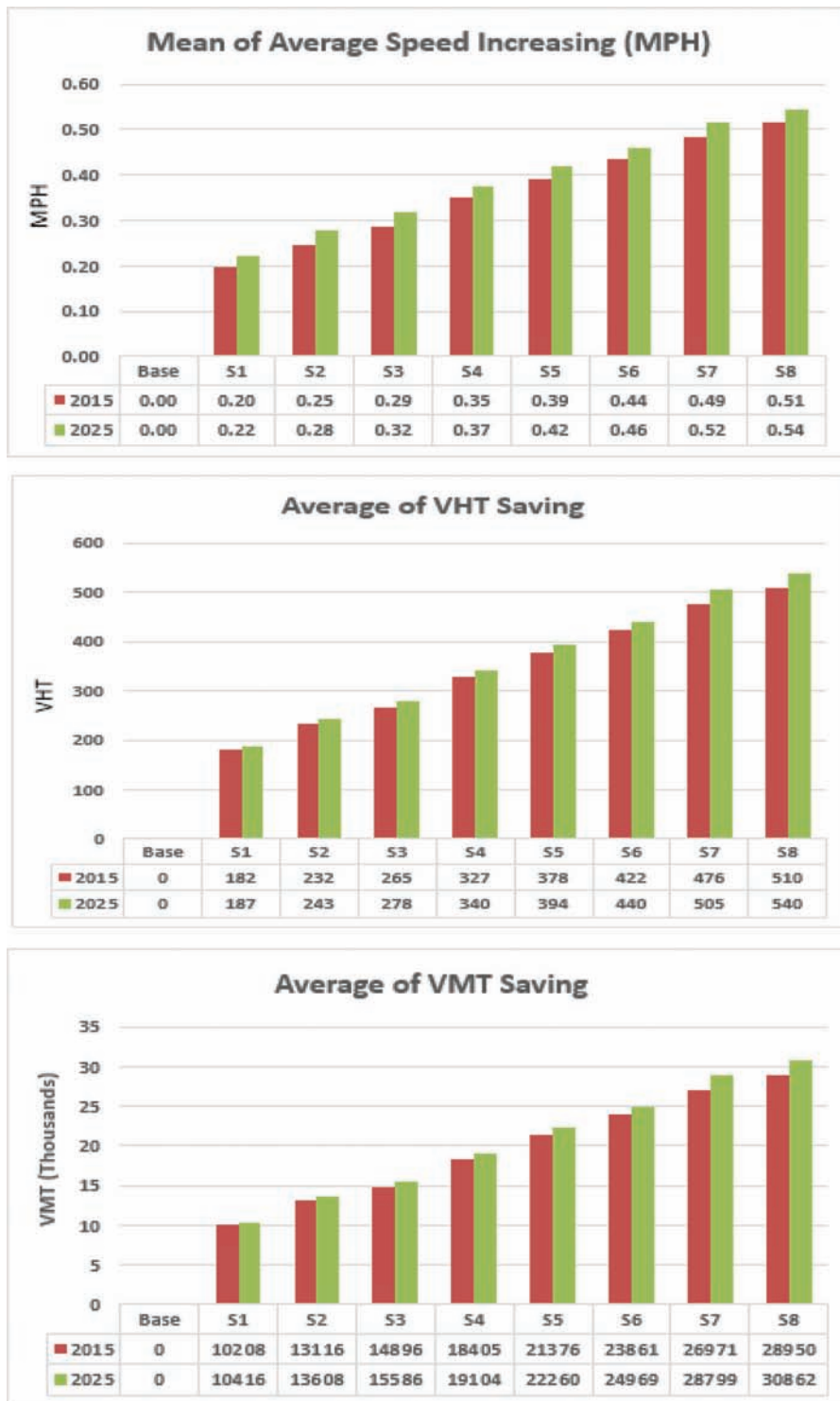
through scenarios. That is possibly because of the VMT on I-465 is shifting to the rest of the network as toll costs increase.

Moreover, the VHT for I-465 and other roads in the nine counties (excluding I-465), which has similar trends with VMT, manifests in Table 5.5. The VHT for I-465 decreases as the levels of toll increase. Travelers using I-465 save travel time by paying a toll. In contrast, those who change their route to avoid the toll experience higher VHT. As a result, the VHT for users of other roads in the nine counties (excluding I-465) grows as the toll is increased.



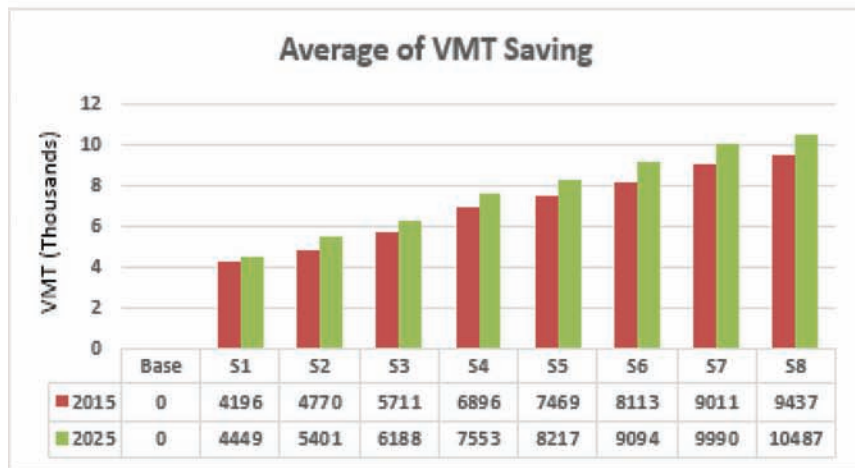
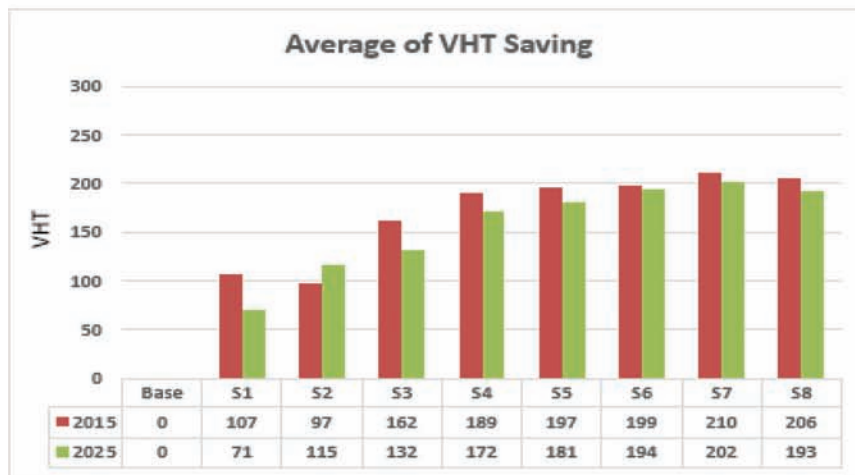
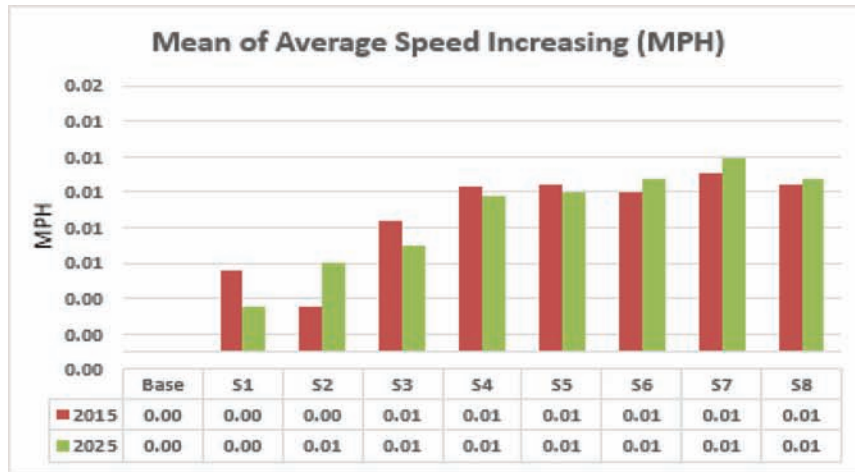
(a) Three-hour block option

Figure 5.13 Scenario-wise annual savings of speed, VHT and VMT, I-465. (Figure continued on next page.)



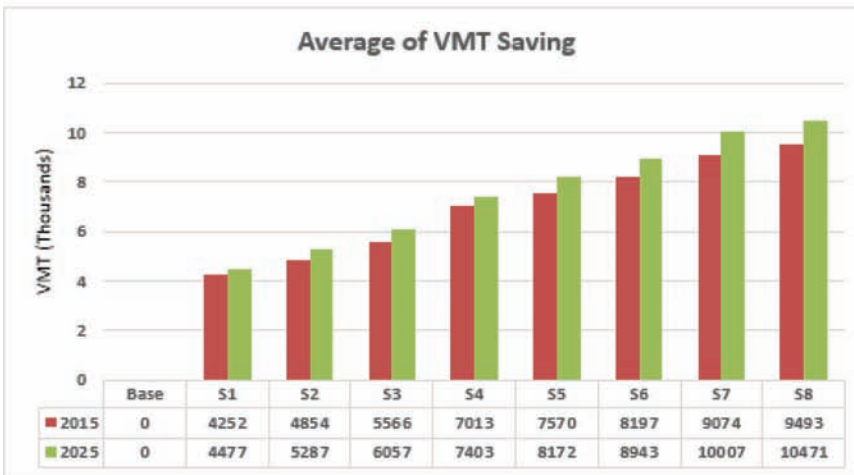
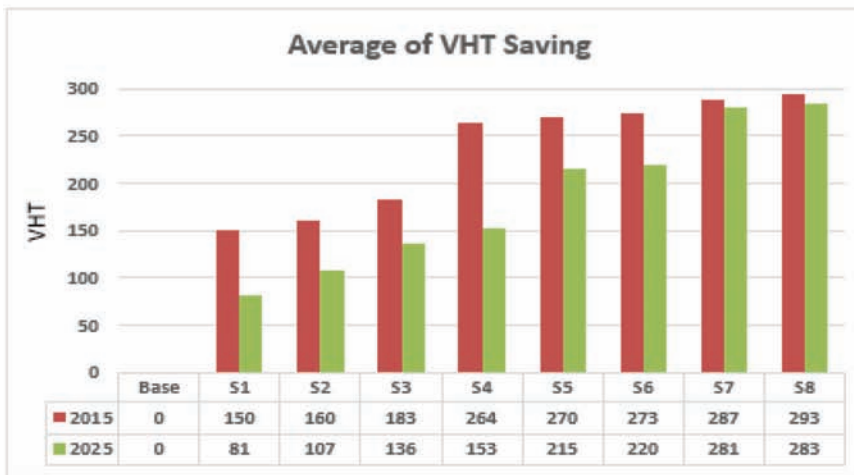
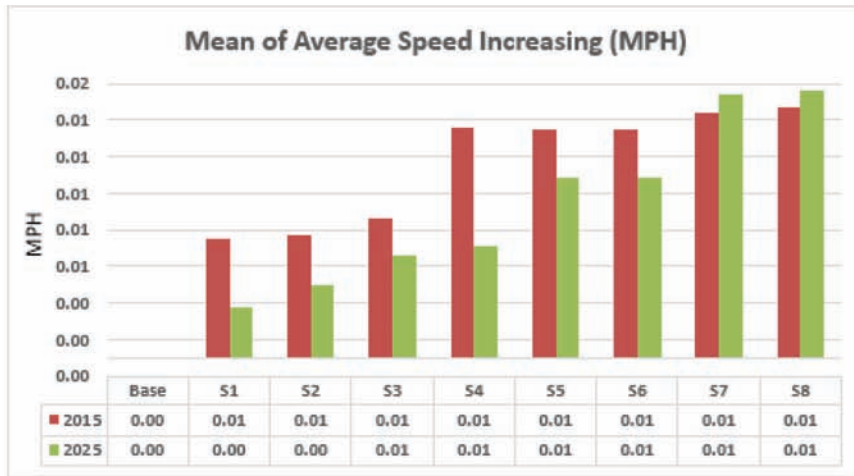
(b) One-hour block option

Figure 5.13 Continued.



(a) Three-hour block option

Figure 5.14 Scenario-wise annual savings of speed, VHT and VMT, nine-county region around I-465. (Figure continued on next page.)



(b) One-hour block option

Figure 5.14 Continued.

5.3.8 Visualization

5.3.8.1 Traffic diversion. Under different tolling scenarios, travelers behave differently with regard

to route. The TOD Tolling Analysis Pack provides a function to visualize traffic diversion under any specific tolling scenario. Figure 5.15 illustrates traffic diversion under a tolling scenario on I-465. The different colors

TABLE 5.4
VMT for I-465 and the other roads in the nine counties (excluding I-465) for the one-hour block option.

Scenario	I-465		Other roads in the nine counties (excluding I-465)	
	2015	2025	2015	2025
Base	3,417,260	3,490,712	16,122,667	17,967,461
Scenario_1	3,190,989	3,245,717	16,246,894	18,104,996
Scenario_2	3,126,657	3,175,926	16,296,767	18,155,355
Scenario_3	3,087,603	3,133,209	16,318,735	18,179,599
Scenario_4	3,021,455	3,048,995	16,350,153	18,231,517
Scenario_5	2,951,987	2,977,695	16,406,272	18,284,351
Scenario_6	2,898,270	2,918,056	16,444,937	18,325,496
Scenario_7	2,829,505	2,843,410	16,492,637	18,374,584
Scenario_8	2,783,948	2,795,924	16,528,145	18,410,941

TABLE 5.5
VHT for I-465 and other roads in the nine counties (excluding I-465) for the one-hour block option.

Scenario	I-465		Other roads in the nine counties (excluding I-465)	
	2015	2025	2015	2025
Base	57,212	56,717	412,725	457,722
Scenario_1	52,792	52,358	413,548	460,136
Scenario_2	51,553	51,139	414,537	460,730
Scenario_3	50,760	50,351	414,793	460,836
Scenario_4	49,426	48,857	414,168	461,914
Scenario_5	48,141	47,637	415,320	461,646
Scenario_6	47,133	46,588	416,253	462,583
Scenario_7	45,854	45,305	417,185	462,402
Scenario_8	45,017	44,487	417,876	463,153

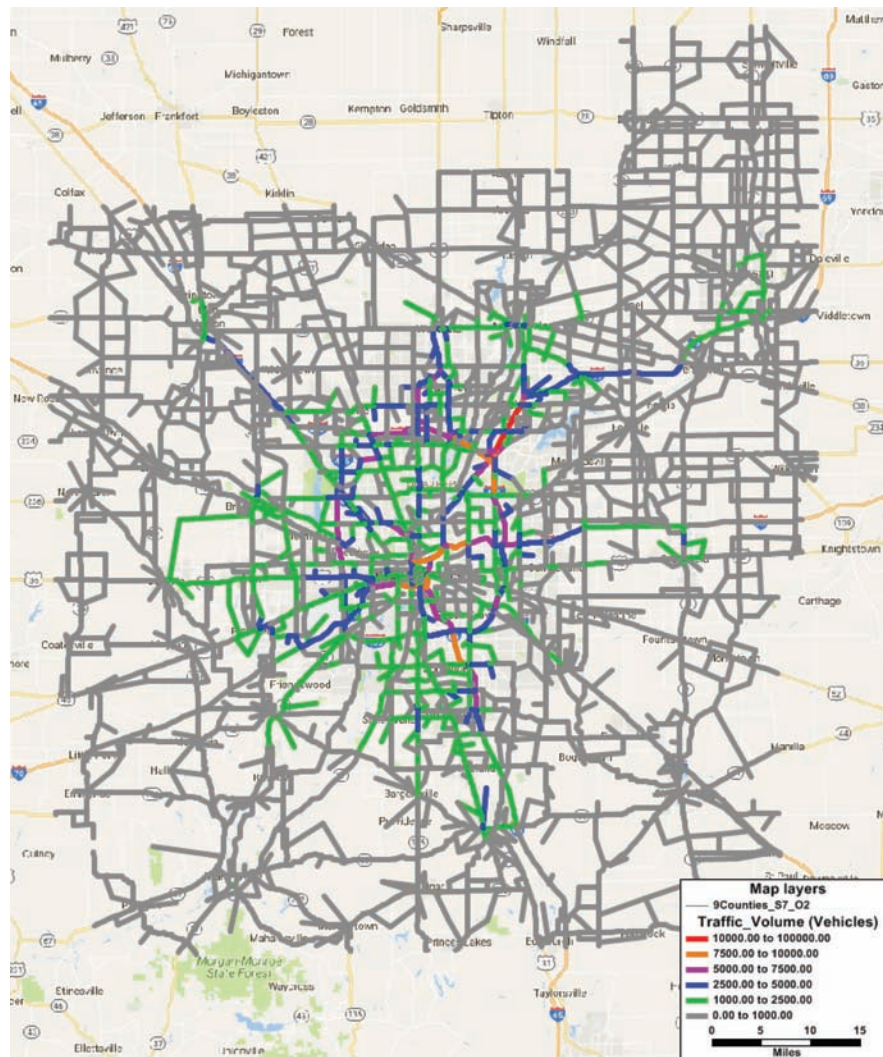


Figure 5.15 An example of traffic impacts at adjacent roads due to tolling on I-465.

of layers represent different levels of traffic flow on the network. In addition, since the TOD Tolling Analysis Pack integrates well with Google Maps, it

provides informative visualization for users. Hence, users can easily identify the impacted roads and their details.

