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Exploration of Corridor-Based Tolling Strategies for Virginia's Express Toll Lanes

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16. Abstract:

Virginia has invested significant resources in the development of express toll lanes (ETLs), which adjust toll rates dynamically based on the level of toll lane usage. A tool is needed to investigate the potential impact of the I-66 Outside-the-Beltway (OTB) ETLs on regional traffic patterns. This study developed a microscopic traffic simulation model in TransModeler to evaluate a set of corridor-based tolling strategies for the I-66 ETLs in NOVA. This model also considered the changes in vehicle occupancy, mode split, and departure time among travelers because of tolls based on locally collected data. An interactive map-based analyzer based on the simulation results was created to support quick scenario analysis and decision-making.

I-66 OTB ETLs are estimated to bring tangible travel time improvements to the entire corridor. The simulation model showed that, compared to traffic conditions before the opening of the I-66 OTB ETLs, eastbound travel time along the general purpose lanes improved during the morning peak period by as much as 36.1% for the segment between Gainesville and Rt. 28, and 13.2% for the segment between Rt. 28 and I-495, respectively. During the afternoon peak period, Westbound travel time improved by as much as 17% for the segment between I-495 and Rt. 28, and 7.4% between Rt. 28 and Gainesville, respectively.

The simulation model showed that the I-66 OTB ETLs would serve about 6,645 and 8,774 vehicles at a point right before the interchange with I-495, during the morning peak and the afternoon peak periods, respectively. When combined with the traffic on the general purpose lanes, the total throughputs increased to 30,783 (+6.8%) and 35,914 (+5.1%) vehicles, compared to the current throughputs of about 28,813 and 34,160 vehicles respectively during each peak period. The simulation model also showed that US 29 and US 50 do not serve as good alternatives for trips along I-66 OTB. The introduction of the ETLs created less than a 5% impact on the overall traffic volumes along the arterial roads.

The choice of a dynamic pricing algorithm affected the number of ETL users and played a critical role in maintaining sufficient levels of service for the ETLs. Other factors, such as the value of time distribution, the vehicle occupancy requirement for free access, and the overall travel demand also have a significant impact on ETL usage and corridor traffic patterns. Among all the single factor scenarios, the policy of tolling only single occupant vehicles (HOT2+) instead of vehicles with one or two occupants (HOT3+) has the most significant impact on the performance of the corridor.

The models developed in this study also have some limitations, such as the limited quantity of data for model calibration, the small number of scenarios tested, and uncertainties that may not be fully considered at this point (e.g., COVID-19). Users should use these results with an appropriate understanding of the caveats. With these constraints considered, this study does provide a proactive assessment of the potential impact of the I-66 OTB ETLs under different scenarios, which can provide information to VDOT stakeholders for future decisions. The value of time, the vehicle occupancy, and the mode switch models estimated in this study can be applied in other studies in the region when no better data sources are available.

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Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

Virginia has invested significant resources in the development of express toll lanes (ETLs), which adjust toll rates dynamically based on the level of toll lane usage. A tool is needed to investigate the potential impact of the I-66 Outside-the-Beltway (OTB) ETLs on regional traffic patterns. This study developed a microscopic traffic simulation model in TransModeler to evaluate a set of corridor-based tolling strategies for the I-66 ETLs in NOVA. This model also considered the changes in vehicle occupancy, mode split, and departure time among travelers because of tolls based on locally collected data. An interactive map-based analyzer based on the simulation results was created to support quick scenario analysis and decision-making.

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The models developed in this study also have some limitations, such as the limited quantity of data for model calibration, the small number of scenarios tested, and uncertainties that may not be fully considered at this point (e.g., COVID-19). Users should use these results with an appropriate understanding of the caveats. With these constraints considered, this study does provide a proactive assessment of the potential impact of the I-66 OTB ETLs under different scenarios, which can provide information to VDOT stakeholders for future decisions. The value of time, the vehicle occupancy, and the mode switch models estimated in this study can be applied in other studies in the region when no better data sources are available.

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INTRODUCTION

Express toll lanes (ETLs) are dedicated managed lanes within highway rights-of-way that motorists may use by paying a variably priced toll (Perez *et al.* 2012). Differing from conventional toll roads (e.g., turnpikes), recently opened ETLs in the U.S. usually adopt dynamic pricing strategies that adjust toll rates based on the levels of congestion along the road. Dynamic pricing algorithms (DPAs) are used to adjust the toll rates in real time to manage the travel demand on ETLs. Toll rates are generally increased during peak demand periods to control the inflow to ETLs, so that a desired level of services (LOS) is maintained for ETL users. These lanes can also offer discounted rates for high occupancy vehicles (HOVs) to promote ridesharing. According to the Federal Highway Administration (FHWA), ETLs can help 1) improve mobility and reliability of travel time in existing corridors; 2) provide new travel choices for travelers in congested highway corridors; 3) generate new revenue to support the needs of all modes of transportation; and 4) enhance transit services by accommodating express bus services. However, charging tolls and converting HOV lanes to ETLs could also be opposed by the public. To achieve the promised benefits and win public "buy-in", ETL operators must make tradeoffs between these competing objectives and carefully design toll strategies.

Virginia has invested significant resources in the development of ETLs along I-95, I-395, I-66, and I-495 in Northern Virginia (NOVA), as well as for I-64 in the Hampton Roads region. These facilities use dynamic congestion (volume or density)-based pricing strategies. Moreover, all ETLs are critical components of inter-connected, multi-modal regional transportation networks. The Virginia Department of Transportation (VDOT) is operating some of these lanes (such as I-66 Inside-the-Beltway), while other ETLs are operated by private concessionaires, whose pricing algorithms may not be fully disclosed. It is critical to understand potential pricing strategies and their impacts on the rest of the highway network that the VDOT operates. For example, a media survey (Iacone, 2018) showed that regular HOV and bus commuters expressed positive opinions of the new tolls on I-66 Inside-the-Beltway (ITB), whereas 47.58% of the respondents said that the new tolls and changes had made their commutes significantly worse. Therefore, more analysis is needed to better understand motorist behavior and to balance the various objectives for the upcoming I-66 Outside-the-Beltway (OTB) ETLs. This will not only help optimize the tolling strategies, but also facilitate public outreach to address commuters' concerns with informative findings and appropriate action.

Given the dynamic nature of DPAs used by ETLs, conventional analysis tools, based on static travel demand models, cannot meet the modeling needs of ETLs. Weris Inc. developed a tool in TransModeler to investigate travelers' route choice between the toll road and the non-toll alternative and the resulting traffic dynamics along I-66 ITB ETLs. This study extends the work to the I-66 OTB ETLs and considers alternative travel modes or departure times because of the changes in travel costs caused by tolls. A multi-dimensional travel demand model is developed and integrated with a traffic simulation model to account for these potential demand reactions to tolls and their impact on the regional traffic patterns.

Developing such a modeling system is challenging. Travelers make tradeoffs between tolls and travel time savings when choosing between ETLs and non-toll alternatives. The value of time (VOT) is an important parameter that may significantly affect travelers' decisions. In the literature, empirically estimated VOT spans a wide range, and there is a lack of consensus on real VOT distributions. A distribution estimated using locally collected data can provide a better description of travel behavior among local travelers. In addition, travel demand and travel behavior characteristics fluctuate over time because of many external factors. The COVID-19 pandemic, which has significantly reduced the demand for travel, according to the Bureau of Transportation Statistics (2021), is another example of such travel demand uncertainties. Therefore, it is important to conduct sensitivity analyses of travel demand and important travel behavior characteristics, such as VOT, to fully understand the potential impact of ETLs on regional traffic patterns.

Finally, running a microscopic traffic simulation for a regional network is computationally intensive and time-consuming. ETL operators and traffic management agencies, such as VDOT, may need to consider different combinations of various objectives (e.g., LOS, number of users served, revenue maximization, etc.) under different demand and network conditions. Since the number of potential scenarios is very high, exhaustive evaluation of all scenarios is not practical. Instead, a subset of scenarios is defined and analyzed in this study that considers various factors that may affect ETL operations. Therefore, the main objective is to evaluate the impacts of a selected set of toll strategies and scenarios that are recommended by the project TRP (technical review panel). These scenarios are described later in Methods. To better inform VDOT stakeholders, an interactive map-based analyzer was developed based on the results of the scenarios tested in this study to support quick scenario analysis and decision-making.

PURPOSE AND SCOPE

The purpose of this study was to develop a microscopic traffic simulation model in TransModeler to evaluate a set of corridor-based tolling strategies for the I-66 ETLs in NOVA. An interactive map-based analyzer, based on simulation results, was also created to support quick scenario analysis and decision-making.

The model development effort was explorative and the scope of this project included the assessment of whether the simulation model in TransModeler, augmented by additional travel demand models, is effective for evaluating dynamic pricing strategies along the I-66 corridor in NOVA. A custom VOT model for I-66 ITB was developed with actual express lanes and arterial travel times and toll data.

The evaluated toll strategies included the DPA that is currently implemented for I-66 ITB, and several of its variants, and as specified by modified DPA parameters and occupancy restrictions. This study also evaluated the performance of the ETLs under different travel demand levels, current and alternative VOT distributions, and potential scenarios when COVID-19 travel and business restrictions are eased. A total of 28 scenarios were evaluated.

The simulation model covered the I-66 corridor from Gainesville, VA to the Washington, D.C. boundary, parallel arterials such as US 29 and US 50, and other freeways as well as major and minor arterials in the study area. That area also included I-495 from the American Legion Bridge to the I-495/I-395/I-95 interchange at Springfield (but did not include the interchange itself).

METHODS

Six tasks were undertaken to achieve the study objectives:

1. Review literature.
2. Estimate value of time.
3. Develop and calibrate a simulation model in TransModeler.
4. Develop behavioral models to capture demand changes.
5. Simulate different scenarios and conduct impact analyses.
6. Disseminate results through workshops and an interactive web portal.

Literature Review

A literature review was undertaken to obtain relevant information regarding models that have been developed and applied to the evaluation of ETLs, particularly those that use dynamic pricing strategies. The literature review also covered empirical studies on the performance of existing ETLs in the U.S., and VOT estimations based on empirical data. A summary of the literature review is given in the next section.

Value of Time Estimation

This task estimates the VOT distribution, which is a critical parameter for the travelers' choice between a toll road and a non-tolled alternative, using locally collected data.

VOT is traditionally estimated using stated preference surveys. However, such studies are infrequent and the sample size is usually limited. The 2016 Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis (FHWA 2016) recommends a VOT range of 35% to 60% of hourly income, which is equivalent to a range of $9.50 to $16.30 for local personal trips and a range of $20.30 to $30.50 for local business trips, as a national average. The recommended mean is 50% of hourly income and Table 1 summarizes the VOT estimation based on FHWA guidance and 2019 U.S. Census data. The estimate is rough because we assumed only one earner per household and a constant 2,080 hours per year working load. Moreover, the FHWA guidance also acknowledges a lack of consensus about research findings on the value of time distribution and states that "estimates derived by reliable and focused research may be superior for predicting behavioral responses in specific cases".

Table 1. Time Valuation Based on the Federal Highway Administration Guidance and 2019 Census Data

County	Population	Medium Household Income ($)	Hourly Earnings ($/hour)	VOT ($)
Arlington	236,842	120,071	57.7	28.9
Fairfax	1,147,532	124,831	60.0	30.0
Loudoun	413,538	142,299	68.4	34.2
Prince William	470,335	107,132	51.5	25.8
Average				29.8

A constant 2,080 hours per year working load is assumed for all counties.

An alternative data source for local VOT estimation is the Metropolitan Washington Council of Governments (MWCOG) regional planning model. This model was originally developed using the 2007/2008 Transportation Planning Board Household Travel Survey Data and was updated periodically using newly collected data (MWCOG 2021). However, the model documentation of recent years does not show any changes in VOT estimation. Although the VOT estimation in the MWCOG model looks rough (values are apparently rounded to $5 increments for most values and are uniform), it offers different estimates for different time periods and different vehicle classes, which is very important for differentiating the behavioral reactions of different vehicle classes to tolls. Table 2 shows the VOT assumption adopted in MWCOG Model Version 2.3.78 (NCRTPB 2018).

Table 2. Time Valuation by Vehicle Type and Time Period in Metropolitan Washington Council of Governments Planning Model Version 2.3.78

Vehicle Class	Value of Time ($/hour)			
	AM Peak	Midday	PM Peak	Night
SOV	24	20	20	20
HOV2	40	15	30	15
HOV3+	60	15	60	15
COM	30	30	30	30
TRK	30	30	30	30
APV	30	30	30	30

SOV: Single occupancy vehicle
HOV2: High-occupancy vehicle with two persons
HOV3+: High-occupancy vehicle with three or more persons
COM: Commercial vehicles
TRK: Medium and heavy trucks
APV: Airport passengers traveling to/from the three commercial airports
AM peak period: 6:00 AM to 9:00 AM
Midday period: 9:00 AM to 3:00 PM
PM peak period: 3:00 PM to 7:00 PM
Night/early morning period: 7:00 PM to 6:00 AM

To better understand the VOT distribution in the region and to improve the VOT estimate to the extent possible, this study used the toll transaction data collected at the I-66 ITB ETLs to re-estimate the VOT distribution. I-66 ITB ETLs, which run from the I-495 Capital Beltway to the D.C. line at the Theodore Roosevelt Bridge (see Figure 1), started operation in December 2017. It is a high occupancy and toll (HOT) facility which only operates during peak periods (5:30 am to 9:30 am Eastbound and 3:00 pm to 7:00 pm Westbound during regular workdays). The facility is divided into four segments, and a gantry is installed at each segment to detect vehicles and charge tolls (see Figure 1 for locations of gantries). The facility includes two lanes in each direction, for the most part. SOVs pay a toll that is dynamically adjusted based on the level of congestion (higher tolls with increasing levels of density), while vehicles with two or more occupants (HOV2+) can currently use it for free. All vehicles using the corridor must be equipped with an E-Z Pass transponder. For those without a transponder, a bill that includes the toll and an extra processing fee is sent to the registered address, based on the license plate. I-66 ITB ETLs do not have additional GP lanes running parallel to the HOT lanes. Single drivers who do not want to pay the toll during the operation periods have to use arterial corridors, such as US 50 and US 29, which usually have a much longer travel time.

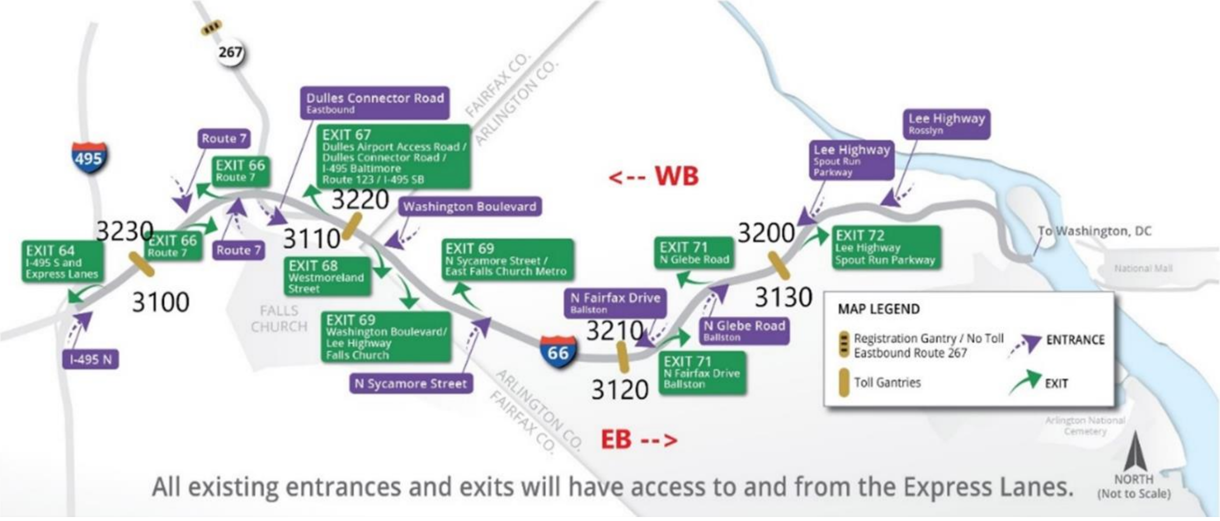


Figure 1. I-66 Corridor Inside-the-Beltway, Access Points, and Toll Gantries (3100, 3110, etc.). Source: Virginia Department of Transportation.

As shown in Figure 1, there are eight toll gantries along the I-66 ITB ETLs labeled as 3100, 3110, 3120, and 3130 in the east-bound direction, and 3200, 3210, 3220, and 3230 in the west-bound direction. Vehicles are detected at these gantries by E-Z Pass (a radio-frequency identification system) tag readers (or the license plate recognition system, if no active transponder is detected). For the analyses presented in this report, trips from 3100 to 3130 (hereafter called east-bound trips) and 3200 to 3230 (hereafter called west-bound trips) are taken. These represent the longest trips along the corridor and have the largest origin-destination (OD) volumes among all possible OD pairs. For each trip, the toll transaction data include:

- Trip type: Whether it is a HOV or a SOV trip
- Entry and exit gantry identifiers
- Entry and exit time stamps
- Toll amount
- Anonymized vehicle identifier

This study is based on complete transaction data that was collected from March 1, 2018, to May 31, 2018, that included 64 weekdays, during which tolls were collected. Using the anonymized vehicle identifier, the research team first calculated the number of days a vehicle used the toll facility during the study period.

To analyze the VOT (or, interchangeably, the willingness to pay (WTP)) under different conditions, travel time data from alternative routes, parallel to the I-66 ITB corridor, were estimated from probe data and compared to those on the I-66 ITB ETLs. Figure 2 shows the I-66 corridor and two key parallel corridors: US 29 and US 50. These two alternative corridors are not freeways and include traffic signals. Using INRIX probe data, travel times were computed for each of the three routes in Figure 2, for every 30-minutes of each day within the study duration (i.e., March 1, 2018 to May 31, 2018).

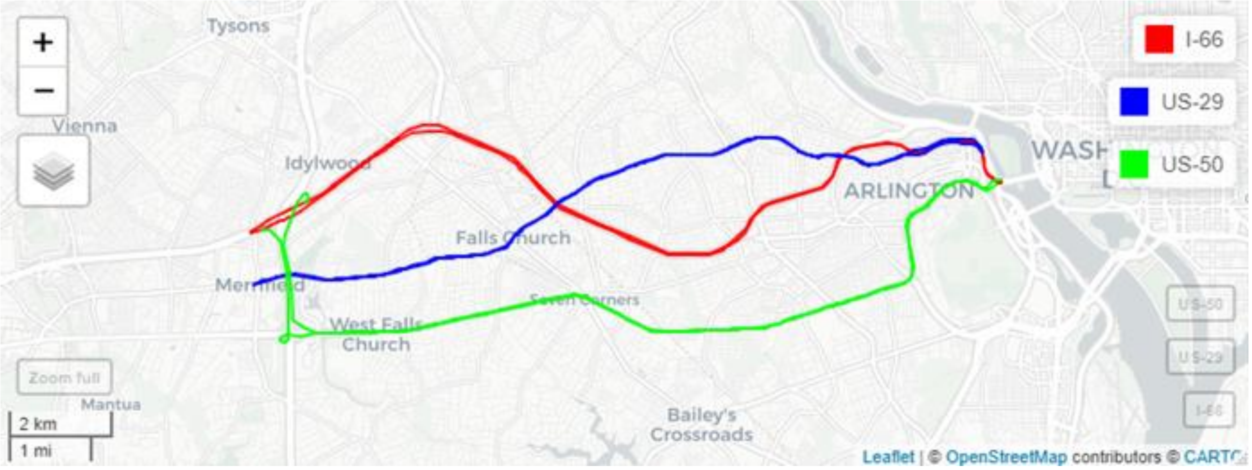


Figure 2. Two Major Alternative Routes Parallel to I-66 Selected for Travel Time Comparison.

Although INRIX probe data has been widely used in the transportation sector (e.g., INRIX speed data has been used to support the development of the Urban Mobility Report by Texas A&M Transportation Institute (TTI) since 2014 (Cookson and Pishue, 2017)), the data quality still varies (Kim and Coifman 2014). The travel time values represent average conditions and their accuracy may vary depending on the vehicle sample sizes. The TTI Urban Mobility Report only uses a 15-minute average in its analysis. For the same reason, this study only estimates instantaneous travel time at 30-minute intervals. These travel times are then matched with the toll transactions data using the time stamps recorded at the entry gantry. For each trip, the travel time saving (TTS), based on real data, is computed as follows:

$$\text{TTS} = \min(\text{TT}_{\text{US-29}}, \text{TT}_{\text{US-50}}) - \text{TT}_{\text{I-66}}$$

In other words, the travel time on I-66 is subtracted from the shorter (or minimum) travel time of the two alternatives to estimate the travel time saved. To analyze the willingness to pay among different groups, for each individual trip, the following VOT is computed:

$$\text{VOT} = \text{toll}/\text{TTS}$$

In the literature, the terms value of time (VOT), value of travel time (VOTT), and value of travel time savings (VTTS) are often used interchangeably by transportation professionals. In this report, we use VOT to refer to the particular value that is derived using the method described above and, when referring to the literature, we use whichever terms that were used in the original publication (value of time is more common).

It should be noted that there may be other factors, beyond the travel time, that may influence the route choice behavior of the users. These factors include the reliability of travel times, familiarity with the alternative routes, trip purpose, etc. As indicated in the literature, if the VOT is estimated by simply dividing the toll by the realized time savings, it may be over-estimated (Brent and Gross, 2018). However, it is challenging to collect field data that quantify these additional factors. In addition, it is impractical to incorporate these additional factors into a regional traffic simulation model. Therefore, we will limit ourselves to the VOT estimation without considering these additional factors. Future research may address this issue and improve the VTTS/VOT estimations when data becomes available.

Developing and Calibrating a Simulation Model in TransModeler

TransModeler was chosen as the modeling tool for developing a microscopic traffic simulation model for the study area, based on findings in the literature. Choosing TransModeler also allowed the research team to leverage previous research efforts, which included a simulation network for the I-66 corridor inside the Capital Beltway, developed by Weris Inc., and the network for the I-66 corridor between the Capital Beltway and Rt. 28, developed by the research team.

The research team developed a microscopic simulation model for the study area through four major steps: 1) developing the simulation network, 2) extracting and preparing the initial origin-destination (OD) matrices through a sub-area analysis, 3) conducting a dynamic OD estimation for model calibration, and 4) developing the network, toll setting scripts, and other supporting files for the new I-66 OTB ETLs.

Developing the Simulation Network in TransModeler

The research team first merged the simulation networks within the study area that were developed by previous research efforts, and then extended the network to cover the entire study area. The transportation network was accurately reproduced in TransModeler, based on Google Earth imagery, and was automatically geo-referenced. The network covers the I-66 corridor from Gainesville, VA in the west, to the Washington, D.C. line in the east, and the I-495 Capital Beltway, from the American Legion Bridge in the north, to the end of the 495 express lanes in the south. The network also covers other freeways (e.g., George Washington Parkway and part of Rt. 28) and major arterial roads, such as US 29, US 50, and Rt. 123 in the study area. To improve computational efficiency, the network does not cover minor arterial roads. Figure 3 uses grey lines to illustrate the network developed for this study.

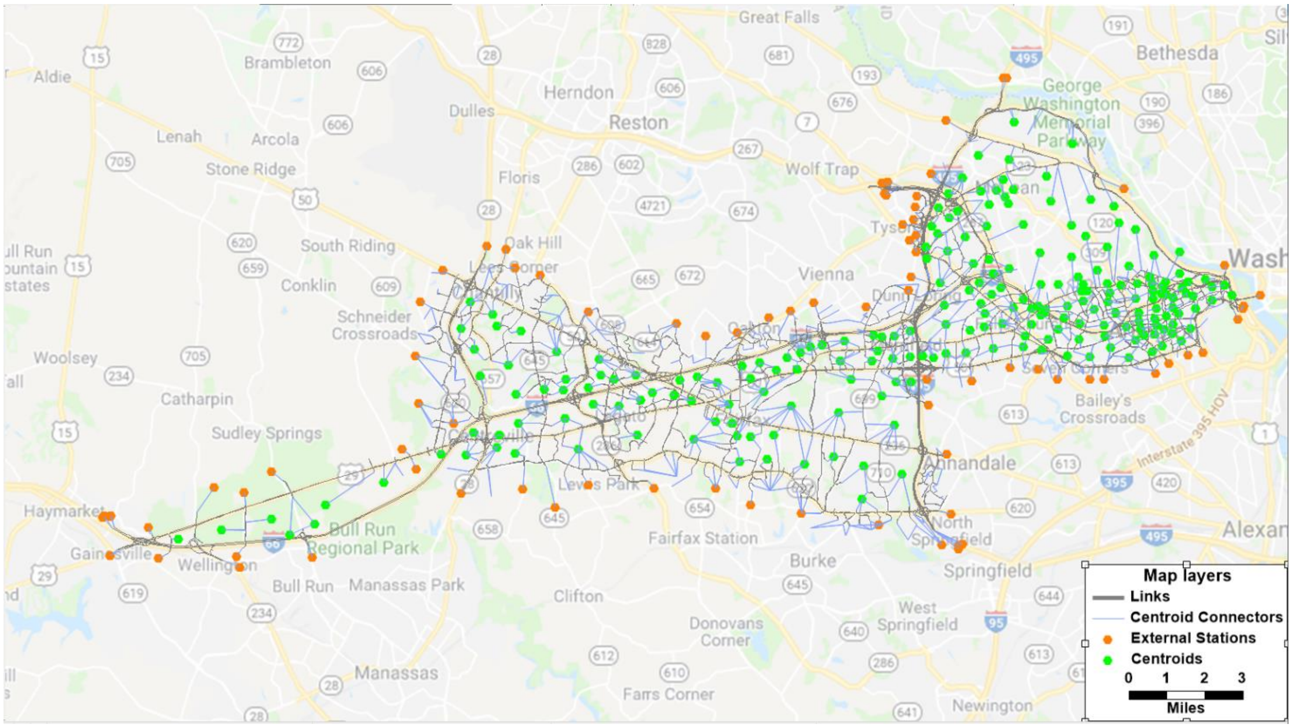


Figure 3. Traffic Network, Centroids, and External Stations of the Simulation Model in TransModeler.

Following common industry practice, centroids and external stations were added to represent the points where traffic emerges and leaves in the simulation system. The number and locations of the centroids used in the simulation model were based on the Traffic Analysis Zones of the Metropolitan Washington Council of Governments (MWCOG) travel demand model. The external stations were added at locations where major highways pass through the boundary of the study area. In Figure 3, green hexagons represent centroids and orange hexagons represent external stations. Both centroids and external stations were connected to the simulation network through centroid connectors (blue lines in Figure 3). The model includes a total of 223 internal zones (centroids) and 83 external stations.

Signal control plans are an important part of the simulation network. Many intersections in the study area use actuated and/or coordinated control plans, which have a significant impact on the capacity of the arterial roads. It is a very time-consuming task to set signal control plans manually in TransModeler. In this study, the research team first obtained the actual signal control plans implemented in the field from VDOT and the City of Fairfax. These plans are coded in Synchro (.syn files). They were converted to the Universal Traffic Data Format, which can be imported in TransModeler in batches. The research team then manually checked them, one by one, and made necessary edits (e.g., adding sensors that are necessary for actuated control plans). Appendix A gives one example of each signal control plan that is coded in Synchro and in TransModeler. For signals that are managed by Arlington County, the plans were inherited from the model developed by Weris Inc. The model developed in this study included a total of 433 signalized intersections.

Preparing the Initial OD Matrices through a Sub-area Analysis

Estimating time-dependent OD matrices is a critical step for calibrating a microscopic traffic simulation model. Given that the OD estimation process is an under-identified problem, since the number of unknowns (travel demand for each OD pair) is much larger than the number of control variables (link flow observations), the quality of the initial OD matrices has a significant impact on the accuracy of the estimated OD demand. For a regional network, estimating the initial OD matrices is a challenging task, primarily due to the lack of data. To consider different ETL usage patterns by different classes of vehicles, this study needs to differentiate vehicles by occupancy for OD estimation.

The only known data source that can provide OD information on different vehicle classes for the study area is the MWCOG travel demand model. Leveraging research work from a previous study, conducted by this research team in collaboration with the University of Maryland (Xiong et al. 2015), the latest MWCOG travel demand model (version 2.3.75) was converted to a dynamic traffic assignment model. Based on assigned path flow patterns for each hourly window, the number of trips was extracted for travel between OD pairs within the study area (yellow arrow in Figure 4), between a zone within the study area and a zone outside the study area (blue arrow), and between OD pairs outside the study area, but whose trips must go through the study area (red arrow). The sub-area OD matrices were constructed accordingly.

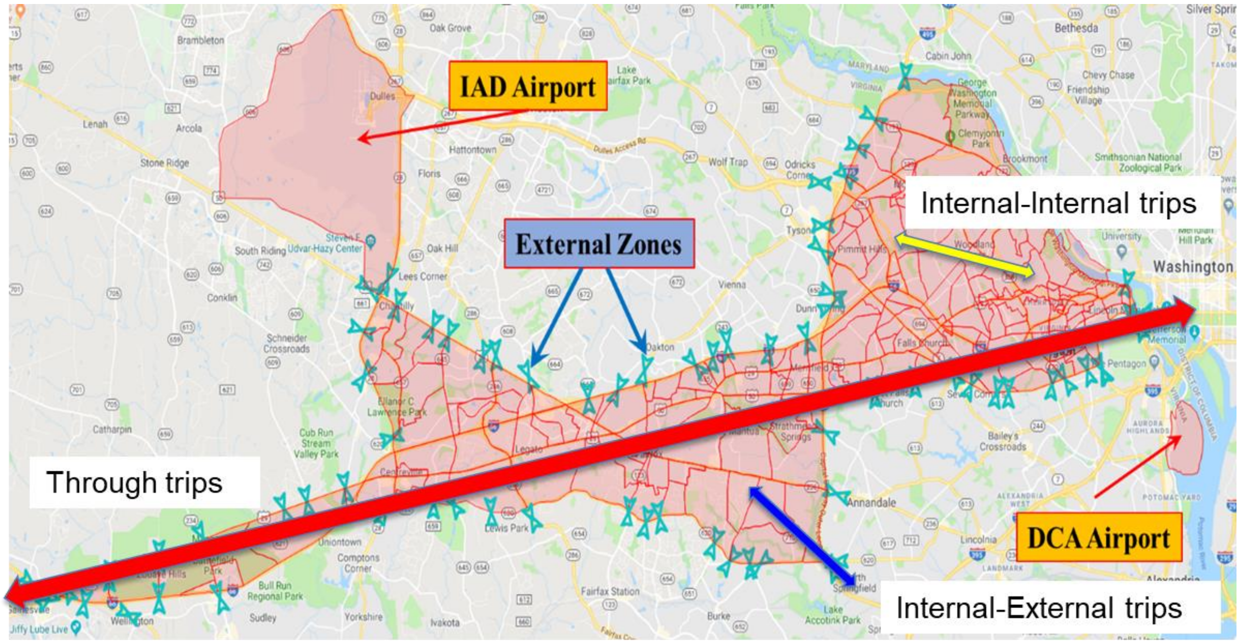


Figure 4. Illustration of the Sub-area Analysis. The yellow arrow represents the internal trips, the blue arrow represents the internal-external trips, and the red arrow represents the through trips. Zones in red are based on traffic analysis zones of the Metropolitan Washington Council of Governments planning model; Arrows in light blue represent external stations serving as major entrances and exits for the study area.)

The MWCOG model (National Capital Region Transportation Planning Board 2018) includes six vehicle classes: SOV, high occupancy vehicles with two persons (HOV2), high occupancy vehicles with three or more persons (HOV3), medium and heavy trucks (TRK), commercial vehicles (COM), and airport passenger vehicles (APV). Since APVs can no longer use ETLs for free, there is no need to treat them separately. According to MWCOG, the average vehicle occupancy for these vehicles is 1.6. The airport passenger vehicle matrices were therefore merged with single and high occupancy vehicle matrices, based on this average occupancy, assuming that all HOVs have an occupancy of two (40% to SOV and 60% to HOV). Moreover, commercial vehicles and trucks were only separated since version 2.2 of the MWCOG model with the objective to support the option of using passenger car equivalents in the traffic assignment process. This option has not been implemented in the MWCOG model. The current study thus did not separate these two vehicle categories as using a single category for trucks does not affect the operation of ETLs. Using a single vehicle category for trucks also improves computing efficiency.

Conducting Dynamic OD Estimation for Model Calibration

A microscopic traffic simulation model involves a lot of parameters that can be calibrated using locally collected data. Some of these parameters are related to driving behavior (e.g., acceleration rate, deceleration rate, braking rate, perception-reaction time, etc.) and are used in the car-following models. Some are used in route choice behavior (e.g., VOT, the dispersion factor in the stochastic route choice model, etc.). Others are used to simulate more subtle behaviors (e.g., look ahead distance for lane-changing, compliance rate for lane-control regulations, etc.). The purpose of this study is not to improve the modeling tool itself for microscopic simulation and the research team does not have the data to calibrate many of the aforementioned factors. For a corridor-level analysis, OD matrices and route patterns are usually directly observed and used as inputs to the modeling process. Therefore, the car-following behavior may be more important for model calibration. For a regional-level analysis, the uncertainty in OD matrices and path patterns are much more influential in linking volumes and corridor speeds. Given these considerations, this study used the default settings for most parameters and focused on dynamic OD matrices and VOT distributions for model calibration.

The VOT is estimated through a separate process, that is described in the following subsection where it is treated as a given in the dynamic OD estimation process. The objective of the dynamic OD estimation process was to adjust the time-dependent OD matrices in such a way that the simulated link flow matches the observed link flow for each hour of the study period at selected locations. This task differs from the conventional OD estimation process in that it needs to consider both the temporal (matrices of the current hour or of the previous hour) and geographic dimensions (which OD pairs) when adjusting the OD matrices. Given the dynamic nature of the problem, this is not an optimization problem that can be solved by a readily available numerical solution algorithm and there is no established method for dynamic OD estimation. This study used a method designed for a study aimed at developing a microscopic traffic simulation model for the Inter-County Connector corridor in Maryland (Zhang et al. 2013). This algorithm is a variation of the Multiple Path Matrix Estimation Method proposed by Nielsen (1997), which is designed for static OD estimation. The algorithm seeks to match the observed link flow by adjusting the OD demand that uses a specific link along its path. It differs from its static counterpart by considering the time required to reach a specific link along the path and mapping its impact to the OD demand with a corresponding departure time.

Given the scale of a regional simulation network and the number of uncertainties involved in the process (e.g., demand fluctuation and capacity fluctuation over time and space), calibrating a regional simulation model is very different from calibrating a simulation model for a corridor or calibrating a static model. There are no well-established guidelines for calibrating a regional microscopic simulation model. This study followed the principles for setting the calibration target, as outlined in VDOT's Traffic Operations and Safety Analysis Manual (TOSAM) (VDOT, 2020) and the methods used in the study by Weris Inc. Table 3 summarizes the calibration targets.

Table 3. Calibration Thresholds for the Corridor Toll Strategies Study

Simulated Measure	Calibration Threshold	Tolerance
Simulated traffic volumes (vehicle/hour) measured at selected locations and other major arterials shall meet the calibration thresholds for each hour during the study period.	Within 15% for freeways. Within 20% for arterials.	At least 85% of reported traffic volumes on links shall meet the criteria.
Simulated travel time (s) as measured on selected corridors along I-66 and other major arterials shall meet the calibration thresholds for peak hour/peak period.	Within 20% for average observed travel times on freeways. Within 30% for average observed travel times on arterials.	At least 85% of reported travel times on routes/segments shall meet the criteria.

Traffic volume data were collected from sensors deployed for the I-66 ITB HOT project, continuous counting stations maintained by VDOT and by the National Park Services (one each for US 29, US 50, and George Washington Parkway), traffic detectors deployed for the I-66 OTB Integrated Corridor Management project, and temporary traffic sensors deployed along I-66 OTB and parallel arterial roads by the I-66 Express Mobility Partners for design and planning purposes. These data sources provided good coverage for I-66, but only limited data for George Washington Parkway and arterial roads, and no data for I-495.

To supplement these data sources and expand the data coverage for arterial roads, the research team worked with VDOT and collected traffic detector data that is used for signal operations. For intersections with actuated signal plans, multiple sensors were deployed to measure traffic volumes for different lanes and/or turning movements. These data were aggregated at 15-minutes intervals and documented by VDOT. Each lane may have been covered by multiple detectors (e.g., a stop-line detector and an upstream detector) and some lanes may not have been covered at all (e.g., at intersections with only semi-actuated signal plans). Detailed maps of detectors were provided and the research team developed mapping for different turning movements between detectors and traffic volumes. Based on this mapping, the raw data were aggregated into traffic volumes for different turning movements and used to expand data coverage for arterial roads. Appendix B shows an example of such a process.

Data for May 2018, the selected modeling period, were collected from the aforementioned data sources. Data from Tuesdays, Wednesdays, and Thursdays were extracted and aggregated into hourly traffic volumes. The modeling periods were 5 to 10 AM for the morning peak period and 2 to 8 PM for the afternoon peak period. The I-66 OTB ETLs are scheduled to charge tolls on a 24/7 basis, while the I-66 ITB ETLs charge tolls on weekdays between 5:30 am and 9:30 am for the eastbound and between 3:00 pm and 7:00 pm for the westbound.

Traffic speed was derived from INRIX XD data. The XD data was aggregated into 5-minute intervals. Data for some XDs and time stamps could be missing. In these cases, the route travel times were prorated from the available data. The route travel times were calculated from the instantaneous speeds for each XD segment that was a part of that route. The data were also aggregated into hourly averages for selected corridors.

The model calibration followed an iterative process using the volume data until the calibration target had been met. Minor adjustments were then introduced to improve the match for speed profiles.

Developing the Network and Modeling Files for I-66 OTB ETLs

The I-66 OTB project is a public-private partnership between VDOT, the Department of Rail and Public Transportation, and a private partner, I-66 Express Mobility Partners. The project includes 22.5 miles of new express lanes, alongside three regular lanes on I-66 from I-495 to University Boulevard in Gainesville, and several important interchange improvements, including auxiliary lanes between interchanges. The new ETLs will be dynamically-tolled and free for vehicles with an occupancy of three or more, based on the information posted on the project website (http://outside.transform66.org/). The project is currently under construction and is scheduled to open in December 2022.

The research team developed the simulation network of the I-66 OTB ETLs, based on the detailed concept plans published on the project website (dated as March 2017). For most sections, this project includes two lanes each way for the ETLs and three lanes each way for the general purpose (GP) lanes. ETLs run in the middle of the corridor that includes GP lanes on each side. ETLs and GP lanes are physically separated for the entire project, except for a small segment near the interchanges with US 29 at Centerville, where ETLs and GP lanes are merged and vehicles can change lanes between them, if desired. At other locations, users need to use ramps to enter the ETLs. Figure 5 illustrates the locations of entrances and exits of the I-66 ETLs. Pink arrows represent entrances while blue arrows represent exits. Black arrows represent the locations where drivers can both enter the ETLs or exit from them. The orientation of the arrows shows that a particular entrance or exit can be used by traffic in only one direction (e.g., eastbound or westbound) or in both directions (arrows perpendicular to the ETLs).