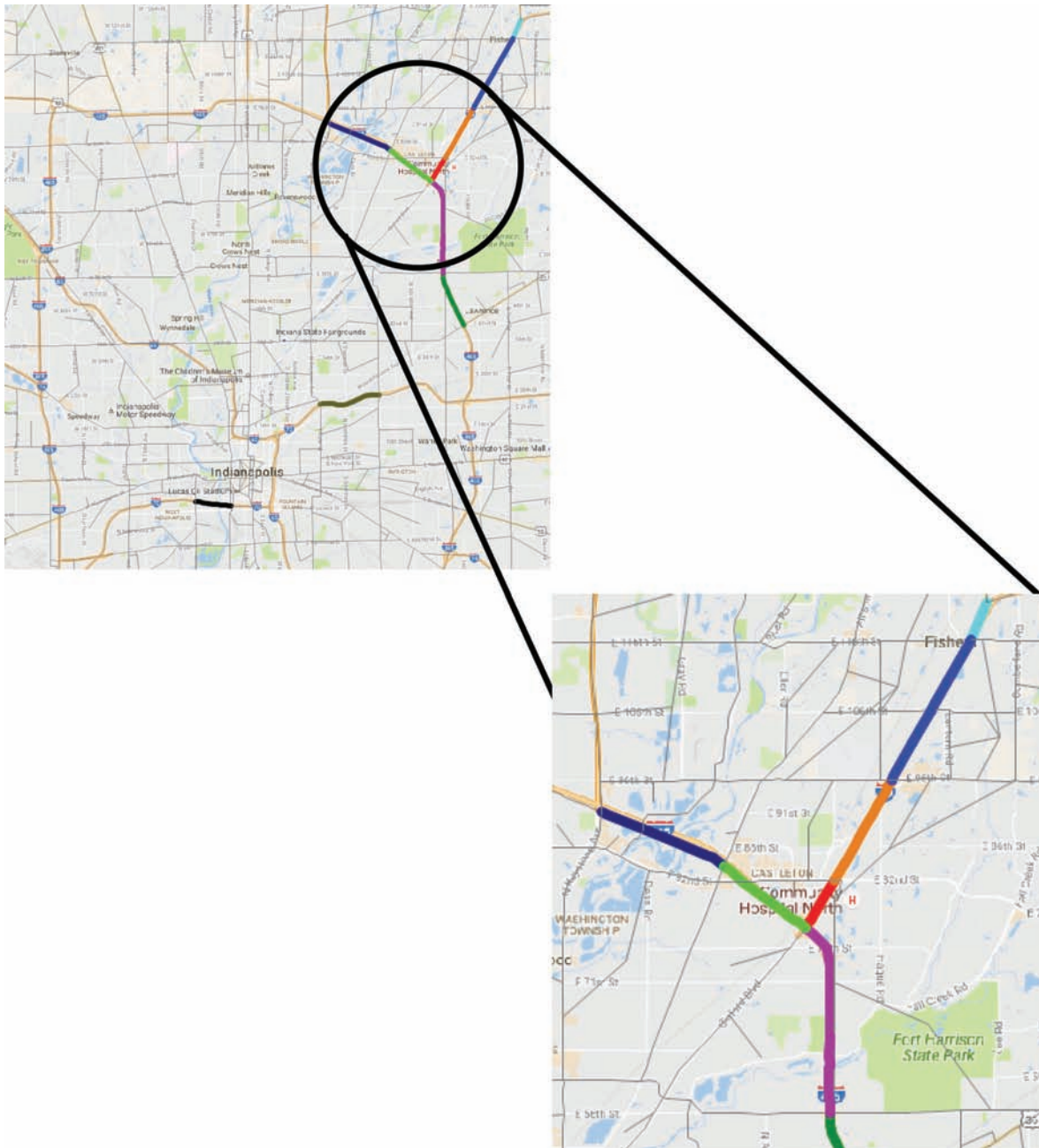


Figure 5.16 An example of the top ten most-affected roads.

5.3.8.2 Top ten most affected roads. Identification of the most impacted roads subsequent to tolling and preparation for countermeasures are vital tasks of a highway agency. Therefore, the TOD Tolling Analysis Pack also has features that facilitate quantifications of the impacts of tolling. The feature highlights the top ten most affected road segments. This function can also be integrated with Google Maps to provide additional information for the users. An example of top ten most impacted roads is presented in Figure 5.16.

The top ten most impacted roads/links (in descending order) in Figure 5.16 are: Binford Blvd (2 links), I-465, I-69, I-465 (4 links), I-69, I-70 (2 links).

5.3.9 Welfare Analysis

The consequences of congestion pricing has been studied in the literature using welfare analysis by Parry and Bento (2002), Kalmanje and Kockelman (2004) and others. We are using the welfare analysis framework to measure the effects of TOD tolling. In our framework, we use only travel time, and the travel demand is assumed inelastic. The welfare benefits accrued after tolling for the nine counties is observed to be negative across 2015 to 2025. A negative welfare indicates that the total monetary cost for a given scenario (i.e., the monetary equivalent of travel time

TABLE 5.6
Welfare for nine counties, 2015 (tolls applied all day).

County Name	Sum_Welfare S1_2015	Sum_Welfare S2_2015	Sum_Welfare S3_2015	Sum_Welfare S4_2015	Sum_Welfare S5_2015	Sum_Welfare S6_2015	Sum_Welfare S7_2015	Sum_Welfare S8_2015
Boone	4249.26	2933.63	1920.96	882.28	531.29	1242.88	1190.87	-924.78
Hamilton	34353.59	32729.41	32573.12	64627.54	63468.66	61988.82	66826.21	65046.04
Hancock	-1493.69	-1794.66	-1958.70	-2625.94	-2777.29	-3386.24	-3725.85	-4265.55
Hendricks	-901.19	-1773.54	-1430.48	-1837.85	-2954.69	-3627.90	-3380.29	-4871.35
Johnson	-1739.06	-1771.82	-2013.20	-2080.79	-2076.83	-2189.27	-2274.88	-2390.38
Madison	4.18	18.50	10.71	33.94	37.25	63.56	58.24	55.70
Marion	-87364.67	-118070.21	-144855.43	-166055.70	-195066.74	-224440.18	-249886.96	-271392.71
Morgan	-304.26	-341.50	-551.39	-632.97	-603.85	-674.04	-867.40	-1229.38
Shelby	26.92	-4.85	-11.10	-18.05	-49.96	-107.93	-119.81	-155.46
Grand total	-53168.92	-88075.04	-116315.51	-107707.54	-139492.15	-171130.30	-192179.87	-220127.87

TABLE 5.7
Welfare for nine counties, 2025 (tolls applied all day).

County Name	Sum_Welfare S1_2025	Sum_Welfare S2_2025	Sum_Welfare S3_2025	Sum_Welfare S4_2025	Sum_Welfare S5_2025	Sum_Welfare S6_2025	Sum_Welfare S7_2025	Sum_Welfare S8_2025
Boone	5737.10	4107.96	3241.68	1634.04	1240.59	2062.01	1923.32	892.91
Hamilton	8886.35	17312.53	26445.32	25545.66	62366.12	61877.58	101489.76	98779.52
Hancock	-2041.20	-2490.15	-2768.43	-3676.73	-3947.25	-4768.11	-5278.86	-5985.53
Hendricks	-1991.95	-2542.14	-3221.71	-3992.55	-4757.42	-5810.24	-9999.53	-11812.18
Johnson	-2243.51	-2490.29	-2950.56	-3815.62	-3880.33	-4191.74	-4501.32	-4723.16
Madison	10.91	29.96	27.31	59.79	68.54	101.09	97.54	103.19
Marion	-98796.88	-129982.98	-160859.12	-182090.38	-215525.22	-245727.41	-270611.74	-295320.00
Morgan	-484.13	-554.43	-702.56	-805.53	-823.29	-929.23	-1159.05	-1250.37
Shelby	-2.97	-75.56	-92.88	-114.36	-172.35	-291.61	-312.06	-381.99
Grand total	-90926.29	-116685.09	-140880.96	-167255.68	-165430.60	-197677.64	-188351.93	-219697.60

plus the toll paid) is higher than the base case monetary equivalent of the travel time. We assume \$1 of toll cost paid by user has the same weight as \$1 of user travel time reduction. The monetary equivalent of travel time equals to the value of time (VOT) multiplied by the travel time (Eq. 3.4). The consumer welfare is negative, as the monetary equivalent of travel time savings on the toll road is not enough to offset the toll that the consumers have to pay to use I-465. This pattern of negative welfare is observed across all scenarios from 2015 to 2025. From Table 5.6 and Table 5.7 we see that Marion County is most negatively impacted due to tolling and Hamilton County is positively impacted in both 2015 and 2025.

A significant portion of I-465 is located in Marion County. In addition, a high percentage of the traffic volume on I-465 is in that county. Therefore, we observe a high fraction of the overall negative welfare across the nine counties can be attributed to Marion. On the other hand, it is seen that Hamilton County benefits positively as Hamilton has a high number of trips generating from Hamilton to Marion, and has a high number of trips in the reverse direction. The Indiana commuting trips data for 2014 presented in Figure 5.17, Figure 5.18, Table 5.8, and Table 5.9 from Indiana’s

Public Data Utility (StatsIndiana, n.d.) support our beliefs.

The trips data provide the following observation:

- 38.6% of the total work trips from top five counties that enter Marion are from Hamilton, which constitutes 7.6% of the Marion County workforce.
- 90% of work trips from Hamilton County to top five counties go into the Marion County which constitutes 27% of the Hamilton County workforce.

These numbers indicate that the total trips taking place between Hamilton and Marion are significant, and the introduction of tolling on I-465 results in substantial benefits for individuals who travel between the two counties.

Figure 5.19 presents the visualization of the welfare benefits accrued in each county for tolling scenarios from 1 to 8 from 2015 to 2025. As discussed above the highest impacts due to tolling is on Marion County and Hamilton County. The Marion County sees a welfare impact which worsens as the toll rate increases and hence the county in the visualization is represented with increasingly darker shade of green color with progressively higher tolling rate. On the other hand, Hamilton County has a higher positive welfare impact as the toll

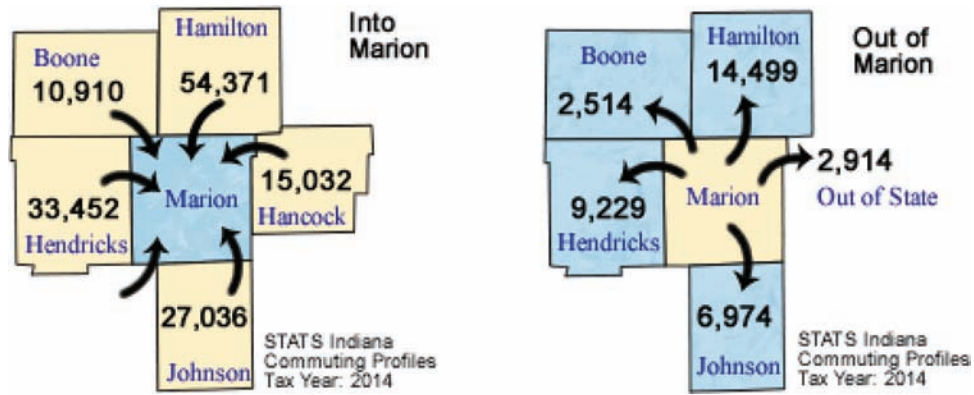


Figure 5.17 Counties with highest trips to and from Marion County.

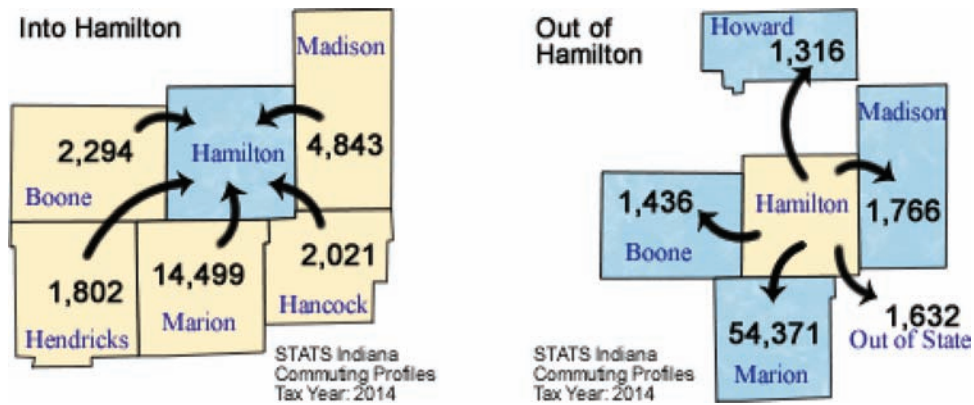


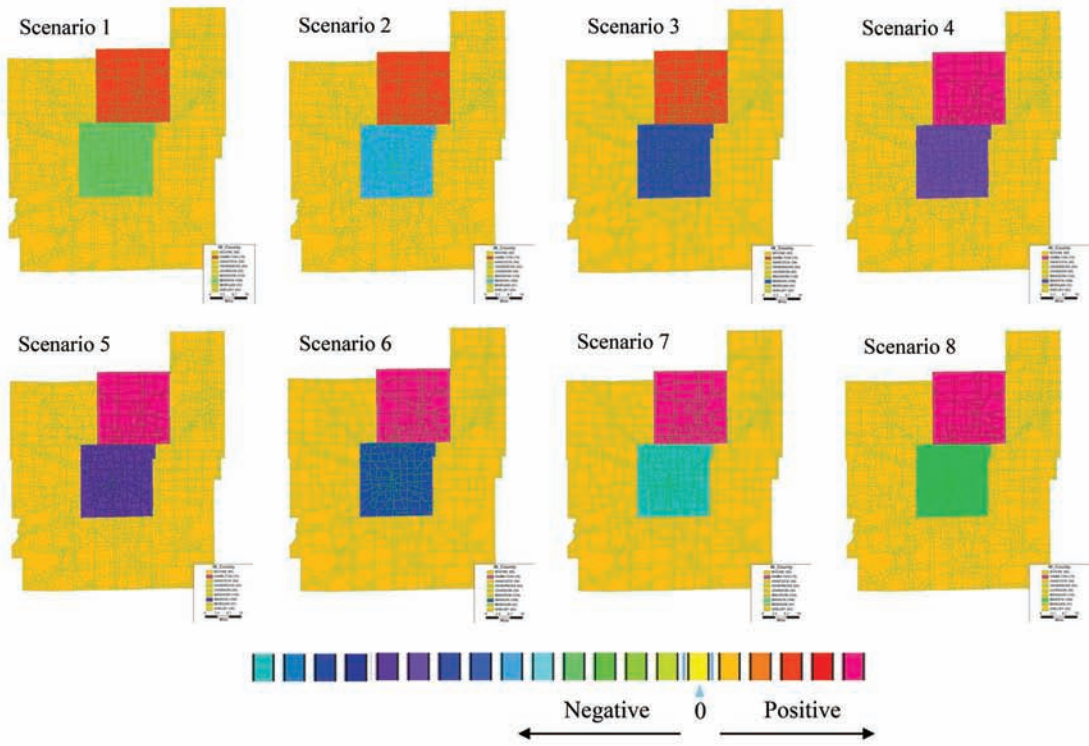
Figure 5.18 Counties with highest trips to and from Hamilton County.