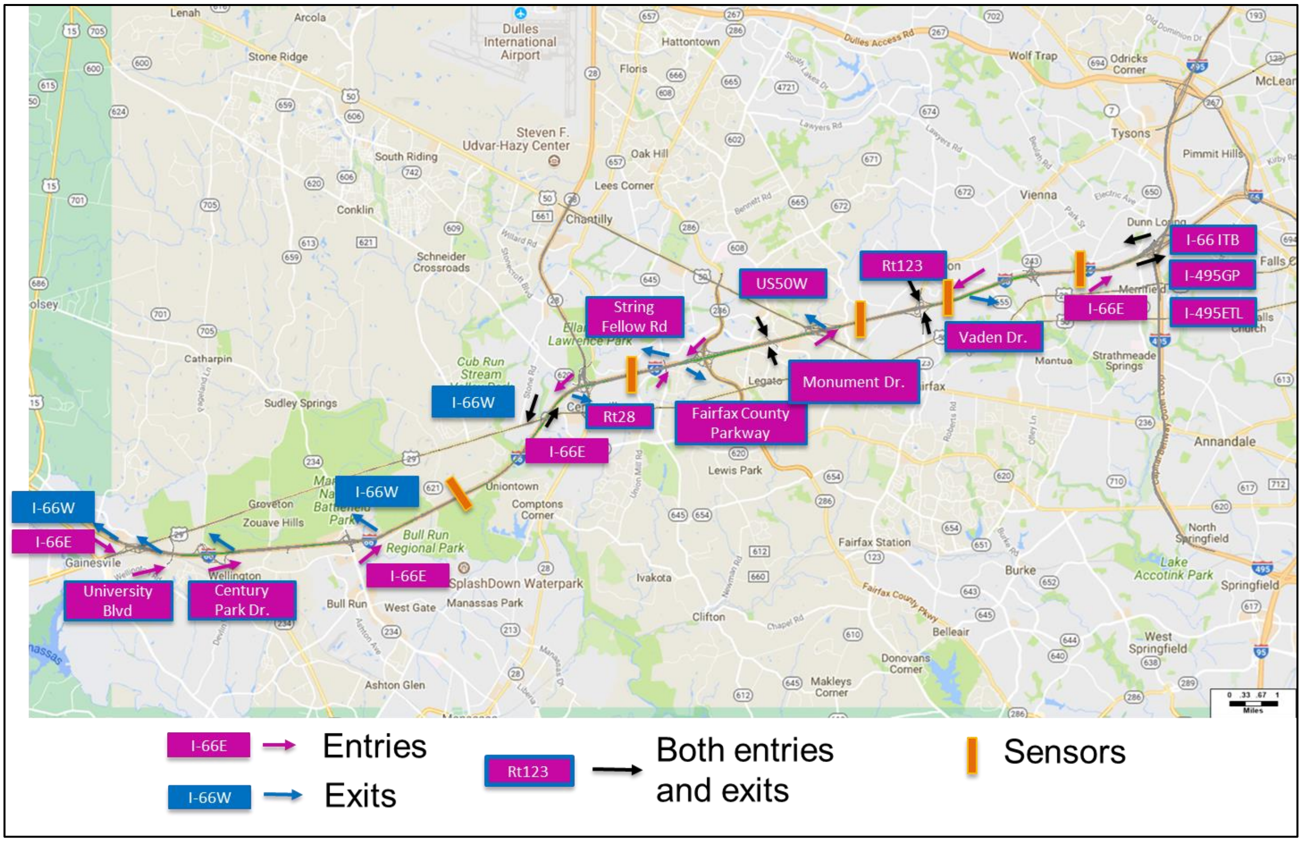


Figure 5. Entrances and Exits of the I-66 Outside-the-Beltway Express Toll Lanes.

The I-66 OTB project also involves several important interchange improvements, including the interchange with Rt. 28 at Centerville, the interchange with Rt. 123 near the City of Fairfax, and the conversion of the segment of Nutley Street over I-66 into a diverging diamond interchange. These improvements may provide improved access to the I-66 OTB ETLs and, at the same time, improve traffic flows on local roads. The research team modified the simulation network to accurately replicate these alignment changes.

Because the I-66 OTB project is a P3 project, the DPA to be used is proprietary and is not available to the research team. This research project assumed that the DPA, to be used by the I-66 OTB, would be the same as the one currently used by the I-66 ITB ETLs. Based on the current DPA, the toll rate per mile is a function of the traffic density on the ETLs, as described by the equation below:

$$\tau_t = (\theta \times D_t)^{\beta} \qquad (1)$$

Where:

τ_t is the toll rate per unit distance at time t, measured in dollar/mile;

D_t is the density of the ETL measured for the time interval right before t in vehicle/mile/lane;

θ is a scaling parameter related to the critical density beyond which the toll rate will increase rapidly; and

β is an exponent.

The current DPA applied for the I-66 ITB project (labeled as DPA10A) used 0.047 for θ and 1.75 for β.

The toll charged for each trip is the product of the per-mile toll rate at the moment of use and the distance travelled, summing through all ETL zones that a particular user has gone through. As the detailed toll setting plan is not available, this project assumed that the entire I-66 OTB project was split into five zones, similar to the plan used by the I-66 ITB project. Figure 6 shows the five zones for the eastbound traffic and the locations where traffic sensors are located in each zone. Table 4 shows the starting point, ending point, and the length of each toll zone. For westbound traffic, traffic would go through the corridor in reverse order, from Zone 5, located at the east end (I-495) of the project, to Zone 1, located at the west end (Gainesville).

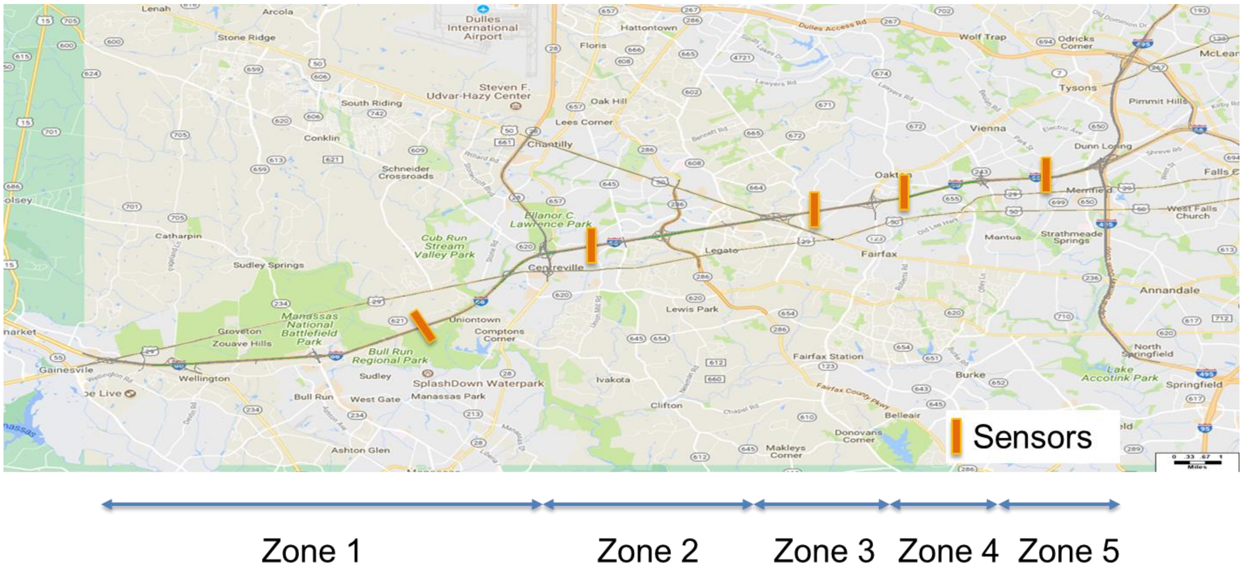


Figure 6. Toll Zones for I-66 Outside-the-Beltway Express Toll Lanes.

Table 4. Starting Point, Ending Point and Length of Each Zone for I-66 Outside-the-Beltway Express Toll Lanes Eastbound Traffic

Zone ID	**1**	**2**	**3**	**4**	**5**
From	Gainesville	Rt. 28	Monument Dr.	Rt. 123	Vaden Dr.
To	Rt. 28	Monument Dr.	Rt. 123	Vaden Dr.	I-495
Length (mile)	9.94	3.79	3.13	1.89	2.56

There may be multiple entrances and exits for each toll zone. However, this study assumed that a user, who enters a particular toll zone, pays the same toll (using the zone length as specified in Table 4), no matter which entrance or exit is used. This simplified toll structure is more practical, as we can only show a very small number of destinations with associated tolls for each sign. This plan is also consistent with the current practice for the I-66 ITB project.

A GISDK (a script language for Geographical Information Systems software produced by Caliper) script was developed to read density from each sensor at 1-minute intervals, and the density was smoothed on a rolling horizon for the last 6 minutes. The toll rate for each zone was updated once every 6 minutes, following Equation 1. For each entrance and exit pair, the per-trip toll was calculated based on the toll rates of zones to be used and the length of the corresponding zones, which was also updated at 6-minute intervals. Toll signs were placed at the upstream of each ETL entrance in the simulation model. When vehicles were passing through the toll signs, during the simulation, the system fed them with the travel time and cost (including tolls), at that moment, for the path using the ETL and the non-tolled alternative. Vehicles chose the path stochastically, following a logit model.

Developing Behavioral Models to Capture Demand Changes

Travelers may react to travel cost changes, because of tolls, by changing routes, mode, or departure time. To capture travel demand changes, in reaction to tolls beyond route switches, the research team augmented the microscopic traffic simulation model by integrating it with an agent-based departure time choice model and a mode choice model.

Mode Split Model

The I-66 OTB ETLs are an important commuting corridor for travelers, who live in the Northern Virginia suburban area, but need to commute to business districts, either in Arlington County or in downtown Washington, D.C. The Washington Metro Orange Line and Silver Line serve the same corridor and offer a competing mode for driving. Several commuting bus lines also run along the corridor. As the I-66 OTB ETLs will change the travel time and travel costs along the corridor, they may also affect the mode choice of travelers in the region. Moreover, given that the toll to be charged is affected by vehicle occupancy, it is likely that travelers may also choose the carpool/vanpool mode because of the opening of these ETLs. To account for such impacts, this study integrates the simulation model with an agent-based mode split model. Mode choice is usually modeled using a nested-logit model. Figure 7 shows the structure of the nested-logit model adopted by the MWCOG planning model, which includes two upper-level nests: driving and transit. Driving modes include SOV, HOV2, and HOV3+. Transit modes include combinations of four major modes and three access modes, leading to a total of 12 modes. The MWCOG planning model skims the transit network, including access/egress links to collect the travel time and costs for different modes, and to run the nested-logit model for mode split. However, the detailed implementation method and parameters to be used are not available in the users’ manual (NCRTPB 2018). Moreover, the manual also recommends that the mode splits are only used at the metropolitan region level due to the lack of calibration for finer zones.

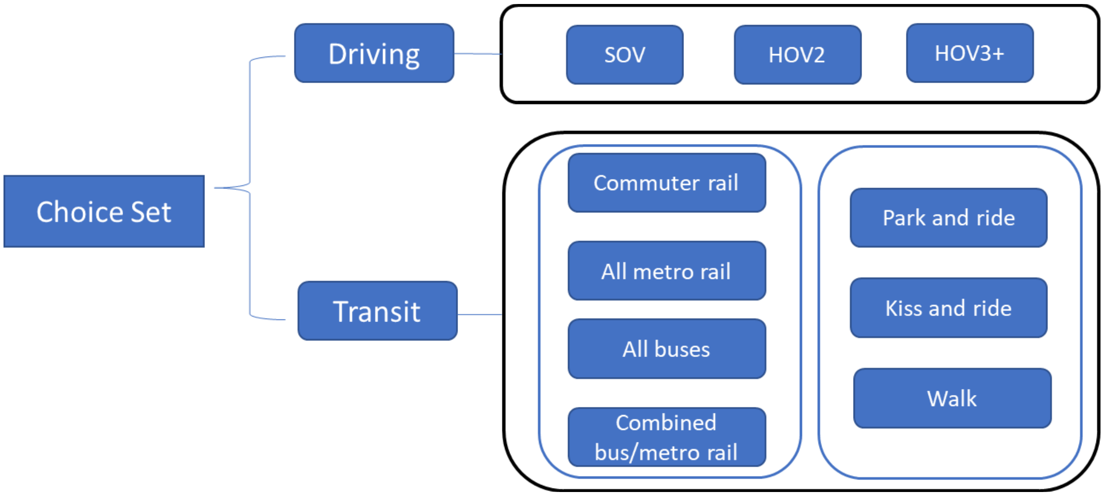


Figure 7. Structure of the Nested-logit Model in the Metropolitan Washington Council of Governments Planning Model.

To overcome this data challenge, this study used a similar nested-logit model that was developed using locally collected data. The research team recently collected a set of mode choice data through a series of surveys conducted before, during, and after the Washington Metro Safetrack project (Zhu et al. 2017). The data included home and work locations, the metro stations used by survey respondents, the mode used during the Safetrack project, and social demographic variables. The research team reconstructed travel time and costs for each possible mode that all respondents may face using Google, Metro, and Uber APIs. A nested-logit model was estimated. Figure 8 shows the structure of the Nested-logit Model (Yang 2018).

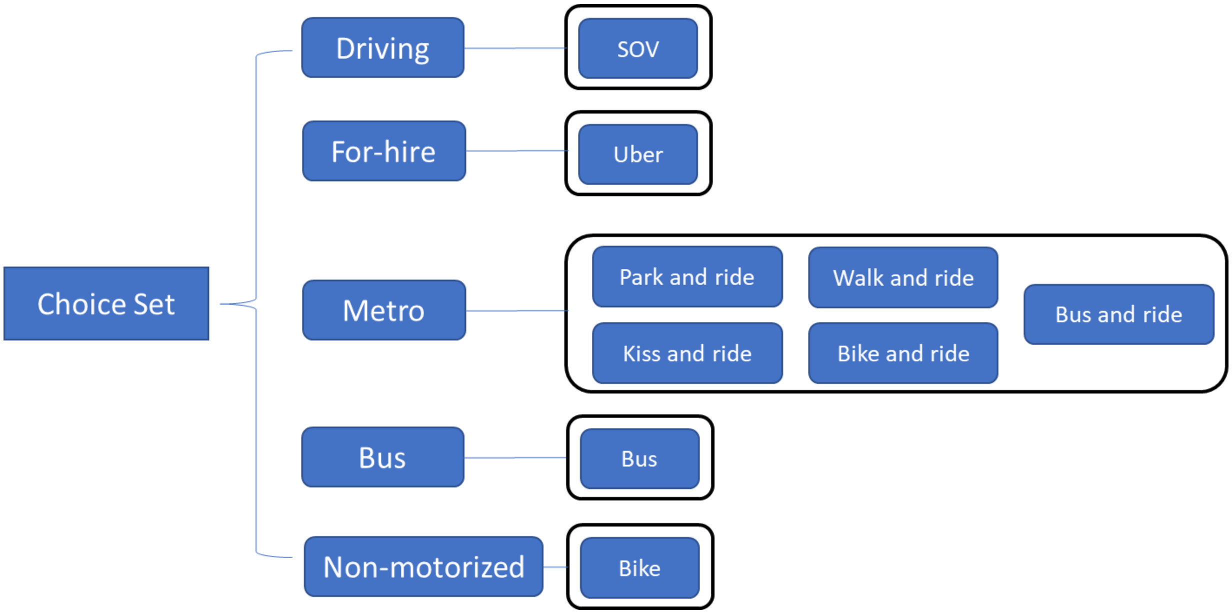


Figure 8. Structure of the Nested-logit Model in the Washington Metro Safetrack Study.

The model includes the travel time, out of pocket travel costs, and type of Safetrack disruptions as lower-level variables, and the age, income, and gender as upper-level variables. The model yields a VOT estimate of $31.89/hour among metro riders.

In this study, we do not have travelers' social demographic information. In addition, it is impractical to consider so many modes and develop a specific network structure to skim the travel time and travel costs for each mode. The main objective is to consider the impact of ETLs on the splits between SOV, HOV2, HOV3+, and riding transit. To achieve this objective, this study kept the nested-logit modeling structure and the VOT parameters that were estimated in previous studies to predict the mode splits. This study calibrated the constants in the model to keep the overall mode splits consistent with current field observations.

The corridor is served by the Washington Metro Orange line, regional express buses, and local buses. Two Metro stations, along the Orange line, are located along the I-66 OTB corridor: Vienna and Dunn Loring. Since the Dunn Loring station is very close to the interchange between I-66 and I-495, the impact of travel time improvement along I-66 OTB should have minimal direct impact on the mode shift from this station. We only consider the ridership from the Vienna station.

The cross-elasticity of the mode share for the metro, as a function of travel time for driving, is defined as:

$$E_{x_{jk}}^{P_i} = \frac{\partial lnP_i}{\partial lnx_{jk}} = -P_j x_{jk} \beta_k \qquad (2)$$

Where $E_{x_{jk}}^{P_i}$ is the cross elasticity between the probability for riding a metro (P_i) and the travel time of driving (x_{jk}), β_k is the parameter associated with travel time in the logit model. As a first-order approximation, we ignored the difference between park-and-ride, kiss-and-ride, walk-and-ride, and bus-and-ride. This cross-elasticity was then applied to estimate the changes of the metro ridership as a result of travel time changes due to ETLs. These changes were then distributed to relevant OD pairs along the corridor.

According to the project website (https://outside.transform66.org/), the I-66 OTB project also includes new and improved bus service and transit routes. However, details are not available as to what such improvements could be. Ridership data on existing bus routes is also very rough. Most agencies only provide ridership for the entire line for a day (thus, no OD information), making it hard to associate travel time improvement with a particular OD pair, or even a corridor. The number of bus riders is also much smaller, as compared to the metro ridership. Therefore, this project did not consider the impact on bus ridership due to the lack of data. Future studies could address this.

Agent-based Departure Time Choice Model

To avoid congestion during the peak period or paying a high toll rate, travelers may adjust their departure time. However, considering route choice, mode choice, and departure time choice within the same modeling framework is very challenging. There have been some studies that tried to address this problem analytically under a discrete choice modeling framework. However, calibrating such a model is very difficult because of the lack of data and computational resources. This study adopted a framework that treats each traveler as an independent decision maker who tries to improve overall utility by trying to adjust the departure time through a learning process. Compared to the current condition, if the overall travel costs associated with a different departure period decline, then travelers departing at a neighboring time window may consider changing their departure times. The change is related to the magnitude of potential utility gains. This method has been implemented in an integrated travel demand and traffic simulation model that was developed for the Inter-County Connector corridor in Maryland (Zhang et al. 2013).

The mode split and departure time choice models were implemented as an outer-loop to the traffic simulation model to adjust travel demand in reaction to travel cost changes. In each iteration, the simulation model skims the network for travel time and travel costs for selected OD pairs (OD pairs, along the I-66 OTB corridor, with a demand higher than 100 vehicles/hour). The agent-based departure time choice model simulates the departure time choice, while the mode split mode estimates the changes in demand for driving. These two models run independently, and new travel demand tables are calculated. Considering the computing time, this study adopts the practice of the MWCOG model and limits the total number of out-loop runs to four (NCRTPB, 2018).

Simulating Different Scenarios and Conducting Impact Analyses

Based on discussions with the TRP and other VDOT stakeholders, the research team identified five high priority factors and the corresponding values to be investigated. These factors include: 1) alternative parameters for the dynamic pricing algorithm, 2) occupancy requirements for using the ETLs free of charge, 3) higher or lower traffic growth rates, 4) different assumptions about vehicle occupancy changes in reaction to toll policies, and 5) different value of time distributions. To keep the analysis tractable, this study first investigated these factors, one at a time. Table 5 summarizes 12 single factor scenarios, including the baseline scenario, that were investigated in this study.

Table 5. One Factor Scenarios (with Levels/Cases)

ID	Strategies/Scenarios	Parameters	No. of Cases
A	I-66 OTB DPA as the I-66 ITB *This will serve as the baseline scenario.*	Beta=1.75, theta=0.047 (*DPA10A)*	1
B	HOT2->HOT3	Categorical *HOT3 is the default.*	1
1	Alternative DPA *Theta decides the critical density beyond which the toll rate would increase rapidly (0.026 corresponds to 38.5 veh/mi/lane), beta is the exponent that decides the speed of toll increase.*	1) Beta=2, theta=0.02 2) Beta=1.5, theta=0.026 *These are alternatives that were used in the Weris study.*	2
2	Higher traffic growth rate *This scenario captures the impact of different traffic growth rates. A traffic reduction scenario is introduced to capture potential impact of post COVID-19 conditions or a recession.*	1) 2.5% more traffic along the corridor 2) 5% more traffic along the corridor 3) 5% less traffic along the corridor	3
3	Occupancy change vs. no-change *This scenario considers the impact if vehicle occupancy is insensitive to the introduction of HOT for some reason (e.g., COVID-19)*	Categorical *(Flexible SOV/HOV as default and fixed SOV/HOV split as the alternative)*	1
4	VOT change *This scenario tests the sensitivity of the model to alternative VOT distributions.*	VOT of +10%, +20%, -10%, and -20%	4
Total			12 cases

HOT2: High occupancy and toll lanes where a vehicle of two or more occupants can use them for free
HOT3: High occupancy and toll lanes where a vehicle of three or more occupants can use them for free
I-66 OTB: I-66 Outside-the-Beltway
I-66 ITB: I-66 Inside-the-Beltway
DPA: Dynamic pricing algorithm
SOV: Single occupancy vehicle
HOV: High occupancy vehicle
VOT: Value of time

The research team assumed that the per-mile toll rate would be calculated using Equation 1 once the I-66 OTB ETLs are in operation. The default DPA is the one used for the I-66 ITB project (DPA10A). The two alternative sets of DPA parameters were selected based on discussions with the TRP. Figure 9 shows the corresponding toll rates, as a function of ETL density, under different DPAs. The two alternative DPAs selected for analysis generate milder toll rate increase, as compared to the baseline DPA.

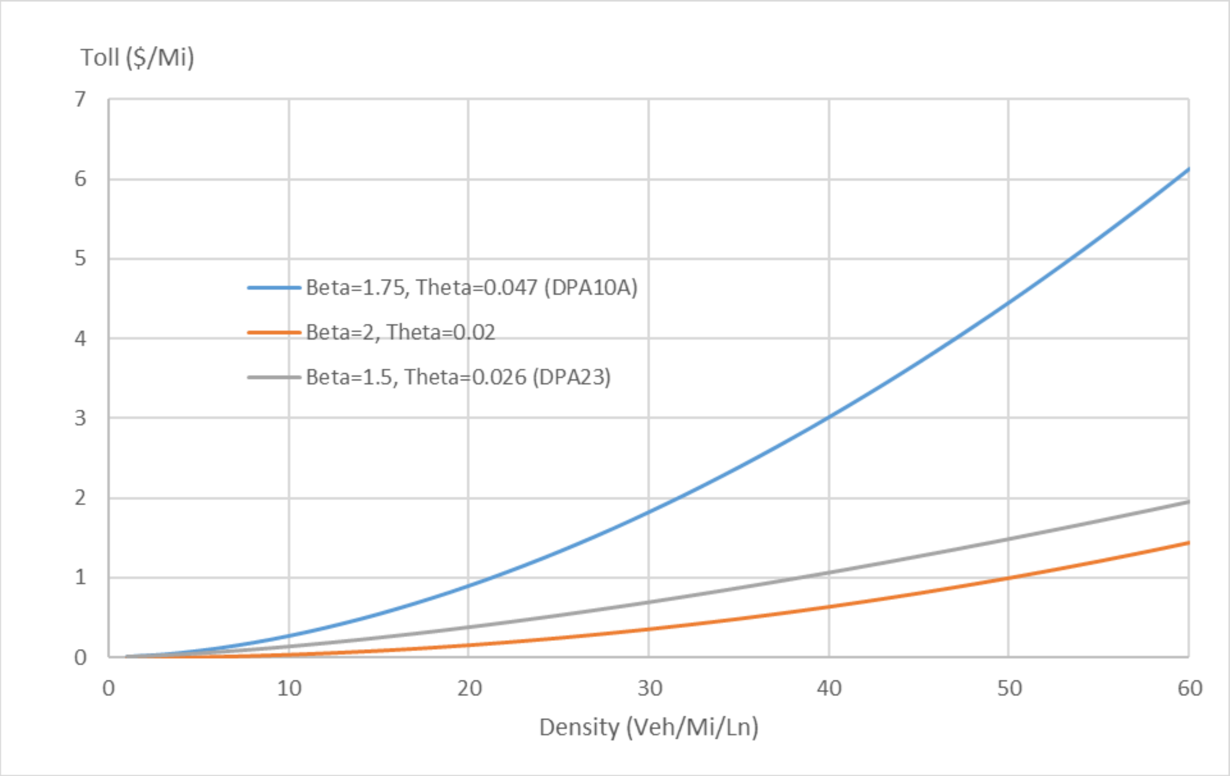


Figure 9. Toll Rates as a Function of Density Under Different Dynamic Pricing Algorithms.

In baseline scenario A, the research team assumed that the I-66 OTB ETLs are free for vehicles of three or more occupants, while vehicles with one or two occupants need to pay a toll based on the current plan (I-66 Express Mobility Partners, 2019). In scenario B, the research team evaluated the impact on the corridor if the toll policy were changed from HOT3 to HOT2.

Unlike a traffic simulation study of a single corridor, it is impossible to control exactly the amount of traffic entering the simulation network, based on field observations, in a regional-level study. Instead, the OD matrices are estimated through a dynamic estimation process that aims at matching the simulated traffic with field observations to the extent possible. In addition, future travel demand is also uncertain due to factors such as economy or behavioral changes caused by COVID-19. To account for all of these uncertainties, this study also evaluated traffic conditions under scenarios of higher (2.5% and 5%) or lower (5%) total travel demand.

Most corridor-level simulation studies assume that vehicle occupancy is fixed. This study integrated the traffic simulation model with travel demand models to account for potential mode shifts, including changes in vehicle occupancy. This study also conducted a sensitivity test to evaluate a scenario in which vehicle occupancy is assumed to be fixed to show the difference.

Estimating VOT distributions for a region is a big challenge for researchers and practitioners. Although this study improved the VOT estimation, using locally collected data, it still relied on a range of generalized assumptions for the region. This project also conducted a sensitive test to evaluate traffic conditions if alternative value of time distributions were assumed ($\pm 10\%$ and $\pm 20\%$).

Interactions among two or more factors, based on their likelihood of happening and VDOT’s ability to respond to them, were also deemed important. Among the multi-factor scenarios, the impact of the COVID-19 pandemic on travel demand is a hotly debated research and policy question. Some researchers (e.g., by Rohr, 2020) argued that the total demand for driving may become larger because travelers may move away from car-pooling and public transit due to a preference for increased social distancing. Other researchers argued in the media coverage (e.g., Papandreou, 2020) that the demand for travel could drop for a longer period because of factors such as an increased use of telecommuting. There is no consensus in the research community on the overall impact of the pandemic on travel demand in the long term. To investigate the potential impact of COVID-19 on the performance of the I-66 OTB ETL corridor, this study conducted a sensitivity analysis, based on assumptions that favor either end of the debate. Two scenarios were selected as the boundary conditions, following discussions with the VDOT technical review panel.

Both scenarios assume that travelers exhibit an increased desire for social distancing in the post COVID-19 era, which leads to a 20% reduction for high occupancy vehicles in the traffic and a 20% reduction in transit ridership. The first scenario assumes a 10% decrease in overall travel demand, because of the increased use of telecommuting and a slower economy after the pandemic, while the second scenario assumes a 10% increase in overall travel demand, because of the reduced use of ridesharing and transit, increased use of delivery services, and a stronger rebound of the economy.

Table 6 summarizes all two-factor scenarios, while Table 7 summarizes the multi-factor scenarios. Given the time limit of this project, only scenarios of high priority were analyzed. Scenarios of medium priority (in italic font) were left for future studies. Particularly, M1 scenarios in the multi-factor analysis were designed to analyze the potential impact of COVID-19 on the network, based on discussions with the TRP and other VDOT stakeholders.

Table 6. Two Factor Scenarios (with Single Factor Scenario Levels/Cases in parentheses)

		Factor 2	
		Traffic growth * (2)	**Value of time change$^+$ (2)**
Factor 1	Alternative dynamic pricing algorithm	4	4
	Traffic growth		4

* Only traffic demand +5% and -5% were considered, as bounding conditions.
+ Only value of time +10% and -10% were considered, as bounding conditions.
The total number of two-factor cases under each factor-combination is presented in each cell.
Occupancy change vs. no-change *scenarios were not studied in this project.*

Table 7. Multi-factor Scenarios and Factors (with Levels/Cases in parentheses)

ID	Strategies/Scenarios	Parameters	No. of Cases
M1	Post COVID-19 (less split for HOV, less demand for transit, potentially lower overall demand for travel due to telecommuting and a slower economy; need for social distancing my increase overall road traffic demand with reduced HOV and transit usage)	HOV -20%; transit -20%; travel demand -10% (1 case) HOV -20%; transit -20%; travel demand +10% (1 case)	2
M2	Scenarios favoring higher demand for ETL (higher traffic growth/ higher VOT/DPA for slower toll growth)	Traffic + 2.5% and +5% (2) VOT +10% and +20% (2) Alternative DPA (2)	*8*

ETL: Express toll lanes
HOV: High occupancy vehicle
VOT: Value of time
DPA: Dynamic pricing algorithm
Numbers in italics represents scenarios of medium priority that were not studied in this project due to time limit.

Disseminating Results through Workshops and an Interactive Web Portal

A total of 28 scenarios were analyzed for this project. Analyzing and reporting the large volume of simulation outputs is challenging. In addition, it is difficult to highlight the multi-dimensional results (e.g., revenue, throughput, etc.) in regard to various contributing factors. To help VDOT stakeholders visualize the results and make informed decisions, the research team developed a web-based tool for this project. This tool is GIS-based and shows important modeling outputs, including average speed and flows of super-links (super-links are a set of links that are connected and should be analyzed as a whole in TransModeler to avoid local fluctuation) in different hours of the simulation period. This web-based tool facilitates decision-making by providing comparative analyses of the impact of different tolling strategies on target corridors and parallel arterials across different periods in a day. This tool can be further expanded should new scenarios emerge that VDOT is interested in exploring. Appendix E provides some screen shots of the web-based tool.

The research team hosted two workshops to engage VDOT stakeholders, share research findings, and collect feedback. The first workshop (conducted online on May 19, 2020) focused on the model development and model calibration. The second workshop (conducted online on January 29, 2021) focused on the findings from the scenario analysis and the web-based tool for supporting informed decision-making. The research team also discussed toll setting mechanism and route choice behavior in the simulation model developed in the current study to help VDOT stakeholders better understand the capacity and limitations of the model.

RESULTS

Literature Review

Microscopic Simulation Model for Express Toll Lane Studies

Microscopic traffic simulation models have been widely applied to evaluate transportation projects of small (i.e., a single intersection) or medium (i.e., a freeway or arterial corridor of limited size) scales. However, they have rarely been applied to investigate a HOT project with regional impacts. The National Cooperative Highway Research Program Report 722: Assessing Highway Tolling and Pricing Options and Impacts (NCHRP, 2012) provided a comprehensive review of the modeling tools that have been applied to evaluate highway tolling and pricing options and impacts. The majority of models that have been applied to evaluate highway pricing projects were essentially modifications of existing regional planning models. These models are static in nature and cannot effectively consider dynamic tolling strategies and corresponding traffic dynamics. Examples of this approach even include the I-394 HOT Lanes in the Twin Cities, Minnesota, and the Managed Lanes Study in Northern Virginia (conducted by the MWCOG), both of which involve dynamic pricing strategies.

The practice of using microscopic traffic simulation models to evaluate highway tolling strategies has not been widely adopted for several potential reasons. Dynamic toll strategies, that change toll rates based on real-time level of congestion observed in the field, have not been popular, until very recently. Without dynamic tolls, the need for applying a microscopic traffic simulation model to an impact analysis is not as strong. Moreover, developing a microscopic traffic simulation model for a regional network is very time-consuming. It also requires a lot of data for model development and calibration. Such an investment may not always be economically viable. Finally, running such a model may take a lot of computing resources and requires a deep understanding of the simulation environment, which may be beyond the capacity of the agency that develops and/or operates the toll road. A search of mainstream databases of transportation literature only returned two examples of such an effort: one by Kerns and Paterson (2012), which developed a microscopic traffic simulation model in TransModeler to analyze the Capital Beltway HOT Lanes; and the other by Nikolic et al. (2014), which described a similar effort for Ontario, Canada, under the simulation environment of AIMSUN. The presentation of these two studies was very brief because details about the implementation method are considered proprietary information.

Empirical Studies of Express Toll Lanes and Value of Time Estimation

As transaction data for most HOT lanes or ETLs are proprietary, there have been very few studies in the literature that analyze their demand characteristics based on real facility usage data. Instead, many studies relied on stated preference survey data for VOT estimation. For example, Brownstone et al. (2003) analyzed a set of stated preference data collected at the San Diego I-15 HOT lanes and found an average VOT of $30/hour. Li et al. (2010) and Carrion and Levinson (2012) provided a comprehensive review of this field.

Among a few exceptions, Burris et al. (2012) analyzed the VOT using data collected from the I-394 MnPASS express lanes in Minneapolis, Minnesota, and the I-15 express lanes in San Diego, California. They found an average $73/h in the morning and $116/h in the afternoon for MnPASS users and an average of $49/h in the morning and $54/h in the afternoon for I-15 users. Wood et al. (2014) analyzed the data from I-85 Express Lanes in Atlanta and found a median willingness to pay for express lane travel time savings of $19.45 per hour across all time periods and $33.17 per hour for southbound a.m. peak travel. The corresponding mean value for both directions, and across all periods, was $36.07/h, while the mean value was $49.95/h for the southbound during the peak period. Morgul and Ozbay (2015) analyzed HOT lanes data from State Road 167 in Washington to study the value of schedule delays (VSD) and found that VSD could be as high as $17/hr.

Liu et al. (2011) differentiated users as frequent and non-frequent users, using transaction data collected from the SR-167 HOT lane in Washington State, and found a mean VOT of $17.9/h for infrequent users and $18.1/h for frequent users. They used data from 21 workdays (Tuesday through Thursday) in February and March 2009. They defined frequent users as those who used the corridor 14 days (two-thirds of the days) or more, during the study period. The difference between the two is statistically significant. Sheikh et al. (2014) evaluated the VOT distributions by t time of day, using transaction data collected at I-85 Express Lanes in Atlanta, Georgia, and found a VOT distribution resembling a gamma distribution, with the southbound data yielding a higher mean ($55/h) and more dispersion than the northbound (a mean of $34/h). The corresponding median value of time was $36/h for the southbound direction and $26/h for the northbound direction. They found little difference in VOT among infrequent (<75 trips in 9 months), frequent (>=75 and <115 trips), and very frequent users (>=115 trips). The estimated VOTs were significantly larger than those reported by Wood et al. (2014). Sheikh et al. (2014) used data collected from September 2012 to May 2013, and only trips that traversed the entire ETLs were considered. In comparison, Wood et al. (2014) used data collected from February 25, 2012, to August 24, 2012 and considered all trips that were recorded. This difference in data may explain the significant difference in estimated results, and also highlights the challenges in empirical studies and the need for more evidence.

In one of two more recent studies, Burris and Brady (2018) analyzed the VOT among the users of the Katy Freeway in Houston, Texas, and the North Tarrant Express in the Dallas–Fort Worth metropolitan area, using complete toll transaction data for 3 months from each facility. They found that 80.7% of the Katy Freeway express toll lane users and 72.8% of the North Tarrant Express ETL users were infrequent users, with a monthly usage of 1 to 3 trips, on average. They found a mean willingness to pay to use the Katy Freeway express toll lane of $44/hour, and the difference between user groups of different frequency (1 trip, 2-5 trips, 6-10 trips, and 11+ trips) was not significant. The authors also found that about 9% of express toll lane trips would be shorter in travel time if users were to take the general purpose alternative, leading to a negative value of time estimation.

The other recent study was by Hallenbeck and Iverson (2019), who used 1-year of transaction data along the I-405 ETLs in the Puget Sound (Seattle) region, Washington. They found that 48.2% of the users recorded in 2018 only used the facility once, 43.7% of them had between 2 to 40 trips, 4.7% had between 41 to 120 trips, 2.1% had between 121 and 250 trips, 1.1% had between 251 and 600 trips, and 0.1% had over 600 trips. Instead of calculating the willingness to pay by directly comparing the time savings and the toll paid, the authors estimated a linear regression model. They estimated a VOT of $53/hour and a value of reliability of $26/hour. The authors argued that a direct comparison is unreliable as users may not know exactly the potential time savings offered by the ETLs, and replaced it with an estimated surrogate measure using the current toll level, the time of day, the route, the speed and volume of the GP lanes at that location, and the speed and volume of the HOT lanes. However, this difference in estimation approach makes the results less comparable with previous studies. In addition, this study did not differentiate the value of time by frequency of express toll lane usage.

Empirical analysis of usage of HOT/ETL facilities, based on actual transaction data, is still rare. Among a few studies that were reported in the literature, the estimated VOTs span over a wide range due to differences in local conditions, express toll lane designs, and value of time estimation methods.

Value of Time Estimation

As described in the Methodology Section, this project estimated the VOT using the toll transaction data and the INRIX speed data collected along the I-66 ITB ETL corridor during a 3-month period in 2018. Table 8 shows the number of trips per user classes and for each hour of the tolling period. Frequent users are defined as those who used the I-66 ITB ETLs at least once per week, on average, during the 3-month study period. A total of 46% of the SOV trips during the morning peak, and 30% during the afternoon peak, were made by frequent users, respectively. The percentage of trips made by frequent users was much higher in the HOV groups. Appendix F presents the percentage of the number of unique users, instead of the number of trips. Since HOVs do not have to pay for using the toll facility, only SOV trips were used in the VOT calculation.

Using the VOT definition described in the Methodology Section, empirical density plots were created for EB and WB SOV trips, as shown in Figure 10. The best fitting log-normal distributions were overlaid on the density plots. From the plots in Figure 10, the VOT of the EB users was higher than that of the WB. While there did not seem to be a significant difference between the distributions of the WB frequent users and the non-frequent VOTs, this was not the case for the EB users. The average VOT was $62/hour for non-frequent users, as opposed to $45/hour for the frequent EB users. This corresponded to a 36% higher VOT for non-frequent users.

The empirical VOT density plots during the morning peak period, as shown in the upper half of Figure 10, show a bi-modal distribution with two distinct peaks for both the frequent and non-frequent users. No such patterns have been reported in the literature. It is unclear if this bi-modal distribution is due to the small sample size, the distinct distribution of tolls calculated/set by the DPA, or if there are, indeed, two distinct user groups with different VOT distributions. Future research studies with more data are needed to further explore this issue.

Table 8. Number of Trips Between I-495 and the DC Line along I-66 Inside-the-Beltway Express Toll Lanes and Their Breakdown by Frequent and Non-Frequent Groups

Dir.	**Time**	**SOV and HOV**	**SOV**			**HOV**		
		Trips/hr	**Trips/hr**	**% Freq**	**% Non-freq**	**Trips/hr**	**% Freq**	**% Non-freq**
EB	5:30-6:30	845	493	61%	39%	352	76%	24%
	6:30-7:30	1,034	385	52%	48%	649	80%	20%
	7:30-8:30	963	294	36%	64%	669	76%	24%
	8:30-9:30	690	278	21%	79%	412	64%	36%
	Total	**3,531**	**1,449**	**46%**	**54%**	**2,082**	**75%**	**25%**
WB	15:00-16:00	811	496	24%	76%	315	58%	42%
	16:00-17:00	1,068	519	33%	67%	550	69%	31%
	17:00-18:00	1,074	482	33%	67%	592	72%	28%
	18:00-19:00	743	410	31%	69%	332	65%	35%
	Total	**3,695**	**1,906**	**30%**	**70%**	**1,790**	**67%**	**33%**

EB: Eastbound
WB: Westbound
SOV: Single occupancy vehicle
HOV: High occupancy vehicle
Frequent users are defined as those who used the I-66 ITB ETLs at least once per week, on average, during the 3-month study period.