TABLE 5.8
Marion County workforce and commuter data.

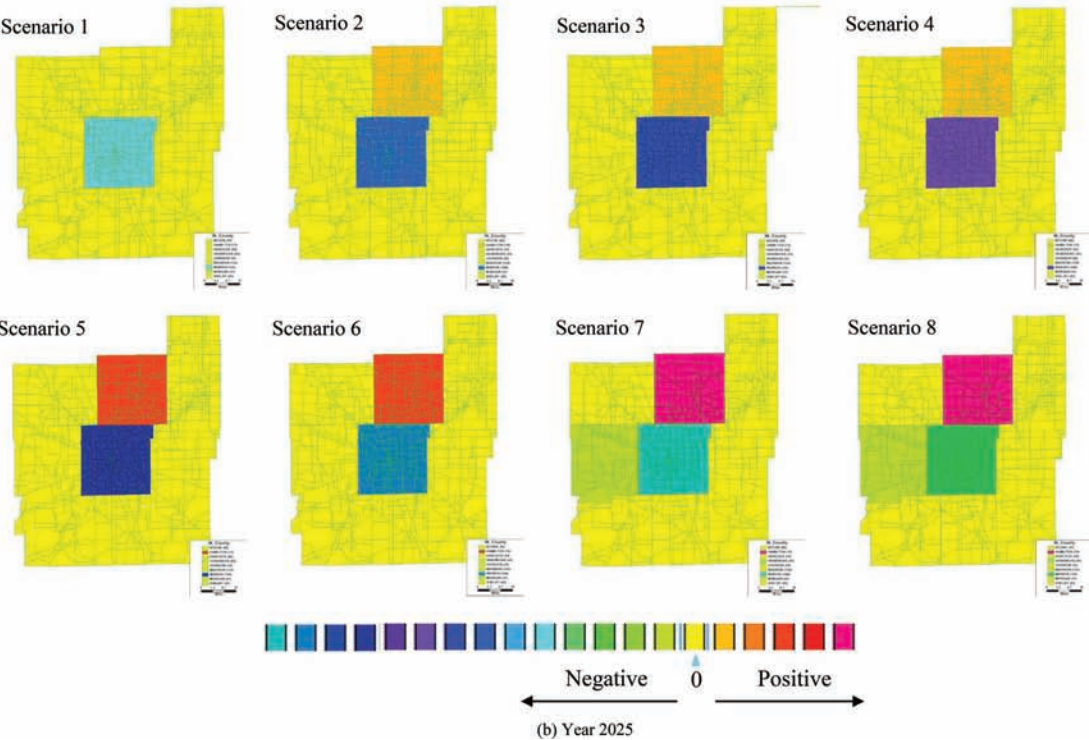
Workers	
Number of people who live in Marion County and work (implied resident labor force)	557,109
Number of people who live AND work in Marion County	509,356
Total number of people who work in Marion County (implied workforce)	694,067
Commuters	
Number of people who live in Marion County but work outside the county	47,753
Number of people who live in another county (or state) but work in Marion County	184,711

TABLE 5.9
Hamilton County workforce and commuter data.

Workers	
Number of people who live in Hamilton County and work (implied resident labor force)	203,501
Number of people who live AND work in Hamilton County	136,646
Total number of people who work in Hamilton County (implied workforce)	168,833
Commuters	
Number of people who live in Hamilton County but work outside the county	66,855
Number of people who live in another county (or state) but work in Hamilton County	32,187



(a) Year 2015



(b) Year 2025

Figure 5.19 Welfare outcomes visualization (2015 and 2025).

rate increases and hence the county is represented with increasingly lighter shade of green color with progressively lower tolling rate.

5.4 Chapter Summary

This chapter presents the results of the impacts analysis of time-of-day tolling on (1) I-465 and (2) nine-county region in Indianapolis area. Additional analysis for two subareas encompassing I-465 are presented in the appendix.

The results reveal an increasing trend in revenue from 2015 to 2025, and across the different scenarios.

Revenue

- The revenue reaches peaks at 8 AM and during the 4 PM–6 PM block.
- Relatively low revenues are collected from midnight to 6 AM.
- The highest revenues are from implementing the most expensive toll option in scenario 8.

VMT

- VMT also varies during times of day.
- It is lowest for the 12 AM–6 AM block while highest at 8 AM and for the 4 PM–6 PM block.
- VMTs generally increase at peak times in either of the two years. Moreover, the average travel times have patterns similar to those of the VMTs.

Average speed

- Average speeds have trends inverse to those of average travel time.
- Speeds are lower during peak hours but they are stable at other times.
- For higher toll rates, faster travel speeds are observed. Therefore, it can be inferred that toll prices may assure higher speeds and improve the travel time reliability.

VHT

- As expected VHTs fall as the toll are increased. The highest sensitivity of VHT to toll rates is during the peak hours.

Welfare

- It is seen that the impact of tolling on I-465 does not result in drivers being better off as compared to the no toll case scenario. This is mainly because the highway capacity for the years analyzed is able to accommodate the traffic volumes for most periods of the day.
- As a result, the savings in monetary equivalent of travel times is not enough to cover for the toll that is levied on the road. Therefore, it does not generate enough benefit for people who use the toll road.

6. SUMMARY, DISCUSSION AND CONCLUSIONS

6.1 Summary and Discussion

This project uses ISTDM model to capture the relationships between time-of-day tolls and route choices based on empirical data. Subsequently, the impacts of time-of-day tolls can be computed for various state roadways based on anticipated changes in the route choices. This study used I-465 as the hypothetical toll road and investigates the impacts of toll rates on nine-county region in the Indianapolis area.

The contributions of this study are:

- The successful establishment of a model to capture the relationship between the time-of-day toll and route choice.
- The successful development of a TOD analysis software that is convenient for quickly evaluating the impacts of various time-of-day tolling scenarios.
- An easy visualization of traffic flows on roadways through various tolling scenarios (also, the TOD Tolling Analysis Pack can display the top ten most impacted roads under the tolling implementation).
- The graphical illustration of the revenue, monetary savings, travel times, speeds, VHT, VMT, and welfare from the results.

The TOD Tolling Analysis Pack can be used to:

- Compute the impacts of fixed toll rate scenarios by setting fixed values for all times of day.
- The outputs from the TOD Tolling Analysis Pack can be helpful for policymakers and transportation officers to decide which scenario to implement and which roads to give management priority, i.e., capacity expansions.

Some key observations on the welfare analysis calculations are:

- We observe that the volume on I-465 does not exceed its capacity during most hours of the day. Therefore, applying tolls for the whole duration of the day, result in negative welfare as the commuters do not enjoy enough time-savings from the tolls during off-peak hours.
- To increase the welfare for drivers, a possible solution is to implement the toll on I-465 only at certain peak hours when the forecast demand exceeds the capacity, i.e., 7 AM–8 AM block, and 4 PM–6 PM block.
- The results of the analysis confirm to our hypothesis as the welfare benefits are significantly higher for all counties in this case as can be seen from Table 6.1 and Table 6.2.
- Marion County has a much lower welfare loss compared to the earlier case where toll was applied for the entire day. Hamilton County continues to enjoy significantly high positive welfare in the new tolling scenarios.
- In Table 5.6 and Table 5.7 we show the welfare values for the counties when the tolls have been applied for the whole day, and Table 6.1 and Table 6.2 indicate the welfare values for the counties when the tolls are applied only during selected time periods 7 AM–8 AM and 4 PM–6 PM. The welfare in the latter case is seen to increase because the tolls have been removed from the time periods where they have not been found effectual in reducing travel time for the commuters.

TABLE 6.1

Welfare for nine counties, 2015 (tolls applied only during selected time periods 7 AM–8 AM and 4 PM–6 PM).

County Name	Sum_Welfare S1_2015	Sum_Welfare S2_2015	Sum_Welfare S3_2015	Sum_Welfare S4_2015	Sum_Welfare S5_2015	Sum_Welfare S6_2015	Sum_Welfare S7_2015	Sum_Welfare S8_2015
Boone	1126.62	723.52	275.17	-90.80	79.41	744.15	865.50	-21.43
Hamilton	31162.46	30722.22	32286.68	49640.39	49430.55	48991.31	52590.58	52247.40
Hancock	-583.25	-651.95	-718.35	-879.39	-934.50	-1279.24	-1459.19	-1758.11
Hendricks	-373.88	-688.40	-244.74	-469.21	-849.53	-1077.74	-1114.15	-1869.83
Johnson	-485.89	-490.21	-591.74	-633.35	-621.14	-694.57	-732.84	-692.29
Madison	5.80	12.53	6.53	14.34	15.36	24.20	25.09	27.93
Marion	-21136.69	-31511.90	-40195.20	-40373.34	-51584.19	-61212.20	-67982.53	-73059.55
Morgan	-100.77	-111.46	-239.64	-269.80	-252.43	-281.14	-397.25	-459.11
Shelby	3.13	-11.39	-12.09	-16.09	-27.95	-53.91	-60.31	-83.97
Grand total	9617.52	-2007.03	-9433.38	6922.75	-4744.42	-14839.14	-18265.11	-25668.95

TABLE 6.2

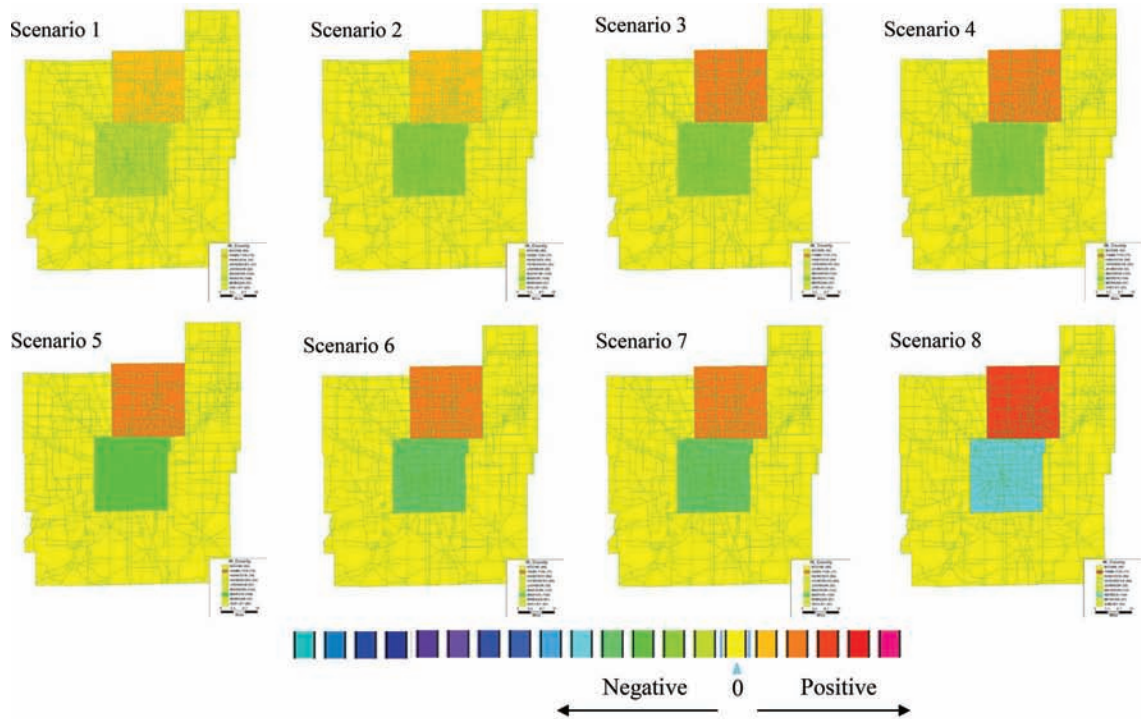
Welfare for nine counties, 2025, (tolls applied only during selected time periods 7 AM–8 AM and 4 PM–6 PM).

County Name	Sum_Welfare S1_2025	Sum_Welfare S2_2025	Sum_Welfare S3_2025	Sum_Welfare S4_2025	Sum_Welfare S5_2025	Sum_Welfare S6_2025	Sum_Welfare S7_2025	Sum_Welfare S8_2025
Boone	1712.40	1238.93	859.80	205.73	397.81	1179.84	1312.47	970.61
Hamilton	8663.64	16433.09	26427.37	27196.60	57776.52	58205.95	89631.25	88819.50
Hancock	-807.58	-918.23	-1023.44	-1248.87	-1341.37	-1806.51	-2058.62	-2448.79
Hendricks	-690.55	-847.60	-797.19	-1081.42	-1443.55	-1752.49	-3400.92	-4044.32
Johnson	-873.96	-900.00	-1008.33	-1270.12	-1301.69	-1484.14	-1639.62	-1683.52
Madison	9.73	17.93	13.83	25.84	28.31	41.34	42.21	48.92
Marion	-29811.11	-40556.43	-50756.13	-55045.92	-68363.15	-78729.07	-85715.76	-92652.52
Morgan	-172.74	-195.17	-243.31	-279.35	-285.53	-328.66	-427.73	-470.05
Shelby	-11.30	-44.68	-45.96	-58.19	-75.93	-125.86	-136.55	-183.18
Grand total	-21981.46	-25772.15	-26573.36	-31555.70	-14608.57	-24799.61	-2393.28	-11643.33

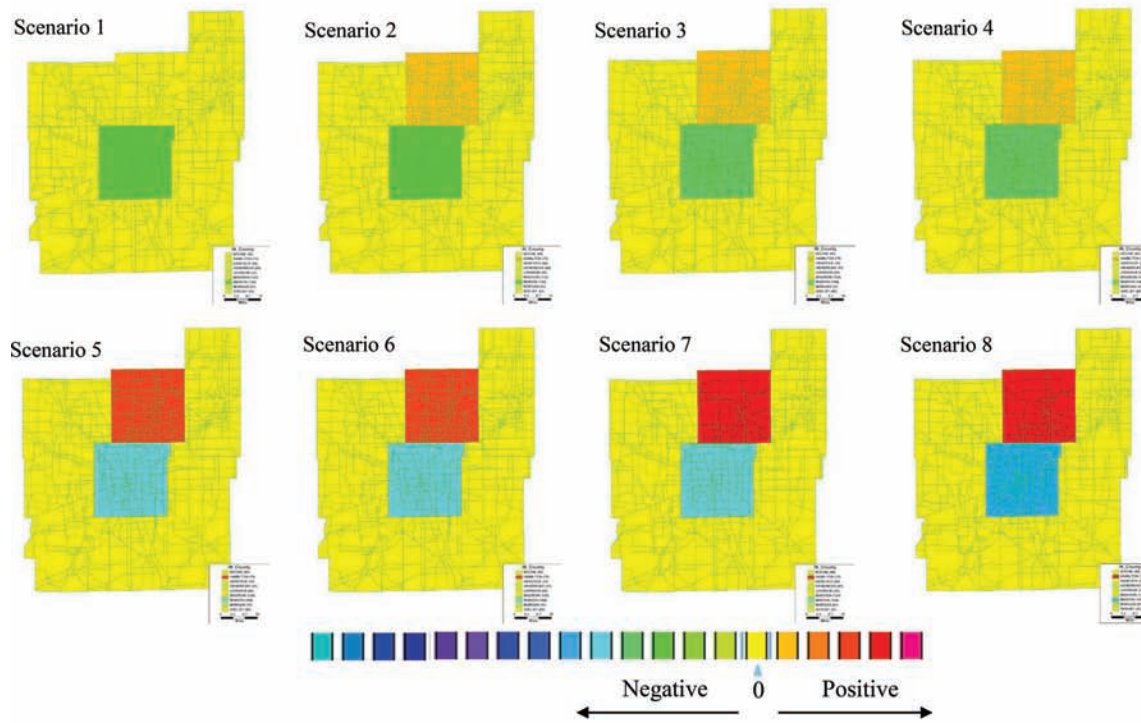
- In order to keep a balance between revenue maximization and consumer welfare maximization, INDOT can design a time-of-day toll, which would address the needs of the agency in terms of generating revenue while preserving drivers' welfare.

Some key findings of welfare visualization are:

- Figure 6.1 presents visualization of the welfare benefits accrued in each county for tolling rates used in tolling scenarios from 1 to 8 from 2015 to 2025 but applicable only for the peak hours.
- The visualization of in these scenario results highlight the two counties that are most impacted due to tolling, i.e., Marion and Hamilton.
- The Marion County has a higher negative welfare impact as the toll rate increases (increasingly darker shade of green color) with progressively higher tolling rate.
- Hamilton County has a higher positive welfare impact as the toll rate increases and hence the county is represented with increasingly lighter shade of green color with progressively higher tolling rate.



(a) Year 2015



(b) Year 2025

Figure 6.1 Welfare outcomes visualization (2015 and 2025), only for peak hours.

6.2 Concluding Remarks

The TOD Tolling Analysis Pack can be used to analyze the impacts of time-of-day tolling on any highway. An advantage is that the TOD Tolling Analysis Pack can be easily compiled with TransCAD software, which is commonly used in transportation agencies. Along with the TOD Tolling Analysis Pack, the User's Manual and the Post Analysis tools are also provided.

The TOD Tolling Analysis Pack can help reduce drastically the time and effort in analyzing the impacts of any time-of-day tolling project. It also provides a convenient and flexible tool for testing the impacts of various tolling scenarios for any highway. The visualization features can illustrate the diversion of traffic due to tolling implementation, and can display the top ten most impacted roads. Moreover, the TOD Tolling Analysis Pack can be integrated with Google Maps, which provides additional information for users.

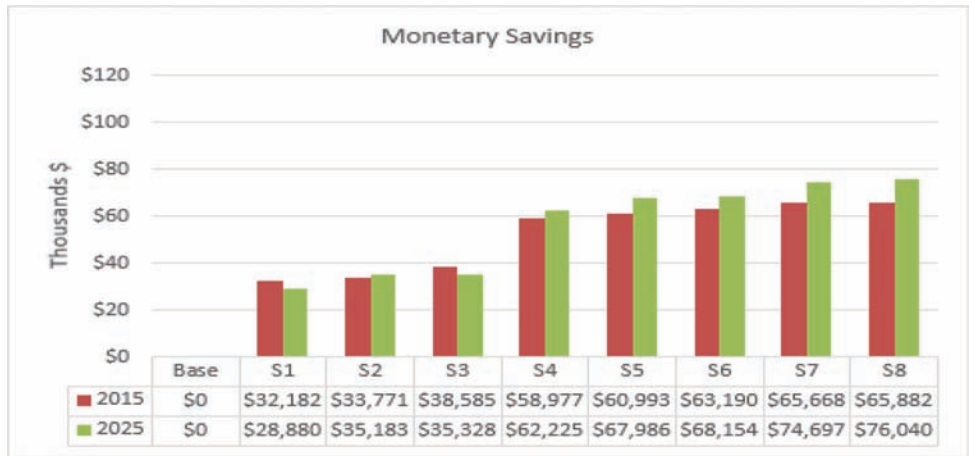
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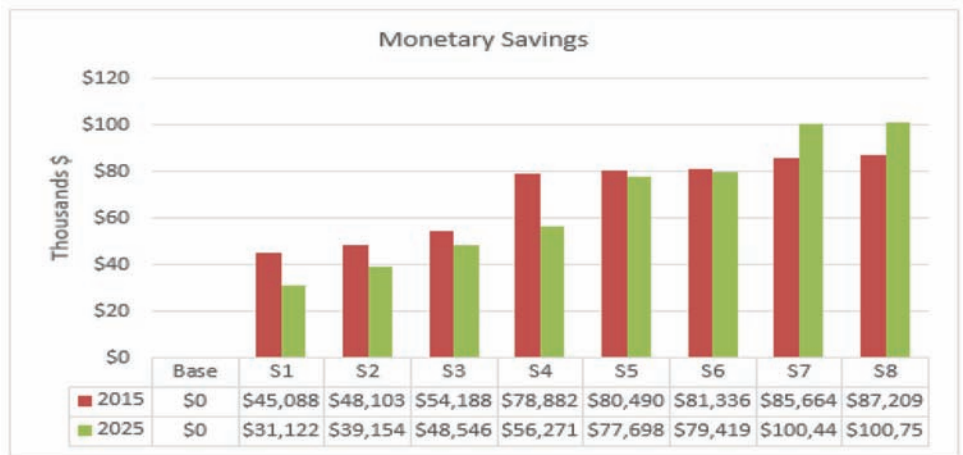
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APPENDIX

A.1 Monetary Savings

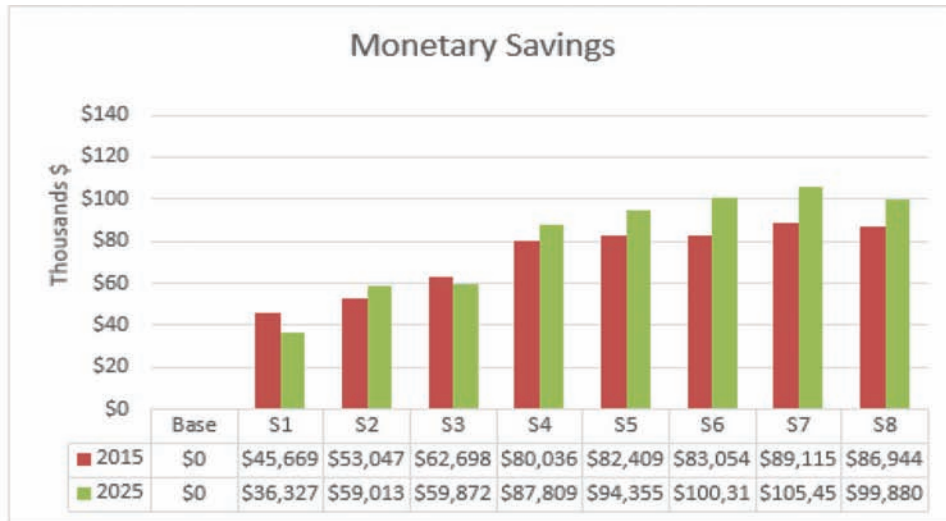


(a) Three-hour block option

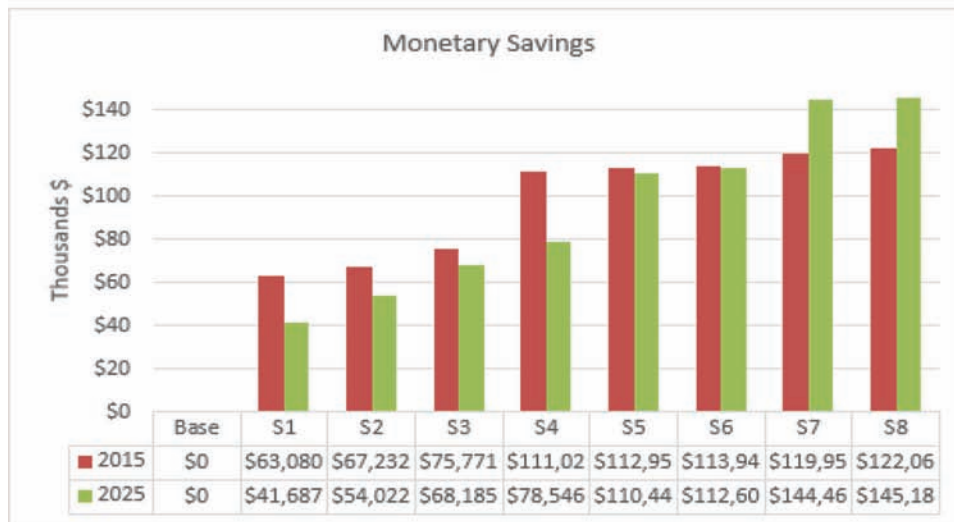


(b) One-hour block option

Figure A.1 Monetary savings for sub-region 1 around I-465.



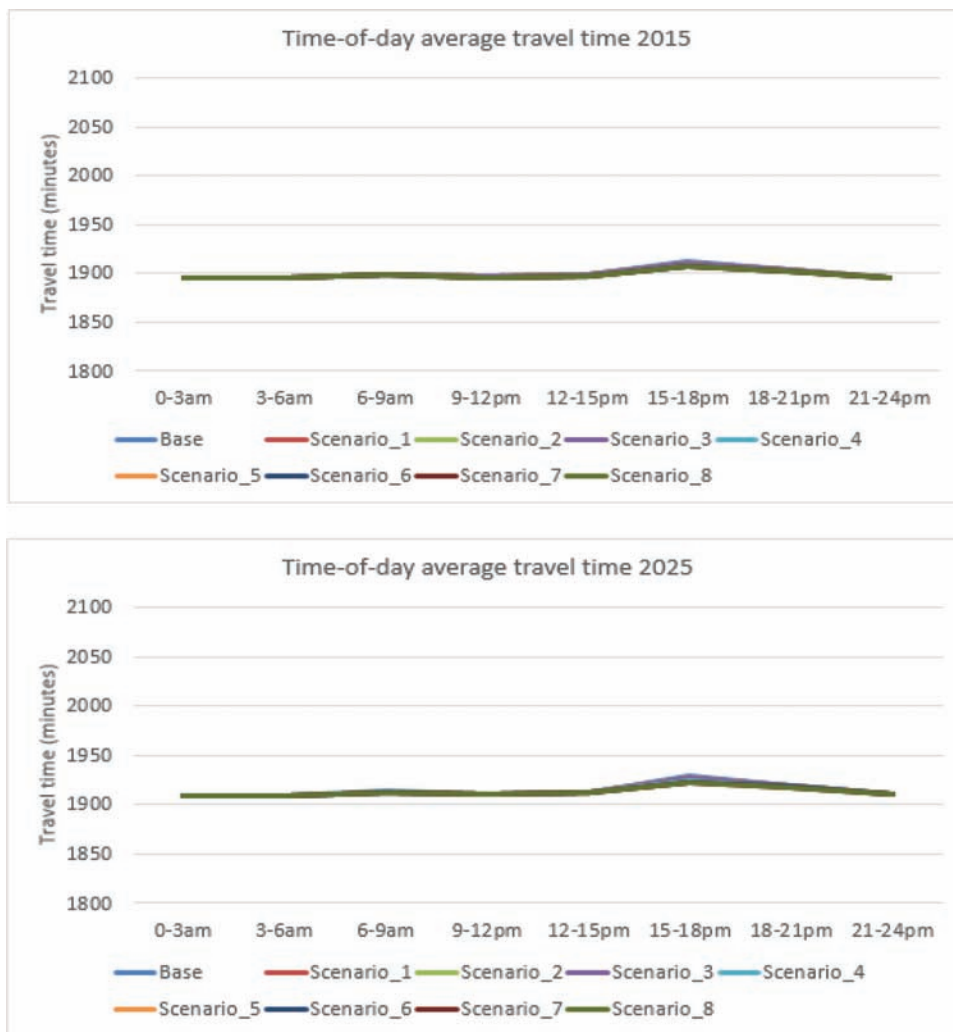
(a) Three-hour block option



(b) One-hour block option

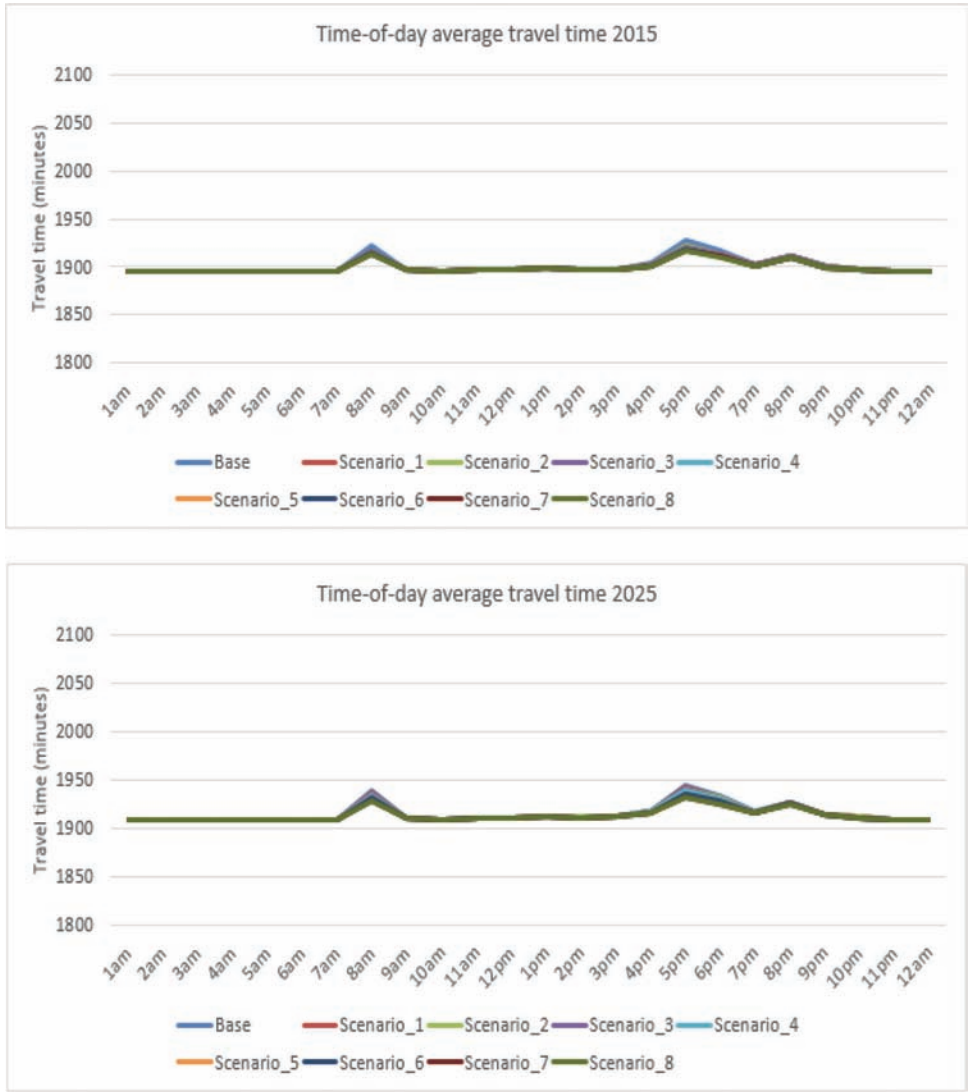
Figure A.2 Monetary savings for sub-region 2 around I-465.