To generalize the findings of this analysis for the VOT distribution of all travelers in the region, we still needed to address a few additional questions. Figure 10 (based on the SOV travelers who went through the entire I-66 ITB ETLs) refers to trips, instead of unique users. As shown by the difference between the VOT observed, during the morning peak and the afternoon peak periods, travelers had different VOT for different trips. Therefore, there is no reason to reject an estimation based on trips instead of users. From a modeling perspective, it is impractical at this point to assume different VOT distributions for users going to different destinations. We decided to use this estimation to infer the VOT distribution for travelers in the entire region until better data sources become available to support a more accurate distribution. To directly use the VOT distribution (estimated in Figure 10) is problematic because of the self-selection issue (trips with higher VOT were more likely to use I-66 ITB ETLs, as compared to those who did not). Based on an early study conducted by Weris Inc., traffic using I-66 represented 59.8% of all traffic crossing the screen line drawn along the Patrick Henry Drive (at the approximate mid-point of the I-66 ITB ETLs) during the morning peak, and 51.5% of all traffic during the afternoon peak period. Without better data sources, we assumed a VOT, used by the MWCOG model, for all other trips without a direct estimate. The mean VOTs were calculated, based on the estimated VOTs of different trip classes and the corresponding weights, as documented in Table 9. A mean VOT of \$30.50/h for the morning peak period, and \$25.80 for the afternoon peak period, were used for SOVs in this study. The values used for the region in this study were slightly higher during the morning peak period than those used by Weris Inc. in a previous study, and lower during the afternoon peak period. They were also higher than the values derived based on the FHWA recommendation, but were surprisingly consistent with the VOT estimated for metro riders, as shown in Appendix C. For other vehicle classes, this study adopted the same VOT values as those used by the MWCOG planning model. As shown in the literature review section, it was challenging to estimate VOT distributions that were applicable for a region. As new data sources or better methods emerge, these VOT assumptions could be updated in future studies.

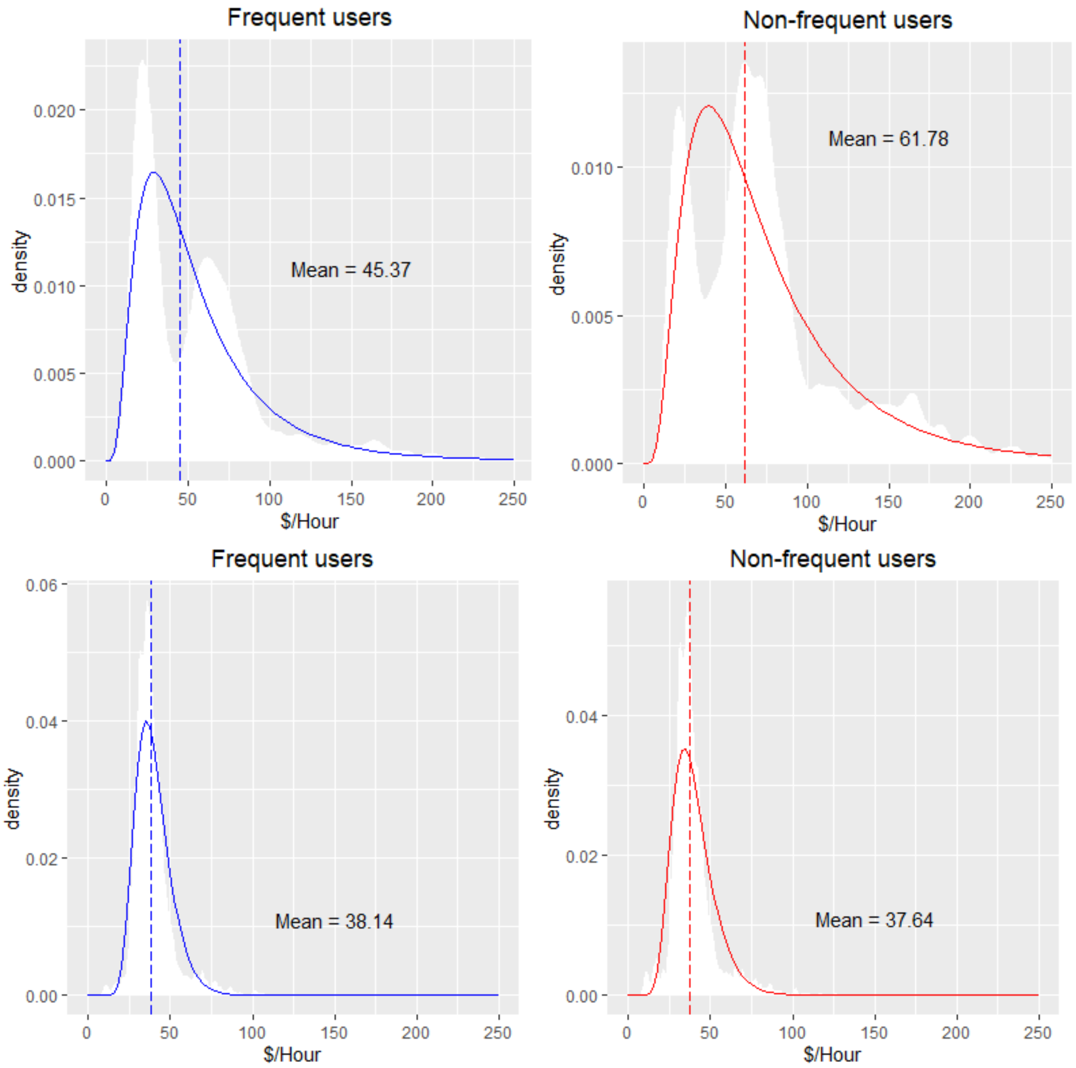


Figure 10. Value of Time Distributions for Eastbound (top) and Westbound (bottom) Trips
Vertical lines indicate the mean.

Table 9. Value of Time Estimation Used in this Study

	Trip Classes	Trips of Parallel Roads	I-66 ITB ETLs Frequent SOV Trips	I-66 ITB ETLs Non-frequent SOV Trips
AM	**VOT**	$24/h	$45.37/h	$61.78/h
	Percentage	59.8%	0.402*0.41*0.46=7.6%*	0.402*0.41*0.54=8.9%*
	Weighted Mean	$30.5/h		
PM	**VOT**	$20/h	$38.14/h	$37.64/h
	Percentage	51.5%	0.485*0.516*0.3=7.5%*	0.485*0.516*0.7=17.5%*
	Weighted Mean	$25.8/h		

** The percentage of frequent Single Occupancy Vehicle (SOV) trips in AM peak period is calculated as the percentage of I-66 trips (40.2%) times the percentage of SOV trips (41% based on Table 8) and times the percentage of frequent trips (46% based on Table 8). The calculations of the percentage of other trip classes follow the same method using information summarized in Table 8.*

Calibration of Simulation Model in TransModeler

Estimating the Initial OD Matrices based on Sub-area Analysis

Following the method described in the Methodology Section, this study first estimated the initial OD matrices through sub-area analysis based on the MWCOG planning model. Table 10 and Table 11 summarize the total number of trips by vehicle classes during the morning peak and the afternoon peak periods, respectively. Airport passenger vehicles and light commercial vehicles have been reassigned, using the method described in the Methodology Section. OD matrices of four vehicle classes, SOV, HOV2, HOV3, and TRK, were loaded into the TransModeler for dynamic OD estimation.

Table 10. Number of Trips during the AM Peak Period by Trip Classes Estimated Through the Sub-area Analysis

Hour	SOV	HOV2	HOV3	TRK	Total
5-6	27,730	7,691	3,290	3,818	*42,529*
6-7	86,958	16,799	4,903	18,299	*126,959*
7-8	87,914	17,016	4,796	18,149	*127,875*
8-9	87,495	16,599	5,066	17,908	*127,068*
9-10	63,499	19,517	8,819	17,259	*109,094*
Total	*353,595*	*77,623*	*26,874*	75,433	*533,525*

SOV: Single occupancy vehicle
HOV2: High occupancy vehicle with two occupants
HOV3: High occupancy vehicle with three or more occupants
TRK: Trucks

Table 11. Number of Trips during the PM Peak Period by Trip Classes Estimated Through the Sub-area Analysis

Hour	SOV	HOV2	HOV3	TRK	Total
2-3 PM	42,798	13,356	5,149	9,278	*70,581*
3-4 PM	82,269	25,634	10,097	16,920	*134,920*
4-5 PM	82,253	25,572	9,919	16,776	*134,520*
5-6 PM	82,091	25,182	9,957	16,823	*134,053*
6-7 PM	83,419	25,664	10,234	17,023	*136,340*
7-8 PM	26,284	7,199	3,109	3,319	*39,911*
Total	*399,115*	*122,606*	*48,465*	80,139	*650,325*

SOV: Single occupancy vehicle
HOV2: High occupancy vehicle with two occupants
HOV3: High occupancy vehicle with three or more occupants
TRK: Trucks

Model Calibration

Using the seed OD matrices, derived from the subarea analysis, the research team conducted dynamic OD estimation to match the simulation traffic volumes and those observed at the field sensors. The field data covered Tuesdays, Wednesdays, and Thursdays of May 2018, and were collected by a variety of entities. Figure 11 shows the locations of sensors whose data have been used in the model calibration process. Locations of some sensors overlap (e.g., those for the eastbound and westbound traffic on freeways), and such sensors are represented by the same blue circle in Figure 11. In total, hourly traffic volumes of 50 sensors were used for model calibration. These sensors cover the I-66 ITB and OTB corridors, George Washington Parkway, US 29 and US 50. No sensor data were available on I-495.

Figure 12 compares the simulated and observed traffic volumes for model calibration. A more detailed comparison of the model outputs and field counts is provided in Appendix F. Among the 250 data points used in model calibration, 216 points, or 86.4% of the total, have a percentage difference smaller than the threshold. The mean absolute error is 10.0%. The model meets VDOT’s calibration requirement.

Table 12 compares observed travel time and model-output travel time along I-66 for different hours during the morning peak period. The calibrated model of the morning peak period has a mean absolute error of 9.2%, compared to field-observed travel time, with 90% of data points within the required threshold.

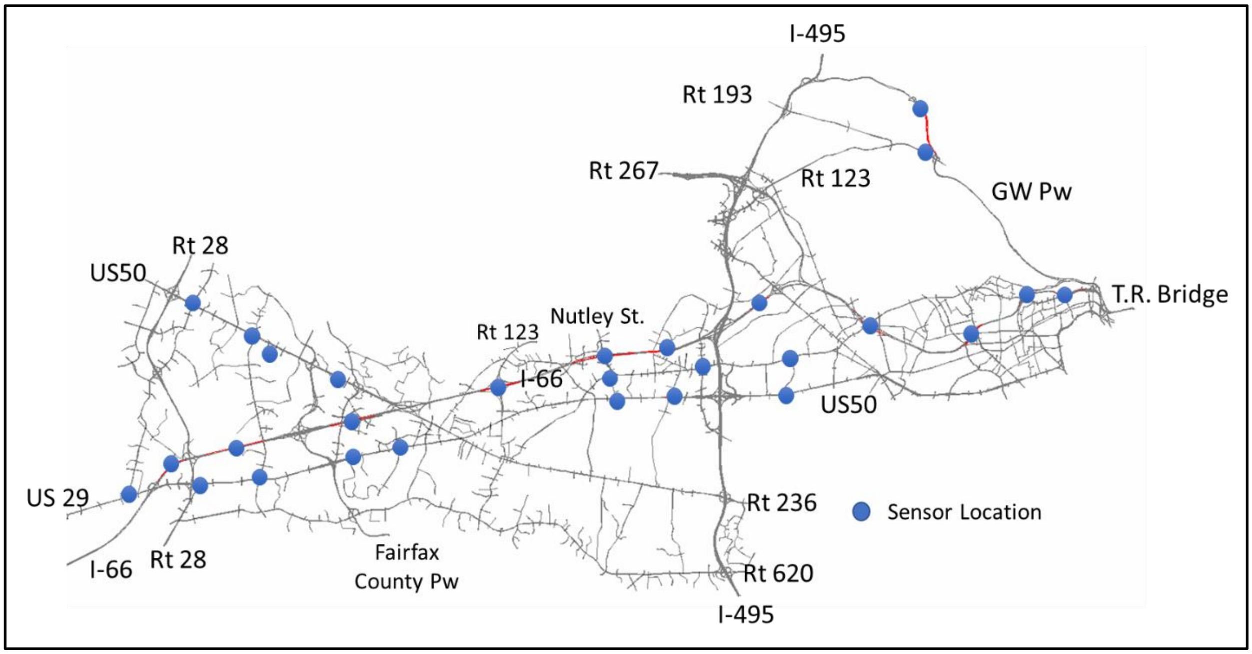


Figure 11. Locations of Traffic Volume Sensors Used for Model Calibration.

Redlines are links in TransModeler model where sensors are located. Blue dots are added to improve the visibility.

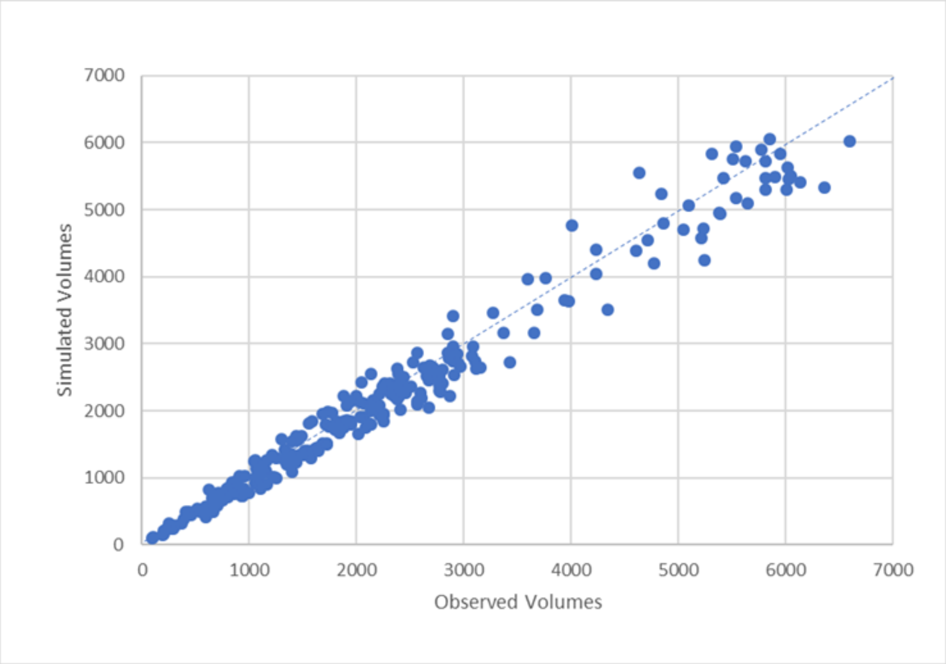


Figure 12. Simulated Hourly Volumes Versus Field-observed Hourly Volumes (Morning Peak).

The dashed line represents the 45-degree reference line.

Table 12. Travel Time Calibrations on I-66 (Morning Peak)

		EB			**WB**		
	Hour	**INRIX Travel Time (Min)**	**Model Outputs (Min)**	**%Diff**	**INRIX Travel Time (Min)**	**Model Outputs (Min)**	**%Diff**
I-66 OTB from Rt. 28 to I-495	5	11	12.2	10.7%	10.8	12.2	12.6%
	6	16	16.2	1.4%	10.7	12.4	15.6%
	7	22.6	21.9	-3.0%	11.9	12.5	5.3%
	8	23	24.2	5.4%	12.8	12.6	-1.7%
	9	18.5	17.8	-3.7%	12.2	12.4	2.0%
I-66 OTB from US 29 at Gainesville to Rt. 28	5	10.1	10.0	-1.4%	8.3	8.9	7.4%
	6	21.3	15.5	-27.2%	8.2	8.9	8.8%
	7	32.2	29.5	-8.4%	8.1	9.1	12.9%
	8	34.8	29.8	-14.4%	8	9.0	12.2%
	9	23.3	15.9	-31.8%	8.1	8.9	10.2%
I-66 ITB from I-495 to DC Line	5	10.1	10.5	4.4%	10.5	10.7	1.8%
	6	10.1	10.5	4.2%	10.2	10.6	4.3%
	7	11.5	11.4	-0.7%	12.1	11.2	-7.5%
	8	16	13.6	-14.7%	15.8	12.0	-24.2%
	9	14.3	12.3	-13.7%	12	11.4	-4.8%
Mean Absolute Error = 9.2%							
Percentage of Data Points Within Calibration Objectives = 27/30=90%							

Hour 5 represents the period from 5 am to 6 am.

Similarly, Figure 13 compares the simulated and observed traffic volumes for model calibration during the afternoon peak, while Appendix F provides more detailed comparisons. Among the 300 data points used in model calibration, 269 points, or 89.7% of the total, have a percentage difference smaller than the threshold. The mean absolute error is 8.7%. The model meets VDOT’s calibration requirements.

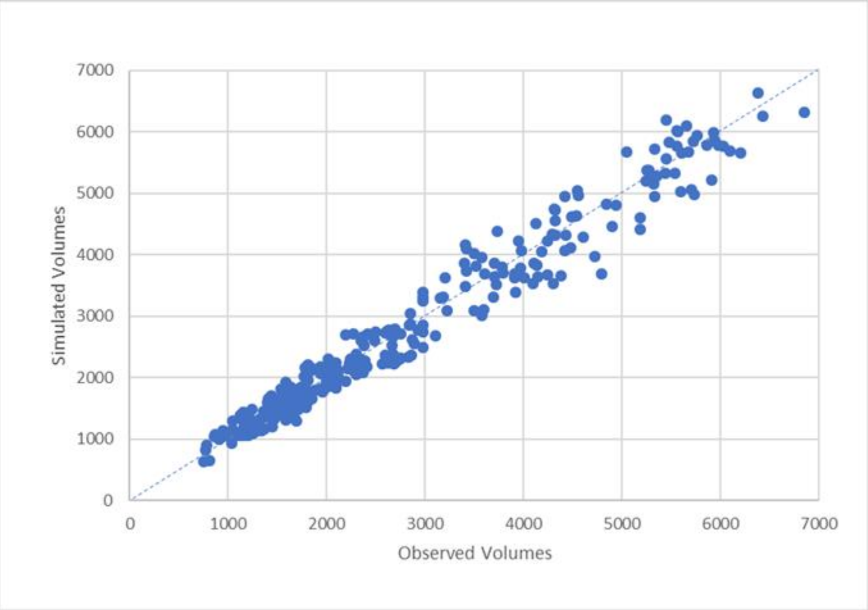


Figure 13. Simulated Hourly Volumes Versus Field-observed Hourly Volumes (Afternoon Peak).
The dashed line represents the 45-degree reference line.

Table 13 compares observed travel time and model-output travel time along I-66 for different hours during the afternoon peak period. The calibrated model of the morning peak period has a mean absolute error of 8.2%, compared to field-observed travel time, with 97.2% of data points within the required threshold.

Table 13. Travel Time Calibrations on I-66 (Afternoon Peak)

	Hour	**EB**			**WB**		
		INRIX Travel Time (Min)	**Model Outputs**	**%Diff**	**INRIX Travel Time (Min)**	**Model Outputs**	**%Diff**
I-66 OTB from Rt. 28 to I-495	14	12.5	12.2	-2.6%	14.5	14.6	0.6%
	15	12.1	12.1	0.3%	21.4	20.2	-5.5%
	16	12.4	12.5	0.7%	30	25.8	-14.1%
	17	11.9	12.8	7.4%	35.1	30.8	-12.4%
	18	12.3	13.0	5.5%	28.7	25.8	-10.2%
	19	11.6	12.2	5.0%	17.2	16.2	-5.6%
I-66 OTB from US 29 at Gainesville to Rt. 28	14	8.5	9.1	7.2%	8.2	9.1	11.1%
	15	8.5	9.2	8.0%	9.8	10.5	6.8%
	16	8.5	9.2	7.9%	12.1	13.2	9.5%
	17	8.5	9.0	6.4%	12.6	14.9	17.9%
	18	8.4	9.1	8.7%	12.3	13.2	7.0%
	19	8.4	8.9	6.1%	9.4	9.6	2.4%
I-66 ITB from I-495 to DC Line	14	11.3	11.3	0.3%	12.6	12.3	-2.3%
	15	15	14.0	-6.8%	12.1	10.5	-12.8%
	16	20	18.2	-9.1%	11.2	10.3	-7.7%
	17	26.3	21.5	-18.4%	12.6	10.5	-16.4%
	18	23.2	17.7	-23.9%	11.3	10.7	-5.4%
	19	15.1	13.0	-14.0%	13.8	12.7	-8.0%
Mean Absolute Error = 8.2%							
Percentage of Data Points Within Calibration Objectives = 35/36=97.2%							

Hour 14 represents the period from 2 pm to 3 pm.

Calibration of Mode Split Model

I-66 OTB ETLs offer free access to vehicles with three or more occupants. Therefore, travelers may consider carpooling or vanpooling modes to take advantage of free access. As described in the methodology section, this project considered the mode split, using a discrete choice modeling framework. The utilities for driving alone (SOV), driving with an additional passenger (HOV2), and driving with two or more additional passengers (HOV3) are:

$$U_{SOV} = \beta_{0,SOV} + \beta_1 T + \beta_{2,SOV}\tau + \varepsilon \qquad (3)$$

$$U_{HOV2} = \beta_{0,HOV2} + \beta_1 T + \beta_{2,HOV2}\tau + \varepsilon \qquad (4)$$

$$U_{HOV3} = \beta_{0,HOV3} + \beta_1 T + \beta_{2,HOV3}\tau + \varepsilon \qquad (5)$$

Where β_1 is the parameter for travel time and $\beta_2$is the parameter for out-of-pocket costs (i.e., toll), while ε is the random utility. Because only relative scale matters, we can normalize β_1 as 1. Since β_1/β_2 represents the value of time, and the value of time for SOV, HOV2, and HOV3 has been defined as \$30.5, \$40, and \$60, respectively, $\beta_{2,SOV} = -1.97$, $\beta_{2,HOV2} = -1.5$, and $\beta_{2,HOV3} = -1$. The three constants, $\beta_{0,SOV}$, $\beta_{0,HOV2}$, and $\beta_{0,HOV3}$, represent intrinsic preferences for the three modes among travelers, given that everything else is equal. Because only the difference in utility matters for the mode preference, we can make $\beta_{0,SOV} = 0$. This project assumed it followed the Gumbel distribution, and the mode split is decided by the logit model:

$$P_i = \frac{e^{\frac{U_i}{\theta}}}{\sum_j e^{\frac{U_j}{\theta}}} \qquad (6)$$

Where P_i represents the split for mode i and θ is a scale factor to be calibrated. As discussed in the literature review and the Methodology Section, there is no established method for estimating the mode split model for a region, except for conducting a large-scale household travel survey, which is infeasible for this study. The MWCOG planning model did not provide the parameters used. This study estimated the parameters using the data collected along the I-66 corridor, with some additional assumptions. Without tolls, the mode split along the corridor was assumed to be consistent with the overall mode split of the metropolitan area. According to Table 10, the SOV, HOV2, and HOV3 modes account for 81.3%, 13.6%, and 5.0% of traffic, respectively. When no toll is charged, $\tau = 0$ and T is the same for all three modes. By plugging these numbers in Equation 5, we can derive that:

$$\beta_{0,HOV2} = -1.787\theta \qquad (7)$$
$$\beta_{0,HOV3} = -2.781\theta \qquad (8)$$

When a toll is charged for I-66 ITB ETLs, vehicles with two or more occupants are expected to switch to the toll facility to benefit from the faster speed and free access. If we assume all HOV2 vehicles would switch to the toll facility if possible, based on Table 8, SOVs account for 76.3% of total traffic while HOV2 and HOV3+ vehicles account for 23.7%, an increase of 5.1% from the original total of 18.6%. In addition, SOV users have to pay $14, on average, for access to the toll facility during the AM peak hour. We further assume that traffic is in equilibrium, which means SOV drivers have the same level of utility, no matter if they are using the toll facility or not. With these assumptions, we applied Equation 5 to the I-66 ITB corridor to evaluate the mode split, which gave:

$$\theta = 91.12 \qquad (9)$$

Therefore, all parameters that are needed for evaluating the mode split have been calibrated. Equations 2-5 were then applied to relevant OD pairs for the I-66 OTB corridor to estimate the impact on the mode split, because of the new ETLs. For example, for travelers who need to go through the entire length of the I-66 OTB corridor, the travel time along the toll facility is approximately 22 minutes and the average toll rate is $11.90. For this case, the model predicted the mode split for SOV, HOV2, and HOV3+ would be 79.5%, 14.1%, and 6.4%, respectively. HOV3+ would experience a 26.4% increase (or a 1.3% increase of the OD total). Given the large number of OD pairs, this process was only applied to OD pairs along the I-66 OTB corridor. The overall increase of HOV3+ at the toll facility was due to both the mode shift and rerouting processes.

For the afternoon peak period, the MWCOG planning model (see Table 11) estimates that vehicles with two occupants account for 18.2% of the overall travel demand between 3 pm and 7 pm, and vehicles with three or more occupants account for 7.4% of the overall travel demand during the same time period. The combined percentage of these two categories account for 25.6% of the overall travel demand. However, vehicles with two or more occupants only account for 48.4% of trips going through the I-66 ITB corridor, and 12.8% of the overall travel demand if we assume all high occupancy vehicles traveling along the corridor will use the toll facility. The low percentage of high occupancy vehicles, estimated in this way, implies that trips during the afternoon peak have more diverse trip purposes while a significantly lower percentage of trips crossing the screen line were actually going through the entire corridor (and would use the toll facility). A lot more trips may be heading to local destinations, so using the toll facility does not help reduce travel time. Therefore, we cannot estimate a separate dispersion factor θ for the afternoon peak model. This study used the same dispersion factor estimated for both the morning and afternoon peak models. However, given the different percentages of HOV2 and HOV3+ from the morning peak, we did re-estimate the constant based on the mode split for the afternoon peak period, which gave $\beta_{0,HOV2} = -1.408\theta$ and $\beta_{0,HOV3} = -2.300\theta$. The parameters for toll also changed because the value of time changed for the afternoon peak model. We have $\beta_{2,SOV} = -2.32$, $\beta_{2,HOV2} = -2$, and $\beta_{2,HOV3} = -1$, which correspond to values of time of \$25.8, \$30, and \$60, respectively. Applying assumptions, similar to those in the morning peak model, the highest afternoon peak split of HOV2 went from 18.2% to 18.3%, and the split of HOV3 went from 7.4% to 9.2%.

The change of corridor travel time may also lead to mode shifts between the automobile and the public transit modes. Table 14 shows the number of entries at the Vienna metro station by different times of day during Tuesdays, Wednesdays, and Thursdays in May 2018.

Table 14. Average Number of Entries by Time Periods during Tuesdays, Wednesdays, and Thursdays in May 2018

	Vienna
AM Peak (Open – 9:30 am)	6,900
Midday (9:30 am – 3 pm)	1,400
PM Peak (3 pm – 7 pm)	900
Evening (7 pm – 12 am)	215
Late Night (12 am – Close)	N/A

Source: Washington Metropolitan Area Transit Authority Ridership Portal, https://www.wmata.com/initiatives/ridership-portal/Rail-Data-Portal.cfm

The total number of metro trips during the morning peak period (5 am – 10 am) was $6900 + \frac{1400}{11} = 7027$ trips in May 2018. The total number of driving trips along the three competing routes (I-66, US 50, US 29) were $28813 + 9129 + 5715 = 43657$. Considering only the binary case of driving vs. transit,

$$P_{driving} = \frac{43657}{43657+7027} = 0.861 \qquad (10)$$

Based on Appendix D, $\beta_t = -0.026$. We assumed most Metro riders at the Vienna station would go to either Arlington or Washington, D.C., and the average travel time to the D.C. line, by driving along the corridor, is about 20 minutes, on average, based on INRIX data. Therefore,

$$E_{x_{jk}}^{P_i} = -0.861 * 20 * (-0.026) = 0.448 \quad (11)$$

This implies that a 1% reduction of corridor travel time would lead to a 0.448% decrease in metro ridership, which is the equivalent of 31.5 trips during the entire morning peak period. Because this number is relatively small, we applied this cross-elasticity as a constant. However, if the change were significant, we would have to re-evaluate the cross-elasticity in multiple steps as the overall mode share for the metro changes. No data for the number of exits is provided at the Metro data portal. We assumed the same value for the cross-elasticity and for the afternoon peak period.

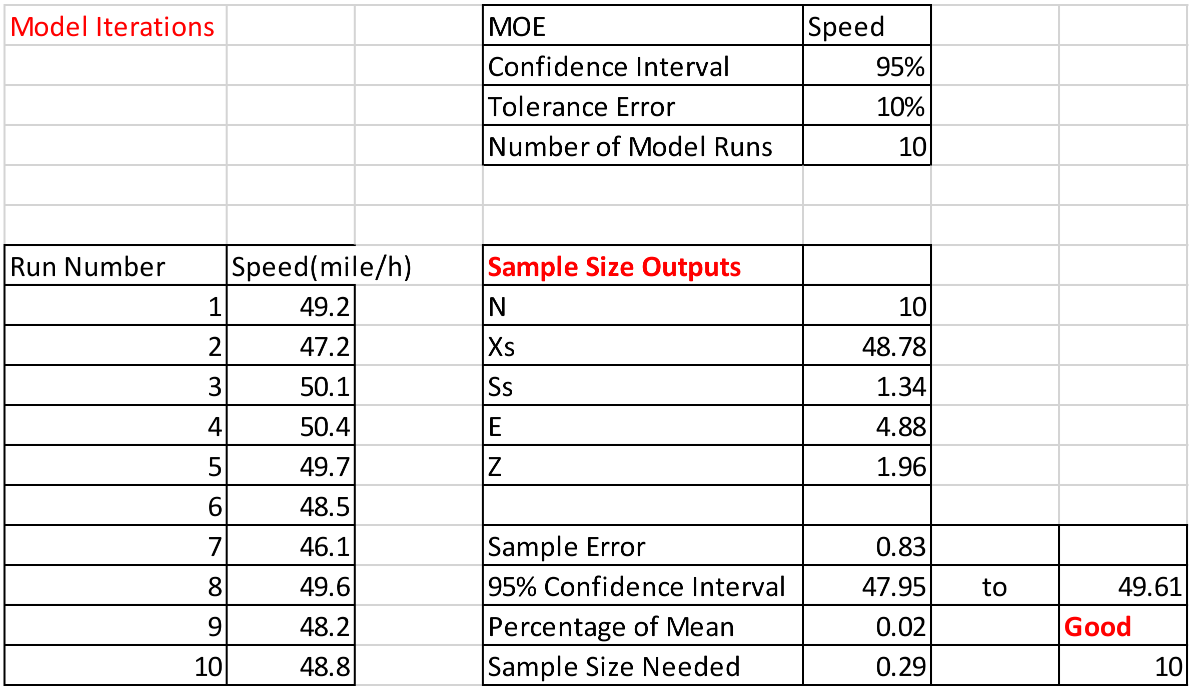
The calibrated mode split model was applied to the integrated modeling framework to adjust the OD demand in response to new traffic conditions, because of the toll strategies. As shown in this section, the changes were small in magnitude, when compared with the overall demand along the corridor. Therefore, in most scenarios, it was sufficient to apply the mode split model one time.

Baseline Scenario of the I-66 Outside-the-Beltway Express Toll Lanes

The research team first investigated the performance of the I-66 OTB ETLs and its impact on traffic conditions in the region under the baseline scenario. The baseline scenario assumes that the I-66 OTB ETLs operate as high-occupancy with toll lanes that have free access for vehicles of three or more occupants (HOT3+). The toll rate is set dynamically, once every 6 minutes, based on the real-time traffic density that follows the formula presented in the Methodology Section. The entire corridor is divided into five zones and the toll rate of each zone is set independently. For each trip, the expected toll is the sum of tolls to be charged for each zone at the moment of entrance.

Determination of Sample Size

The simulation model, developed in TransModeler, uses a simulation-based optimization process to determine the route for each simulated vehicle under equilibrium. Random numbers are used in many sub-processes during the simulation, including the car-following models, lane-changing models, etc. Compared to other types of uncertainties in the real world, including the day-to-day fluctuation of travel demand and randomness in road capacity, the impact of randomness in car-following behavior is not significant. Following the steps listed in the VDOT's Sample Size Determination Tool (see Figure 14), this study evaluated the number of model runs that is required using the eastbound speed for the I-66 OTB ETLs between Vaden Drive and I-495 for the period of 8-9 AM. It was determined that ten runs were sufficient. Given the large number of scenarios to be evaluated in this study, and based on discussions with the Technical Review Panel, this study only used the average of ten model runs for reporting the final results. For all intermediate steps (simulation runs that generate further demand shifts), model outputs from a single model run were used for calculations.



Model Iterations			MOE	Speed		
			Confidence Interval	95%		
			Tolerance Error	10%		
			Number of Model Runs	10		
Run Number	Speed(mile/h)		**Sample Size Outputs**			
1	49.2		N	10		
2	47.2		Xs	48.78		
3	50.1		Ss	1.34		
4	50.4		E	4.88		
5	49.7		Z	1.96		
6	48.5					
7	46.1		Sample Error	0.83		
8	49.6		95% Confidence Interval	47.95	to	49.61
9	48.2		Percentage of Mean	0.02		**Good**
10	48.8		Sample Size Needed	0.29		10

Figure 14. Direct Output from the Simulation Sample Size Determination Tool Based on VDOT's Traffic Operations and Safety Analysis Manual.

Results of the Morning Peak Model

Figure 15 shows the traffic density, the corresponding toll rate based on the dynamic pricing algorithms, and traffic volume for each of the five toll zones of the I-66 OTB ETLs along the eastbound direction, during the morning peak period, based on the simulation outputs using data aggregated at 6-minute intervals. The density was measured by the sensors shown in Figure 4 and the toll rate was calculated using Equation 1. For eastbound traffic, Zone 1 is the western-most zone between Gainesville and Centerville, while Zone 5 is the eastern-most zone where the I-66 OTB ETLs meet the I-495 Capital Beltway. Figure 15 shows that the overall demand and congestion patterns at the five zones are very similar, with the highest demand between 8 AM and 9 AM. The toll rate also reaches the highest level during this hour. Although the toll rate is set based on the traffic density of each zone, the toll is charged based on the entire trip. Except for a short segment right before the interchange with Rt. 28, I-66 OTB ETLs are physically separated from the parallel GP lanes. If a traveler decides to switch between the ETLs and the GP lanes in the middle, she or he must first exit from the freeway and reenter from ramps connecting arterial roads to the ETLs, or the GP lanes. This change usually involves a significant detour and is unlikely to happen in most cases. However, if either facility is blocked because of an accident the other facility might be an option, even if it means driving a few extra miles. Therefore, travelers are likely to make their decisions about whether to choose the ETLs based on the performance of the entire corridor, instead of a single zone. Many travelers along the corridor are commuters whose destinations are located within the I-495 Capital Beltway, which implies a strong correlation between the travel demands of the five zones.

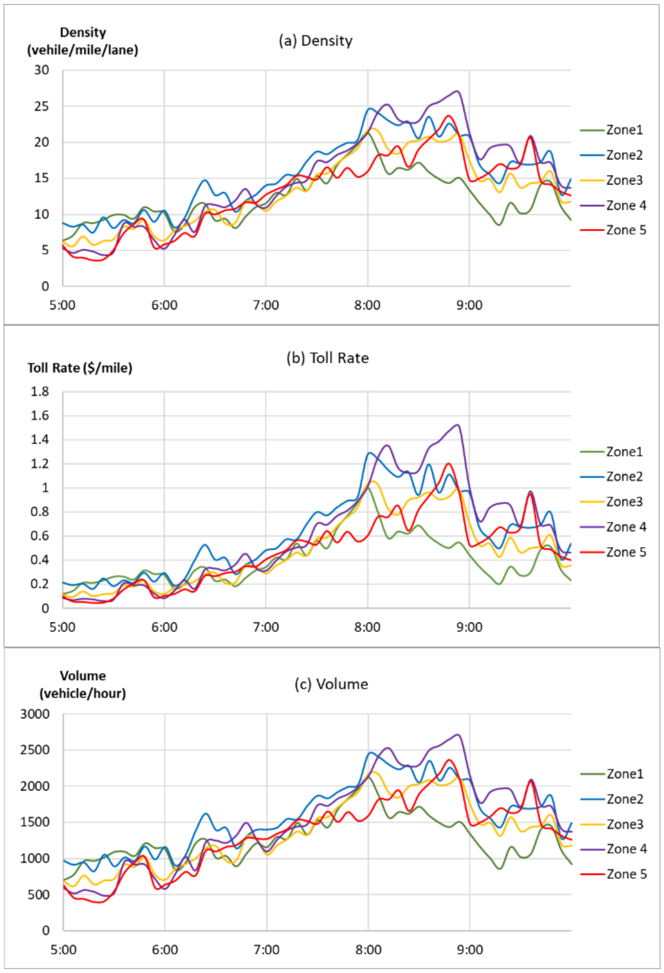


Figure 15. Density (a), Toll Rate (b), and Volume (c) for Each Zone of the I-66 Outside-the-Beltway Express Toll Lanes Eastbound During the Morning Peak Period in the Baseline Scenario.

Zone 1: Gainesville to Rt. 28
Zone 2: Rt. 28 to Monument Dr.
Zone 3: Monument Dr. to Rt. 123
Zone 4: Rt. 123 to Vaden Dr. (West of Nutley St.)
Zone 5: Vaden Dr. to I-495 Interchange

Despite the strong correlation, demand at the five zones still shows some minor differences. The demand in the western-most zone (i.e., Zone 1) picks up sooner during the early morning and drops faster at the end of the morning peak period than in the zones further to the east. The overall demand is the highest for Zone 4, with some travelers exiting before Nutley Street. The period between 8 am and 9 am is the most congested hour, with 2,438 vehicles traveling in Zone 4. Based on the criteria of the Highway Capacity Manual (TRB, 2016) (see Table 15), the level of service only reaches D for a short period. The ETLs are likely to provide a satisfactory level of service under the baseline scenario.

Table 15. Freeway Level of Service Criteria by the Highway Capacity Manual

Level of Service	**Density (vehicle/mile/lane)**
A	<=11
B	11-18
C	18-26
D	26-35
E	35-45
F	>45

Figure 16 shows the traffic density, the corresponding toll rate based on the dynamic pricing algorithms, and traffic volume for each of the five toll zones of the I-66 OTB ETLs along the westbound direction during the morning peak period, based on simulation outputs. For westbound traffic, travelers enter the I-66 O corridor from Zone 5 to the east and exit from Zone 1 to the west, if they choose to use the entire toll facility. As the off-peak direction, the westbound direction is less congested than the eastbound direction. Therefore, the toll rate and the traffic volume are both lower for the westbound direction. Zone 5 and Zone 4, which are the segments between the I-495 Capital Beltway and Rt. 123, have more users, as compared to the segments located further west.