A.2 Average Travel Time



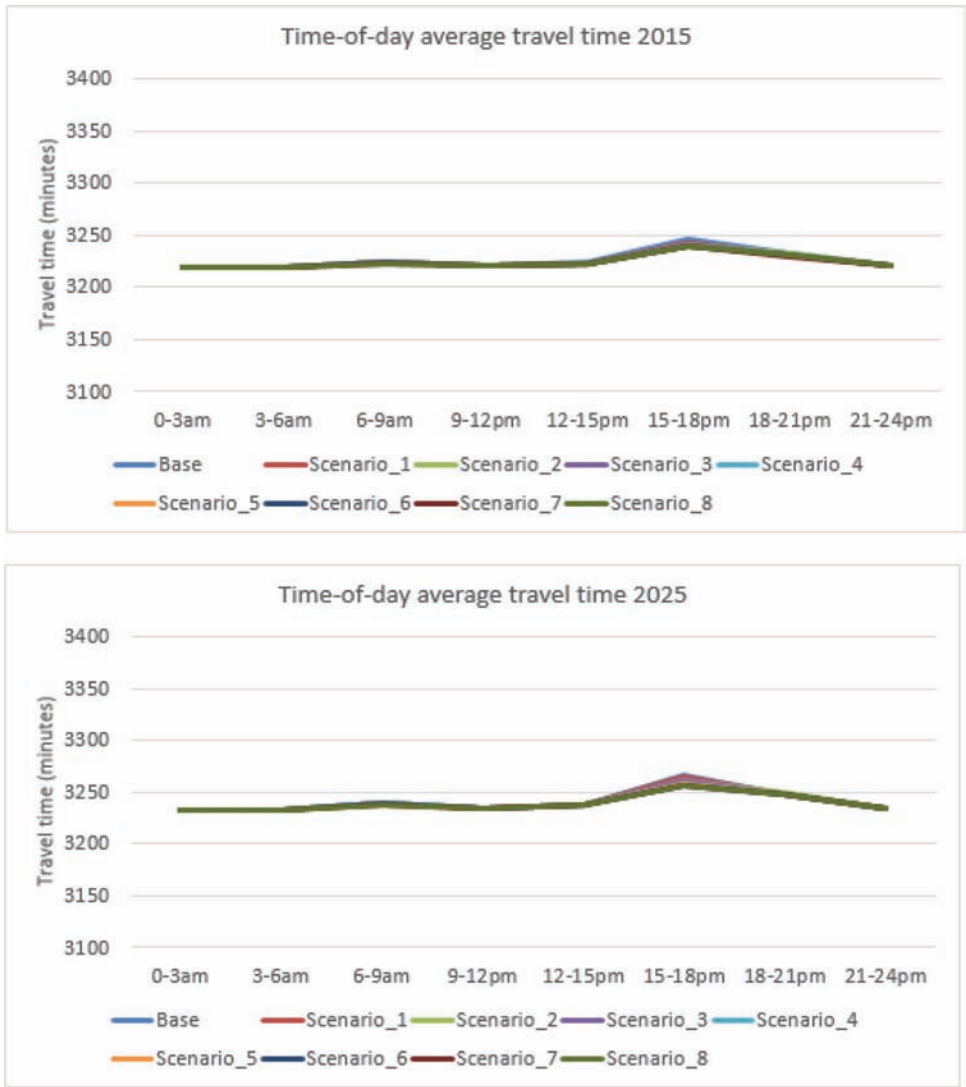
(a) Three-hour block option (2015 and 2025)

Figure A.3 Scenario-wise average travel time across different times of day for sub-region 1 around I-465. (Figure continued on next page.)



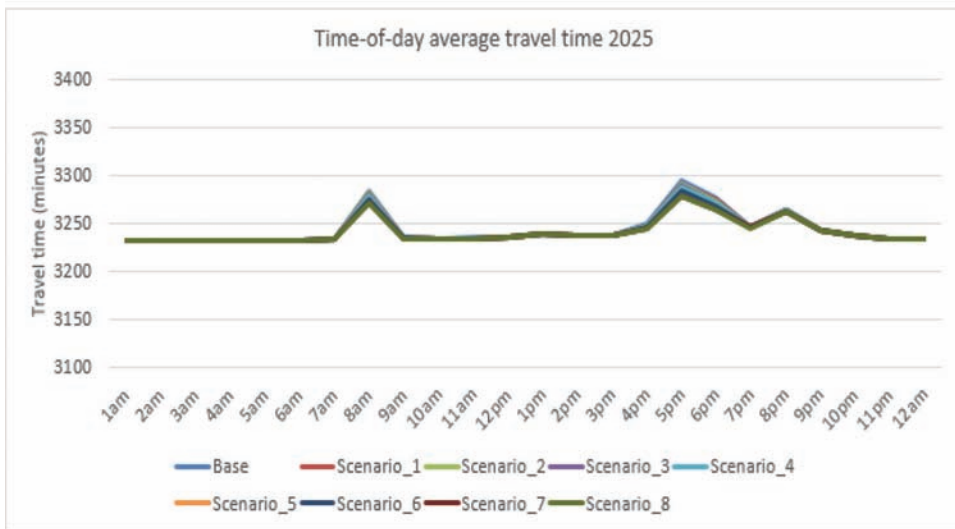
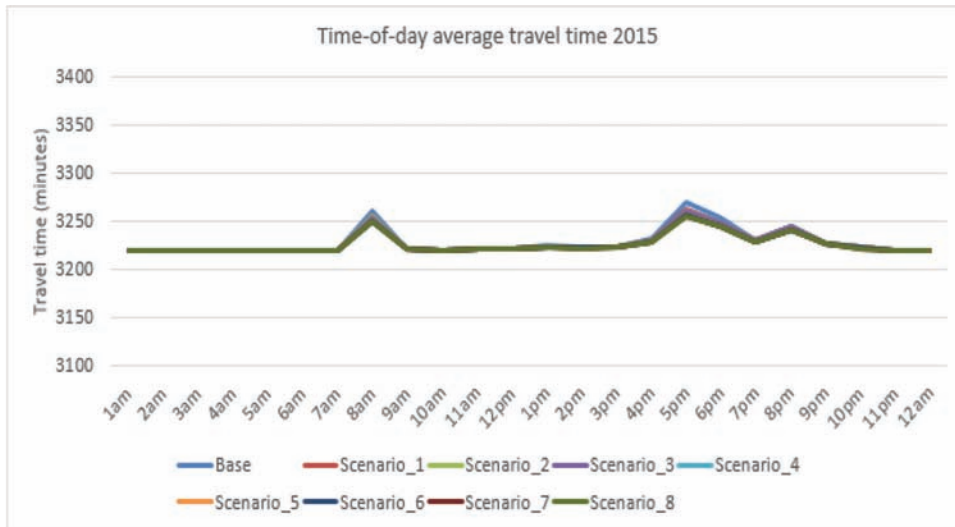
(b) One-hour block option (2015 and 2025)

Figure A.3 Continued.



(a) Three-hour block option (2015 and 2025)

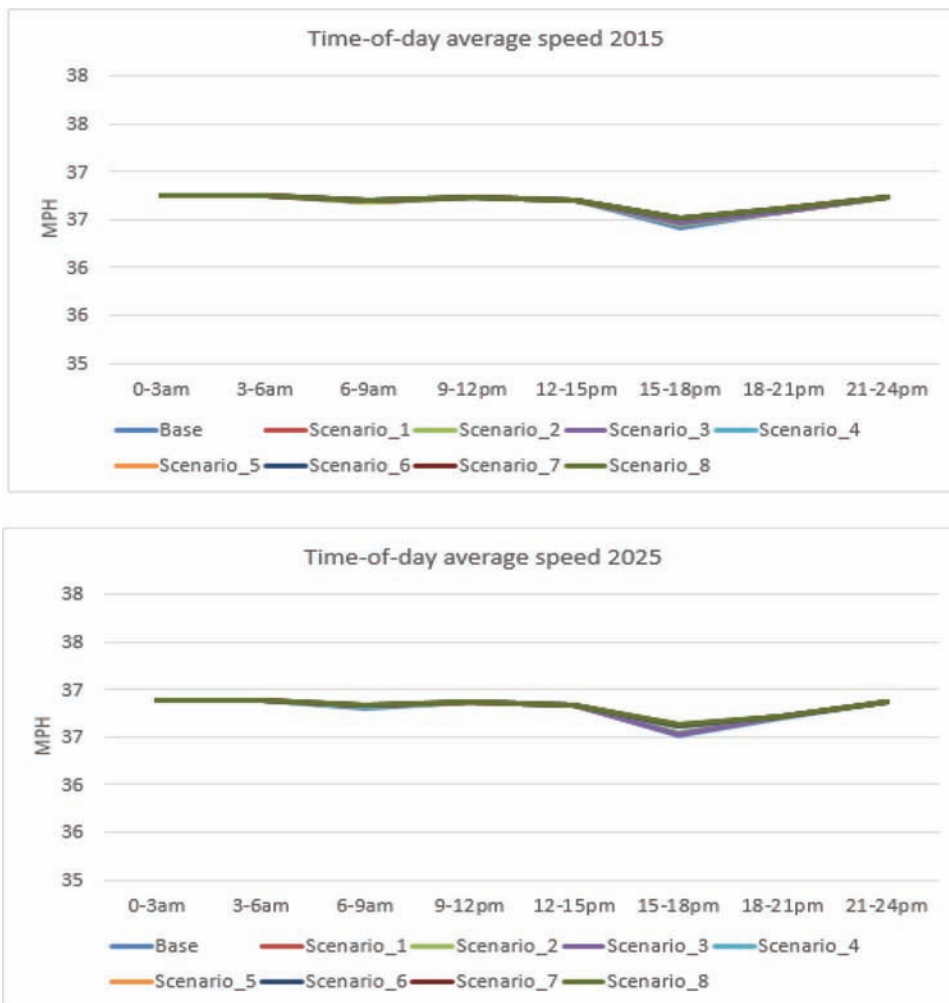
Figure A.4 Scenario-wise average travel time across different times of day for sub-region 2 around I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

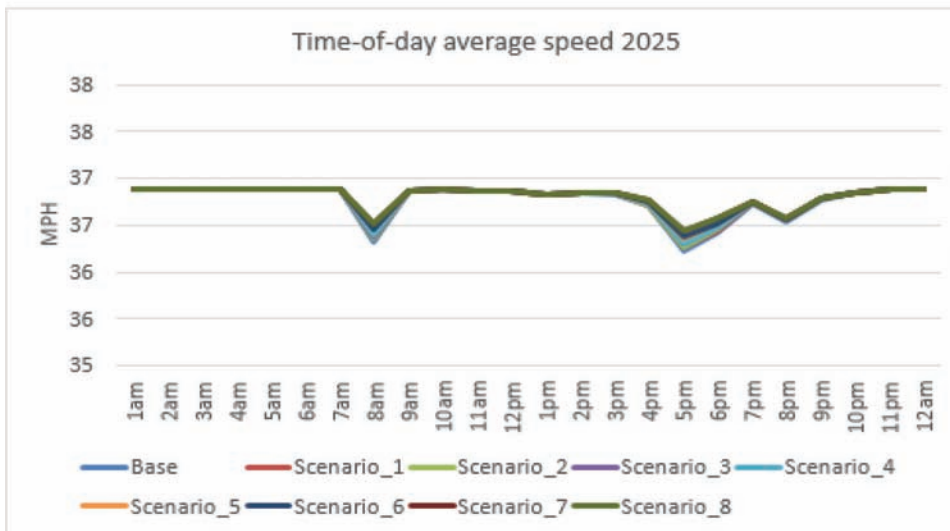
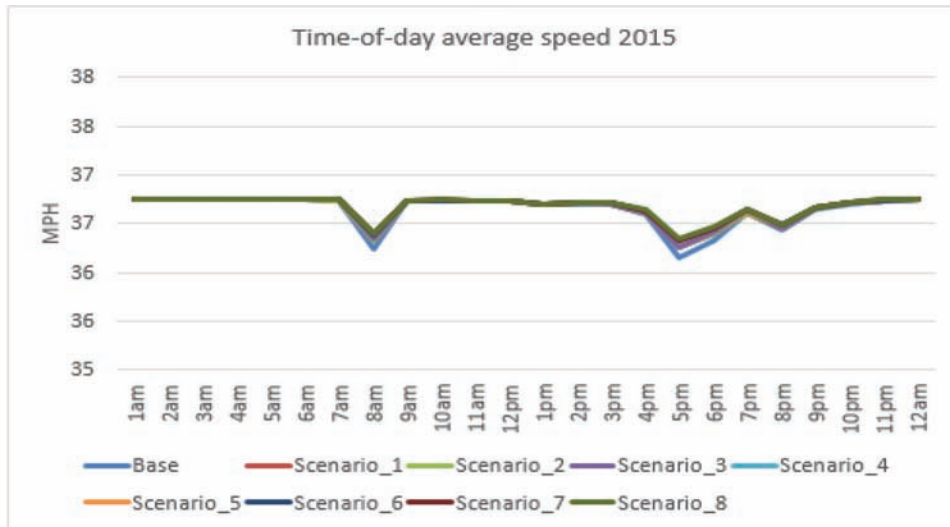
Figure A.4 Continued.

A.3 Average Speeds



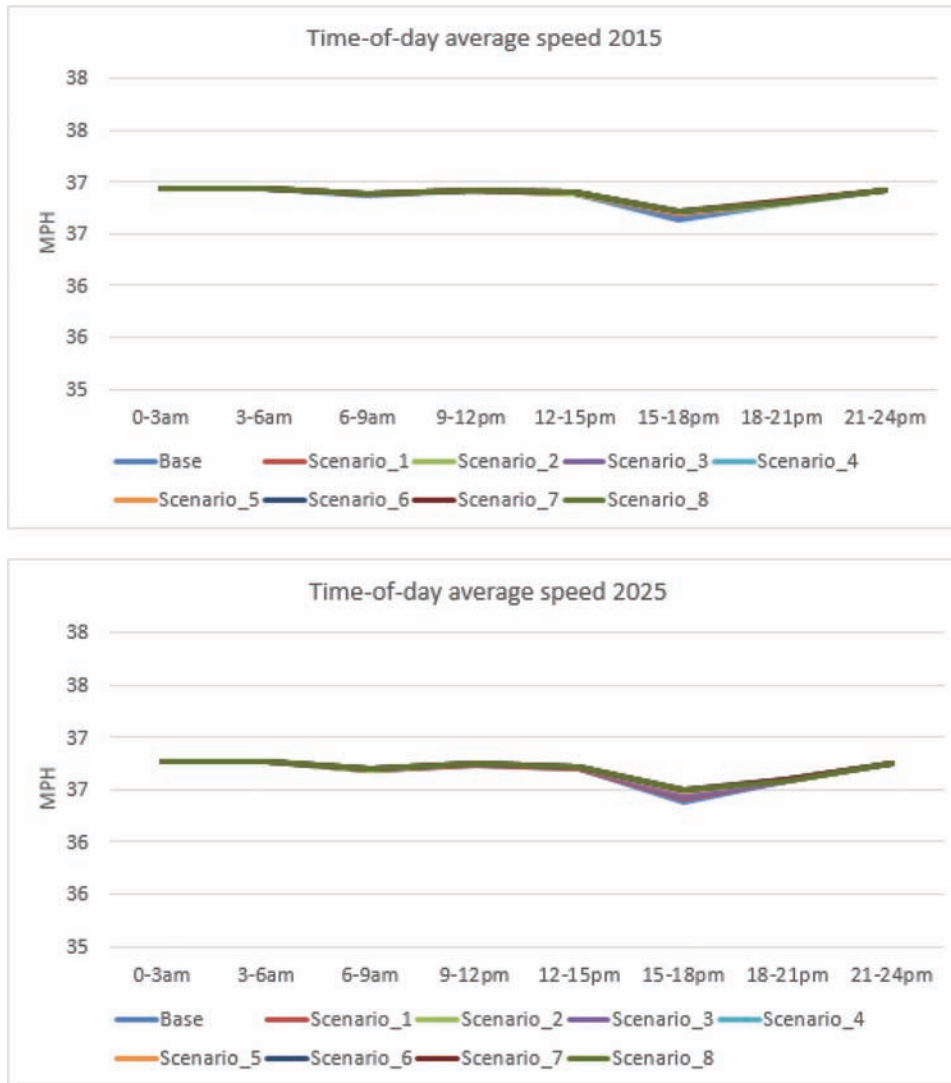
(a) Three-hour block option (2015 and 2025)

Figure A.5 Scenario-wise average travel speed across different times of day for sub-region 1 around I-465. (Figure continued on next page.)



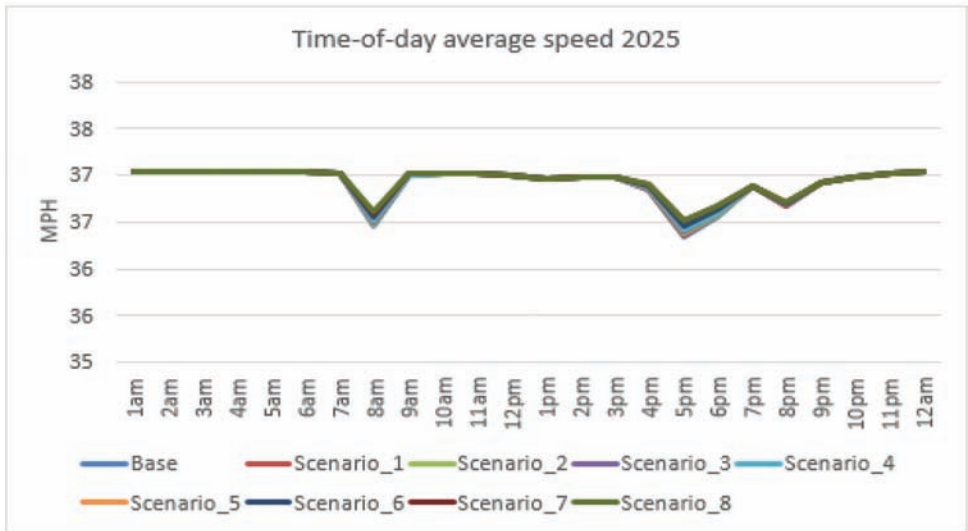
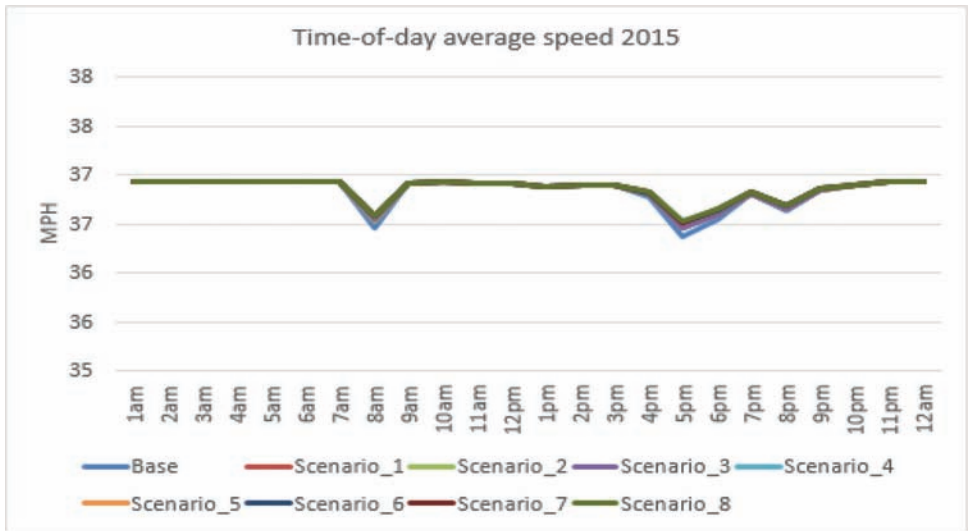
(b) One-hour block option (2015 and 2025)

Figure A.5 Continued.



(a) Three-hour block option (2015 and 2025)

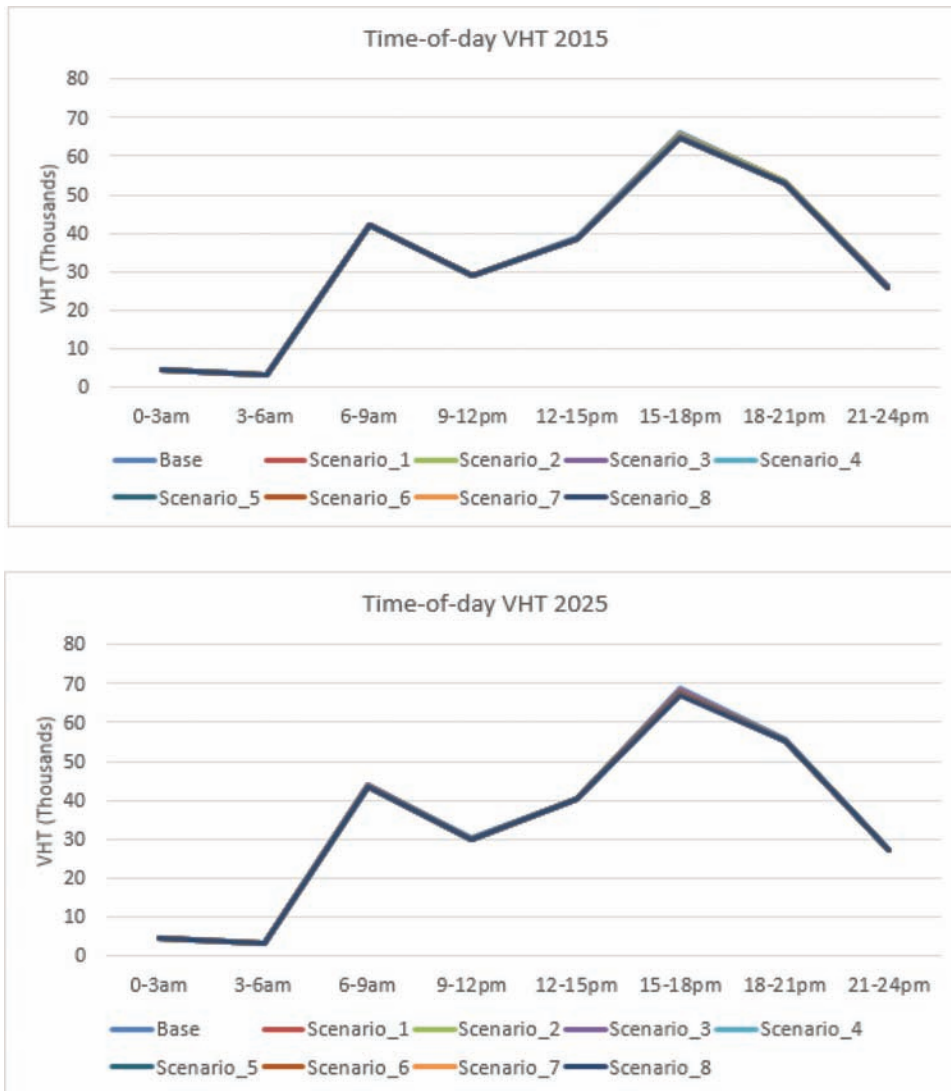
Figure A.6 Scenario-wise average travel speed across different times of day for sub-region 2 around I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

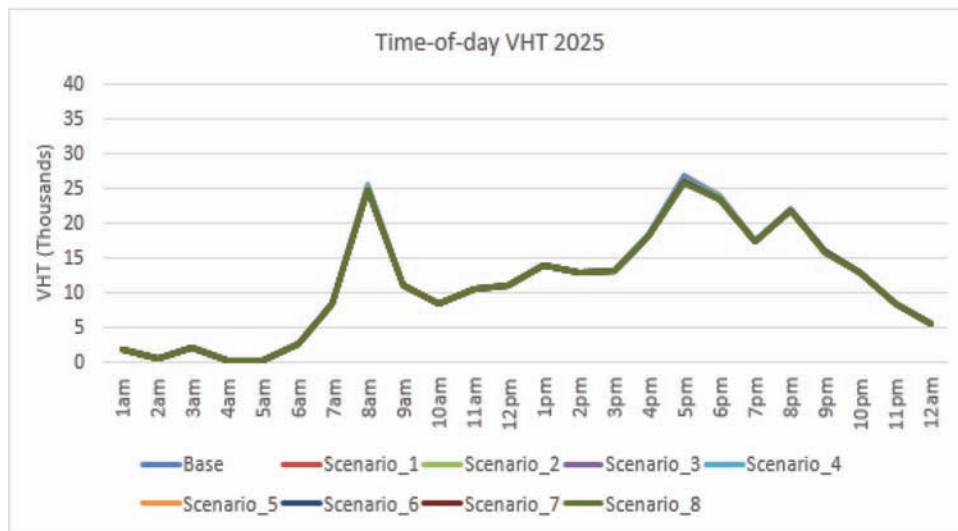
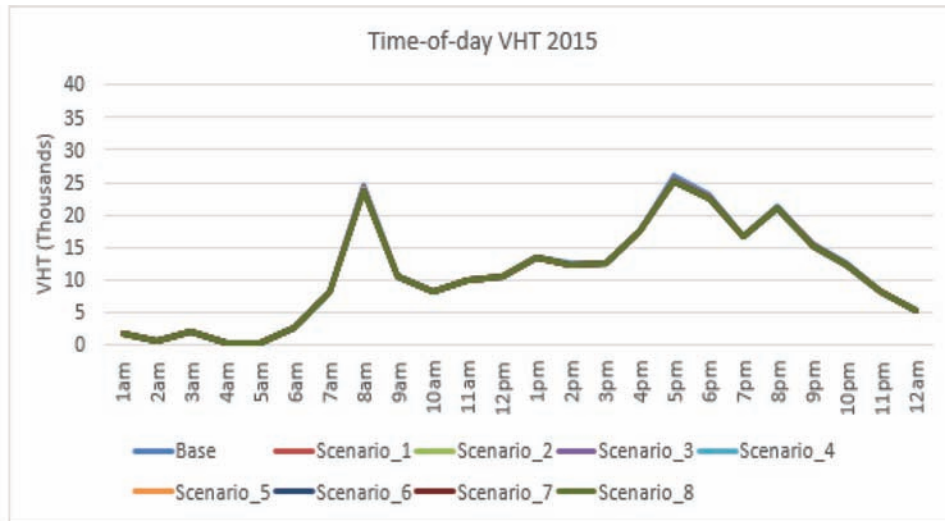
Figure A.6 Continued.

A.4 Vehicle Hours Traveled (VHT)



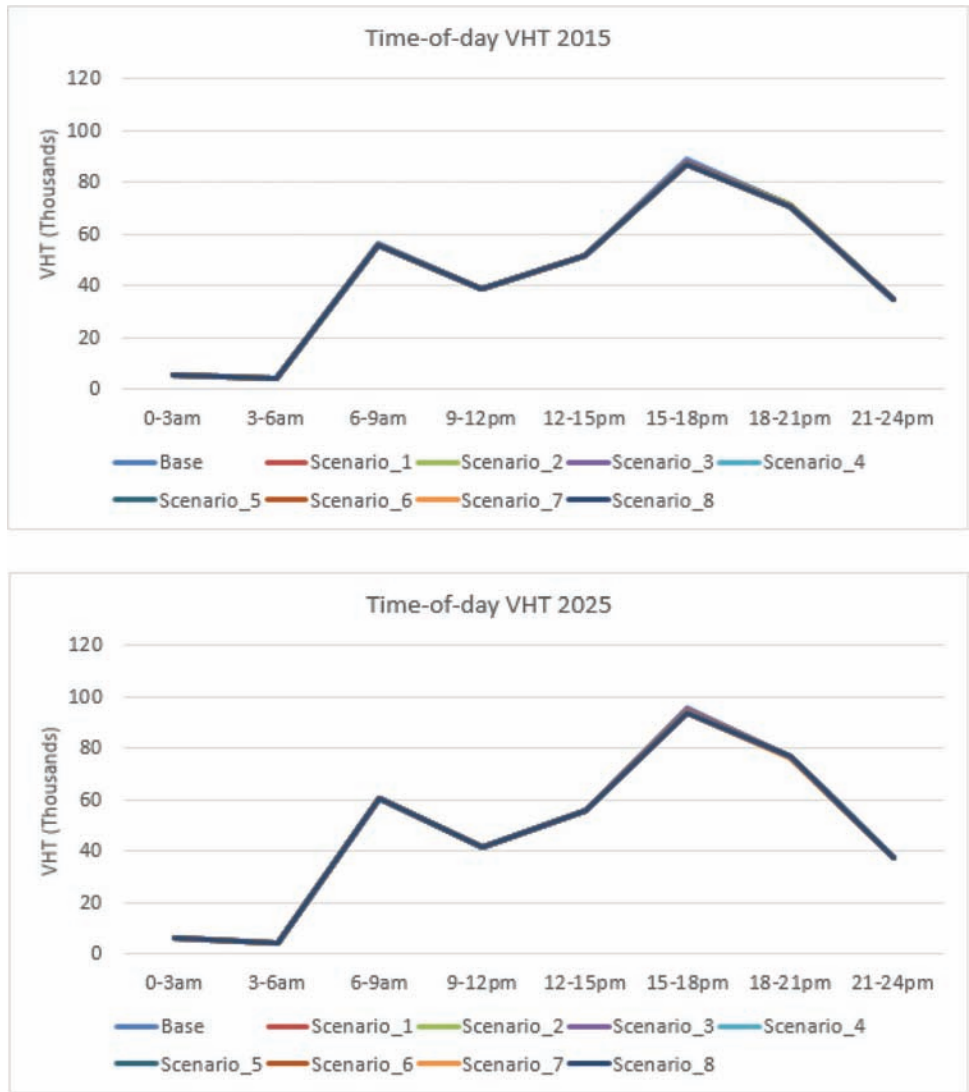
(a) Three-hour block option (2015 and 2025)

Figure A.7 Scenario-wise VHT across different times of day for sub-region 1 around I-465. (Figure continued on next page.)



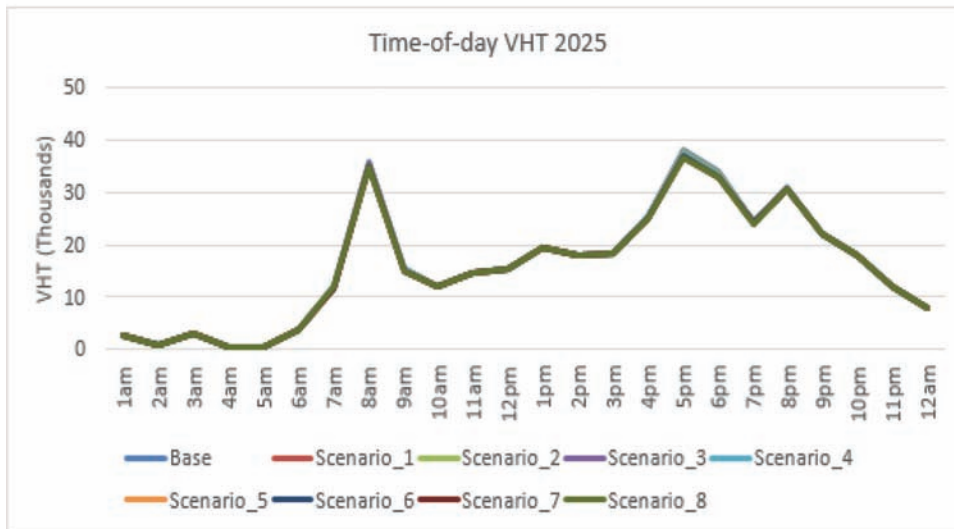
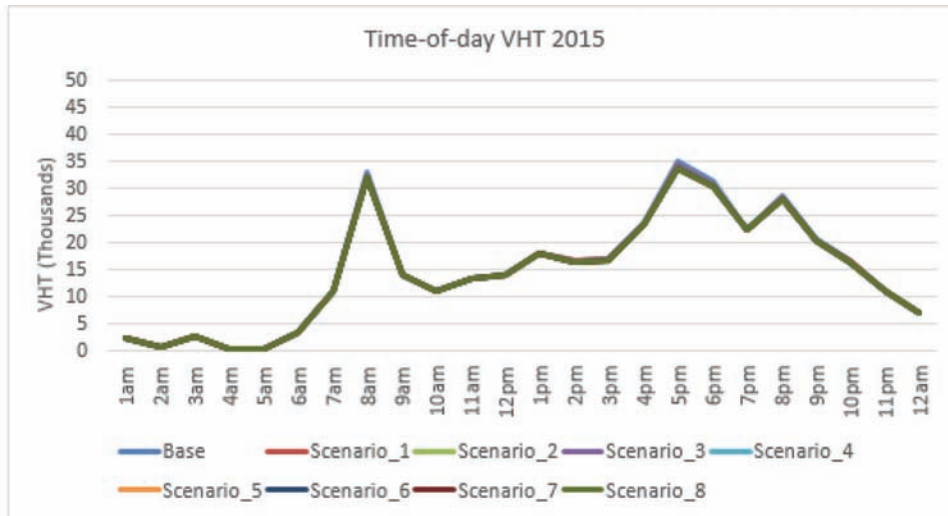
(b) One-hour block option (2015 and 2025)

Figure A.7 Continued.