Figure 17 shows the toll rate for using the entire I-66 OTB ETLs during the morning peak period. As discussed earlier, the toll rate was set based on instantaneous density measured by the five sensors along the corridor, and the toll is the sum of tolls to be charged for each zone. For the eastbound, the highest toll is around $21.50, and the toll rate is the highest between 8 am and 9 am. For the westbound, the highest toll is around $6.50 and the toll reaches the highest level around 9 am.

Table 16 shows the impact of the ETLs on corridor travel time. Consistent with the speed changes, the travel time along the ETLs only increased moderately as compared to free-flow travel time for eastbound traffic at the segment between Gainesville and Rt. 28 (Zone 1), and between Rt. 28 and I-495 interchange (Zone 2 to 5). Westbound travel time along the ETLs stayed as free-flow travel time at both segments. Compared to the traffic conditions measured before the opening of the ETLs, travel time along the GP lanes improved by about 10% at the segment between Rt. 28 and I-495, and by about 35% between 7 am and 9 am at the segment between Gainesville and Rt. 28.

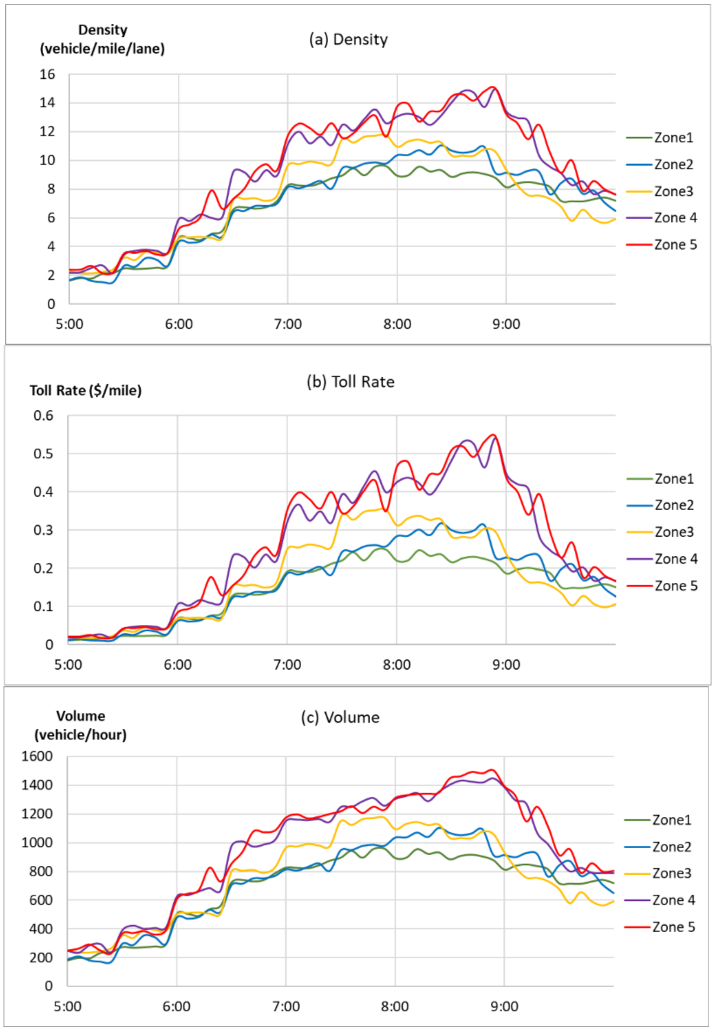


Figure 16. Density (a), Toll Rate (b), and Volume (c) for Each Zone of the I-66 Outside-the-Beltway Express Toll Lanes Westbound During the Morning Peak Period in the Baseline Scenario.

Zone 1: Gainesville to Rt. 28
Zone 2: Rt. 28 to Monument Dr.
Zone 3: Monument Dr. to Rt. 123
Zone 4: Rt. 123 to Vaden Dr. (West of Nutley St.)
Zone 5: Vaden Dr. to I-495 Interchange

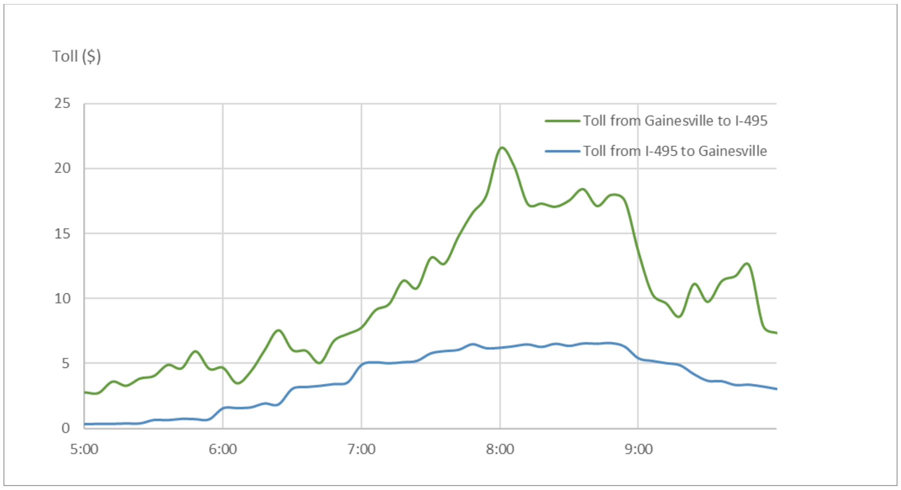


Figure 17. Toll Charged for Using the Entire I-66 Outside-the-Beltway Express Toll Lanes During the Morning Peak Period in the Baseline Scenario.

Table 16. Corridor Travel Time Changes during the Morning Peak Period

Corridor		**I-66 OTB from Rt. 28 to I-495**				
Direction		**Eastbound**				
Hour		**5-6 AM**	**6-7 AM**	**7-8 AM**	**8-9 AM**	**9-10 AM**
ETL Travel Time (min)		10.5	10.8	11.8	12.9	12.2
GPL	**Current Conditions**	12.2	16.2	21.9	24.2	17.8
	With ETL, Baseline	12.4	14.7	19.0	21.7	16.2
	%Diff	1.3%	-9.2%	-13.2%	-10.3%	-9.2%
Direction		**Westbound**				
Hour		**5-6 AM**	**6-7 AM**	**7-8 AM**	**8-9 AM**	**9-10 AM**
ETL Travel Time (min)		10.5	10.7	11.4	11.7	11.1
GPL	**Current Conditions**	12.2	12.4	12.5	12.6	12.4
	With ETL, Baseline	12.3	12.4	12.6	12.5	12.3
	%Diff	0.6%	0.0%	0.5%	-0.5%	-0.5%
Corridor		**I-66 OTB from Gainesville to Rt. 28**				
Direction		**Eastbound**				
Hour		**5-6 AM**	**6-7 AM**	**7-8 AM**	**8-9 AM**	**9-10 AM**
ETL Travel Time (min)		9.2	9.5	10.7	11.0	9.6
GPL	**Current Conditions**	10	15.5	29.5	29.8	15.9
	With ETL, Baseline	9.9	13.8	18.9	19.2	13.4
	%Diff	-1.3%	-10.9%	-36.1%	-35.7%	-15.7%
Direction		**Westbound**				
Hour		**5-6 AM**	**6-7 AM**	**7-8 AM**	**8-9 AM**	**9-10 AM**
ETL Travel Time (min)		9.0	9.0	9.0	9.0	9.0
GPL	**Current Conditions**	8.9	8.9	9.1	9	8.9
	With ETL, Baseline	9.0	9.0	9.1	9.0	9.0
	%Diff	0.9%	1.0%	-0.4%	0.2%	0.9%

ETL: Express toll lanes
GPL: General purpose lanes

Results of the Afternoon Peak Model

Figure 18 shows the traffic density, the corresponding toll rate based on the dynamic pricing algorithms, and traffic volume for each of the five toll zones of the I-66 OTB ETLs along the westbound (peak) direction, during the afternoon peak period, based on the simulation outputs. Compared to the traffic pattern during the morning peak, traffic during the afternoon peak period is flatter. The travel demand for the I-66 OTB ETLs picks up before 3 pm and the peak period lasts until around 7 pm. However, the highest density, during the afternoon peak period, is lower than that of the morning peak period. Zone 5, which is close to the I-495 interchange, sees the highest demand. Traffic volume drops as we move further west along the corridor. However, the difference in traffic volumes between different zones is smaller when compared to the morning peak period.

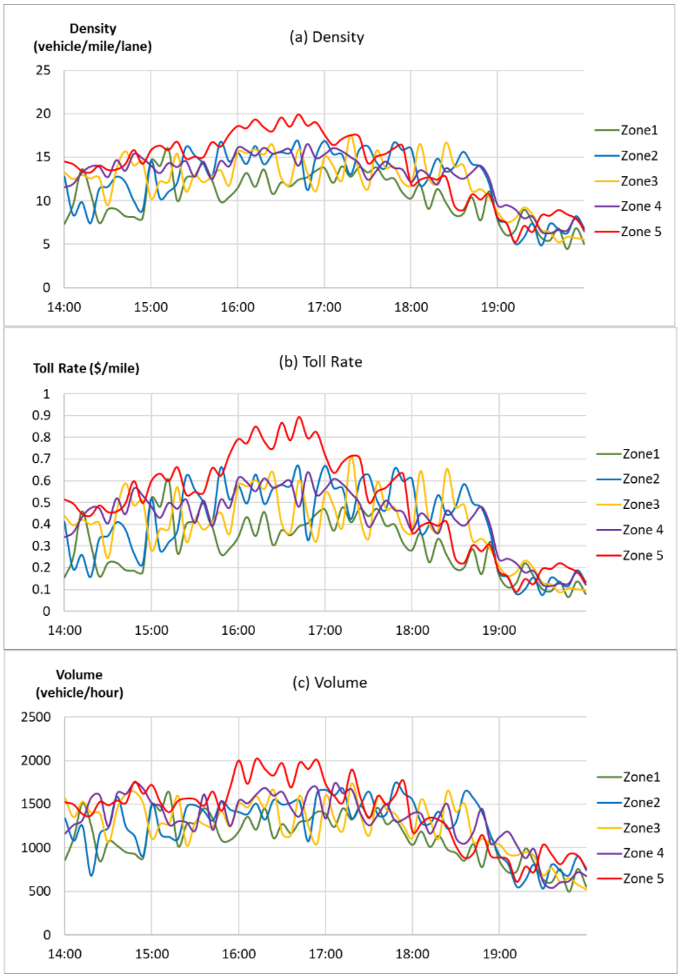
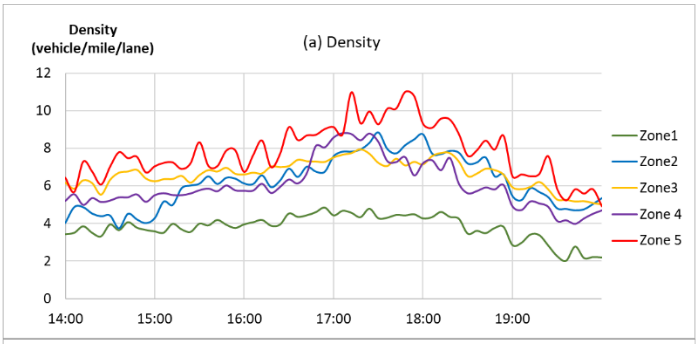
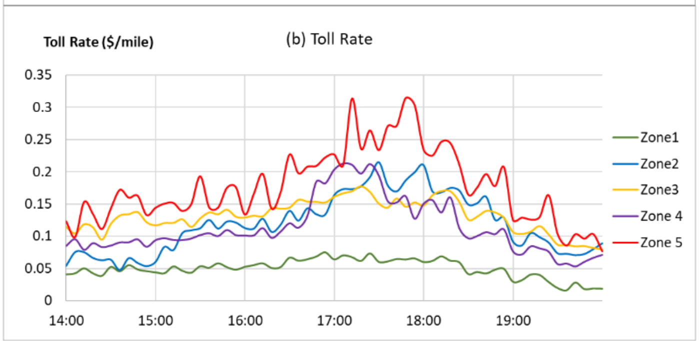


Figure 18. Density (a), Toll Rate (b), and Volume (c) for Each Zone of the I-66 Outside-the-Beltway Express Toll Lanes Westbound During the Afternoon Peak Period in the Baseline Scenario.

Zone 1: Gainesville to Rt. 28
Zone 2: Rt. 28 to Monument Dr.
Zone 3: Monument Dr. to Rt. 123
Zone 4: Rt. 123 to Vaden Dr. (West of Nutley St.)
Zone 5: Vaden Dr. to I-495 Interchange

Figure 19 shows the traffic density, the corresponding toll rate based on the dynamic pricing algorithms, and traffic volume for each of the five toll zones of the I-66 OTB ETLs along the eastbound (off peak) direction, during the afternoon peak period, based on the simulation outputs. The traffic volume in Zone 1 (close to Gainesville) is much lower than the other four zones east of Rt. 28. The demand is relatively flat and the highest flow rate shows between 5 pm and 6 pm.





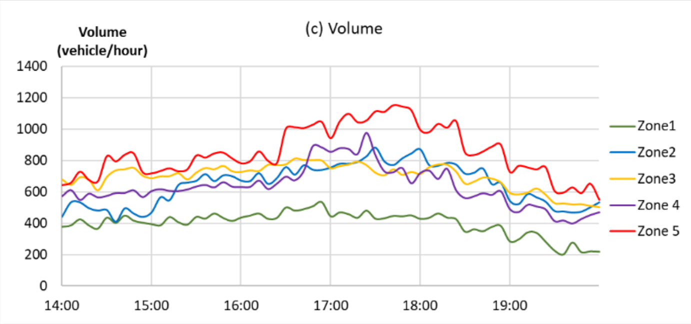


Figure 19. Density (a), Toll Rate (b), and Volume (c) for Each Zone of the I-66 Outside-the-Beltway Express Toll Lanes Eastbound During the Afternoon Peak Period in the Baseline Scenario.

Zone 1: Gainesville to Rt. 28
Zone 2: Rt. 28 to Monument Dr.
Zone 3: Monument Dr. to Rt. 123
Zone 4: Rt. 123 to Vaden Dr. (West of Nutley St.)
Zone 5: Vaden Dr. to I-495 Interchange

Figure 20 shows the toll rate for using the entire I-66 OTB ETLs during the afternoon peak period. For the westbound direction, the highest toll is around $12. Differing from the pattern seen during the morning peak period, the toll charged during the afternoon peak period picks up early (around 3 pm) and stays high for a much longer period (around 7 pm). For the westbound direction, the highest toll is around $3, and the toll is very flat during the entire afternoon period.

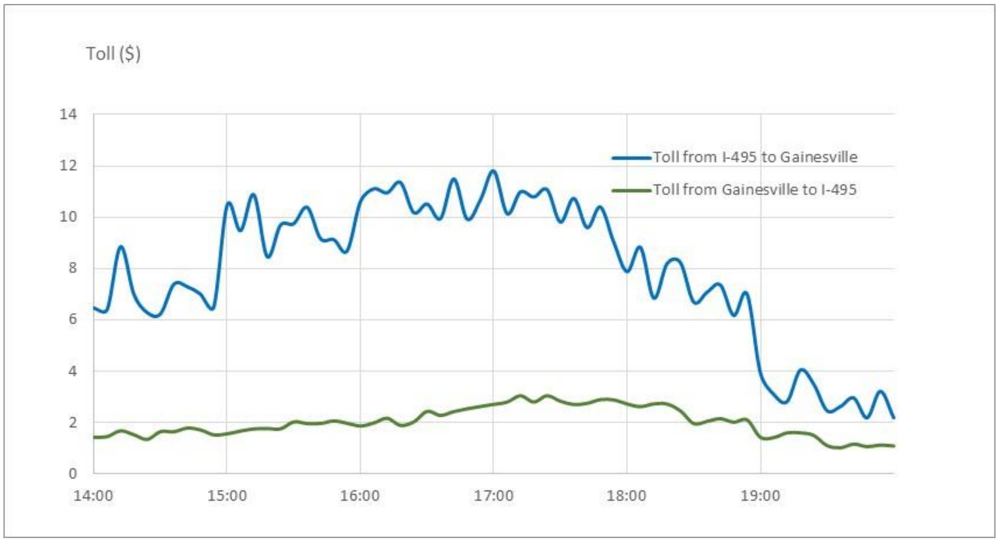


Figure 20. Toll Charged for Using the Entire I-66 Outside-the-Beltway Express Toll Lanes During the Afternoon Peak Period in the Baseline Scenario.

Table 17 shows the impact of the ETLs on corridor travel time during the afternoon peak period. Similar to the patterns we observed during the morning peak period, the travel time along the ETLs stayed close to the free-flow travel in the off-peak direction (eastbound during the afternoon peak period) at the segment between Gainesville and Rt. 28 (Zone 1) and between Rt. 28 and the I-495 interchange (Zones 2 to 5). Eastbound travel time along the GP lanes did not worsen or improve much either, when compared to the traffic conditions observed before the opening of the ETLs. Travel time in the peak direction (westbound) saw significant improvement when we traveled along the GP lanes, particularly during the period between 5 pm and 7 pm. Travel time was reduced by as much as 5.2 minutes (17%) for the segment between I-495 and Rt. 28. The improvement was smaller for the segment to the west of Rt. 28.

Table 17. Corridor Travel Time Changes during the Afternoon Peak Period

Corridor		I-66 OTB from Rt. 28 to I-495					
Direction		**Eastbound**					
Hour		**2-3 PM**	**3-4 PM**	**4-5 PM**	**5-6 PM**	**6-7 PM**	**7-8 PM**
ETL Travel Time (min)		10.5	10.5	10.6	10.7	10.6	10.5
GPL	**Current Conditions**	12.2	12.1	12.5	12.8	13.0	12.2
	With ETL, Baseline	12.4	12.3	12.5	12.7	12.3	12.4
	%Diff	1.5%	2.0%	0.0%	-0.9%	-5.1%	1.3%
Direction		**Westbound**					
Hour		**2-3 PM**	**3-4 PM**	**4-5 PM**	**5-6 PM**	**6-7 PM**	**7-8 PM**
ETL Travel Time (min)		11.5	11.6	12.6	12.4	11.6	10.6
GPL	**Current Conditions**	14.6	20.2	25.8	30.8	25.8	16.2
	With ETL, Baseline	13.6	17.9	23.1	25.6	21.5	14.1
	%Diff	-6.9%	-11.4%	-10.4%	-17.0%	-16.8%	-12.8%
Corridor		**I-66 OTB from Gainesville to Rt. 28**					
Direction		**Eastbound**					
Hour		**2-3 PM**	**3-4 PM**	**4-5 PM**	**5-6 PM**	**6-7 PM**	**7-8 PM**
ETL Travel Time (min)		9.0	9.0	9.0	9.0	9.0	9.0
GPL	**Current Conditions**	9.1	9.2	9.2	9.0	9.1	8.9
	With ETL, Baseline	9.1	9.0	9.0	9.0	9.0	9.0
	%Diff	-0.1%	-1.8%	-1.8%	-0.1%	-1.2%	1.0%
Direction		**Westbound**					
Hour		**2-3 PM**	**3-4 PM**	**4-5 PM**	**5-6 PM**	**6-7 PM**	**7-8 PM**
ETL Travel Time (min)		9.1	9.7	9.8	10.0	9.9	9.1
GPL	**Current Conditions**	9.1	10.5	13.2	14.9	13.2	9.6
	With ETL, Baseline	9.2	10.1	12.6	14.2	12.2	9.4
	%Diff	0.7%	-3.5%	-4.2%	-4.8%	-7.4%	-2.1%

ETL: Express toll lanes
GPL: General purpose lanes

Impact on Vehicle Throughput

Table 18 compares the total throughput of the I-66 OTB ETLs and the GP lanes by vehicle class and by time during the morning peak period. Vehicles with three or more occupants account for about 35.7% of all I-66 OTB ETL users, and the percentage is lower during early hours but becomes higher during the more congested hours. When traffic using the GP lanes is also combined, HOT3+ traffic accounts for 7.7% of the total throughput of the corridor. This is higher than the share of HOV3+ (5.0%) out of the total travel demand based on the MWCOG planning model, and the increased share of HOV3+ (6.3%) when the vehicle occupancy adjustment is considered. This higher percentage could be due to a higher percentage of HOV3+ among the commuters traveling longer distances (who travel to Arlington or D.C.) and the rerouting from arterial streets.

When the traffic of the ETLs and the GP lanes are combined, the total throughput increased by 6.8%, when compared with the traffic counts observed before the construction of the ETLs. This increase is moderate, given that the combined capacity of the new corridor goes from four lanes to five lanes for most segments during the morning peak period. However, given the high level of congestion on the regional network, the transportation system is operating at its capacity and downstream bottlenecks also limit the throughput of the I-66 corridor. A shift in departure time can also be observed. Total throughput during early hours dropped and the throughputs during the most congested hours improved because of the extra capacity that the ETLs offer.

Table 18. Comparison of Vehicle Throughput at the East End of the I-66 Outside-the-Beltway Express Toll Lanes During the Morning Peak Period in the Peak Direction

			5-6 AM	**6-7 AM**	**7-8 AM**	**8-9 AM**	**9-10 AM**	**Total**
ETL	Total	Counts	627	1004	1489	1941	1584	*6645*
	HOV3+	Counts	163	311	566	699	634	*2372*
		%	26%	31%	38%	36%	40%	*35.7%*
	SOV/HOV2	Counts	464	693	923	1242	951	*4273*
		%	74%	69%	62%	64%	60%	*64.3*
GPL		Counts	4543	4441	5060	5081	4513	*24138*
Corridor Total		Counts	5170	5446	6549	7021	6597	*30783*
Current Total		Counts	5534	5623	6027	5853	5776	*28813*
Difference		Counts	-364	-177	522	1168	821	*1970*
% Difference		%	-6.6%	-3.2%	8.7%	20.0%	14.2%	*6.8%*

ETL: Express toll lanes
GPL: General purpose lanes
Current Total: Traffic flow before the I-66 express toll lanes were constructed.

Table 19 compares the total throughput of the I-66 OTB ETLs and the GP lanes by vehicle class and by time, during the afternoon peak period, in the peak direction (westbound). Vehicles with three or more occupants account for about 31.3% of all I-66 OTB ETL users. This percentage is slightly lower when compared to that of the morning peak period. Similar to the patterns observed during the morning peak period, the percentage of HOV3+ is lower during the early afternoon and becomes higher during the more congested hours. When traffic using the GP lanes is also combined, HOT3+ traffic accounts for 7.6% of the total throughput of the corridor.

Table 19. Comparison of Vehicle Throughput at the East End of the I-66 Outside-the-Beltway Express Toll Lanes During the Afternoon Peak Period in the Peak Direction

			2-3 PM	**3-4 PM**	**4-5 PM**	**5-6 PM**	**6-7 PM**	**7-8 PM**	**Total**
ETL	Total	Counts	1577	1672	1888	1647	1133	857	*8774*
	HOV3+	Counts	331	451	661	642	385	274	*2745*
		%	21%	27%	35%	39%	34%	32%	*31.3%*
	SOV/HOV2	Counts	1245	1220	1227	1005	748	583	*6029*
		%	79%	73%	65%	61%	66%	68%	*68.7%*
GPL		Counts	4029	4338	4799	5075	4848	4051	*27140*
Corridor Total		Counts	5606	6010	6687	6722	5981	4908	*35914*
Current Total		Counts	6428	5552	5480	5651	5451	5598	*34160*
Difference		Counts	-822	458	1207	1071	530	-690	*1754*
% Difference		%	-12.8%	8.2%	22.0%	19.0%	9.7%	-12.3%	*5.1%*

ETL: Express toll lanes
GPL: General purpose lanes
Current Total: Traffic flow before the I-66 express toll lanes were constructed.

When the traffic of the ETLs and the GP lanes are combined, the total throughput increased by 5.1% when compared with the traffic counts observed before the construction of the ETLs. A shift in departure time can also be observed as the total throughput in both the early afternoon and the early evening dropped, while the throughputs during the most congested hours improved.

Total Revenue

Table 20 shows the toll revenue by zone during the morning peak period. It also shows the number of users who paid to use the toll facility and the average toll per trip during the morning peak period. Eastbound trips paid a higher price because of the congestion, with an average toll of $11.99 to go through the entire corridor. The average toll rate for the westbound traffic was $4.71. The total daily revenue for the eastbound and the westbound directions was $53,579 and $12,230, respectively.

Table 20. AM Peak Period Tolling Revenue by Zone and Total

Zone	EB			WB		
	Revenue ($)	**Paid Trips**	**Average Toll Per Trip ($)**	**Revenue ($)**	**Paid Trips**	**Average Toll Per Trip ($)**
Zone 5	7,264	4,917	1.48	3,089	3,577	0.86
Zone 4	7,880	5,268	1.50	2,034	3,286	0.62
Zone 3	7,550	4,200	1.80	1,671	2,376	0.70
Zone 2	13,553	5,060	2.68	2,837	2,339	0.78
Zone 1	17,330	3,820	4.54	3,619	2,068	1.75
Total	53,579		11.99	12,230		4.71

Table 21 shows the toll revenue by zone during the afternoon peak period. It also shows the number of users who paid to use the toll facility and the average toll per trip during the afternoon peak period. Westbound trips paid higher prices because of the congestion, with an average toll of $9.39 to go through the entire corridor. The average toll rate for the eastbound traffic was $2.26. The total daily revenue for the eastbound and the westbound direction was $43,442 and $5,672, respectively.

Table 21. PM Peak Period Tolling Revenue by Zone and Total

Zone	EB			WB		
	Revenue ($)	**Paid Trips**	**Average Toll Per Trip ($)**	**Revenue ($)**	**Paid Trips**	**Average Toll Per Trip ($)**
Zone 5	1,959	3,521	0.51	9,878	6,179	1.55
Zone 4	646	2,461	0.25	5,042	5,187	0.93
Zone 3	1,149	2,366	0.44	6,724	4,439	1.46
Zone 2	1,157	2,061	0.51	8,191	4,272	1.86
Zone 1	761	1,285	0.56	13,607	3,615	3.59
Total	5,672		2.26	43,442		9.39

Impact on Arterial Roads

For travelers along the I-66 OTB ETL corridor, US 50 and US 29 offer two potential competing alternative routes. The speed limit and capacity of other local roads are too low to serve as meaningful alternatives. The selected locations (shown in Figure 21) represent major intersections along U.S. 50 and U.S. 29 before traffic intersects the I-495 Capital Beltway. They were chosen as the screen line for corridor traffic throughput assessment.

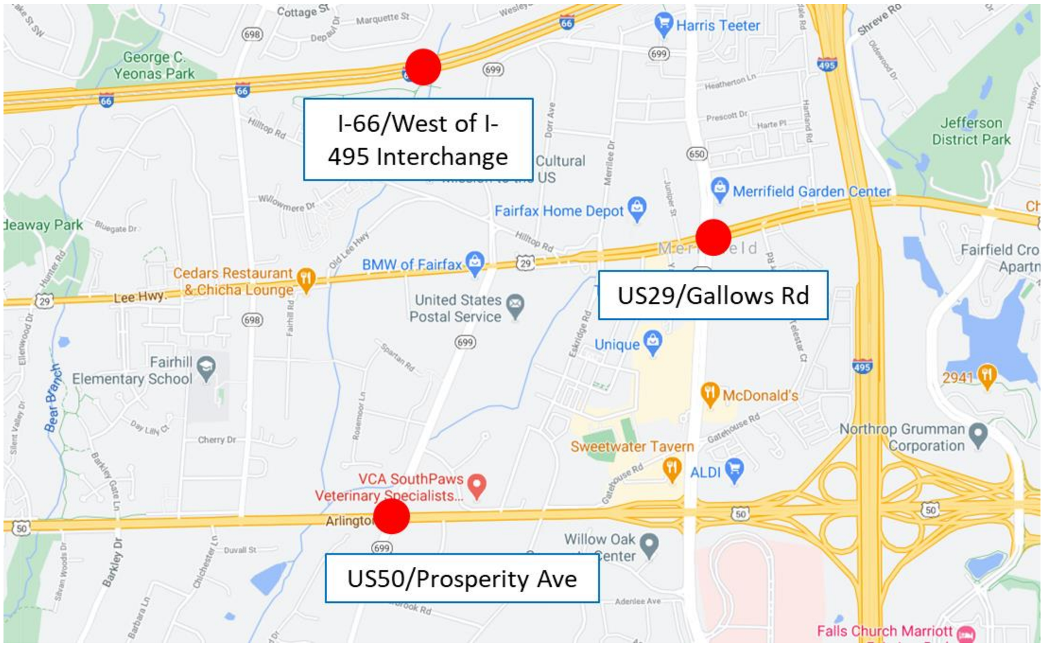


Figure 21. Selected Locations for Throughputs Comparison along I-66 Outside-the-Beltway and Parallel Arterial Corridors

Table 22 and Table 23 compare the traffic throughput in the peak direction during the morning peak and the afternoon peak periods, respectively. The total traffic throughput along US 50 dropped by 1.2% during the morning peak period, while it increased by 0.7% during the afternoon peak period. The total traffic throughput along US 29 dropped by 0.5% and by 4.2% during the morning peak period and the afternoon peak period, respectively. Overall, traffic along these two arterial corridors dropped slightly, and the impact of the I-66 OTB ETLs on arterial road traffic was small in the baseline scenario.

Table 22. Comparison of Arterial Road Traffic Throughputs in the Peak Direction During the Morning Peak Period

		5-6 AM	6-7 AM	7-8 AM	8-9 AM	9-10 AM	Total
US 50/Prosperity Ave.	Current	517	1750	2394	2254	1837	8751
	Baseline	530	1708	2391	2258	1760	8647
	%Diff	2.6%	-2.4%	-0.1%	0.2%	-4.2%	-1.2%
US 29/Gallows Rd.	Current	294	960	1299	1402	1349	5303
	Baseline	269	1081	1236	1451	1237	5275
	%Diff	-8.4%	12.6%	-4.8%	3.5%	-8.3%	-0.5%

Table 23. Comparison of Arterial Road Traffic Throughputs in the Peak Direction During the Afternoon Peak Period

		2-3 PM	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	Total
US 50/Prosperity Ave.	Current	2170	2057	2298	2070	2094	1632	12321
	Baseline	1935	2305	2241	2101	2108	1712	12402
	%Diff	-10.8%	12.1%	-2.5%	1.5%	0.7%	4.9%	0.7%
US 29/Gallows Rd.	Current	1327	1655	1785	1689	1606	1059	9121
	Baseline	1192	1384	1682	1736	1672	1068	8734
	%Diff	-10.2%	-16.4%	-5.8%	2.8%	4.1%	0.9%	-4.2%

Analysis of Alternative Scenarios

This project tested a series of alternative scenarios to better understand the impact of different toll strategies on the performance of the corridor. These scenarios also serve as a sensitivity analysis to test the impact of important modeling parameters, including the value of time, total travel demand, and modal shift behavior, on the performance of the corridor.

Given that the morning peak period and the afternoon peak period models reacted to most of these changes (i.e., different dynamic pricing algorithms, level of demand, value of time distributions, etc.) in a similar way, the presentation of this chapter is based on the results from the morning peak period. Data tables for the afternoon peak period are presented in Appendix F.

Impact of Alternative Dynamic Pricing Algorithms

The dynamic pricing algorithms, which set the toll rate based on the level of congestion, are proprietary information for toll agencies. Therefore, there is very little information in the literature on the actual pricing algorithm used by existing toll roads in the U.S. This study assumed that the toll rate was set based on Equation 1. It included two important parameters: θ decides the critical density beyond which the toll rate increases rapidly; and β is the exponent which decides the speed at which the toll rate increases, once the density exceeds the critical level. In the baseline scenario (DPA10A), $\theta = 0.047$, which is equivalent to a critical density of 21.3 vehicle/mile/lane, and $\beta = 1.75$. This project tested two other sets of parameters for alternative pricing algorithms. The first alternative scenario (DPA23) assumed $\theta = 0.026$, which is equivalent to a critical density of 38.5 vehicle/mile/lane, and $\beta = 2$. The second alternative scenario (there is no formal name for this algorithm, and this study dubbed it as DPA02) assumed $\theta = 0.02$, which is equivalent to a critical density of 50 vehicle/mile/lane, and $\beta = 1.5$. As shown in Figure 9 in the Methodology Section, when compared to DPA10A, the toll rate grows slower under DPA23, and even slower under DPA02.

Figure 22 compares the density, toll rate, traffic volume, and speed of the I-66 OTB ETLs at Zone 5, which is to the west of the I-495 interchange. As DPA23 and DPA02 generate lower toll rates, compared to DPA10A, the ETLs attract more users under these two scenarios and the density becomes higher. The traffic volume passing Zone 5 also picks up earlier under DPA23 and DPA02, and the peak period lasts longer. However, the average speed of the ETLs drops below 45 mile/hour for almost an hour under DPA23, and for almost 2 hours under DPA02. This is because, under DPA02, the toll rate will not grow rapidly until the density exceeds 50 vehicle/hour/lane, which is within the level of service F.

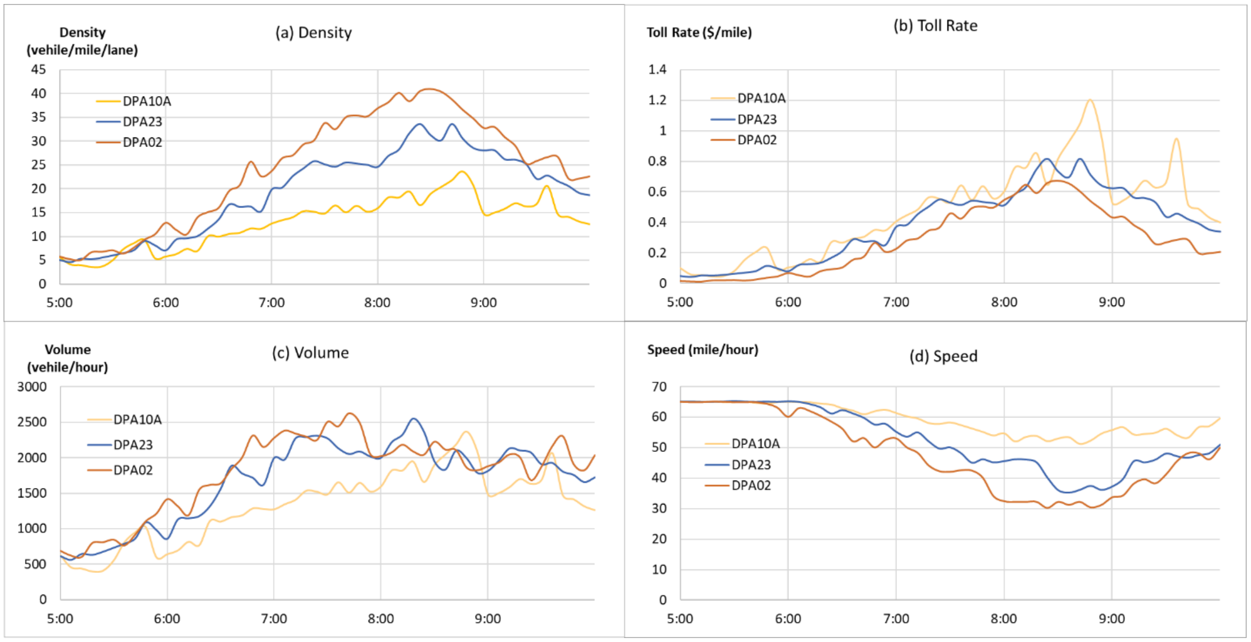


Figure 22. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Eastbound Direction Under Different Dynamic Pricing Algorithms.

Figure 23 shows the eastbound traffic throughput during the morning peak period at locations shown Figure 21. The I-66 OTB ETLs attracted 1,857 (27.9%) and 2,490 (37.5%) more vehicles during the morning peak period under DPA23 and DPA02, respectively. The majority of these vehicles were from the parallel GP lanes. The total counts on US 50 and US 29 were reduced by 4.5% and 3.6%, respectively, under DPA23. The number was slightly higher under DPA02. The total revenue under DPA23 was approximately the same as that under DPA10A, while the total revenue under DPA02 was 21.3% lower.

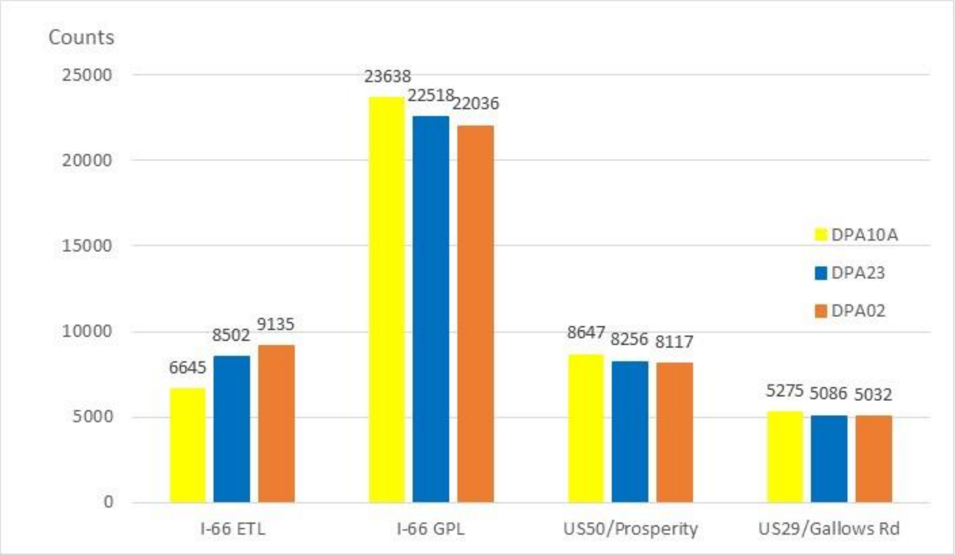


Figure 23. Eastbound Traffic Throughput During the Morning Peak Period Under Different Dynamic Pricing Algorithms

Impact of Adopting a HOT2 Instead of HOT3 Policy Under DPA10A

As the share of vehicles with two occupants is much higher than that of vehicles with three or more occupants (13.6% vs 5.04%), a toll policy change from HOT3 to HOT2, which gives free access to vehicles with two occupants, is expected to have a significant impact on demand. The baseline scenario assumes that the I-66 OTB ETLs only offer free access to vehicles with three or more occupants (HOT3).

Figure 24 compares the AM peak period density, toll rate, traffic volume, and speed of the I-66 OTB ETLs in the eastbound direction at Zone 5 under the HOT2 and HOT3 policies. Not surprisingly, the ETLs attracted more traffic under the HOT2 policy, since more vehicles could use the facility for free. However, as the number of vehicles increased, the toll grew rapidly, which kept more vehicles with single occupants from using the facility. The highest toll rate reached $1.84/mile, which was the equivalent of a $40.50 toll for the 22-mile facility. The average speed was below 45 miles/hour for about half an hour.