(a) Three-hour block option (2015 and 2025)

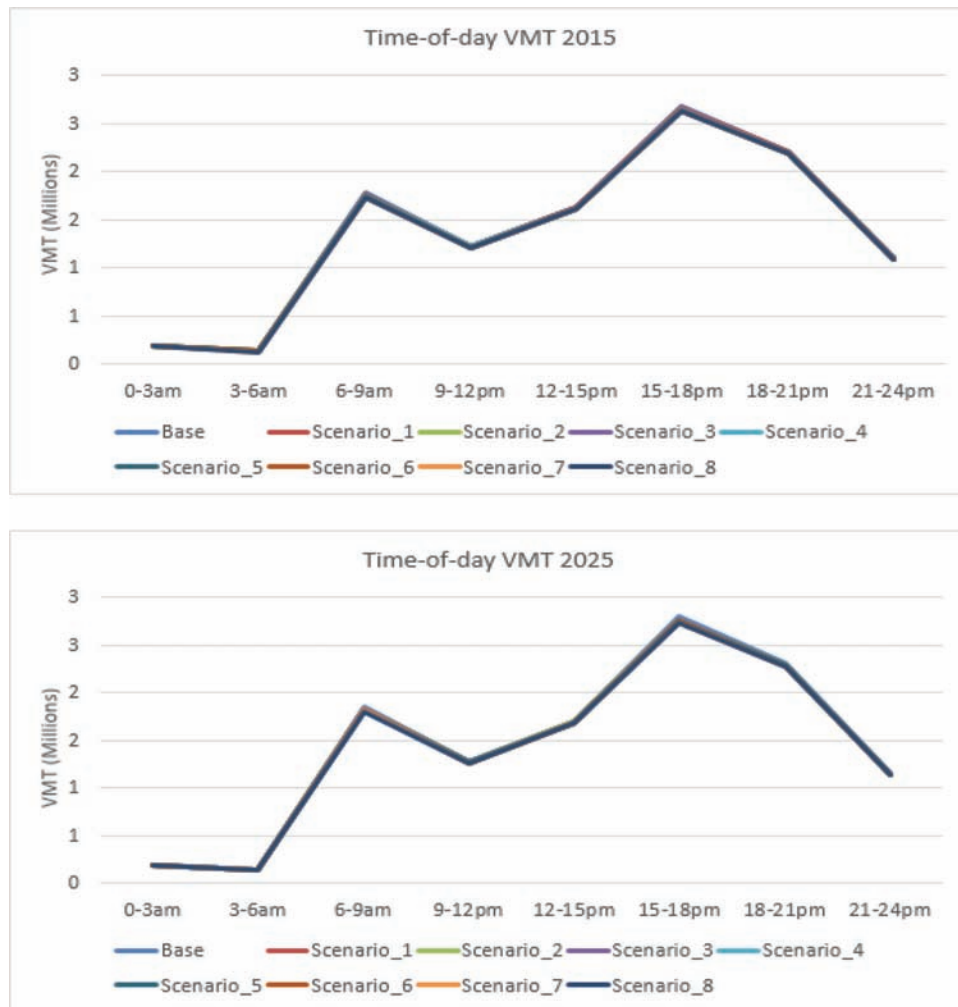
Figure A.8 Scenario-wise VHT across different times of day for sub-region 2 around I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

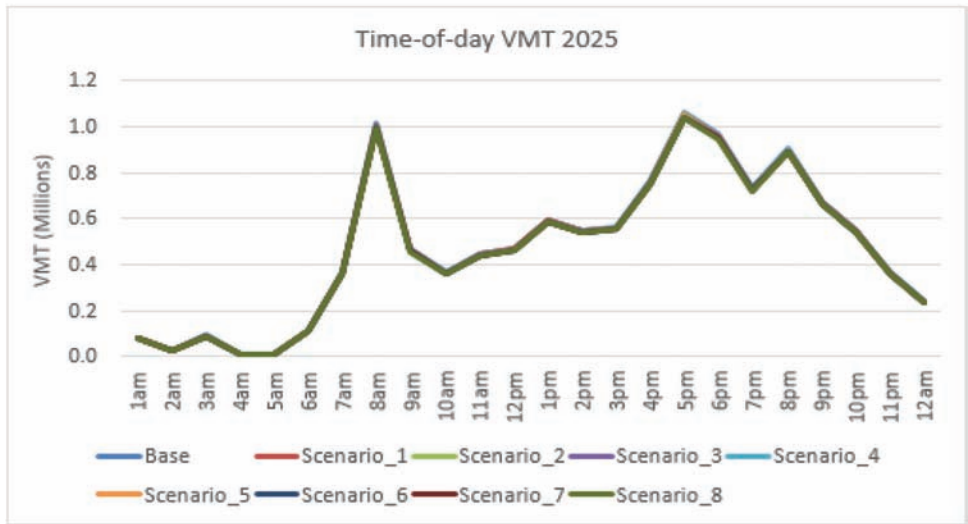
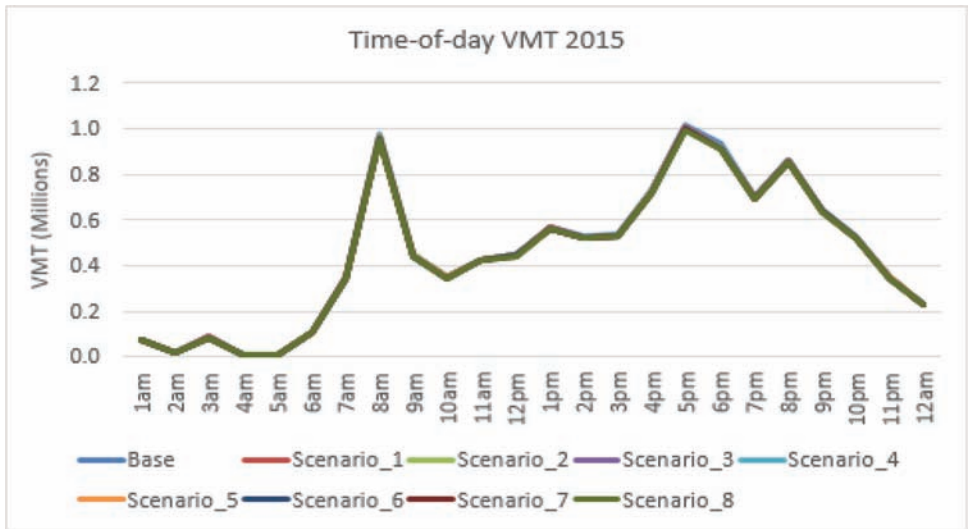
Figure A.8 Continued.

A.5 Vehicle Miles Traveled (VMT)



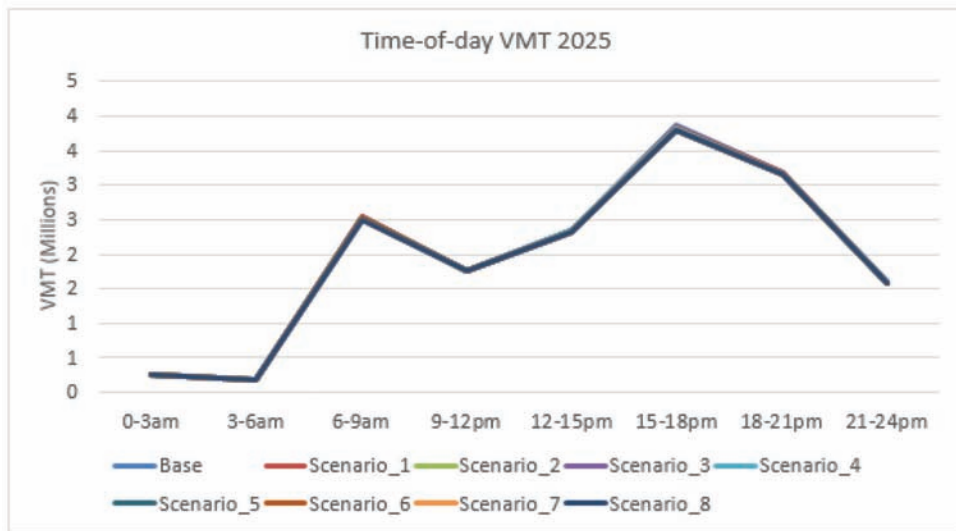
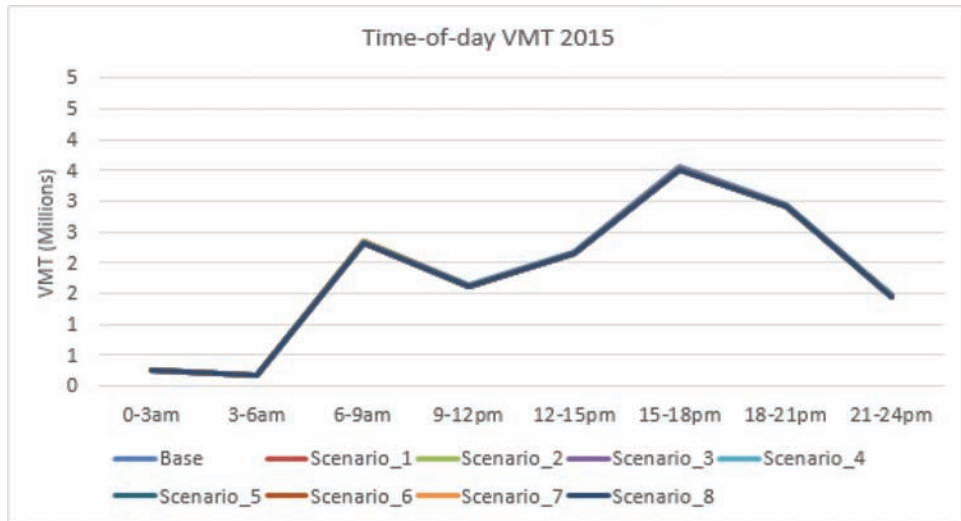
(a) Three-hour block option (2015 and 2025)

Figure A.9 Scenario-wise VMT across different times of day for sub-region 1 around I-465. (Figure continued on next page.)



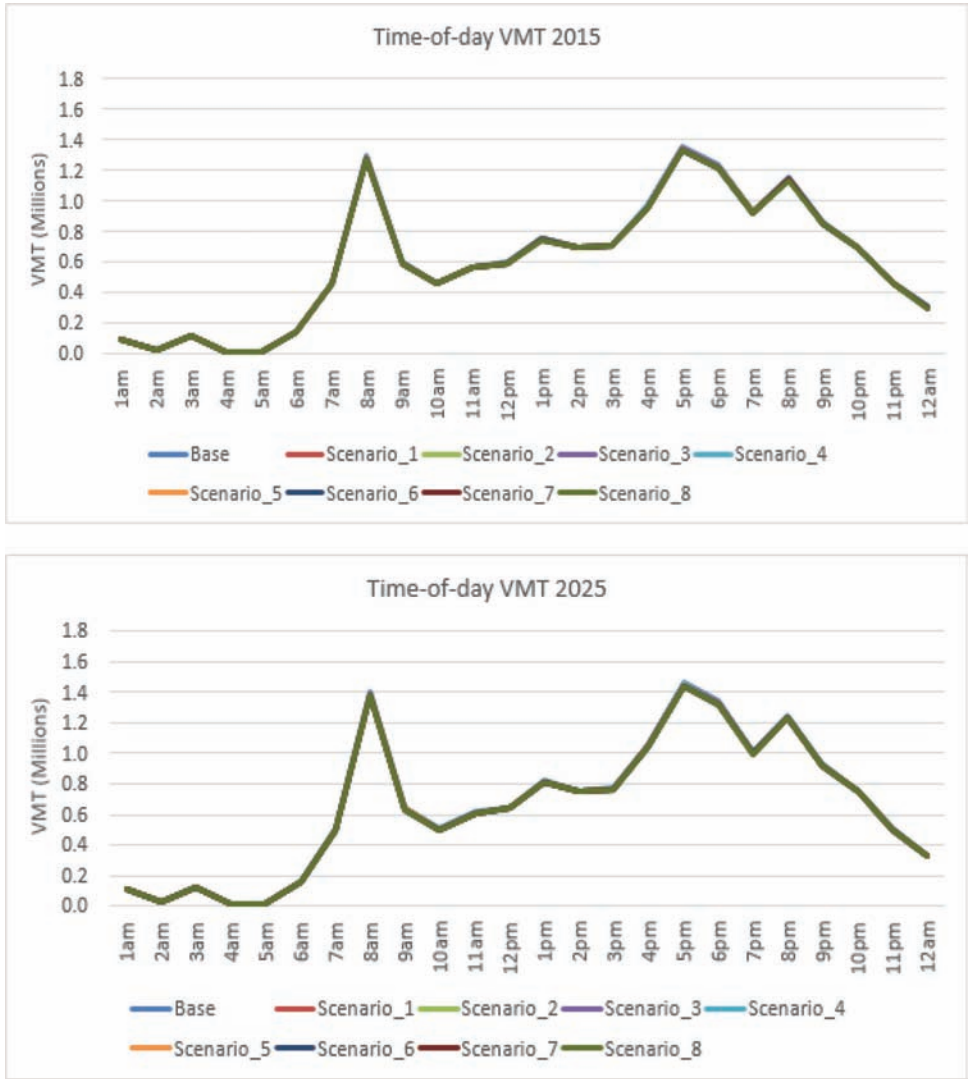
(b) One-hour block option (2015 and 2025)

Figure A.9 Continued.



(a) Three-hour block option (2015 and 2025)

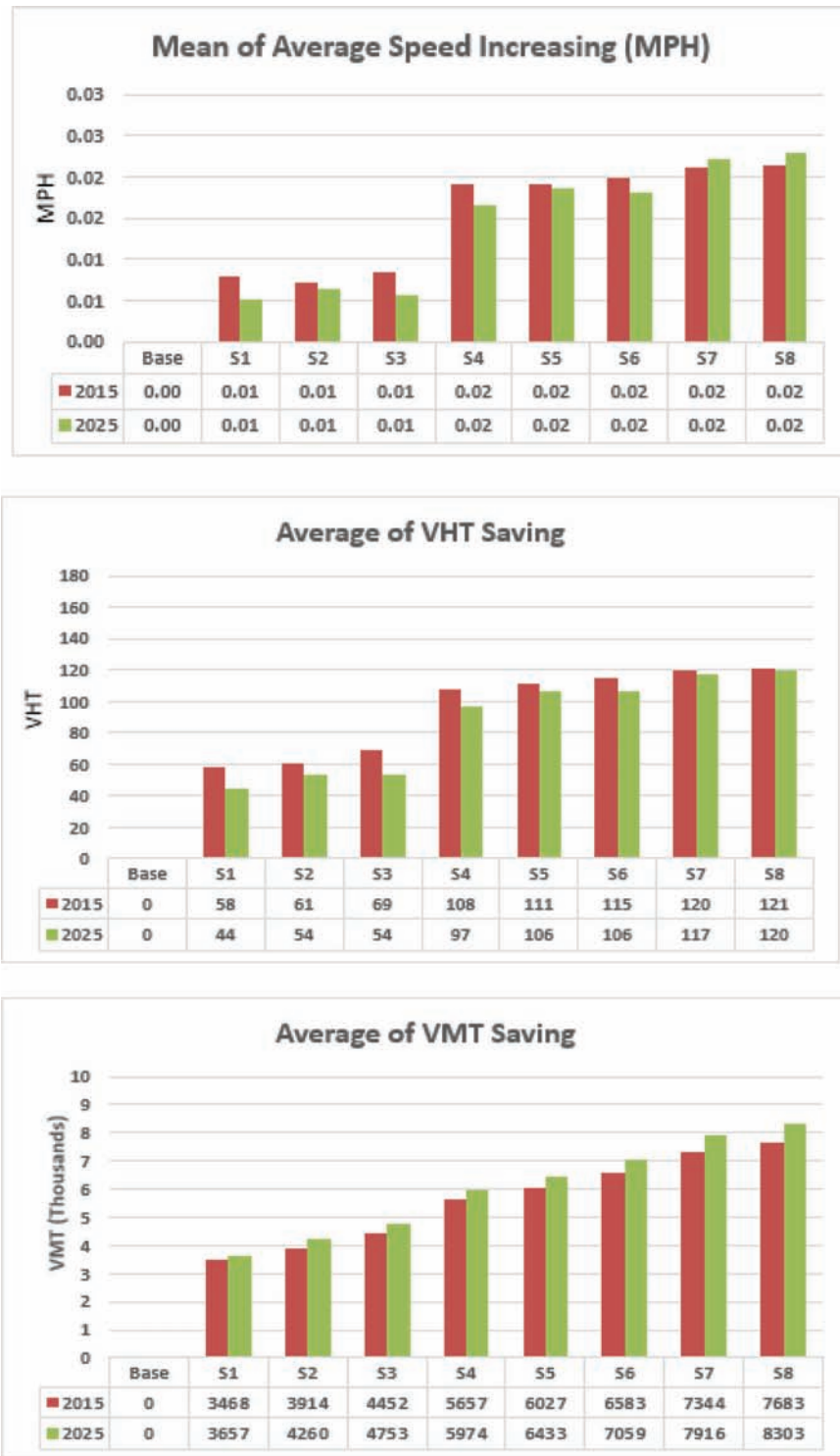
Figure A.10 Scenario-wise VMT across different times of day for sub-region 2 around I-465. (Figure continued on next page.)



(b) One-hour block option (2015 and 2025)

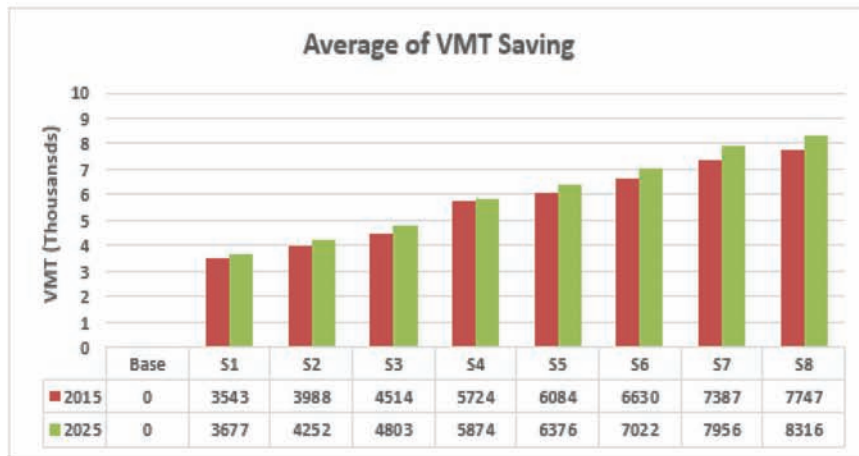
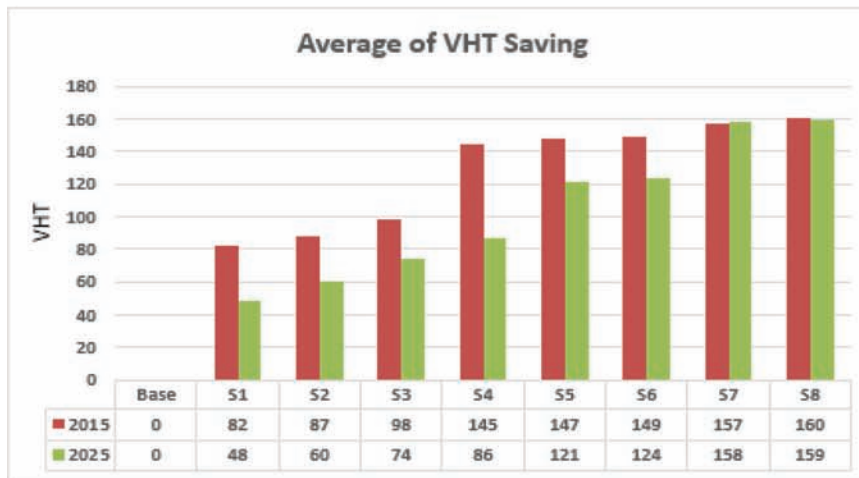
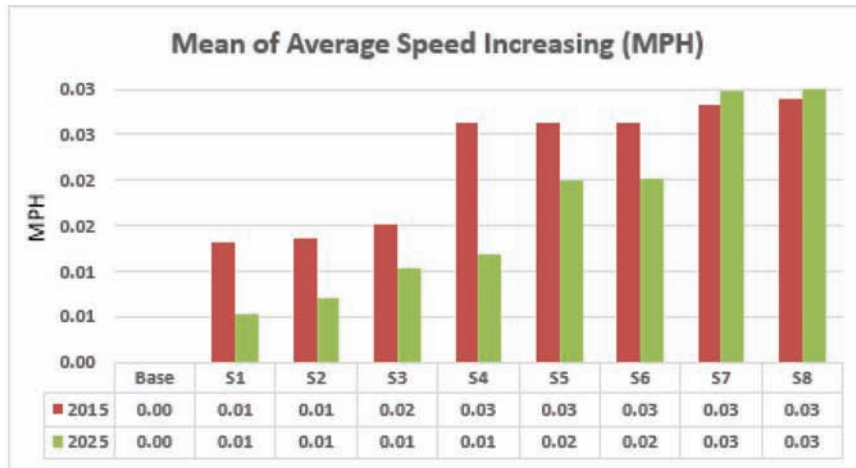
Figure A.10 Continued.

A.6 Summary Results for the Estimated Savings



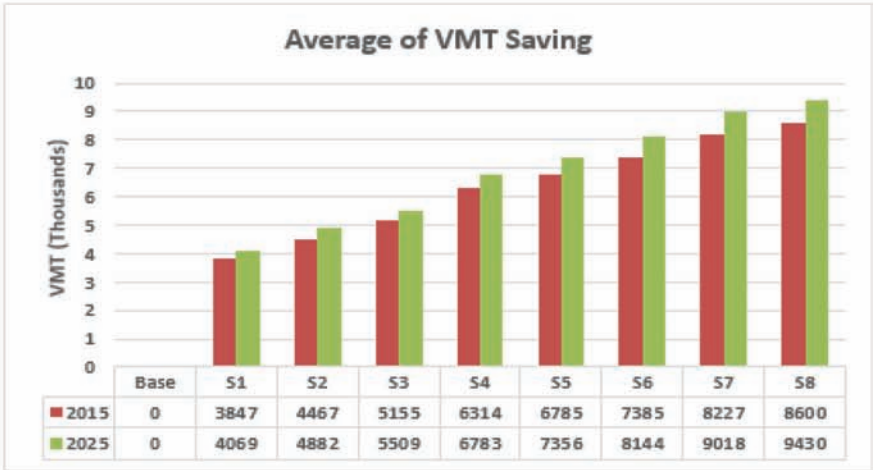
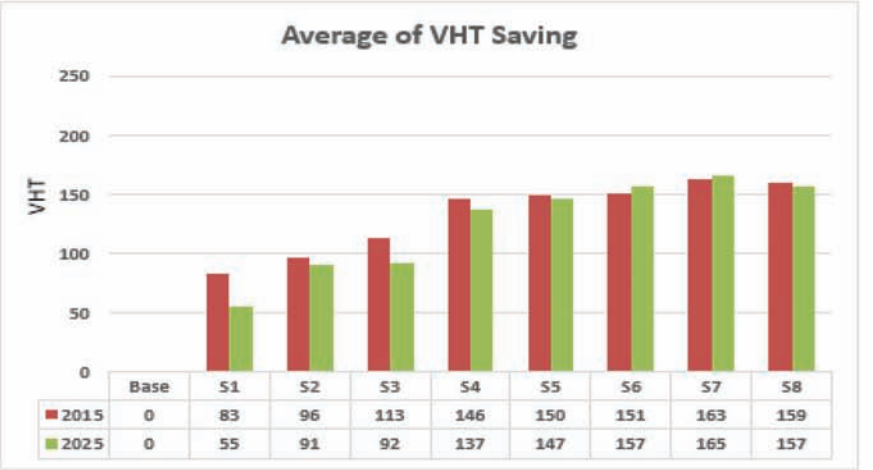
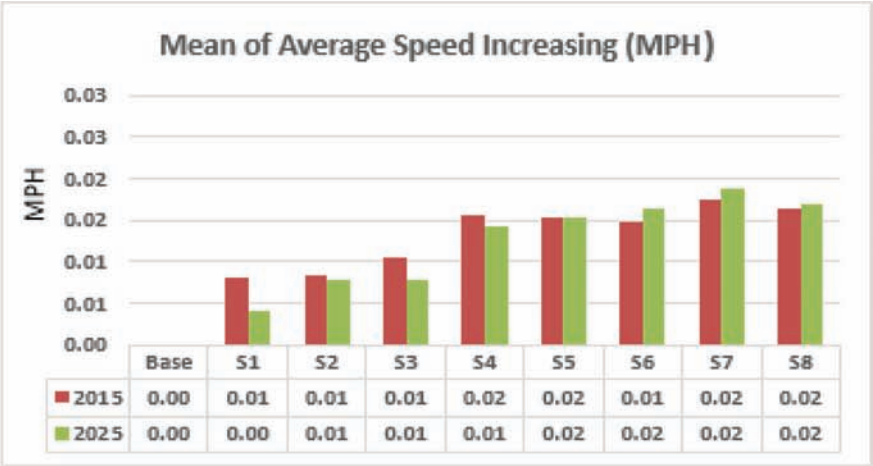
(a) Three-hour block option

Figure A.11 Scenario-wise annual increasing of speed, savings of VHT and VMT for sub-region 1 around I-465. (Figure continued on next page.)



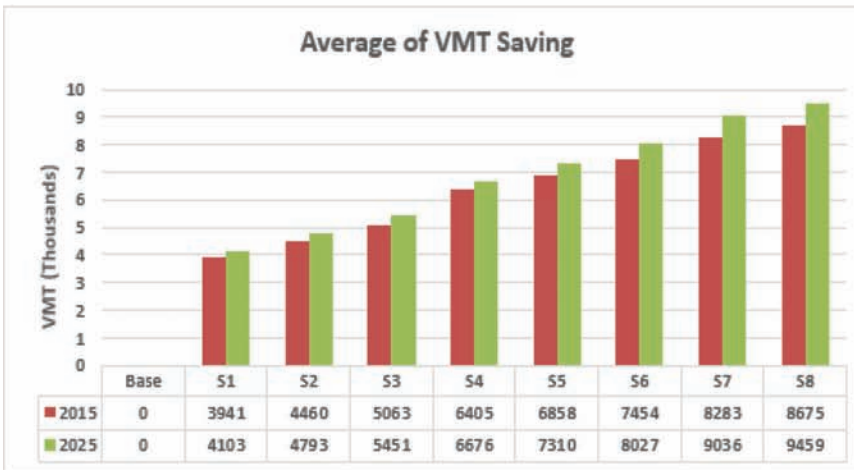
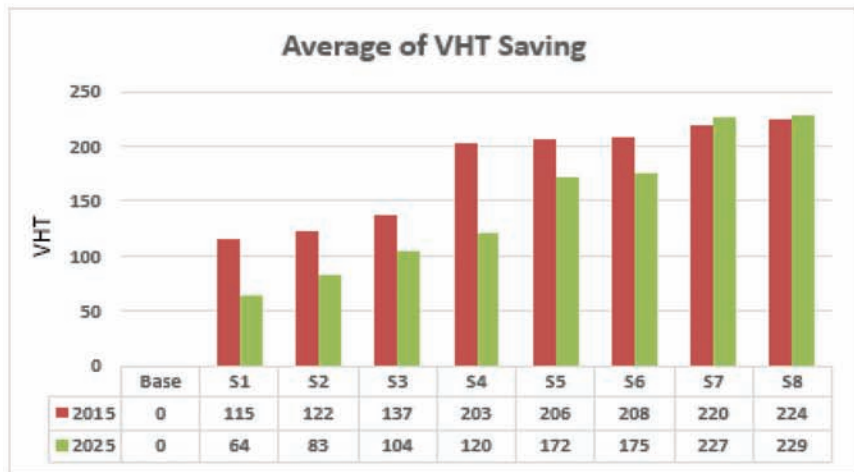
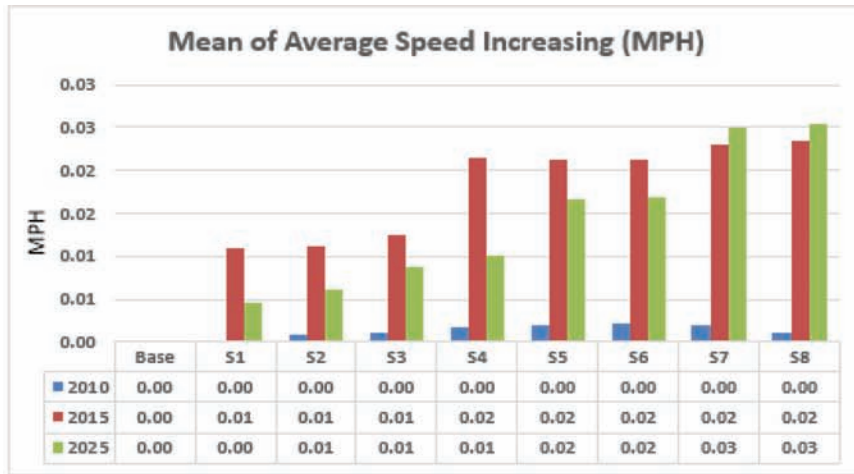
(b) One-hour block option

Figure A.11 Continued.



(a) Three-hour block option

Figure A.12 Scenario-wise annual increasing of speed, savings of VHT and VMT for sub-region 2 around I-465. (Figure continued on next page.)



(b) One-hour block option

Figure A.12 Continued.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: <http://docs.lib.purdue.edu/jtrp>

Further information about JTRP and its current research program is available at: <http://www.purdue.edu/jtrp>

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The recommended citation for this publication is:

Ukkusuri, S., Labi, S., Zhu, F., Le, T., & Sagir, F. (2017). *Evaluating the impacts of time-of-day tolling on Indiana roadways* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/08). West Lafayette, IN: Purdue University. <https://doi.org/10.5703/1288284316508>