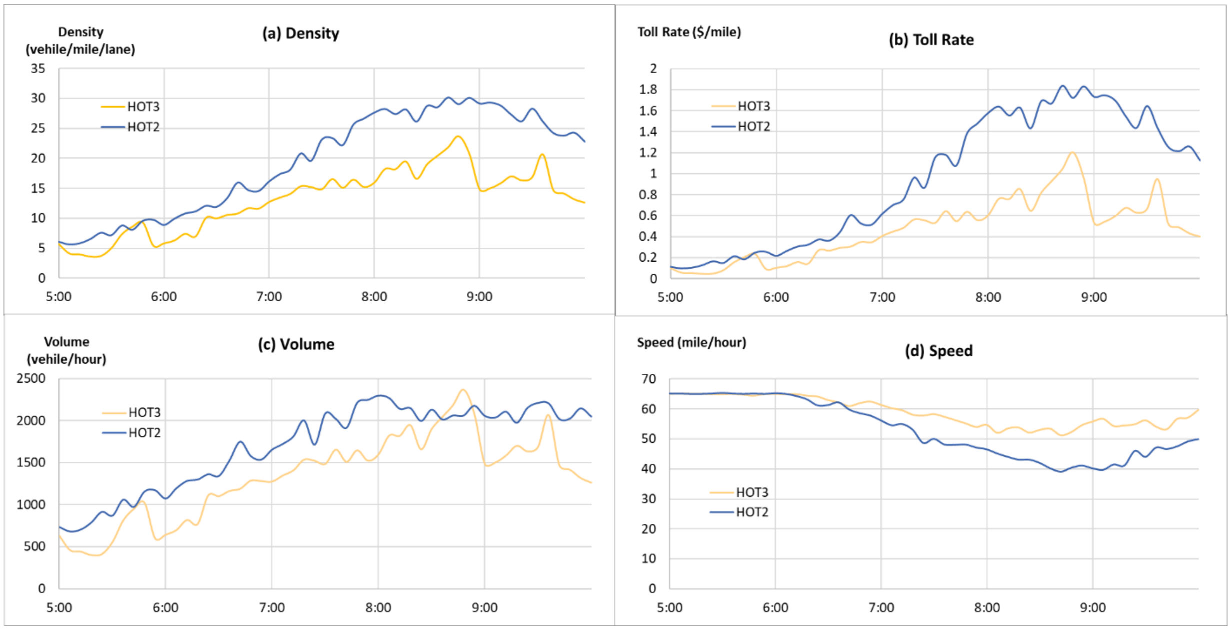


Figure 24. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Eastbound Direction Under HOT2 and HOT3 Policies.

Figure 25 shows the eastbound traffic throughputs during the morning peak period under the HOT2 and HOT3 policies. Although the total number of express toll lane vehicles increased from 6,645 to 8,658 at Zone 5, by changing the toll policy from HOT3 to HOT2, the number of paid vehicles decreased from 4,273 to 3,722. The total revenue at Zone 5 went up from $7,264 to $11,660, a 60.5% increase because of the higher toll rate.

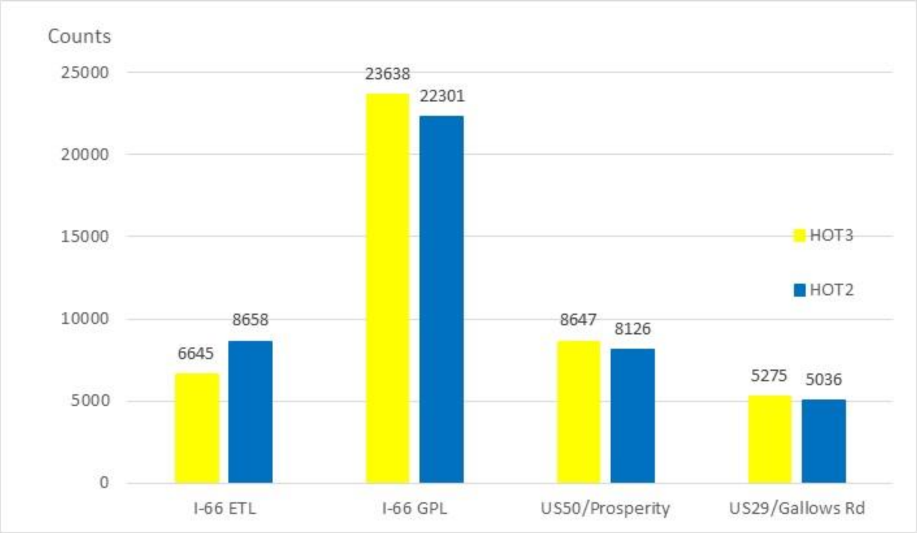


Figure 25. Eastbound Traffic Throughputs During the Morning Peak Period Under HOT2 and HOT3 Policies.

Impact of Higher Traffic Growth

The sensitivity analysis of different traffic growth factors serves two purposes. The first purpose is to evaluate the traffic conditions in future years where travel demand grows/decreases as the population and economic factors change. The growing economy in the region could contribute to the growth, while increasing the level of telecommuting could suppress commuting needs. This sensitivity analysis provides information about these scenarios. The second purpose is to control the uncertainty related to dynamic OD estimation. A sensitivity analysis could help to quantify the impact of such uncertainties. In this project, we investigated three scenarios: the overall travel demand increases by 2.5% or 5%, or decreases by 2.5%. Figure 26 compares the density, toll rate, traffic volume, and speed of the I-66 OTB ETLs in Zone 5 during the morning peak period under these three scenarios. Figure 26 shows that, when traffic grows, the peak traffic density at the ETLs does not change much. Instead, the traffic expands on both sides of the peaks and the peak period becomes longer.

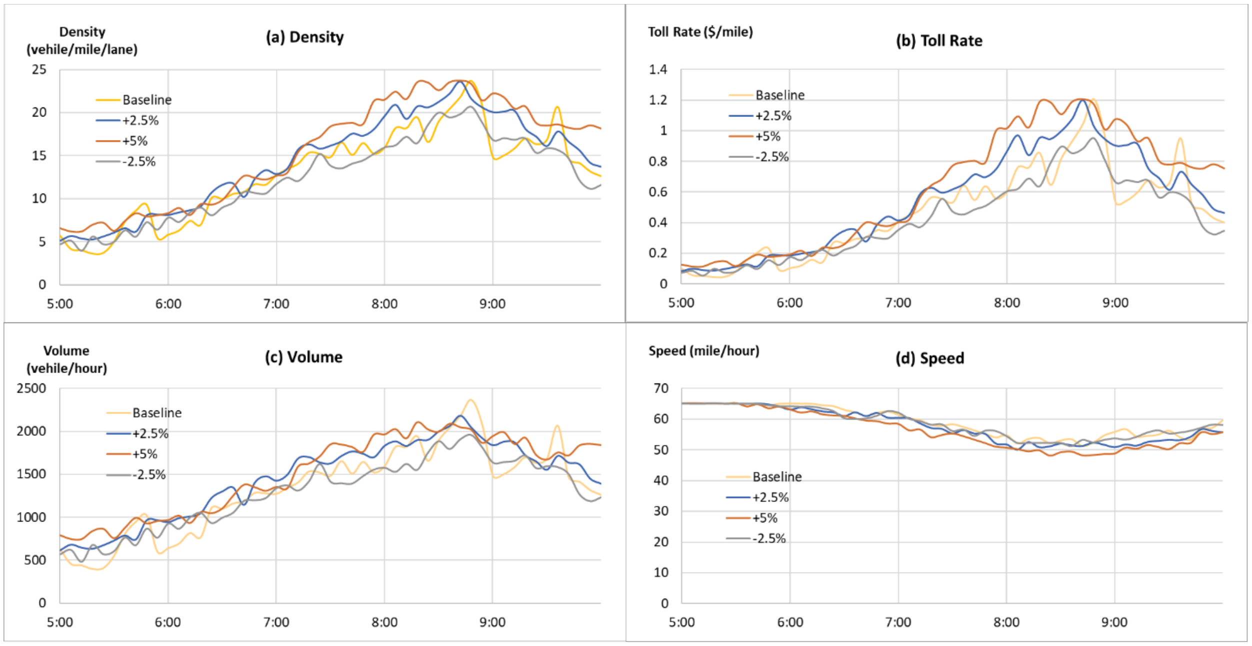


Figure 26. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) in Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Eastbound Direction Under Different Traffic Growth Factors.

Figure 27 shows the eastbound traffic throughput during the morning peak period under scenarios with different traffic growth factors. Table 24 further illustrates the percentage changes of throughput and the revenue under different scenarios. When traffic grows in the region, the throughput on the ETLs grow faster than those of the GP lanes. The latter shows a growth factor smaller than the percentage number of the across-the-board demand changes. This is due to the fact that the GP lanes of the I-66 corridor are already very congested. The traffic growth makes the congestion worse and helps to push more travelers to the ETLs. The number of ETL users increased by 10.8%, when it is assumed that the demand grows by 2.5%, and by 14.2% when the demand grows by 5%. However, when the regional travel demand decreased by 2.5%, traffic on the ETLs and GP lanes did not decrease as much. This is because the corridor may have pulled traffic from local streets when there is less congestion along the I-66 corridor. The magnitude of traffic volume changes are smaller at the two arterial street locations, as compared to those along the freeway under all three alternative scenarios. The capacity of arterial roads is constrained by the signalized intersections and the traffic dynamics are more complicated.

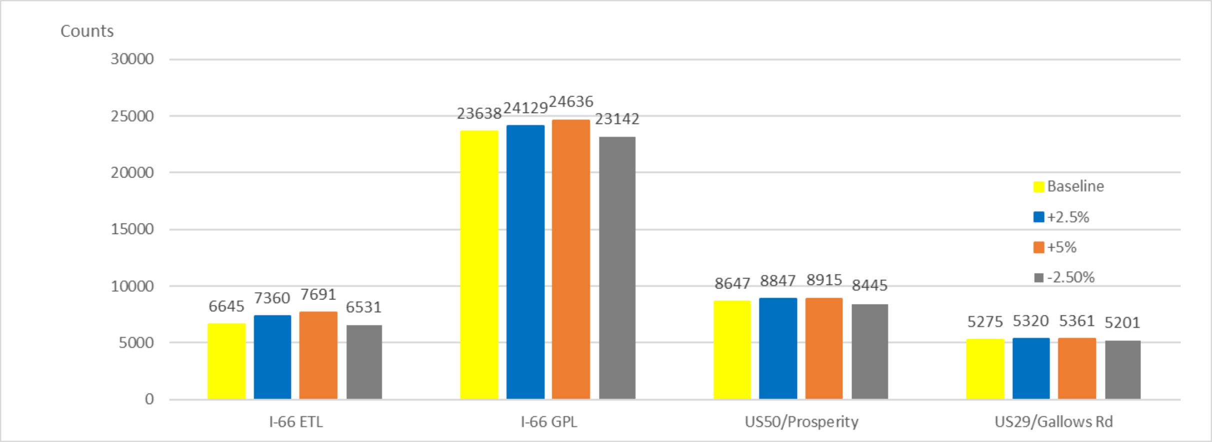


Figure 27. Eastbound Traffic Throughput at the East End of the I-66 Outside-the-Beltway Corridor During the Morning Peak Period Under Different Traffic Growth Factors.

Table 24. Throughput and Revenue Changes During the Morning Peak Period in Eastbound Direction Under Scenarios of Different Traffic Growth/Reduction Factors

Scenario	**Baseline**	**+2.5%**	**+5%**	**-2.5%**
	Counts	% Difference		
I-66 ETL	6645	+10.8%	+14.2%	-1.7%
I-66 GPL	23638	+2.1%	+4.1%	-2.1%
US 50/Prosperity	8647	+2.3%	+3.1%	-2.3%
US 29/Gallows Rd	5275	+0.8%	+1.6%	-1.4%
	$	% Difference		
Revenue at Zone 5	7264	+21.0%	+45.3%	-16.0%

The total revenue for Zone 5 grew by 21% and 45.3% when the demand was assumed to grow by 2.5% and 5%. This growth was due to the compounding effects of a higher number of express toll lane users which, in turn, led to higher toll rates. When overall travel demand decreased by 2.5%, the revenue dropped by a significant 16%, which the toll rate changes possibly caused.

Impact of Not Considering Vehicle Occupancy and Mode Split Changes

In the baseline scenarios, by applying the mode split model, that has been re-calibrated in this project, to selected centroids (with a demand higher than 100 vehicles) along the I-66 OTB corridor, 432 vehicles switched from having one or two occupants to having three or more occupants during the morning peak period. In addition, 236 travelers changed from riding the metro, to driving alone, because of corridor travel time improvement. In total, 432 new HOV3 trips were distributed to the different OD pairs along the corridor, while a net of 184 SOV trips were removed from the OD matrices when the mode split model was applied. When these demand changes were removed, the simulation results were almost identical because of the relative small difference in vehicle numbers and the fact that the I-66 OTB ETLs are not congested in the baseline scenario.

Impact of Alternative Value of Time Ranges

This study estimated a mean VOT of $30.5 for the morning peak period and $25.80 for the afternoon peak period. However, the VOT distribution among travelers could change as socio-economic factors change. This section evaluated the impact that a higher or lower VOT distribution has on the performance of the ETLs. In total, four scenarios were evaluated, with the mean VOT increased by 10% and 20% and decreased by 10% and 20%, respectively. The values used are summarized in Table 25.

Table 25. Mean Values of Time Used in Analysis

	Baseline	**+10%**	**+20%**	**-10%**	**-20%**
Morning Peak	$30.5	$33.6	$36.6	$27.5	$24.4
Afternoon Peak	$25.8	$28.4	$31.0	$23.2	$20.6

Figure 28 plots the probability density function for VOT distributions with different mean values. Because the lognormal distribution is heavily skewed to the left, when the mean is moved to a smaller value, the changes to the tail (accumulated probability for travelers whose VOT is larger than a selected value) are small. However, when the mean is moved to the right, the changes to the accumulative probability for travelers whose VOT is larger than a threshold are significant. This pattern can also be seen in Figure 29, which compares the density, toll rate, traffic volume, and speed of the I-66 OTB ETLs in Zone 5 under different assumptions of the VOT distribution. When the VOT becomes larger, the changes in the ETL density and speed are more significant. The elasticity is larger than 1.

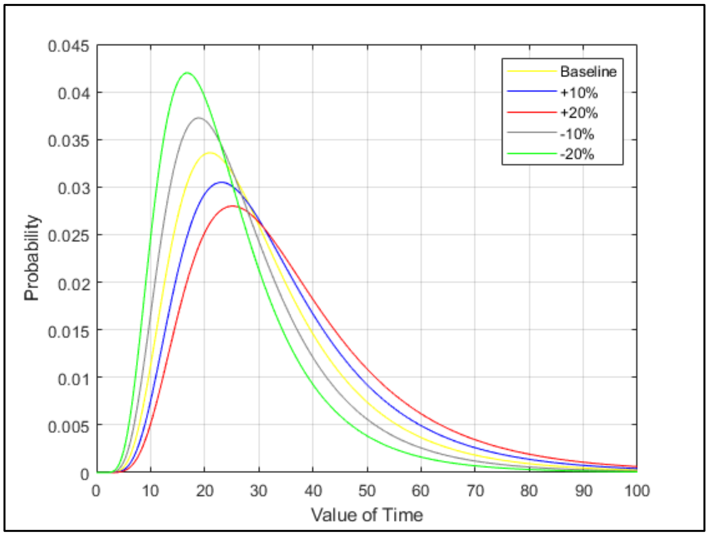


Figure 28. Probability Density Function of the Value of Time Distributions with Different Means.

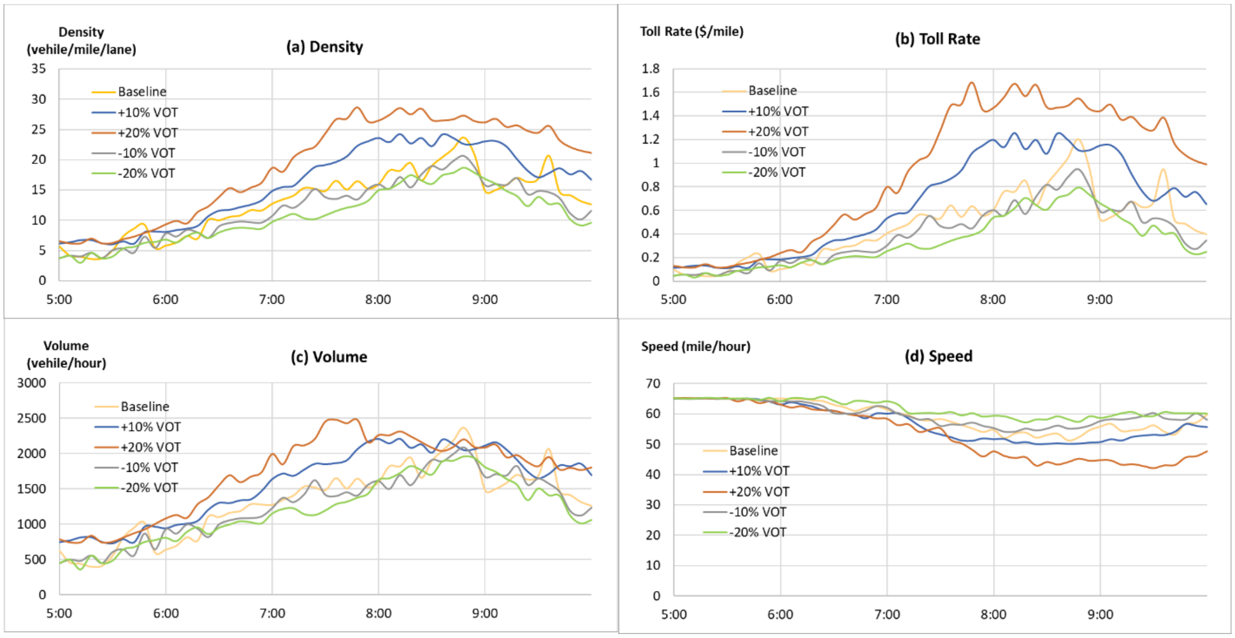


Figure 29. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) in Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Eastbound Direction Under Different Assumptions of Value of Time Distributions.

The changes of VOT distributions primarily affect the split of traffic between the GP lanes and the ETLs. As shown in Figure 30, a higher VOT results in more travelers selecting the ETLs, as compared to a scenario with a lower VOT. A 10% increases in the mean VOT leads to an approximate 5% increase in the cumulative distribution at a critical toll level, which implies about 1500 more vehicle trips whose VOT exceeds the threshold to justify the usage of the ETLs. As the density exceeds 20 vehicles/hour/lane, the toll rate increases rapidly, which prevents more users from choosing the ETLs. These two forces are competing in deciding the number of ETL users. By choosing the right critical density that is related to the dynamic toll algorithm, we could make sure that the number of express toll users (and, thus the density and level of service) falls within an acceptable range, even as the VOT fluctuates. A higher VOT among travelers leads to both more ETL users and higher toll rates, and both factors contribute to higher toll revenue. In contrast, when the mean VOT decreases, there is a group of users whose VOT is located at the tail of the distribution and is not sensitive to the toll rate changes. The impacts of VOT increases and decreases are not symmetric, as the lognormal distribution is skewed.

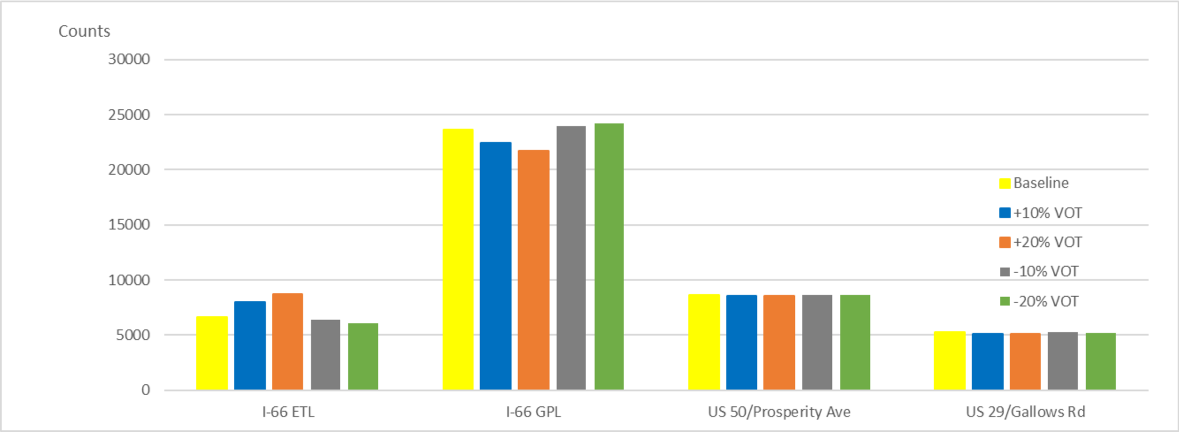


Figure 30. Eastbound Traffic Throughputs During the Morning Peak Period Under Different Assumptions of the Value of Time Distributions.

Table 26 summarizes the average changes in throughput and revenue for Zone 5 during the morning peak period under different assumptions of VOT distributions. Different VOT distributions have a major impact on the number of vehicles using the I-66 OTB ETLs and GP lanes. They have an even more significant impact on the toll revenue because of the compounding effect of more ETL users and higher toll rates. A 10% increase in the average VOT could lead to a 61.5% increase in toll revenue, and an increase of 20% in the average VOT could lead to a 144% increase in toll revenue. The highest toll rate, under a 20% VOT increase scenario, can generate a toll rate as high as $1.66/mile, which is the equivalent of $36.50 for the entire corridor. As shown in Figure 29, the average speed could drop to around 45 miles/hour for about 30 minutes under this assumption. A 10% drop in average VOT leads to a 3.2% decrease in ETL traffic, while a 20% drop in average VOT leads to an 8.3% decrease in ETL traffic. The impact of a VOT increase and a decrease in ETL usage is asymmetric.

Table 26. Throughput and Revenue Changes During the Morning Peak Period in Eastbound Direction Under Scenarios of Different Value of Time Distributions

Scenario	Baseline	+10%	+20%	-10%	-20%
	Counts	% Difference			
I-66 ETL	6645	20.8%	31.5%	-3.2%	-8.3%
I-66 GPL	23638	-5.1%	-8.1%	1.3%	2.5%
US 50/Prosperity	8647	-0.8%	-1.2%	-0.4%	-0.3%
US 29/Gallows Rd	5275	-2.9%	-3.3%	0.0%	-1.2%
	$	% Difference			
Revenue at Zone 5	7264	61.5%	144.0%	-20.4%	-35.0%

Two-factor Scenarios: Impact of Using Alternative Dynamic Pricing Algorithms Under Higher or Lower Demand

This section evaluates the potential compounding effect when two factors change simultaneously. Figure 31 compares the density, toll rate, traffic volume, and speed of the I-66 OTB ETLs at Zone 5 under different traffic growth rates and dynamic pricing algorithm combinations. The major finding is that, the dynamic pricing algorithms play a more significant role in the number of vehicles using the ETLs than the tested demand growth rates. Figure 31(a) shows that all scenarios under DPA23 and DPA02 have a higher density during the peak period, when compared to the baseline scenario (in which DPA10A is used), including the scenarios with a 5% traffic reduction across all OD pairs. Figure 31(d) shows the average speed in Zone 5 of the ETLs in all scenarios where DPA23 and DPA02 are lower than the baseline scenario, which uses DPA10A. Table 27 shows that, even when the overall travel demand is reduced by 5%, the number of ETL users is still higher than that of the baseline scenario.

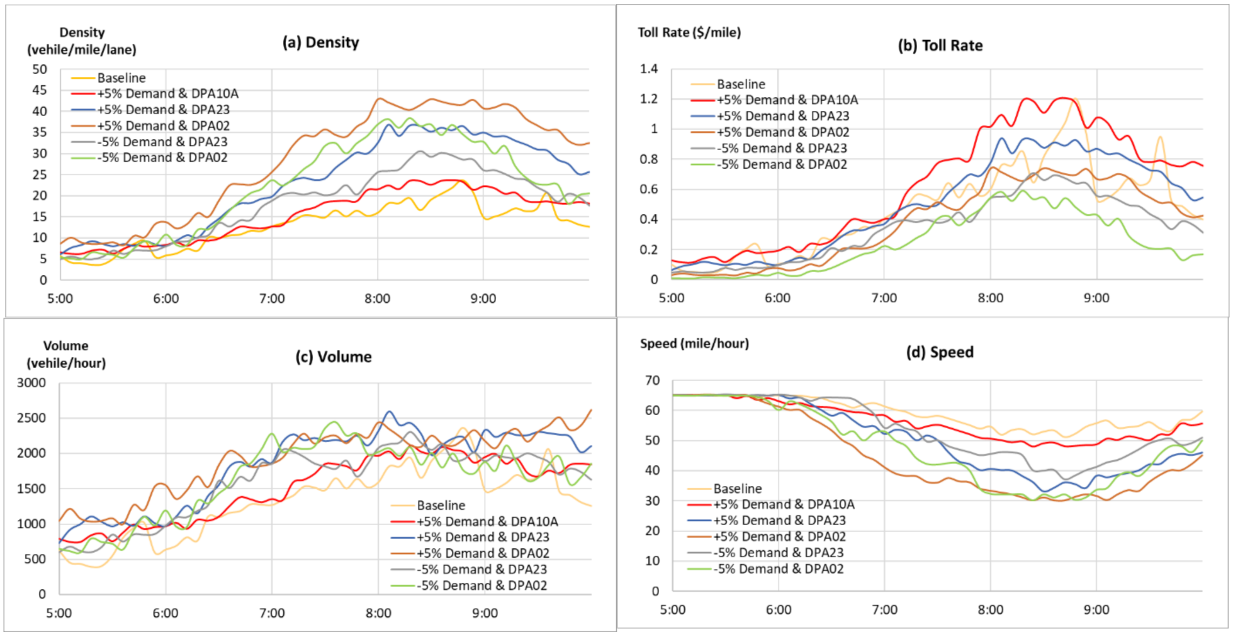


Figure 31. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) in Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in the Eastbound Direction Under Different Combinations of Growth Factors and Dynamic Pricing Algorithms.

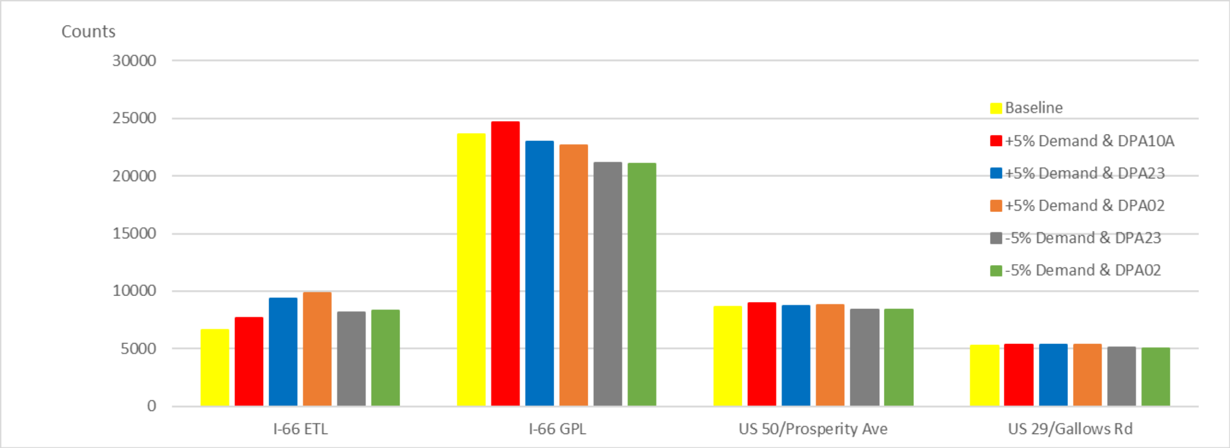


Figure 32. Eastbound Traffic Throughput During the Morning Peak Period Under Different Combinations of Growth Factors and Dynamic Pricing Algorithms.

Table 27. Throughput and Revenue Changes During the Morning Peak Period in the Eastbound Direction Under Different Combinations of Traffic Growth Factors and Dynamic Pricing Algorithms

Scenarios		**5% Traffic Growth**					
	Baseline	**DPA10A**		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	6,645	7,691	15.7%	9,370	41.0%	9,796	47.4%
I-66 GPL	23,638	24,636	4.2%	23,018	-2.6%	22,636	-4.2%
US 50/Prosperity	8,647	8,915	3.1%	8,745	1.1%	8,766	1.4%
US 29/Gallows Rd	5,275	5,361	1.6%	5,315	0.8%	5,371	1.8%
Total	44,206	46,603	5.4%	46,448	5.1%	46,569	5.3%
Revenue	$7264			$10,286	41.6%	$8,063	11%
Scenarios		**5% Traffic Reduction**					
	Baseline	**DPA10A***		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	6,645	N/A	N/A	8,129	22.3%	8,326	25.3%
I-66 GPL	23,638	N/A	N/A	21,107	-10.7%	21,054	-10.9%
US 50/Prosperity	8,647	N/A	N/A	8,385	-3.0%	8,410	-2.7%
US 29/Gallows Rd	5,275	N/A	N/A	5,070	-3.9%	5,046	-4.3%
Total	44,206	N/A	N/A	42,691	-3.4%	42,836	-3.1%
Revenue	$7264			$6,152	-15.3%	$4,555	-37.3%

** This study did not include a scenario of 5% traffic reduction under DPA10A in the analysis of single factor scenarios. The 5% traffic growth results under DPA10A were already discussed; and are presented here only for comparison.*

Under the modeled traffic growth scenario, the projected revenue increased. Under DPA23, with a 5% traffic growth, the revenue grew by 41.6%, compared with the baseline scenario; and the revenue grew by 11% under DPA02 (with no traffic growth, the revenue would have decreased by 21.3%, compared to the baseline scenario, as shown in the analysis of scenarios with a single factor). Similarly, a 5% traffic reduction would have further reduced the revenue while, under both the traffic growth and reduction scenarios, the changes in revenue were always much larger than 5%.

Two-factor Scenarios: Compounding Impact of Value of Time and Traffic Growth

Figure 33 shows that a 10% change in the VOT distribution has a higher impact on the number of vehicles using the ETLs, as compared to a 5% change in the total travel demand. Both of the blue and the orange lines (depicting a 10% increase of mean VOT) in Figure 33(a) run above the line, while the green lines (depicting a 10% reduction of mean VOT) show that the total vehicle throughput of the ETLs presents a similar pattern, when compared to that of the density. This is not surprising as Figure 33(d) further shows that, in all four scenarios, the average speed is well above the 45 mile/hour threshold and no severe congestion is observed on the ETLs.

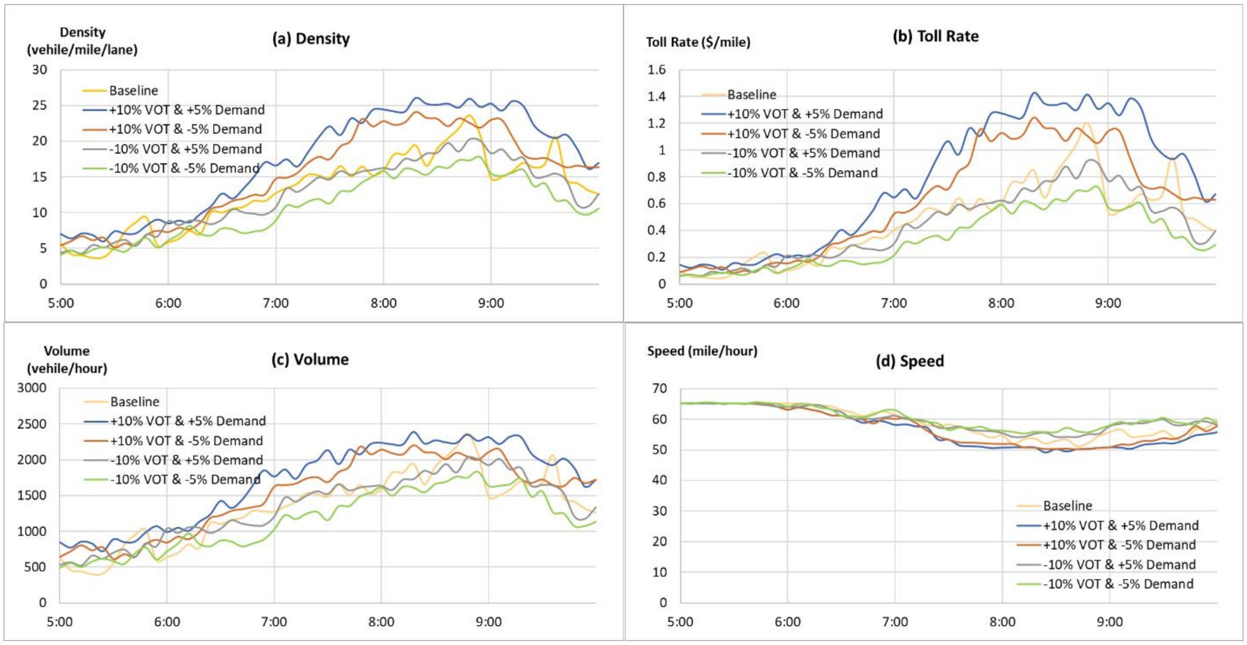


Figure 33. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) in Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in the Eastbound Direction Under Different Combinations of Growth Factors and Value of Time Distributions.

Figure 34 and Table 28 further compare the total vehicle throughput of the four scenarios with that of the baseline scenario. The compounding effect of higher traffic growth and higher VOT distributions is visible. With a 5% increase in total travel demand and a 10% increase in the value of time, the number of users of the ETLs increased by 30.4%, compared to an increase of 15.7%, when only the travel demand grew, and an increase of 20.8% when only the mean VOT grew. However, the combined total (30.4%) is less than the 39.8% (1.157*1.208 = 1.398) obtained by simply multiplying the results obtained from evaluating each factor independently. This is because the higher level of usage of the ETLs, caused by either factor, would push the toll rate to increase at a faster speed, which would, in turn, constrain the growth of ETL vehicles. Although this study did not include a scenario of 5% traffic reduction under the baseline value of time distribution in the analysis of single factor scenarios, the total number of vehicles using the ETLs should have dropped and been slower when the two factors were combined in a single scenario. Following the same logic, this could be compared to what we would get if we ran the two scenarios independently and then multiplied the reduction rates to estimate the compounding effect. The changes in toll revenue would show a similar pattern but, in a larger magnitude, where the increases in the number of vehicles and the toll rate would reinforce one another and contribute to the growth of total revenue.

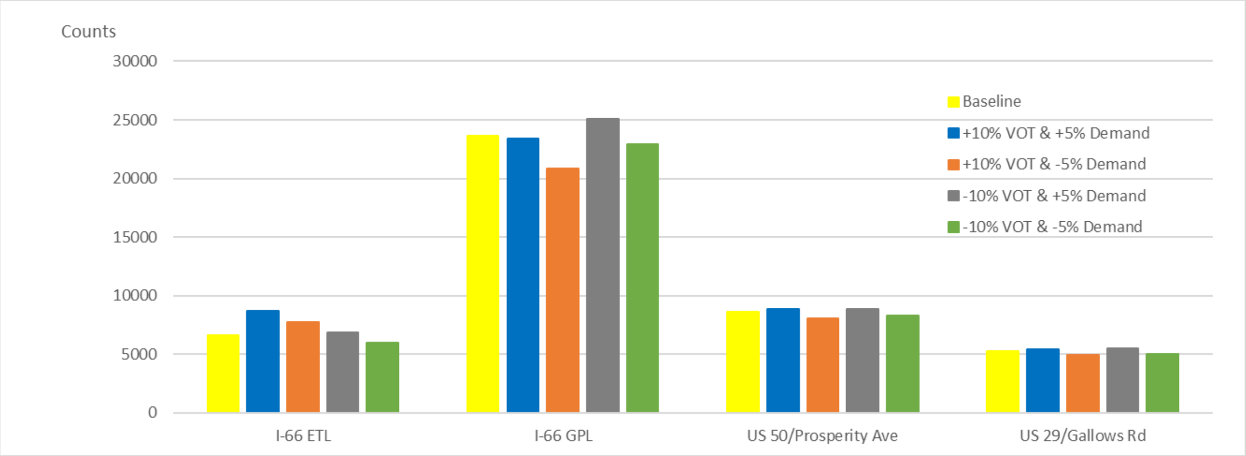


Figure 34. Eastbound Traffic Throughput During the Morning Peak Period Under Different Combinations of Growth Factors and Value of Time Distributions.

Table 28. Throughput and Revenue Changes During the Morning Peak Period in Eastbound Direction Under Different Combinations of Traffic Growth Factors and Value of Time Distributions

Scenarios		**5% Traffic Growth**					
	Baseline	**Baseline VOT**		**+10% VOT**		**-10% VOT**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	6,645	7,691	15.7%	8,665	30.4%	6,840	2.9%
I-66 GPL	23,638	24,636	4.2%	23,358	-1.2%	25,042	5.9%
US 50/Prosperity	8,647	8,915	3.1%	8,880	2.7%	8,862	2.5%
US 29/Gallows Rd	5,275	5,361	1.6%	5,423	2.8%	5,474	3.8%
Total	44,206	46,603	5.4%	46,326	4.8%	46,218	4.6%
Revenue	$7264	$10,555	45.3%	$14,819	104%	$10,852	49.4%
Scenarios		**5% Traffic Reduction**					
	Baseline	**Baseline VOT***		**+10% VOT**		**-10% VOT**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	6,645	N/A	N/A	7,744	16.5%	5,939	-10.6%
I-66 GPL	23,638	N/A	N/A	20,878	-11.7%	22,935	-3.0%
US 50/Prosperity	8,647	N/A	N/A	8,044	-7.0%	8,322	-3.8%
US 29/Gallows Rd	5,275	N/A	N/A	4,902	-7.1%	5,013	-5.0%
Total	44,206	N/A	N/A	41,568	-6.0%	42,209	-4.5%
Revenue	$7264		N/A	$6,647	-8.5%	$4,547	-37.4%

** This study did not include a scenario of 5% traffic reduction under the baseline value of time distribution in the analysis of single factor scenarios.*

Two-factor Scenarios: Compounding Impact of Value of Time and Different Dynamic Pricing Algorithms

As discussed early in the report, DPA23 and DPA02 have a higher critical density beyond which the toll rate would grow at a much faster speed, when compared to DPA10A. Therefore, toll rates under DPA23 and DPA02 increase at a slower pace when demand increases. Different VOT distributions affect how travelers compare the ETLs and the GP lanes, or any other potential routes, when both the travel time and out-of-pocket travel costs are considered. This sub-section evaluates the compounding impact of the two factors.

With a 10% increase in the VOT, the density of the ETLs exceeded 40 vehicles/mile/lane under DPA02 and 35 vehicles/mile/lane under DPA23 during the peak hour, which correspond to LOS E. Correspondingly, the average speed on I-66 OTB ETLs dropped below 45 mile/hour between 8 am and 9 am during the morning peak in these two scenarios. Higher VOT among travelers and slower toll increases, as a function of ETL density, mean more vehicles are diverted from GP lanes to the ETLs as compared to the baseline scenario. The increase of ETL users under these two scenarios is more significant during the shoulder hours, compared to the peak hour within the peak period. The traffic flow of the GP lanes, during the peak hour, does not drop as travelers move to the ETLs. Instead, some travelers move from the shoulder hours to the peak hour on both sides of the morning peak period. ETLs attracted fewer travelers under the assumption of a 10% decrease in the mean VOT (shown in grey and green lines).

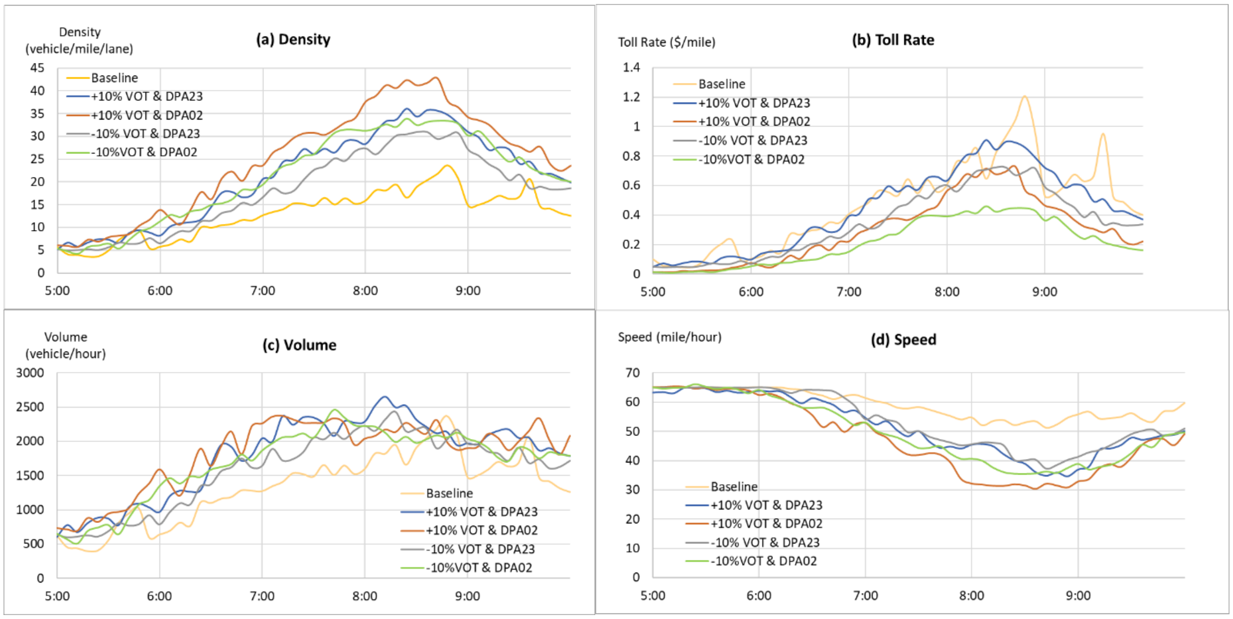


Figure 35. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Eastbound Direction Under Different Value of Time Distributions and Dynamic Pricing Algorithms.

Figure 36 and Table 29 show the changes in vehicle throughput and revenue under different combinations of VOT and DPAs. More travelers are willing to use the ETLs under higher VOT and the impact is higher under DPA23 and DPA02. Overall, the impact of dynamic toll algorithms on the number of express toll lane users is larger than the 10% change in the value of time distribution. However, the value of time distribution has a stronger impact on the total revenue, as it has a stronger impact on setting the toll rate.

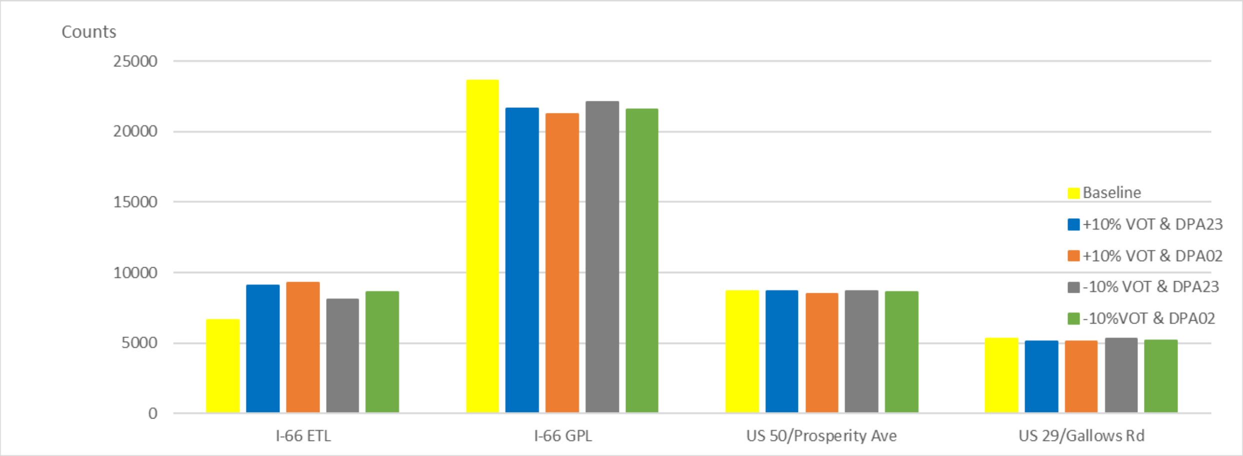


Figure 36. Eastbound Traffic Throughputs During the Morning Peak Period Under Different Combinations of Value of Time Distributions and Dynamic Pricing Algorithms.

Table 29. Throughput and Revenue Changes During the Morning Peak Period in the Eastbound Direction Under Different Combinations of Value of Time Distributions and Dynamic Pricing Algorithms

Scenarios		**+10% Value of Time**					
	Baseline	**DPA10A***		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	6,645	8,026	20.8%	9,089	36.8%	9,284	39.7%
I-66 GPL	23,638	22,425	-5.1%	21,618	-8.5%	21,236	-10.2%
US 50/Prosperity	8,647	8,578	-0.8%	8,645	0.0%	8,466	-2.1%
US 29/Gallows Rd	5,275	5,123	-2.9%	5,115	-3.0%	5,071	-3.9%
Total	44,206	44,152	-0.1%	44,467	0.6%	44,057	-0.3%
Revenue	$7,264	$11,731	61.5%	$8,789	21.0%	$5,898	-18.8%
Scenarios		**-10% Value of Time**					
	Baseline	**DPA10A***		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	6,645	6,430	-3.2%	8,082	21.6%	8,595	29.4%
I-66 GPL	23,638	23,942	1.3%	22,107	-6.5%	21,554	-8.8%
US 50/Prosperity	8,647	8,612	-0.4%	8,685	0.4%	8,610	-0.4%
US 29/Gallows Rd	5,275	5,274	0.0%	5,270	-0.1%	5,196	-1.5%
Total	44,206	44,258	0.1%	44,144	-0.1%	43,956	-0.6%
Revenue	$7264	$5,782	-20.4%	$6,334	-12.8%	$4,097	-43.6%

**These two scenarios have been discussed in detail under single factor analysis and are only included here for comparison.*

Multi-factor Analysis of Potential Post COVID-19 Scenarios

Table 30 summarizes the assumptions adopted for traffic conditions in the post-COVID-19 scenarios.

Table 30. Assumptions for Scenarios Representing Traffic Conditions in the Post COVID-19 Era

Scenario	M1a: Higher Demand for Travel		M2b: Lower Demand for Travel	
	Changes	**Numbers**	**Changes**	**Numbers**
Morning Peak	+10% demand -20% HOV split	50604 more trips overall; HOV3+ reduced to 5.12% from 6.4%, approximately 629 fewer vehicles along the corridor	-10% demand -20% HOV split	50604 less trips overall; HOV3+ reduced to 5.12% from 6.4%, approximately 515 fewer vehicles along the corridor
Afternoon Peak	+10% demand -20% HOV split	61430 more trips overall; HOV3+ reduced to 7.36% from 9.2% , approximately 1161 fewer vehicles along the corridor	-10% demand -20% HOV split	61430 less trips overall HOV3+ reduced to 7.36% from 9.2%, approximately 950 fewer vehicles along the corridor

Under the first scenario of a post-COVID-19 world (M1a), we assumed that the traffic would grow by 10% and the split for high occupancy vehicles would drop by 20%. We would expect a significantly higher level of congestion at the GP lanes, which would motivate more users on the ETLs. Figure 37(a) and Figure 37(c) show that both the density and traffic volume increased at the ETLs. In addition, the peak period of the ETLs extended, particularly to the later shoulder hours (9 am to 10 am). The toll rate could go as high as $1.6/mile, which is equivalent to a toll of $35.2 for the 22-mile segment. The average speed approached the 45 miles/hour threshold at around 9 am (Figure 37d). The results illustrate that with the baseline dynamic pricing algorithm, DPA10A, the ETLs will maintain the required minimal level of service even under a significant increase in travel demand.

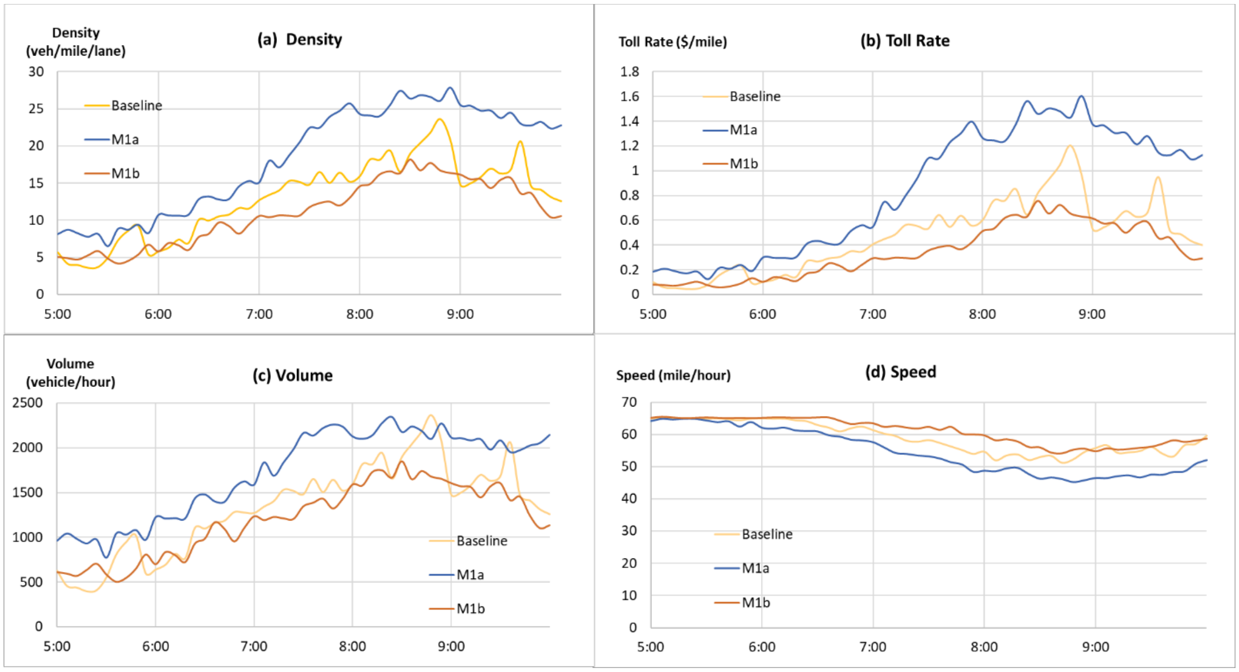


Figure 37. Comparison of AM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Eastbound Direction Under Two Scenarios of Post COVID-19 Traffic Conditions in the AM Peak Period.

M1a: -20% split for High Occupancy Vehicles and +20% of overall traffic
M1b: -20% split for High Occupancy Vehicles and -20% of overall traffic

Under the second scenario of a post-COVID-19 world (M1b), we assumed that the traffic would decrease by 10% and the split for high occupancy vehicles would drop by 20%. The overall travel demand at the I-66 OTB corridor would drop, which reduces the need for using the ETLs. Moreover, fewer vehicles with three or more occupants will use the corridor under this scenario, which further reduces the traffic in the ETLs. The net impact is a drop of toll rate and of the number of ETL users, particularly during the shoulder hours.

Figure 38 and Table 31 show the number of vehicles going through the ETLs, the GP lanes, and the two major parallel arterial roads. Under the M1a scenario, the ETLs attracted 27.4% more vehicles with three or more occupants compared to the baseline scenario. The additional HOVs came from mode switching behavior, and rerouting traffic from arterial roads. The arterial roads were at their capacity, under the baseline scenario, and the throughput would not increase much, even with higher demand, particularly during the peak hour within the peak period. Most of the 4.6% and 6.4% increases of throughput at US 50 and US 29 occurred during the shoulder hours. In contrast, when travel demand dropped by 10% in the M1b scenario, the throughputs in the arterial roads dropped by a similar percentage number.

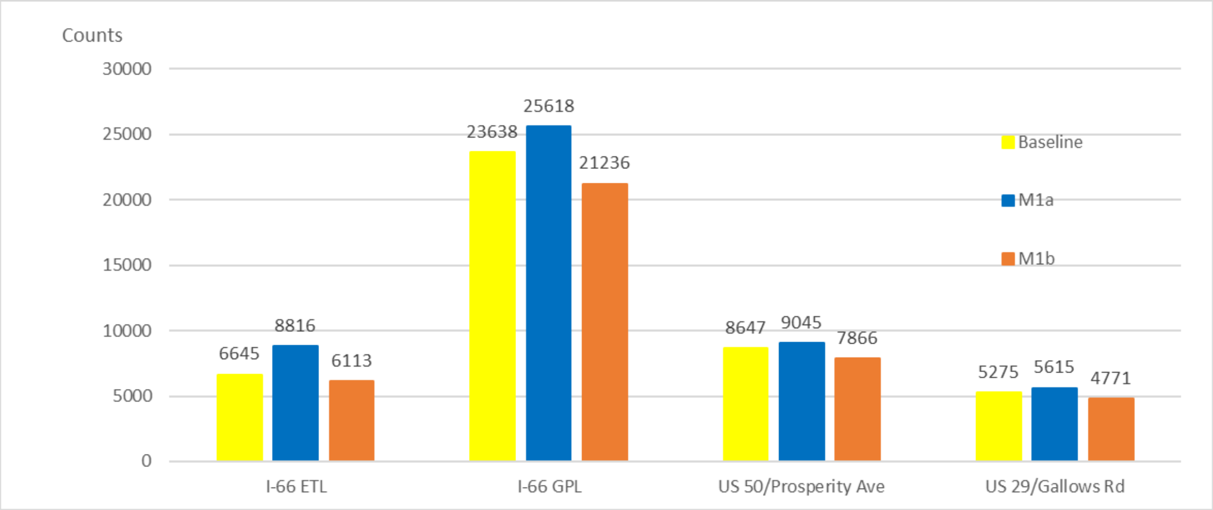


Figure 38. Eastbound Traffic Throughput During the Morning Peak Period Under Two Scenarios of Post-COVID-19 Traffic Conditions.

M1a: -20% split for High Occupancy Vehicles and +20% of overall traffic
M1b: -20% split for High Occupancy Vehicles and -20% of overall traffic

Table 31. Throughput and Revenue Changes in the Peak Direction during the Morning Peak Period under Two Scenarios of Post-COVID-19 Traffic Conditions

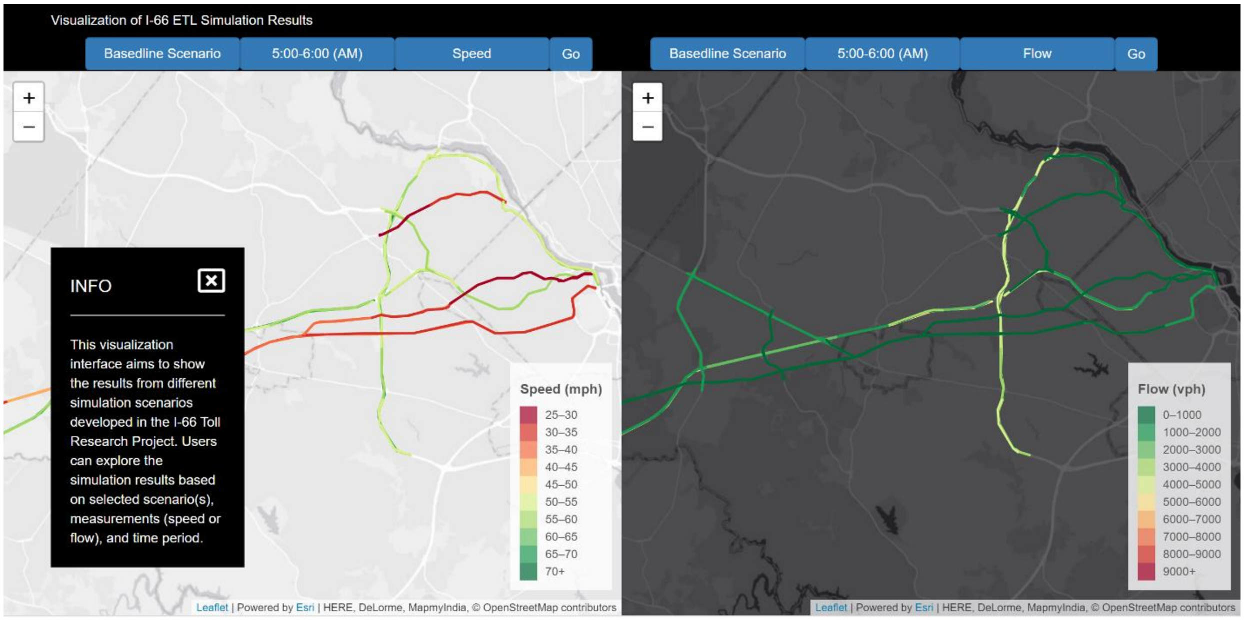
		Baseline	**M1a**		**M1b**	
		Counts	**Counts**	**%Difference**	**Counts**	**%Difference**
ETL	**HOV3+**	2372	3023	27.4%	1852	-21.9%
	SOV/HOV2	4273	5793	35.6%	4261	-0.3%
	Total	6645	8816	32.7%	6113	-8.0%
GPL		23638	25618	8.4%	21236	-10.2%
US 50		8647	9045	4.6%	7866	-9.0%
US 29		5275	5615	6.4%	4771	-9.6%
Total		44206	49094	11.1%	39986	-9.5%
Revenue		$7,264	$16,227	123.4%	$4,729	-34.9%

M1a: -20% of High Occupancy Vehicles and +10% of overall travel demand
M1b: -20% of High Occupancy Vehicles and -10% of overall travel demand

A Web Portal to Support Informed Decisions

The I-66 OTB ETLs are expected to bring a lot of changes to traffic conditions in the region. With the introduction of dynamic pricing algorithms, the toll rates and traffic conditions will vary dynamically at different times of the day. This report summarizes the high-level findings and the most significant impacts of the I-66 OTB, based on outputs from the simulation model. A graphical interface, to allow users to visualize model outputs under different scenarios, was developed to further help decisions makers study and understand the overall traffic conditions in more detail. Figure 39 presents the user interface of the web-based interactive tool. It includes two separate windows that are set side-by-side. Each window is a GIS-based tool that allows users to display selected simulation outputs on an interactive map. Users can zoom in and out and navigate to different parts of the traffic network by clicking on the map. The drop-down boxes, at the top, help users specify the scenario, time period, and types of simulation outputs to be displayed. The outputs are displayed using commonly used color themes. However, users can also inspect a particular value by hovering the cursor on a road segment.

This web portal is hosted on a server located at the Old Dominion University and will be maintained for 2 years from the publication of this report. Additional scenarios and information could be added later, should a need emerge in the future. Users can access the tool by visiting http://senselane.com/i66/.



This visualization interface aims to show the results from different simulation scenarios developed in the I-66 Toll Research Project. Users can explore the simulation results based on selected scenario(s), measurements (speed or flow), and time period.

Figure 39. Interface of the Interactive Web-based Tool.

DISCUSSION

The literature review showed that most existing studies of regional level effects of toll roads are based on static traffic assignment models and cannot fully consider the impact of dynamic toll strategies. The modeling system developed in this project is dynamic and can be applied to investigate dynamic toll scenarios that have not yet been implemented. This modeling system also considers behavioral reactions to tolls, based on locally collected data, including travel mode and vehicle occupancy changes, which are not commonly seen in previous studies.

The models developed in this study also have some limitations. Many parameters may affect the behavior of a traffic simulation model and, ideally, all of them should be calibrated using locally collected data. Limited by data availability and scope, this study did not calibrate some parameters, such as those used in the car-following models. This study calibrated other important parameters, such as the VOT distributions and vehicle occupancy choice models, using locally collected data to the extent possible. However, this study still had to make many assumptions and draw data from a variety of sources, some of which may not have been updated in a timely manner. Moreover, this study only used data from a small period of time for model calibration (traffic data from May 2018 and toll transaction data from March to May, 2018).

Running a regional-level microscopic simulation model is very time consuming. It took up to 2 days to conduct a single model run for this study. Therefore, this project only tested a limited number of model parameters and scenarios. These scenarios may not fully cover the potential traffic conditions (e.g., COVID-19 and other larger traffic factors at play in the region). As a result, users should use these results with an appropriate understanding of the caveats. Future research can further address these limitations.

CONCLUSIONS

- *TransModeler was an effective modeling and simulation tool for analyzing a large area network with dynamically priced ETLs and multiple mode choice alternatives.* Using vehicle traffic volume, signal timing, travel times, toll rates, and transit boarding data that was currently available to VDOT, the TransModeler model developed in this study could be calibrated within the allowable limits of values in VDOT's *Traffic Operations Simulation and Modeling (TOSAM) guidebook*. The directions and magnitudes of impacts on the various roads in the network from the various scenarios tested were deemed reasonable by the research team and the technical review panel.

Conclusions Specific to the I-66 ITB and I-66 OTB Scenarios Tested

- *I-66 ITB ETLs serve many more travelers in the region than the number of regular daily facility users*. Empirical analysis of I-66 ITB ETLs showed that the majority of SOV travelers (94% during the morning peak period and 97% during the afternoon peak period) used the toll facility less than one time per week. Trips made by these non-frequent travelers accounted for 54% of total SOV trips during the morning peak period and 70% of trips during the afternoon peak period.

- *The average value of time for the I-66 corridor users was found to be higher than the FHWA recommendations.* FHWA recommends a VOT between $9.50 and $16.30 per hour for local personal trips at the national level. The empirical analysis of the EZ-Pass transaction data from the I-66 ITB and the INRIX speed data showed that the VOT distribution among the toll facility users has a very long tail, implying that some trips are not sensitive to toll changes. Data collected from March to May 2018, showed a mean value of time of $45.37/hour and $61.78/hour among frequent and non-frequent users, respectively, during the morning peak period. The mean value of time was $38.14/hour and $37.64/hour for frequent and non-frequent users, respectively, during the afternoon peak period. The higher value of time among non-frequent users, during the morning peak period, confirmed that non-frequent facility users may only use the toll facility for urgent travel needs that require timely arrival (e.g., important business trips, hospital visits, etc.). Because the simulation model cannot differentiate users from day to day, this study treated both as one type of trip and estimated the mean VOT for morning and afternoon trips through a weighted average method. The mean VOT was found to be $30.5/hour for the morning peak period and $25.8 for the afternoon peak period, respectively, including the VOT for parallel roads.

- *I-66 OTB ETLs are estimated to bring tangible travel time improvements to the entire corridor.* The simulation model showed that, compared to the traffic conditions before the opening of the I-66 OTB ETLs, eastbound travel time along the general-purpose lanes improved by as much as 36.1% for the segment between Gainesville and Rt. 28, and by 13.2% for the segment between Rt. 28 and I-495, during the morning peak period, respectively. During the afternoon peak period, Westbound travel time improved by as much as 17% for the segment between I-495 and Rt. 28 and 7.4% between Rt. 28 and Gainesville, respectively. The significant improvement for the segment west of Rt. 28, during the morning peak, is partly attributable to the improvement in the interchange between I-66 and Rt. 28.

The results are not directly comparable to that of the I-66 ITB ETLs study, as the I-66 ITB was a HOV-only facility during the peak hour before being converted to a HOV2+ facility. After the conversion, the speed dropped, as SOVs were allowed to use the facility. With a θ of 0.029 and a β of 1.5 default (values in the I-66 ITB ETLs study), the average speed in the most congested zone was estimated to be around 25 miles/hour under HOV2+ and a little bit above 40 miles/hour under HOV3+.

- *I-66 OTB ETLs are estimated to help improve the traffic throughput of the corridor during the peak hour within the peak period by 20% for the morning peak period and 19% for the afternoon peak period.* The simulation model showed that the I-66 OTB ETLs would serve about 6,645 and 8,774 trips at the point right before the interchange with I-495 during the morning peak and the afternoon peak periods, respectively. When combined with the traffic on general purpose lanes, the total throughputs increased to 30,783 (6.8%) and 35,914 (5.1%) vehicles, compared to the current throughputs of about 28,813 and 34,160 vehicles during each peak period. With the additional capacity brought by the ETLs, the total traffic throughputs at this point could improve by about 20% during the peak hour. The improved throughput during the peak hour also attracted traffic from shoulder hours. The departure time choice model showed that traffic would concentrate in the peak hour and the travel demand would drop, during the very early and late morning hours, by about 6.6% and 12.3%, respectively.

- *I-66 OTB ETLs do not exert strong adverse impacts on major parallel arterials like US 29 and US 50.* The introduction of the ETLs created less than 5% impact on the overall traffic volumes along the arterial roads, although the impact during the shoulder hours seems to be slightly larger at around 12-16%.

- *The choice of a dynamic pricing algorithm played a critical role in maintaining sufficient levels of service at the ETLs.* Using the baseline algorithm, currently used inside the beltway (DPA10A), the OTB facility can maintain a speed above the 45 mile/hour threshold, even with higher travel demand and higher value of time distributions tested in this research. However, there is a risk for the speeds to drop below this threshold if either of the two alternative dynamic pricing algorithms, DPA23 or DPA02, are adopted, particularly with higher value of time distributions.

- *Higher travel demand and higher value of time among I-66 OTB travelers lead to higher numbers of express toll lane users and much more toll revenue.* The simulation model showed that a 5% increase in travel demand could lead to a 15.7% increase in the number of OTB users and a 45% increase in toll revenue under DPA10A. This is a result of the compounding effect of the higher number of I-66 OTB facility users and higher toll rates needed to maintain the desirable level of service for travel times. The assumption of the VOT distribution has an even bigger impact on the number of users and revenue expectations. A 20% increase in the mean value of time among travelers would lead to a 31.5% increase in OTB trips and a 144% increase in toll revenue collection under DPA10A. The impact of travel demand and value of time changes is asymmetric, as lower demand and lower value of time among travelers would only reduce the number of ETL users and revenue by a smaller percentage. A 2.5% decrease in travel demand, leads to a 1.7% reduction of ETL users, and a

20% reduction in the mean VOT among travelers, leads to an 8.3% reduction of ETL users under DPA10A.

- *Among all single factor scenarios studied, the strategy of tolling just single occupant vehicles (HOT2+), instead of vehicles with one or two occupants (HOT3+) has the most significant impact on the performance of the corridor.* The average speed could go below the 45 mile/hour threshold briefly, even under the DPA10A algorithm, as the number of users increases by 30% during the morning peak period at the east end of the ETLs, if a HOT2+ instead of a HOT3 policy is applied, with everything else equal. The revenue only increases moderately (17.2%), as the number of paid users decreases.

- *New traffic conditions in the post-COVID-19 era could have significant impacts on the performance of the I-66 OTB ETLs.* There is no consensus in the research community on how COVID-19 may affect travel demand in the long term. This study tested two scenarios as the high and low boundary conditions: a 10% increase or decrease of overall travel demand, along with a 20% drop of the split for high occupancy vehicles in both cases. The model predicted a 32.7% and 30.5% increase in the number of I-66 OTB facility users in the first case during the morning and afternoon peak periods, respectively, and an 8% and 10.1% decrease in the number of I-66 OTB facility users during the morning and afternoon peak periods, respectively, in the second case.

- *Using the mode split model, developed with locally collected data, overall shifts among high occupancy vehicles, SOVs, and the metro were relatively small.* The model could predict the changes in vehicle occupancy in reaction to travel time and travel cost changes. The model also considered the mode shifts among the metro riders. However, the overall shifts were relatively small.

RECOMMENDATIONS

1. *VDOT's TED should assess wider agency needs and consider adding TransModeler to the suite of VDOT simulation software.* Assessing the impacts of operational improvements that change dynamically, such as new integrated corridor management strategies or intelligent transportation systems, can be particularly difficult. Compared to the conventional models based on the static regional planning model, the TransModeler model developed and used in this study is more applicable for assessing such dynamic strategies. VDOT's TED should explore such possibilities to take full advantage of the models and tools developed and delivered in this project.

2. *VDOT's I-66 ITB Tolling Operations and Northern Region Operations should develop a plan to maintain and update the model developed in this study for the long term.* Traffic conditions and important parameters, such as VOT distributions, may change over time. Particularly, such changes may be significant when the region goes into the post-pandemic era, and when I-66 OTB Tolling Operations become active. VDOT's I-66 ITB Tolling Operations and NRO should assess the need to update and maintain the models developed in this project to keep them relevant and useful for potential future applications.

3. *VDOT's I-66 toll managers and Northern Region Operations should widely share the conclusions specific to I-66 ITB and I-66 OTB scenarios with VDOT executive management, the I-66 OTB P3 concessionaire, and the general public, as needed*. This project developed a web-based, interactive, a quick visualization tool that could help inform VDOT stakeholders about the impacts of a number of toll strategies that may be applied to the I-66 OTB corridor. Findings from this project could help facility planning and operations, and communication with stakeholders.

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1: Within 6 months of publication of this report, VTRC will fund an implementation project for the current research team to document their experiences expand the previously developed Weris I-66 ITB model by merging with the newly developed I-66 OTB network, data preparation, skillset (both for data wrangling and for modeling), training, hardware needs, calibration methodologies, etc. in a technical memo. Within 6 months of completion of the above technical memo, VDOT TED will assess wider agency needs for potentially using the TransModeler, and start license procurement, if significant upcoming needs are expected, and if the skillset, training, calibration, development, hardware needs, costs, time needs, etc. of TransModeler are practical.

With regard to Recommendation 2: Within 3 months of publication of this report, VTRC will work with the research team, with input from VDOT *I-66 ITB Tolling Operations* and NRO, to assess the needs and resource requirements to update the parameters and maintain the models, including the costs and time requirements. Potential candidate updates include the VOT distributions, travel demand changes for the period after COVID-19, and travel demand changes following the start of I-66 OTB Tolling Operations under the PPP concessionaire. Given the that the DPA for I-66 OTB may not be available, additional research may be needed to determine how the I-66 ITB DPA should be adjusted in the future to ensure reliable travel times and an acceptable throughput.

With regard to Recommendation 3: Within 2 months of publication of this report, VDOT NRO and the I-66 toll manager will share the I-66 ITB analyses results with the stakeholders mentioned earlier. Specific I-66 OTB scenario results should be shared with the P3 concessionaire for facility planning and operations, and with the VDOT executive management and the general public for communication of strategies and their expected impacts later, on an as-needed basis.

Benefits

The benefits of implementing Recommendation 1 include the potential availability of a new tool in the analysis toolbox for VDOT to better model and understand dynamic operational strategies and multimodal options that are difficult to assess using conventional static modeling tools. The technical memo would be a starting point for VDOT to develop internal expertise in the new model, to procure necessary hardware, and to document lessons learned for future use of this modeling tool.

The benefits of implementing Recommendation 2 include ensuring the availability of a timely, updated, and well-maintained model for the I-66 corridor so that VDOT can take full advantage of the model developed in this study. This would allow VDOT to address future operational needs of the I-66 corridor in a timely manner, including communication of expected and actual traffic conditions in different scenarios to elected officials and motorists.

The benefits of implementing Recommendation 3 include better understanding of the potential impacts of the I-66 OTB express lanes tolling strategies, and communicating them effectively with various stakeholders. The P3 concessionaire and VDOT can make informed decisions about facility planning and operations. There is currently a lack of consensus within the transportation industry about the traffic conditions in the post-COVID-19 era. The various scenarios tested in this project and an understanding of the impacts will help VDOT and the P3 concessionaire to be proactive in anticipating and communicating impacts of specific strategy implementations.

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REFERENCES

Brent, D. A. and A. Gross, "Dynamic Road Pricing and the Value of Time and Reliability", Journal of Regional Science, 2018 58(2) 330-349.

Brownstone, D., Ghosh, A., Golob, T. F., Kazimi, C., and Van Amelsfort, D. (2003). Drivers' willingness-to-pay to reduce travel time: evidence from the San Diego I-15 congestion pricing project. Transportation Research Part A: Policy and Practice, 37(4), 373-387.

Bureau of Transportation Statistics, (2021), Daily Vehicle Travel During the COVID-19 Public Health Emergency, https://www.bts.gov/covid-19/daily-vehicle-travel , accessed on January 31st, 2021.

Burris, M. W., and Brady, J. F. (2018). Unrevealed preferences: Unexpected traveler response to pricing on managed lanes. Transportation Research Record, 2672(5), 23-32.

Burris, M., Nelson, S., Kelly, P., Gupta, P., and Cho, Y. (2012). Willingness to pay for high-occupancy toll lanes: Empirical analysis from i-15 and i-394. Transportation research record, 2297(1), 47-55.

Carrion, C., and Levinson, D. (2012). Value of travel time reliability: A review of current evidence. Transportation research part A: policy and practice, 46(4), 720-741.

Cookson, G., and Pishue, B. (2017). Inrix global traffic scorecard–appendices. INRIX research.

Hallenbeck, M. and V. Iverson (2019) I-405 Express Toll Lanes Usage, Benefits, and Equity, Washington Department of Transportation, https://www.wsdot.wa.gov/publications/fulltext/design/ConsultantSrvs/I-405ExpressTollLanes.pdf

Iacone, A., (2018). Survey: I-66 Commuters Say Tolls, Hours Changes Not Helping. https://wtop.com/dc-transit/2018/01/i-66-survey-results/. Accessed 08/18/2018.

I-66 Express Mobility Partners 2019, Transform 66 Outside the Beltway, VDOT Transportation Advisory Commission Meeting Presentation on September 17, 2019, https://www.fairfaxcounty.gov/transportation/sites/transportation/files/assets/documents/pdf/tac/i-66%20otb%20vdot%20presentation%209-17-19.pdf accessed on 01/31/2021

Kerns, R., and Paterson, D. (2011). Using a Simulation Environment for Dynamic Tolling Analysis-Capital Beltway HOT Lanes. In 18th ITS World Congress, TransCore, ITS America, ERTICO-ITS Europe, ITS Asia-Pacific.

Kim, S., and Coifman, B. (2014). Comparing INRIX speed data against concurrent loop detector stations over several months. Transportation Research Part C: Emerging Technologies, 49, 59-72.

Li, Z., Hensher, D. A., and Rose, J. M. (2010). Willingness to pay for travel time reliability in passenger transport: A review and some new empirical evidence. Transportation research part E: logistics and transportation review, 46(3), 384-403.

Liu, X., Zhang, G., Lao, Y., and Wang, Y. (2011). Quantifying the attractiveness of high-occupancy toll lanes with traffic sensor data under various traffic conditions. Transportation research record, 2229(1), 102-109.

Metropolitan Washington Council of Governments (2021), Currently Adopted Travel Model, https://www.mwcog.org/transportation/data-and-tools/modeling/current-model/ accessed on 01/31/2021

Morgul EF, and Ozbay K (2015). Value of Schedule Delays by Time of Day: Evidence from Usage Data from High-Occupancy Toll Lanes on State Road 167. Transportation Research Record, 2495(1), 42-52.

National Cooperative Highway Research Program (2012). NCHRP Report 722—Assessing Highway Tolling and Pricing Options and Impacts, Volume 2: Travel Demand Forecasting Tools. Transportation Research Board of the National Academies, Washington, DC.

National Capital Region Transportation Planning Board (2018), User's Guide for the COG/TPB Travel Demand Forecasting Model, Version 2.3.78, Metropolitan Washington Council of Governments, National Capital Region Transportation Planning Board

Nielsen, O. A. (1997). Multi-path OD-matrix estimation (MPME) based on stochastic user equilibrium traffic assignment. In Transportation Research Board 76th Annual Meeting.

Nikolic, G., Pringle, R., Jacob, C., Mendonca, N., Bekkers, M., Torday, A., and Rinelli, P. (2014). Dynamic tolling of hot lanes through simulation of expected traffic conditions. In Transportation 2014: Past, Present, Future-2014 Conference and Exhibition of the Transportation Association of Canada//Transport 2014: Du passé vers l'avenir-2014 Congrès et Exposition de'Association des transports du Canada.

Papandreou, Timothy (2020), Is The Coronavirus The Transportation Industry's Opportunity?, Forbes, Mar 27, 2020, https://www.forbes.com/sites/timothypapandreou/2020/03/27/is-the-coronavirus-the-transportation-industrys-opportunity/#4d81f89f752b, accessed on 07/20/2020

Perez, B. G., Fuhs, C., Gants, C., Giordano, R., and Ungemah, D. H. (2012). Priced managed lane guide (No. FHWA-HOP-13-007).

Rohr, Charlene (2020), COVID-19: The Questions Ahead for Future Travel and Transport, https://www.rand.org/blog/2020/04/covid-19-the-questions-ahead-for-future-travel-and.html, accessed on 07/20/2020.

Schrank, D., B. Eisele, and T. Lomax (2019), 2019 Urban Mobility Report, Texas A&M Transportation Institute, https://static.tti.tamu.edu/tti.tamu.edu/documents/mobility-report-2019.pdf, accessed on July 20, 2020

Sheikh, A., Guin, A., and Guensler, R. (2014). Value of Travel Time Savings: Evidence from I-85 Express Lanes in Atlanta, Georgia. Transportation Research Record, 2470(1), 161-168.

Transportation Research Board. 2016. Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis. Washington, DC: The National Academies Press. https://doi.org/10.17226/24798.

Virginia Department of Transportation (2020), Traffic Operations and Safety Analysis Manual (TOSAM), Version 2.0, http://www.virginiadot.org/business/resources/TOSAM.pdf, accessed on May 01, 2021

Wood, N. S., Burris, M., and Danda, S. R. (2014). Examination of Paid Travel on I-85 Express Lanes. Transportation Research Record, 2450(1), 44-51.

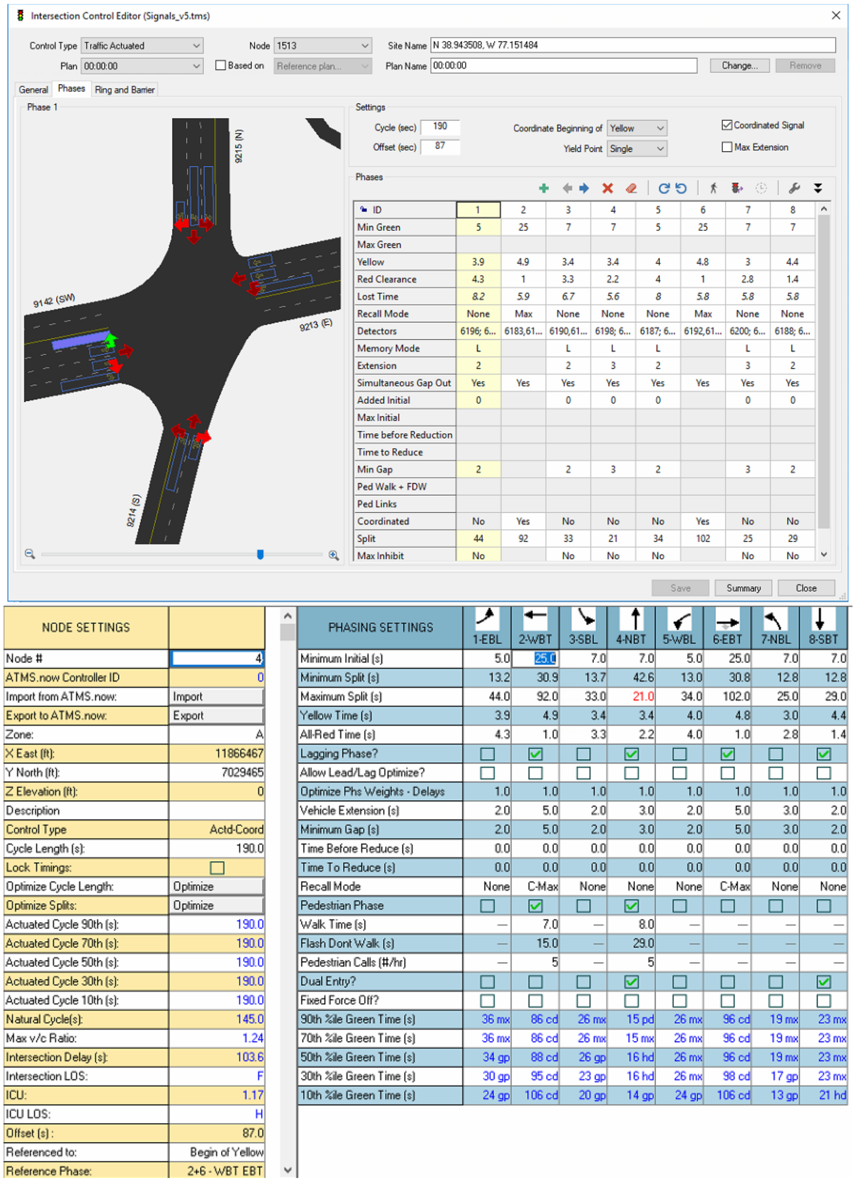
Xiong, C., Zhu, Z., He, X., Chen, X., Zhu, S., Mahapatra, S. & Zhang, L. (2015). Developing a 24-hour large-scale microscopic traffic simulation model for the before-and-after study of a new tolled freeway in the Washington, DC–Baltimore Region. Journal of Transportation Engineering, 141(6), 05015001.

Yang, Z. (2018). Modeling Behavioral Reactions to Transit Network Disruptions through Data Fusion and Integration, Doctoral dissertation, George Mason University.

Zhang, L., Chang, G. L., Zhu, S., Xiong, C., Du, L., Mollanejad, M., & Mahapatra, S. (2013). Integrating an agent-based travel behavior model with large-scale microscopic traffic simulation for corridor-level and subarea transportation operations and planning applications. Journal of Urban Planning and Development, 139(2), 94-103.

Zhu, S., Masud, H., Xiong, C., Yang, Z., Pan, Y., & Zhang, L. (2017). Travel behavior reactions to transit service disruptions: study of metro SafeTrack projects in Washington, DC. Transportation Research Record, 2649(1), 79-88.

APPENDIX A – SIGNAL PLANS IN TRANSMODELER AND IN SYNCHRO



Control Type: Traffic Actuated
Node: 1513
Site Name: N 38.943508, W 77.151484
Plan: 00:00:00
☐ Based on: Reference plan...
Plan Name: 00:00:00

Settings

Cycle (sec): 190
Offset (sec): 87
Coordinate Beginning of: Yellow
Yield Point: Single
☑ Coordinated Signal
☐ Max Extension

Phases

ID	1	2	3	4	5	6	7	8
Min Green	5	25	7	7	5	25	7	7
Max Green								
Yellow	3.9	4.9	3.4	3.4	4	4.8	3	4.4
Red Clearance	4.3	1	3.3	2.2	4	1	2.8	1.4
Lost Time	8.2	5.9	6.7	5.6	8	5.8	5.8	5.8
Recall Mode	None	Max	None	None	None	Max	None	None
Detectors	6196; 6...	6183,61...	6190,61...	6198; 6...	6187; 6...	6192,61...	6200; 6...	6188; 6...
Memory Mode	L		L	L	L		L	L
Extension	2		2	3	2		3	2
Simultaneous Gap Out	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Added Initial	0		0	0	0		0	0
Max Initial								
Time before Reduction								
Time to Reduce								
Min Gap	2		2	3	2		3	2
Ped Walk + FDW								
Ped Links								
Coordinated	No	Yes	No	No	No	Yes	No	No
Split	44	92	33	21	34	102	25	29
Max Inhibit	No		No	No	No		No	No

NODE SETTINGS	
Node #	4
ATMS.now Controller ID	0
Import from ATMS.now:	Import
Export to ATMS.now:	Export
Zone:	A
X East (ft):	11866467
Y North (ft):	7029465
Z Elevation (ft):	0
Description	
Control Type	Actd-Coord
Cycle Length (s):	190.0
Lock Timings:	☐
Optimize Cycle Length:	Optimize
Optimize Splits:	Optimize
Actuated Cycle 90th (s):	190.0
Actuated Cycle 70th (s):	190.0
Actuated Cycle 50th (s):	190.0
Actuated Cycle 30th (s):	190.0
Actuated Cycle 10th (s):	190.0
Natural Cycle(s):	145.0
Max v/c Ratio:	1.24
Intersection Delay (s):	103.6
Intersection LOS:	F
ICU:	1.17
ICU LOS:	H
Offset (s) :	87.0
Referenced to:	Begin of Yellow
Reference Phase:	2+6 - WBT EBT

PHASING SETTINGS	1-EBL	2-WBT	3-SBL	4-NBT	5-WBL	6-EBT	7-NBL	8-SBT
Minimum Initial (s)	5.0	25.0	7.0	7.0	5.0	25.0	7.0	7.0
Minimum Split (s)	13.2	30.9	13.7	42.6	13.0	30.8	12.8	12.8
Maximum Split (s)	44.0	92.0	33.0	21.0	34.0	102.0	25.0	29.0
Yellow Time (s)	3.9	4.9	3.4	3.4	4.0	4.8	3.0	4.4
All-Red Time (s)	4.3	1.0	3.3	2.2	4.0	1.0	2.8	1.4
Lagging Phase?	☐	☑	☐	☑	☐	☑	☐	☑
Allow Lead/Lag Optimize?	☐	☐	☐	☐	☐	☐	☐	☐
Optimize Phs Weights - Delays	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Vehicle Extension (s)	2.0	5.0	2.0	3.0	2.0	5.0	3.0	2.0
Minimum Gap (s)	2.0	5.0	2.0	3.0	2.0	5.0	3.0	2.0
Time Before Reduce (s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time To Reduce (s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recall Mode	None	C-Max	None	None	None	C-Max	None	None
Pedestrian Phase	☐	☑	☐	☑	☐	☐	☐	☐
Walk Time (s)	—	7.0	—	8.0	—	—	—	—
Flash Dont Walk (s)	—	15.0	—	29.0	—	—	—	—
Pedestrian Calls (#/hr)	—	5	—	5	—	—	—	—
Dual Entry?	☐	☐	☐	☑	☐	☐	☐	☑
Fixed Force Off?	☐	☐	☐	☐	☐	☐	☐	☐
90th %ile Green Time (s)	36 mx	86 cd	26 mx	15 pd	26 mx	96 cd	19 mx	23 mx
70th %ile Green Time (s)	36 mx	86 cd	26 mx	15 mx	26 mx	96 cd	19 mx	23 mx
50th %ile Green Time (s)	34 gp	88 cd	26 gp	16 hd	26 mx	96 cd	19 mx	23 mx
30th %ile Green Time (s)	30 gp	95 cd	23 gp	16 hd	26 mx	98 cd	17 gp	23 mx
10th %ile Green Time (s)	24 gp	106 cd	20 gp	14 gp	24 gp	106 cd	13 gp	21 hd

Figure A1. A Signal Control Plan Implemented in TransModeler (top) and in Synchro (bottom).

APPENDIX B – EXTRACTING VOLUME DATA FROM SIGNAL DETECTORS

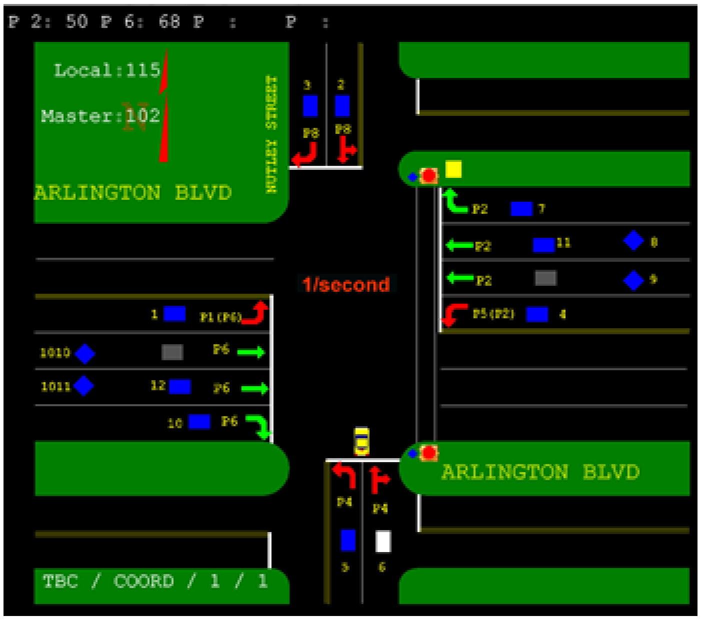


Figure B1. An Example of Extracting Traffic Volumes from Signal Detectors.

Traffic volumes measured by Detector 1, 1010, 1011, and 10 are aggregated for eastbound traffic.
Traffic volumes measured by Detector 4, 7, 8, and 9 are aggregated for westbound traffic.
Traffic volumes measured by Detector 2, and 3 are aggregated for southbound traffic.
Traffic volumes measured by Detector 5 and 6 are aggregated for northbound traffic.
Data from redundant sensors are not used.

APPENDIX C – PARAMETERS OF THE NESTED-LOGIT MODEL ESTIMATED IN THE WASHINGTON METRO SAFETRACK STUDY

Table C1. Parameters of the Nested-logit Model Estimated in the Washington Metro Safetrack Study

Wald chi2(15) = 66.80			**Prob > chi2 = 0.0000*** **	
	Variable	Coef.	S. D	P>z
Model	Duration (min)	-0.026***	0.005	0.000
	Out of Pocket Cost ($)	-0.049***	0.019	0.009
	Disruption Type	-0.874***	0.216	0.000
Nest Equation				
Drive Nest	Age	(base)		
	Gender	(base)		
	Income	(base)		
Uber Nest	Age	0.067	0.432	0.877
	Gender	-0.159	0.423	0.707
	Income	-0.001	0.004	0.924
Transit Nest	Age	0.301	0.268	0.262
	Gender	0.069	0.261	0.791
	Income	0.001	0.002	0.531
Bus Nest	Age	0.733*	0.431	0.089
	Gender	0.344	0.422	0.415
	Income	0.001	0.004	0.971
Non-motorized Nest	Age	-1.035	0.679	0.128
	Gender	0.859*	0.506	0.09
	Income	0.007	0.005	0.119
Mode Equation				
Drive	_cons	(base)		
Bus	_cons	-0.881	0.555	0.113
Bike	_cons	-2.181***	0.735	0.003
Uber	_cons	-0.394	0.484	0.416
Park & Metro	_cons	0.893***	0.329	0.007
Bus & Metro	_cons	0.562	0.370	0.130
Bike & Metro	_cons	-0.594	0.558	0.287
Walk & Metro	_cons	1.139***	0.347	0.001
Kiss & Metro	_cons	0.135	0.413	0.743
Dissimilarity parameters	Car_tau	1.00	784620.5	
	Uber_tau	1.00	760060.2	
	Transit_tau	0.512	0.1200652	
	Bus_tau	1.00	847062.3	
	Non-motor_tau	1.00	2299250	
LR test for IIA (tau=1)		chi2(5) = 8.63	Prob > chi2 = 0.1248	
Note: *** significant at 0.01	** significant at 0.05		*significant at 0.1	

APPENDIX D – FREQUENCY OF USAGE BY I-66 ITB ETL USERS

This study evaluated the frequency of usage by SOV and HOV users of the I-66 ITB Express Lanes. Using the anonymized vehicle identifier, the research team calculated the number of days a vehicle used the toll facility during the study period (64 week days). Figure F shows the bar plots for the number of HOV and SOV users, with different usage frequencies observed during the study period in EB (top row) and WB (bottom row).

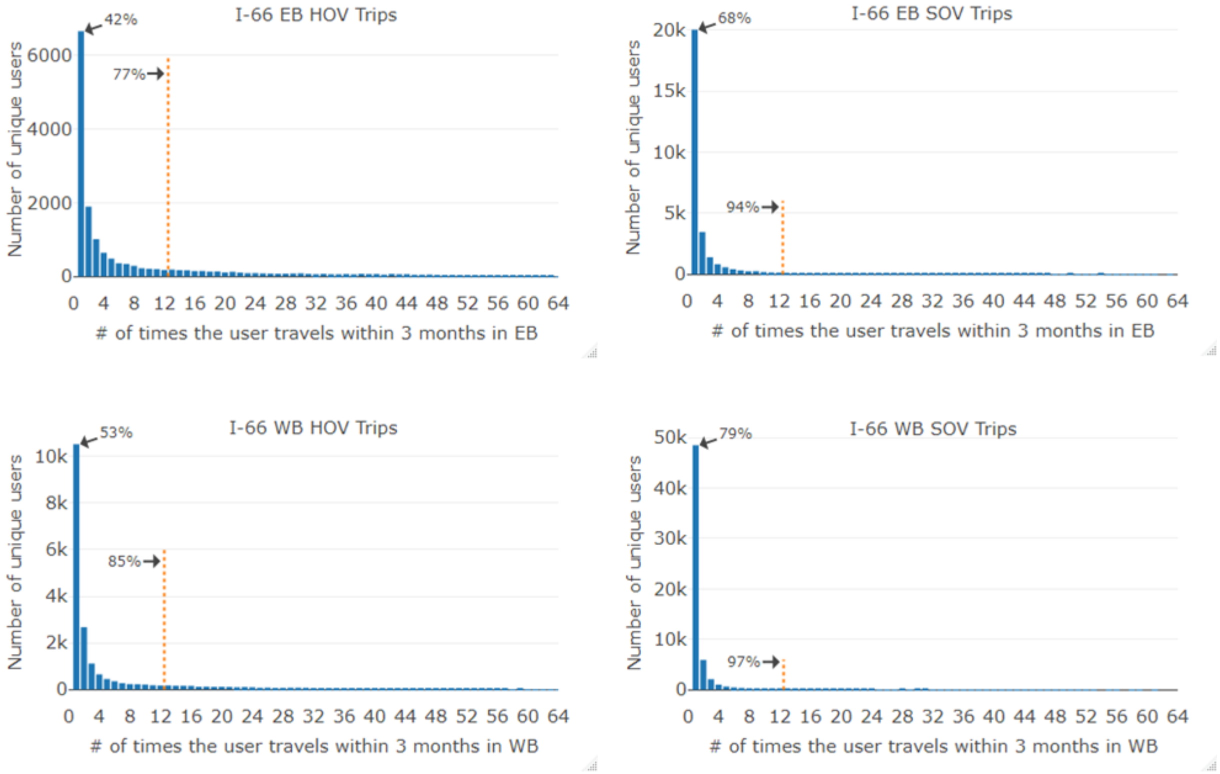


Figure D. The number of high-occupancy-vehicle and single-occupancy-vehicle users with different usage frequencies observed during the 3-month study period in eastbound (top row) and westbound (bottom row) directions.

The users to the right of the dashed vertical line (12 trips or more during the 3-month study period) are considered frequent users.

Among the SOV users, 68% of them used the EB facility (in operation during the morning peak period) only once during the 3-month study period. The number was even higher for the WB facility; at 79% (in operation during the PM peak period). The number of unique users dropped rapidly as the number of days of facility usage increased. The distribution had a very long tail, as some users did use it regularly. A total of 6% of EB SOV users used the toll facility 12 times, or more, during the 3-month study period, while the number was only 3% for the WB SOV users. This usage pattern supports the theory that ETL/HOT facilities are “option lanes”, with a very broad user base, although most travelers only use them occasionally, when a trip with a high VOT is needed. However, this finding is in contrast with that of Liu et al. (2011), who showed a very flat distribution for SOV users of the SR-167 HOT lane system. More studies are needed to determine if the patterns observed at the I-66 ITB Express Lanes are an exception.

HOV users do not have to pay tolls for using the facility. Figure D shows that more HOV users use the facility regularly (23% of HOV users used the EB toll facility 12 times or more during the study period, while 15% of HOV users did so at the WB toll facility). Still, most HOV users only use the toll facility occasionally, despite being free of charge. This shows that the impact of the economic advantage that the carpooling mode offers is not as significant as we would hope, and most travelers only use it occasionally, instead of regularly, for a corridor as congested as I-66 in Northern Virginia.

APPENDIX E – VOLUME CALIBRATION

Table E1. Volume Calibrations on I-66 and Other Major Arterials (Morning Peak)

		EB			WB		
	Hour	**Counts**	**Model Outputs**	**%Diff**	**Counts**	**Model Outputs**	**%Diff**
I-66 OTB near the Interchange with I-495	5	5534	5947	7.5%	2800	2611	-6.8%
	6	5623	5714	1.6%	4229	4042	-4.4%
	7	6027	5460	-9.4%	5641	5092	-9.7%
	8	5853	6048	3.3%	5535	5167	-6.7%
	9	5776	5897	2.1%	5047	4696	-7.0%
I-66 OTB/Nutley St.	5	5395	4931	-8.6%	2120	1889	-10.9%
	6	5816	5477	-5.8%	3154	2842	-9.9%
	7	6140	5409	-11.9%	4011	4360	8.7%
	8	5814	5722	-1.6%	3941	3656	-7.2%
	9	5901	5483	-7.1%	3591	3967	10.5%
I-66 OTB/Rt. 123	5	5508	5752	4.4%	1492	1615	8.3%
	6	5812	5292	-9.0%	2065	1907	-7.7%
	7	5384	4958	-7.9%	2676	2454	-8.3%
	8	4842	5234	8.1%	2895	2741	-5.3%
	9	5096	5065	-0.6%	2601	2183	-16.1%
I-66 OTB/US 50	5	5243	4239	-19.2%	1713	1800	5.1%
	6	5309	5825	9.7%	2769	2518	9.1%
	7	4639	5544	19.5%	3432	2716	20.9%
	8	4231	4397	3.9%	3652	3166	13.3%
	9	4773	4196	-12.1%	3373	3162	6.3%
I-66 OTB/Fairfax County Parkway	5	5243	5679	8.3%	6360	5328	-16.2%
	6	5309	4626	-12.9%	6598	6014	-8.8%
	7	4639	4339	-6.5%	5952	5827	-2.1%
	8	4231	3897	-7.9%	5418	5475	1.0%
	9	4773	4196	-12.1%	6042	5510	-8.8%
I-66 OTB/Rt. 28	5	6008	5291	-11.9%	1053	923	-12.4%
	6	6022	5633	-6.5%	1722	1518	-11.8%
	7	5229	4713	-9.9%	2215	2246	1.4%
	8	4862	4801	-1.3%	2152	2150	-0.1%
	9	5215	4575	-12.3%	2137	1999	-6.5%
I-66 ITB/West of Rt. 7	5	1157	1103	-4.7%	689	756	9.7%
	6	1071	1014	-5.3%	1686	1507	-10.6%
	7	1513	1399	-7.5%	2953	2702	-8.5%
	8	1252	1594	27.2%	2850	3152	10.6%
	9	1552	1808	16.5%	2384	2166	-9.1%
I-66 ITB/East of Washington Blvd Ramp	5	2216	1931	-12.9%	1061	988	-6.8%
	6	2196	2068	-5.8%	2431	2362	-2.8%
	7	2936	2841	-3.3%	3758	3985	6.0%
	8	2713	2916	7.5%	3680	3500	-4.9%
	9	2571	2991	16.4%	3274	3462	5.7%
I-66 ITB/Fairfax Drive	5	1949	2143	10.0%	836	935	11.9%
	6	1997	2212	10.8%	1808	1838	1.7%
	7	2902	3409	17.5%	2771	2384	-14.0%
	8	2804	2415	-13.9%	2391	2554	6.8%
	9	2434	2292	-5.8%	2264	2408	6.3%
I-66 ITB/Before US 29	5	1949	1790	8.2%	894	773	-13.6%
	6	2020	1649	18.4%	1916	1835	-4.2%

	7	3083	2961	4.0%	2786	2287	-17.9%
	8	3073	2814	8.4%	2403	2225	-7.4%
	9	2688	2682	0.2%	2252	1945	-13.6%
I-66 ITB/Before North Fort Meyer Drive	5	948	833	-12.0%	640	556	-13.1%
	6	949	806	-15.1%	1297	1569	20.9%
	7	1401	1298	-7.4%	1837	1750	-4.7%
	8	1619	1429	-11.8%	1644	1398	-15.0%
	9	1327	1263	-4.8%	1441	1619	12.3%
George Washington Parkway/Turkey Run Park	5	1358	1344	-1.1%	411	494	20.4%
	6	2901	2954	1.8%	1124	1096	-2.5%
	7	2457	2267	-7.7%	2349	2221	-5.4%
	8	1910	2077	8.7%	2711	2640	-2.6%
	9	1348	1205	-10.6%	2131	2548	19.6%
US 50/Graham Rd	5	958	1029	7.5%	544	485	-10.8%
	6	2253	1932	-14.3%	1114	1186	6.5%
	7	2315	2409	4.1%	1734	1988	14.6%
	8	2239	1899	-15.2%	1802	1711	-5.0%
	9	1875	1843	-1.7%	1437	1231	-14.3%
US 50/Prosperity Ave	5	603	517	-14.3%	392	379	-3.2%
	6	1876	1750	-6.7%	938	727	-22.4%
	7	2379	2394	0.6%	1402	1096	-21.8%
	8	2321	2254	-2.9%	1585	1849	16.7%
	9	1949	1837	-5.8%	1631	1453	-10.9%
US 50/Stonehurst Dr	5	805	714	-11.4%	199	214	7.7%
	6	2032	1903	-6.3%	521	512	-1.6%
	7	2410	2019	-16.2%	912	1029	12.8%
	8	2375	2621	10.4%	1060	1255	18.4%
	9	2082	1753	-15.8%	1048	1241	18.4%
US 50/Fair Ridge	5	1230	1005	-18.3%	1119	1059	-5.3%
	6	2652	2642	-0.4%	1840	1678	-8.8%
	7	2966	2655	-10.5%	2658	2516	-5.3%
	8	2910	2539	-12.7%	2768	2293	-17.2%
	9	2857	2792	-2.3%	2266	2346	3.5%
US 50/Stringfellow Rd	5	1163	1265	8.7%	1088	940	-13.6%
	6	2567	2863	11.5%	1721	1502	-12.7%
	7	3105	2740	-11.8%	2441	2506	2.7%
	8	2849	2865	0.6%	2626	2648	0.8%
	9	2529	2719	7.5%	2140	1799	-15.9%
US 50/Centerville Rd	5	811	854	5.3%	1090	938	-13.9%
	6	1768	1965	11.1%	1741	1762	1.3%
	7	2048	2422	18.3%	2323	2315	-0.3%
	8	2118	1809	-14.6%	2563	2099	-18.1%
	9	1830	1795	-2.0%	2211	2072	-6.3%
US 29/Graham Rd	5	251	313	24.6%	94	95	0.8%
	6	861	762	-11.5%	259	245	-5.4%
	7	1445	1563	8.2%	616	507	-17.7%
	8	1472	1336	-9.2%	787	837	6.4%
	9	1211	1339	10.5%	628	816	29.9%
US 29/Gallows Rd	5	314	294	-6.3%	199	161	-18.9%
	6	889	960	8.0%	605	470	-22.3%
	7	1578	1299	-17.7%	1084	906	-16.4%
	8	1549	1402	-9.5%	1256	1293	3.0%
	9	1386	1349	-2.7%	1103	831	-24.7%

US 29/Nutley St	5	275	291	5.8%	195	145	-25.7%
	6	717	768	7.2%	454	443	-2.5%
	7	1331	1413	6.1%	875	886	1.2%
	8	1509	1344	-11.0%	932	840	-9.9%
	9	1161	901	-22.4%	879	906	3.1%
US 29/Legato Rd	5	441	493	11.7%	655	698	6.6%
	6	1400	1542	10.2%	598	421	-29.6%
	7	2070	2115	2.2%	998	779	-22.0%
	8	2032	2125	4.6%	819	798	-2.5%
	9	1685	1954	15.9%	732	686	-6.3%
US 29/Rt. 28	5	659	496	-24.7%	373	323	-13.5%
	6	1780	1746	-1.9%	750	661	-11.8%
	7	2254	1838	-18.5%	1214	1004	-17.4%
	8	2245	2360	5.1%	1366	1197	-12.4%
	9	1876	2214	18.0%	1339	1267	-5.4%
US 29/Stone Rd	5	1910	1856	-2.8%	229	245	6.9%
	6	2600	2271	-12.6%	518	535	3.3%
	7	3112	2623	-15.7%	933	724	-22.5%
	8	2868	2225	-22.4%	1151	1245	8.2%
	9	2671	2045	-23.5%	1070	1129	5.5%
Rt. 123/Kirby Rd	5	517	603	16.7%	404	478	18.4%
	6	811	1022	26.1%	1251	1481	18.4%
	7	1603	1726	7.7%	1492	1331	-10.8%
	8	1689	1661	-1.6%	1206	1284	6.5%
	9	995	1122	12.8%	1146	1246	8.7%
Mean Absolute Error = 10.0%							
Percentage of Data Points Within Calibration Objectives = 216/250=86.4%							

Hour 5 represents the period from 5 AM to 6 AM.

Table E2. Volume Calibrations on I-66 and Other Major Arterials (Afternoon Peak)

		EB			WB		
	Hour	**Counts**	**Model Outputs**	**%Diff**	**Counts**	**Model Outputs**	**%Diff**
I-66 OTB near the Interchange with I-495	14	5352	5283	-1.3%	6428	6255	-2.7%
	15	5332	4942	-7.3%	5552	6019	8.4%
	16	5443	5330	-2.1%	5480	5823	6.3%
	17	5561	5759	3.6%	5651	6103	8.0%
	18	4935	4798	-2.8%	5451	6188	13.5%
	19	4475	4113	-8.1%	5598	5027	-10.2%
I-66 OTB/Nutley St.	14	5729	4973	-13.2%	5719	5840	2.1%
	15	5699	5061	-11.2%	4539	4640	2.2%
	16	5925	5990	1.1%	4320	4555	5.4%
	17	6208	5656	-8.9%	4426	4325	-2.3%
	18	5317	5147	-3.2%	4419	4065	-8.0%
	19	4602	4287	-6.9%	5184	4410	-14.9%
I-66 OTB/Rt. 123	14	5603	5651	0.9%	3735	4388	17.5%
	15	5568	5997	7.7%	3498	4013	14.7%
	16	5764	5935	3.0%	3408	4158	22.0%
	17	6094	5695	-6.6%	3396	3862	13.7%
	18	5183	4602	-11.2%	3417	4096	19.9%
	19	4381	3656	-16.5%	3720	3516	-5.5%
I-66 OTB/US 50	14	4098	3532	-13.8%	5863	5778	-1.5%
	15	3970	3782	-4.7%	5974	5788	-3.1%
	16	4309	4748	10.2%	5246	5198	-0.9%
	17	4489	4620	2.9%	4838	4822	-0.3%
	18	3914	3696	-5.6%	4896	4452	-9.1%
	19	3224	3083	-4.4%	5249	5376	2.4%
I-66 OTB/Fairfax County Parkway	14	4792	3689	-23.0%	6850	6324	-7.7%
	15	4560	4962	8.8%	6380	6634	4.0%
	16	4416	4943	11.9%	5532	5328	-3.7%
	17	4544	5045	11.0%	5330	5725	7.4%
	18	4317	4725	9.5%	5674	5670	-0.1%
	19	3572	3962	10.9%	5911	5216	-11.8%
I-66 OTB/Rt. 28	14	4006	3621	-9.6%	6029	5773	-4.3%
	15	3708	3862	4.2%	5938	5863	-1.3%
	16	3708	3648	-1.6%	5299	5208	-1.7%
	17	3908	3623	-7.3%	5275	5365	1.7%
	18	3424	3732	9.0%	5448	5568	2.2%
	19	2619	2760	5.4%	5051	5679	12.4%
I-66 ITB/West of Rt. 7	14	1542	1491	-3.3%	4121	4500	9.2%
	15	1544	1609	4.2%	2752	2720	-1.2%
	16	1717	1807	5.3%	2893	2552	-11.8%
	17	1891	1803	-4.6%	2978	2744	-7.9%
	18	1422	1608	13.1%	2421	2711	12.0%
	19	1247	1487	19.2%	3574	3013	-15.7%
I-66 ITB/East of Washington Blvd Ramp	14	4304	3529	-18.0%	4726	3964	-16.1%
	15	4241	4222	-0.4%	3795	3706	-2.3%
	16	3785	3797	0.3%	3976	4064	2.2%
	17	3515	3806	8.3%	3945	4227	7.1%
	18	3603	3682	2.2%	3201	3628	13.3%
	19	3697	3316	-10.3%	4181	4056	-3.0%
I-66 ITB/Fairfax Drive	14	4140	3642	-12.0%	3916	3391	-13.4%
	15	4109	3864	-6.0%	2830	2327	-17.8%

	16	4135	3823	-7.5%	3408	3481	2.2%
	17	4325	4311	-0.3%	3495	3082	-11.8%
	18	4290	4341	1.2%	2739	2300	-16.0%
	19	4240	3679	-13.2%	3595	3107	-13.6%
I-66 ITB/Before US 29	14	2698	2794	3.5%	3183	3310	4.0%
	15	2860	2369	-17.2%	2377	2517	5.9%
	16	2931	2775	-5.3%	2977	2496	-16.1%
	17	2871	2618	-8.8%	3106	2680	-13.7%
	18	2660	2518	-5.3%	2484	2607	5.0%
	19	2346	2604	11.0%	2976	2861	-3.9%
I-66 ITB/Before North Fort Meyer Drive	14	2077	1919	-7.6%	1772	2014	13.7%
	15	2271	2717	19.7%	1420	1543	8.7%
	16	2683	2224	-17.1%	1837	1681	-8.5%
	17	2704	2259	-16.5%	2061	1861	-9.7%
	18	2562	2229	-13.0%	1799	1776	-1.3%
	19	2013	1880	-6.6%	1837	2107	14.7%
George Washington Parkway/Turkey Run Park	14	1359	1449	6.6%	2369	2126	-10.3%
	15	1548	1708	10.4%	2412	2184	-9.5%
	16	1424	1587	11.4%	2495	2751	10.3%
	17	1611	1667	3.4%	2326	2121	-8.8%
	18	1588	1505	-5.3%	2103	2125	1.0%
	19	1276	1124	-11.9%	2020	1975	-2.2%
US 50/Graham Rd	14	1591	1327	-16.6%	1542	1410	-8.5%
	15	1982	1821	-8.1%	1591	1447	-9.0%
	16	2228	2216	-0.5%	2010	2007	-0.1%
	17	2209	2140	-3.1%	2064	2104	2.0%
	18	2095	1823	-13.0%	2093	1860	-11.1%
	19	1589	1615	1.6%	1581	1309	-17.2%
US 50/Prosperity Ave	14	1404	1589	13.2%	1935	2170	12.2%
	15	1412	1660	17.6%	2305	2057	-10.8%
	16	1533	1814	18.3%	2241	2298	2.5%
	17	1653	1739	5.2%	2101	2070	-1.5%
	18	1480	1637	10.6%	2108	2094	-0.7%
	19	1116	1347	20.7%	1712	1632	-4.7%
US 50/Stonehurst Dr	14	1581	1423	-10.0%	1522	1637	7.6%
	15	1429	1375	-3.8%	1997	1937	-3.0%
	16	1550	1694	9.3%	2116	1956	-7.6%
	17	1552	1675	7.9%	2117	2045	-3.4%
	18	1436	1697	18.2%	2043	2122	3.8%
	19	1150	1169	1.7%	1344	1145	-14.8%
US 50/Fair Ridge	14	2367	2669	12.8%	2196	1936	-11.8%
	15	2592	2728	5.3%	2627	2240	-14.7%
	16	2653	2677	0.9%	2982	3385	13.5%
	17	2855	2864	0.3%	3151	3291	4.5%
	18	2639	2744	4.0%	2842	2849	0.3%
	19	1940	1819	-6.2%	2268	2119	-6.6%
US 50/Stringfellow Rd	14	2369	2083	-12.1%	2385	2277	-4.5%
	15	2672	2668	-0.2%	2977	3309	11.2%
	16	2672	2389	-10.6%	2980	3249	9.0%
	17	2753	2319	-15.8%	2846	3048	7.1%
	18	2599	2361	-9.2%	2636	2774	5.2%
	19	1937	1807	-6.7%	2190	2691	22.9%
US 50/Centerville Rd	14	1718	1481	-13.8%	2014	2301	14.2%

	15	1839	2165	17.7%	2306	2385	3.4%
	16	1814	2211	21.9%	2293	2263	-1.3%
	17	1680	1744	3.8%	1783	2162	21.2%
	18	1778	1677	-5.7%	2063	2236	8.4%
	19	1450	1377	-5.0%	1822	1790	-1.8%
US 29/Graham Rd	14	809	1300	24.6%	859	1036	20.6%
	15	911	928	-10.6%	1236	1259	1.9%
	16	1166	1065	-2.9%	1424	1468	3.1%
	17	1441	1320	11.0%	1506	1598	6.1%
	18	1201	1391	23.4%	1312	1142	-13.0%
	19	786	1070	23.0%	772	821	6.4%
US 29/Gallows Rd	14	1410	1456	3.3%	1150	1327	15.4%
	15	1408	1386	-1.5%	1476	1655	12.1%
	16	1523	1511	-0.8%	1742	1785	2.5%
	17	1548	1525	-1.5%	1670	1689	1.1%
	18	1368	1352	-1.2%	1453	1606	10.6%
	19	1212	1353	11.7%	1136	1059	-6.8%
US 29/Nutley St	14	1043	1228	-6.0%	1324	1323	-0.1%
	15	1038	1162	-15.1%	1583	1697	7.2%
	16	1097	1331	-9.6%	1762	1853	5.2%
	17	1190	1586	-1.5%	1689	1686	-0.2%
	18	1127	1551	-4.8%	1574	1374	-12.7%
	19	870	1206	-16.5%	1186	1204	1.5%
US 29/Legato Rd	14	904	1537	-11.1%	1150	1052	-8.5%
	15	908	1660	-6.6%	1476	1539	4.3%
	16	974	1658	-10.3%	1742	1842	5.8%
	17	1047	1771	-9.5%	1670	1341	-19.7%
	18	947	2221	10.3%	1453	1601	10.2%
	19	750	1446	-8.8%	1136	1383	21.8%
US 29/Rt. 28	14	1306	1300	24.6%	1538	1560	1.4%
	15	1369	928	-10.6%	2100	2232	6.3%
	16	1472	1065	-2.9%	2369	2632	11.1%
	17	1610	1320	11.0%	2356	2287	-2.9%
	18	1630	1391	23.4%	2236	2237	0.0%
	19	1444	1070	23.0%	1527	1662	8.8%
US 29/Stone Rd	14	1729	1023	13.2%	1251	1095	-12.5%
	15	1777	1016	11.9%	1474	1528	3.7%
	16	1848	1081	11.0%	1590	1801	13.3%
	17	1956	1146	9.5%	1793	1508	-15.9%
	18	2014	1050	10.9%	1811	1615	-10.8%
	19	1586	640	-14.7%	1483	1447	-2.4%
Rt. 123/Kirby Rd	14	1180	1192	1.0%	1211	1147	-5.3%
	15	1502	1469	-2.2%	1636	1841	12.5%
	16	1571	1412	-10.1%	1940	2074	6.9%
	17	1634	1475	-9.7%	1813	1949	7.5%
	18	1696	1294	-23.7%	1581	1929	22.0%
	19	944	1139	20.6%	1157	1430	23.6%
Mean Absolute Error = 8.7%							
Percentage of Data Points Within Calibration Objectives = 269/300=89.7%							

Hour 14 represents the period from 2 PM to 3 PM.

APPENDIX F – SCENARIO ANALYSIS OF THE PM PEAK PERIOD

This section presents the analysis of alternative scenarios during the afternoon peak period. These graphs and tables correspond to their counterparts for the AM peak period in the main body of the report from Figure 22 to Figure 38 and Table 24 to Table 31.

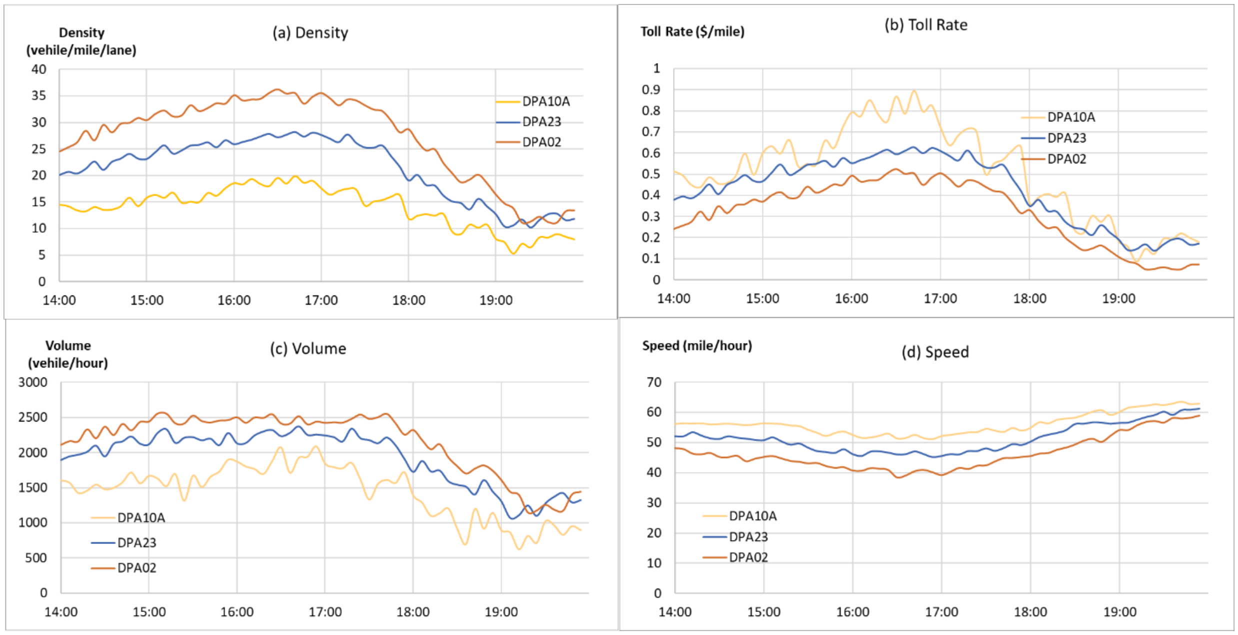


Figure F1. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Different Dynamic Pricing Algorithms.

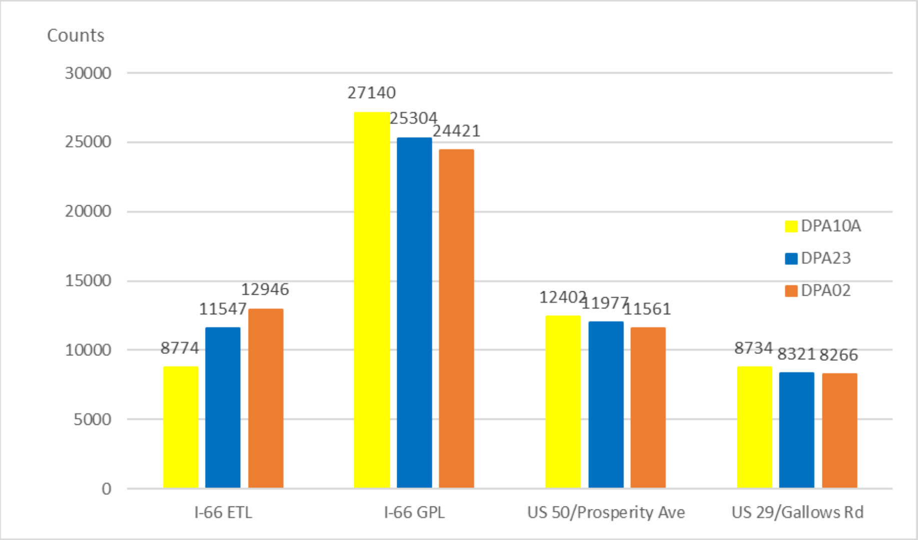


Figure F2. Westbound Traffic Throughput During the Afternoon Peak Period Under Different Dynamic Pricing Algorithms.

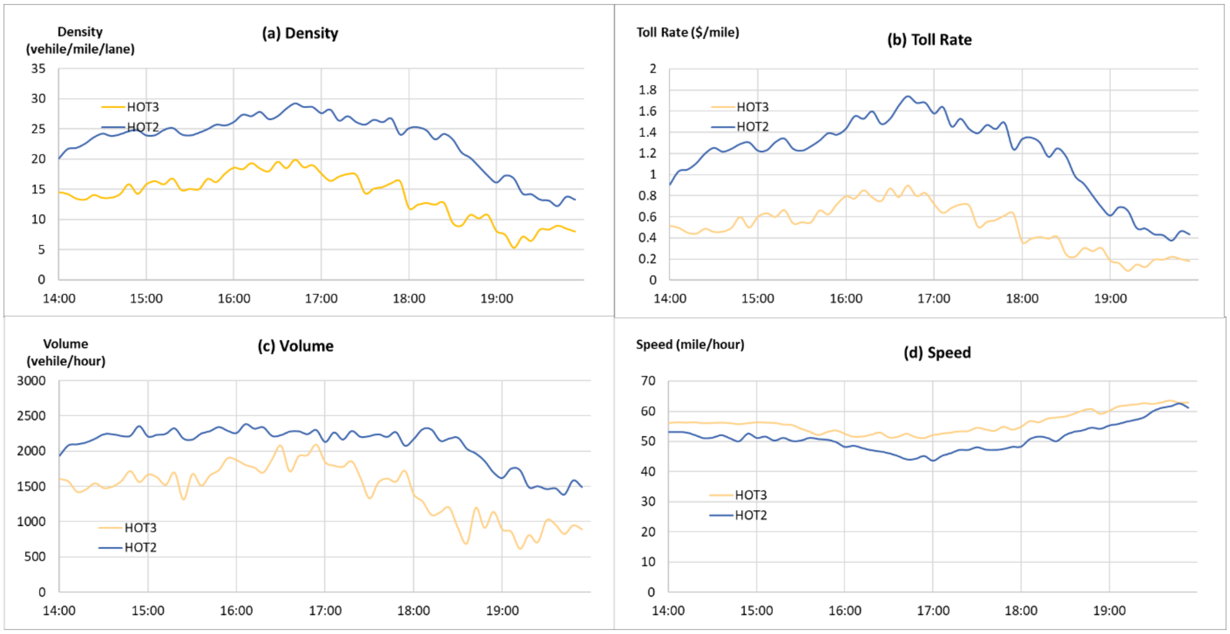


Figure F3. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) in Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under HOT2 and HOT3 Policies.

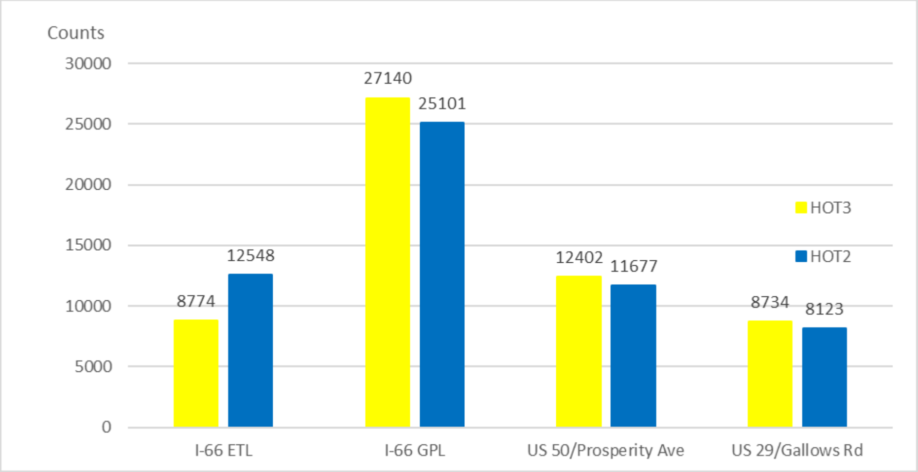


Figure F4. Westbound Traffic Throughputs During the Afternoon Peak Period Under HOT2 and HOT3 Policies.

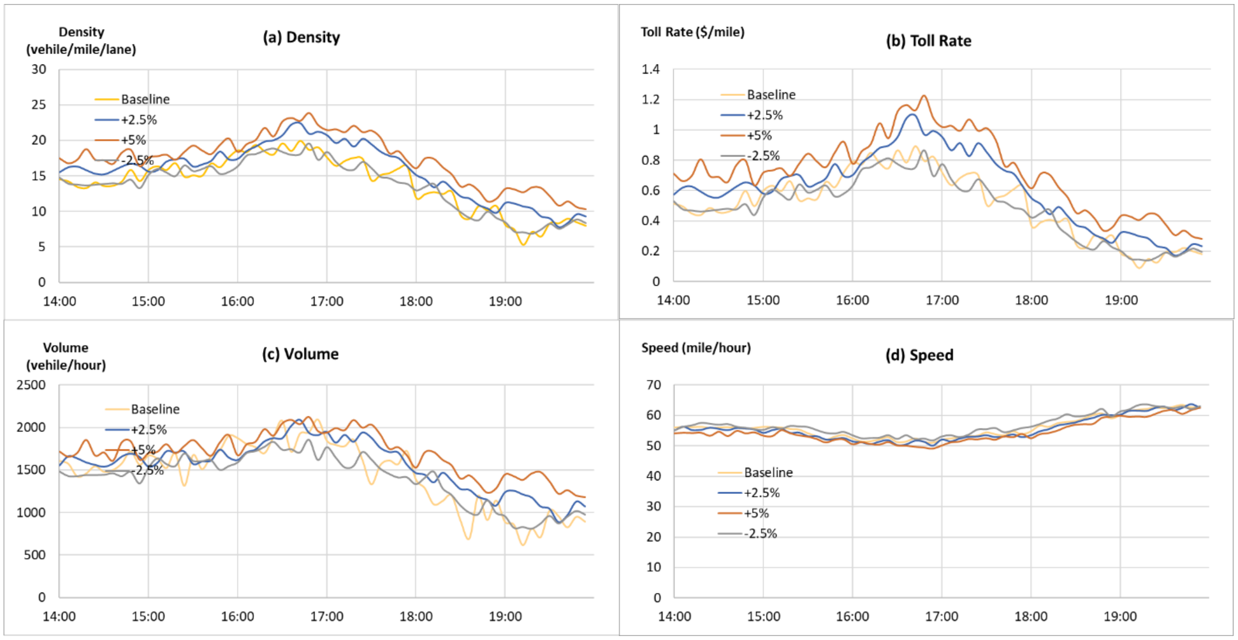


Figure F5. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Different Traffic Growth Factors.

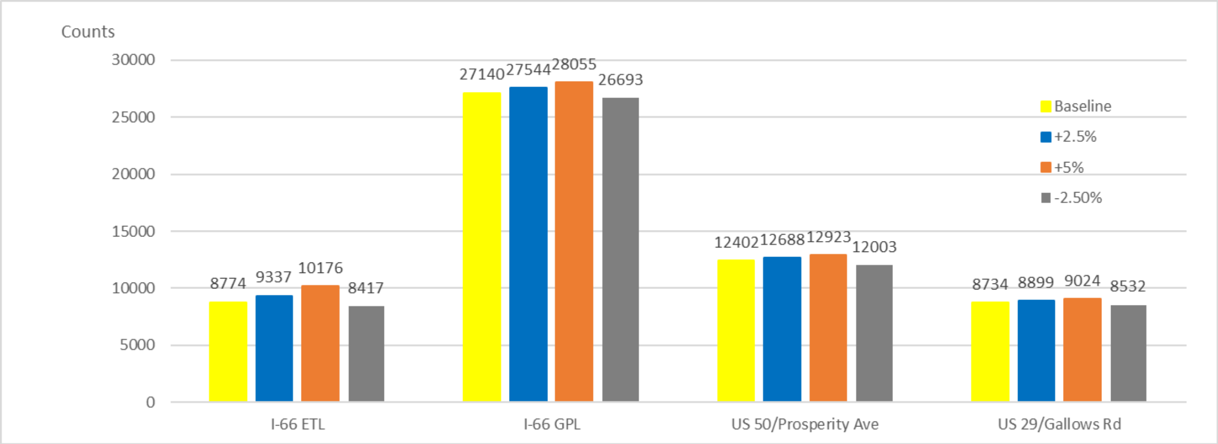


Figure F6. Westbound Traffic Throughput at the East End of the I-66 Outside-the-Beltway Corridor During the Afternoon Peak Period Under Different Traffic Growth Factors.

Table F1. Throughput and Revenue Changes During the Afternoon Peak Period in Westbound Direction Under Scenarios of Different Traffic Growth/Reduction Factors

Scenario	**Baseline**	**+2.5%**	**+5%**	**-2.5%**
	Counts	% Difference		
I-66 ETL	8774	6.4%	16.0%	-4.1%
I-66 GPL	27140	1.5%	3.4%	-1.6%
US 50/Prosperity	12402	2.3%	4.2%	-3.2%
US 29/Gallows Rd	8734	1.9%	3.3%	-2.3%
	$	% Difference		
Revenue at Zone 5	9878	+25.4%	+58.5%	-8.8%

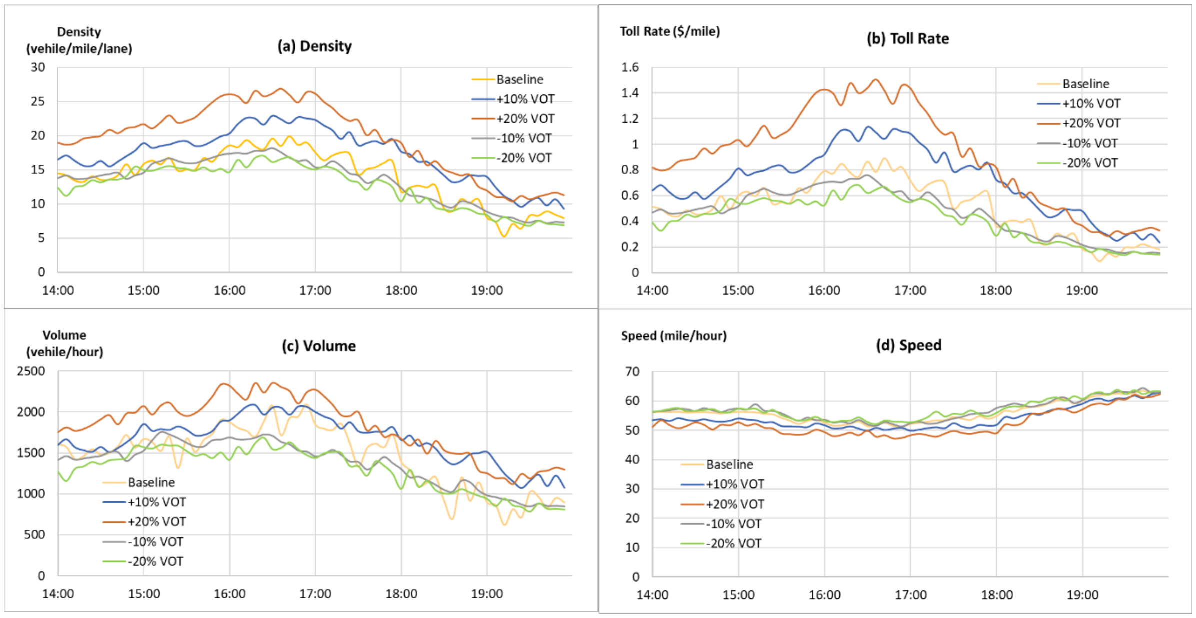


Figure F7. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Different Assumptions of Value of Time Distributions.

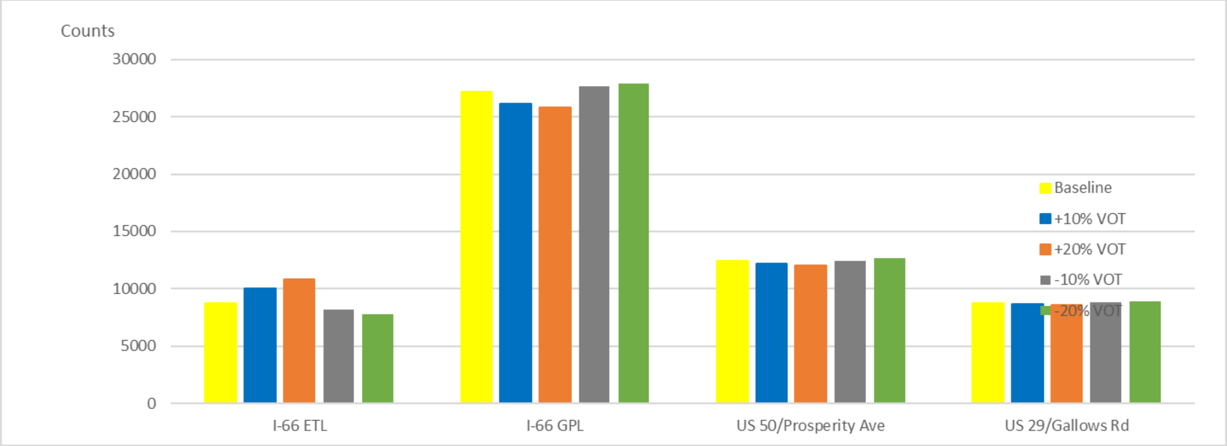


Figure F8. Westbound Traffic Throughputs During the Afternoon Peak Period Under Different Assumptions on the Value of Time Distributions.

Table F2. Throughput and Revenue Changes During the Afternoon Peak Period in Westbound Direction Under Scenarios of Different Value of Time Distributions

Scenario	Baseline	+10%	+20%	-10%	-20%
	Counts	% Difference			
I-66 ETL	8774	13.9%	23.8%	-6.4%	-11.5%
I-66 GPL	27140	-3.6%	-5.0%	1.8%	2.9%
US 50/Prosperity	12402	-1.5%	-3.2%	-0.1%	1.9%
US 29/Gallows Rd	8734	-0.9%	-1.8%	1.0%	2.3%
	$	% Difference			
Revenue at Zone 5	9878	54.8%	120.0%	-15.5%	-28.1%

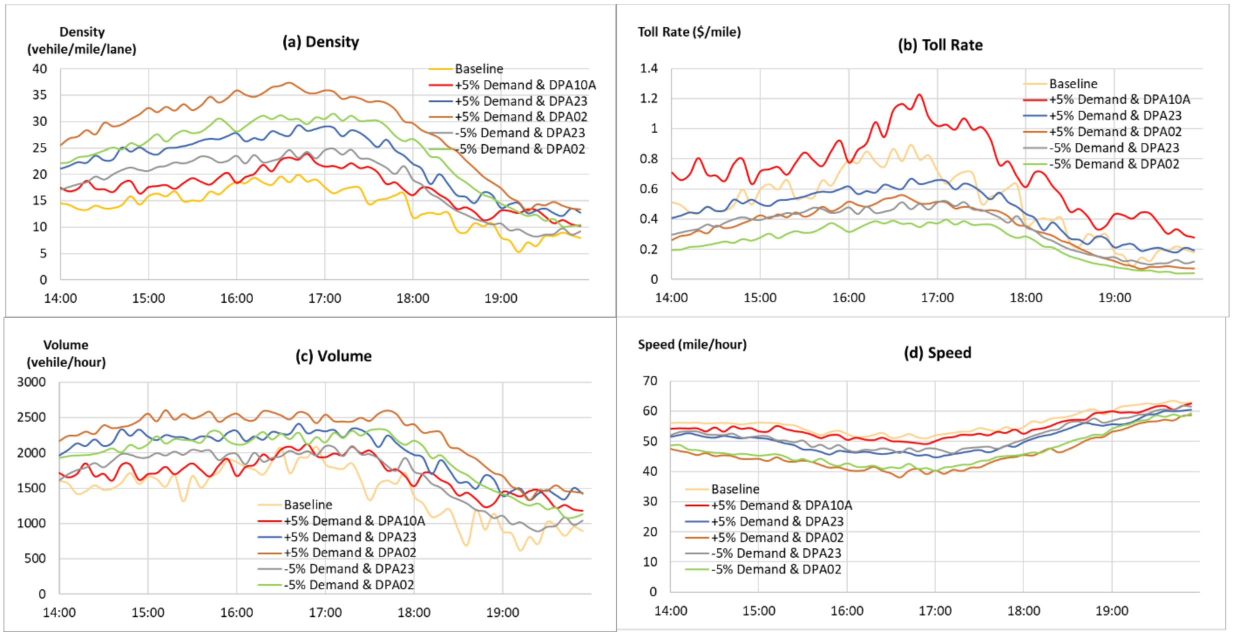


Figure F9. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Different Combinations of Growth Factors and Dynamic Pricing Algorithms.

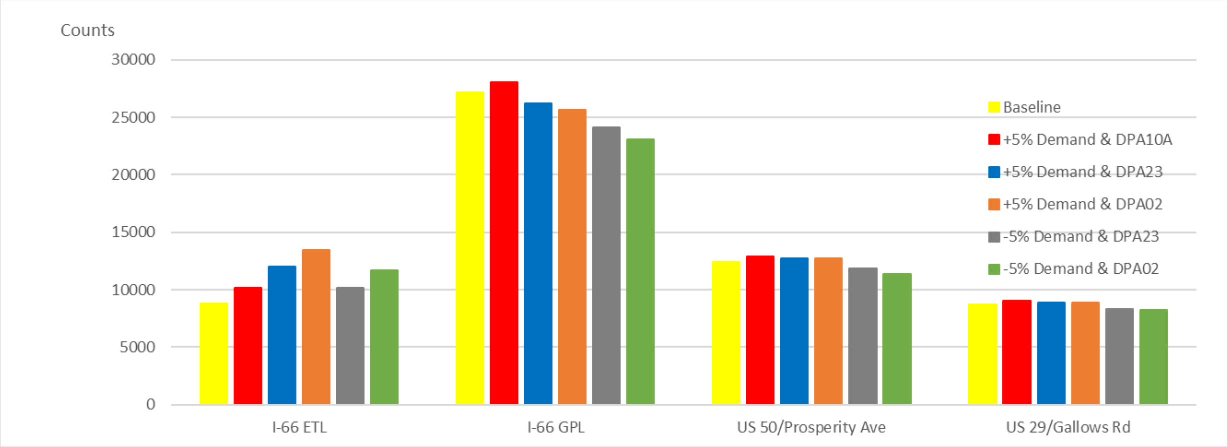


Figure F10. Westbound Traffic Throughput During the Morning Peak Period Under Different Combinations of Growth Factors and Dynamic Pricing Algorithms.

Table F3. Throughput and Revenue Changes During the Afternoon Peak Period in Westbound Direction Under Different Combinations of Traffic Growth Factors and Dynamic Pricing Algorithms

Scenarios		**5% Traffic Growth**					
	Baseline	**DPA10A**		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	8774	10176	16.0%	12020	37.0%	13420	53.0%
I-66 GPL	27140	28055	3.4%	26175	-3.6%	25363	-6.5%
US 50/Prosperity	12402	12923	4.2%	12766	2.9%	12712	2.5%
US 29/Gallows Rd	8734	9024	3.3%	8924	2.2%	8879	1.7%
Total	57050	60178	5.5%	59885	5.0%	60374	5.8%
Revenue	$9878			$11696	18.4%	$10065	1.9%
Scenarios		**5% Traffic Reduction**					
	Baseline	**DPA10A***		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	8774	N/A	N/A	10130	15.5%	11691	33.2%
I-66 GPL	27140	N/A	N/A	24079	-11.3%	23054	-15.1%
US 50/Prosperity	12402	N/A	N/A	11856	-4.4%	11334	-8.6%
US 29/Gallows Rd	8734	N/A	N/A	8345	-4.5%	8223	-5.9%
Total	57050	N/A	N/A	54410	-4.6%	54302	-4.8%
Revenue	$9878			$7725	-21.8%	$6421	-35.0%

** This study did not include a scenario of 5% traffic reduction under DPA10A in the analysis of single factor scenarios. The 5% traffic growth results under DPA10A was already discussed; and are presented here only for comparison.*

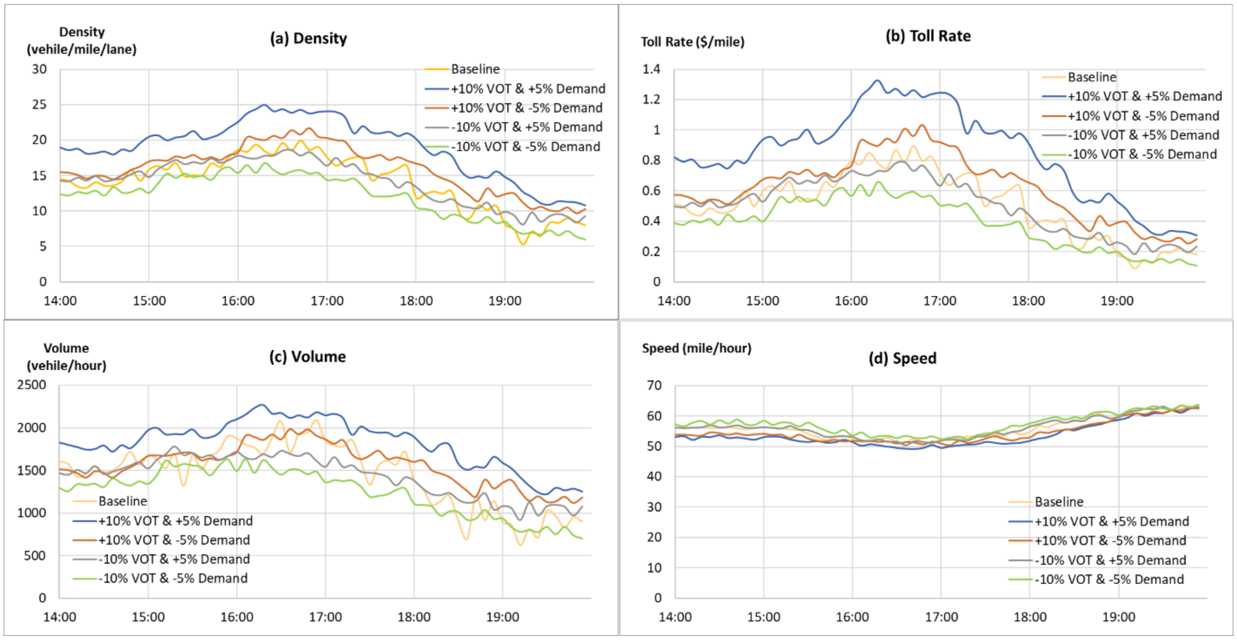


Figure F11. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Different Combinations of Growth Factors and Value of Time Distributions.

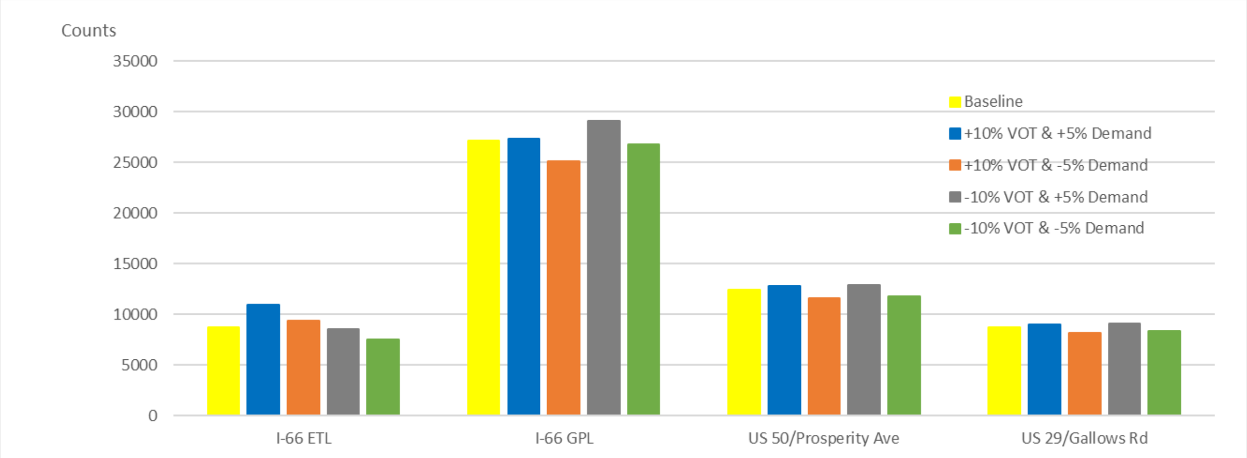


Figure F12. Westbound Traffic Throughput During the Afternoon Peak Period Under Different Combinations of Growth Factors and Value of Time Distributions.

Table F4. Throughput and Revenue Changes During the Afternoon Peak Period in Westbound Direction Under Different Combinations of Traffic Growth Factors and Value of Time Distributions

Scenarios		**5% Traffic Growth**					
	Baseline	**Baseline VOT**		**+10% VOT**		**-10% VOT**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	8774	10176	16.0%	10932	24.6%	8577	-2.2%
I-66 GPL	27140	28055	3.4%	27367	0.8%	29050	7.0%
US 50/Prosperity	12402	12923	4.2%	12823	3.4%	12924	4.2%
US 29/Gallows Rd	8734	9024	3.3%	9012	3.2%	9107	4.3%
Total	57050	60178	5.5%	60134	5.4%	59658	4.6%
Revenue	$9878		58.5%	$19736	99.8%	$9325	-5.6%
Scenarios		**5% Traffic Reduction**					
	Baseline	**Baseline VOT***		**+10% VOT**		**-10% VOT**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	8774	N/A	N/A	9380	6.9%	7501	-14.5%
I-66 GPL	27140	N/A	N/A	25078	-7.6%	26734	-1.5%
US 50/Prosperity	12402	N/A	N/A	11567	-6.7%	11763	-5.2%
US 29/Gallows Rd	8734	N/A	N/A	8224	-5.8%	8324	-4.7%
Total	57050	N/A	N/A	54249	-4.9%	54322	-4.8%
Revenue	$9878		N/A	$12506	26.6%	$6460	-34.6%

** This study did not include a scenario of 5% traffic reduction under the baseline value of time distribution in the analysis of single factor scenarios.*

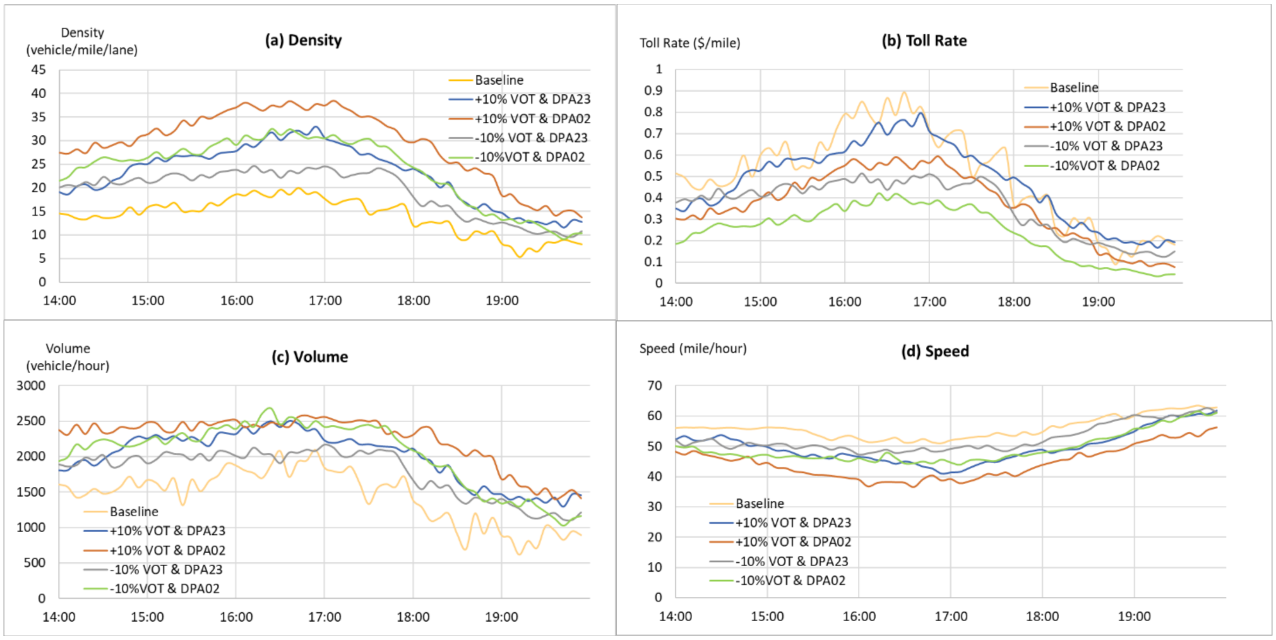


Figure F13. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Different Value of Time Distributions and Dynamic Pricing Algorithms.

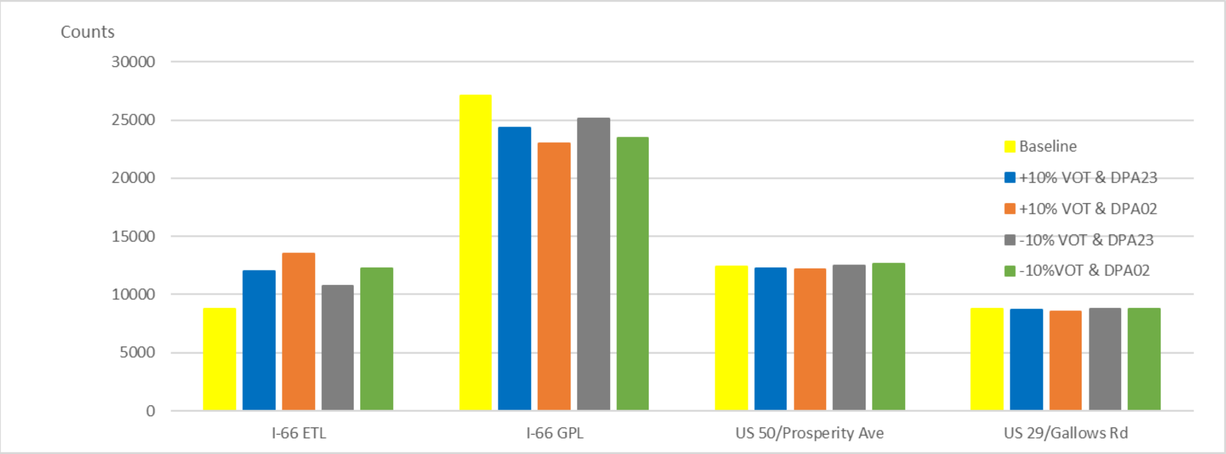


Figure F14. Westbound Traffic Throughputs During the Afternoon Peak Period Under Different Combinations of Value of Time Distributions and Dynamic Pricing Algorithms.

Table F5. Throughput and Revenue Changes During the Afternoon Peak Period in Westbound Direction Under Different Combinations of Value of Time Distributions and Dynamic Pricing Algorithms

Scenarios		+10% Value of Time					
	Baseline	DPA10A*		DPA23		DPA02	
	Counts	Counts	%Diff	Counts	%Diff	Counts	%Diff
I-66 ETL	8774	9993	13.9%	11982	36.6%	13477	53.6%
I-66 GPL	27140	26150	-3.6%	24318	-10.4%	22989	-15.3%
US 50/Prosperity	12402	12210	-1.5%	12256	-1.2%	12189	-1.7%
US 29/Gallows Rd	8734	8655	-0.9%	8677	-0.7%	8555	-2.0%
Total	57050	57008	-0.1%	57233	0.3%	57210	0.3%
Revenue	$9878		54.8%	$12298	24.5%	$10678	8.1%
Scenarios		**-10% Value of Time**					
	Baseline	**DPA10A***		**DPA23**		**DPA02**	
	Counts	**Counts**	**%Diff**	**Counts**	**%Diff**	**Counts**	**%Diff**
I-66 ETL	8774	8210	-6.4%	10739	22.4%	12270	39.8%
I-66 GPL	27140	27642	1.8%	25107	-7.5%	23490	-13.4%
US 50/Prosperity	12402	12388	-0.1%	12455	0.4%	12634	1.9%
US 29/Gallows Rd	8734	8823	1.0%	8787	0.6%	8780	0.5%
Total	57050	57063	0.0%	57088	0.1%	57174	0.2%
Revenue	$9878		-15.5%	$8465	-14.3%	$6816	-31.0%

**These two scenarios have been discussed in detail under single factor analysis and are only included here for comparison.*

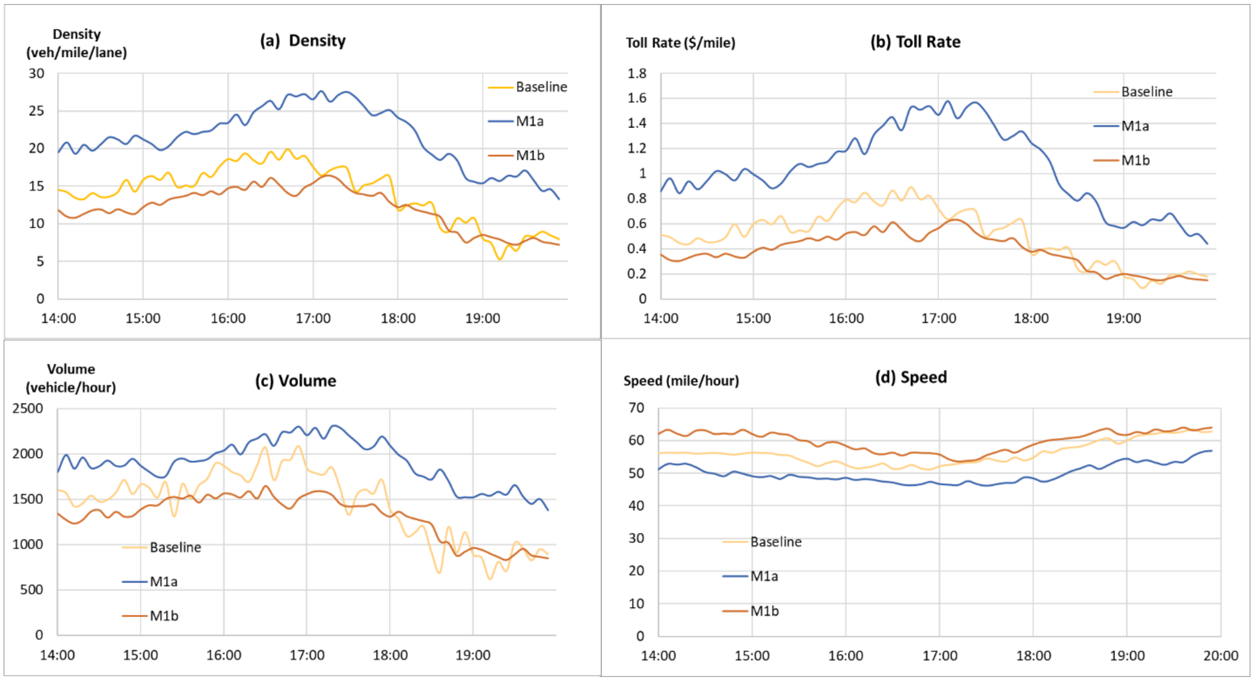


Figure F15. Comparison of PM Peak Period Density (a), Toll Rate (b), Volume (c), and Speed (d) at Zone 5 (West of Interchange with I-495) of the I-66 Outside-the-Beltway Express Toll Lanes in Westbound Direction Under Two Scenarios of Post COVID-19 Traffic Conditions in the PM Peak Period.

M1a: -20% split for High Occupancy Vehicles and +20% of overall traffic
M1b: -20% split for High Occupancy Vehicles and -20% of overall traffic

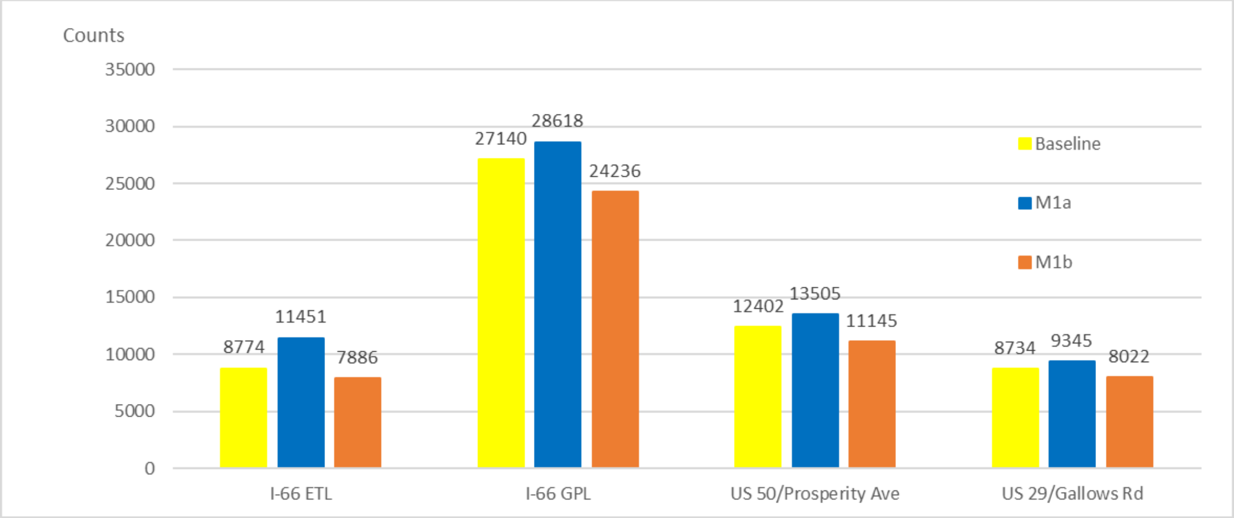


Figure F16. Westbound Traffic Throughput During the Afternoon Peak Period Under Two Scenarios of Post COVID-19 Traffic Conditions.

M1a: -20% split for High Occupancy Vehicles and +20% of overall traffic
M1b: -20% split for High Occupancy Vehicles and -20% of overall traffic

Table F6. Throughput and Revenue Changes in the Peak Direction during the Afternoon Peak Period under Two Scenarios of Post COVID-19 Traffic Conditions

		Baseline	**M1a**		**M1b**	
		Counts	**Counts**	**%Difference**	**Counts**	**%Difference**
ETL	**HOV3+**	2745	2874	4.7%	2052	-25.2%
	SOV/HOV2	6029	8577	42.3%	5834	-3.2%
	Total	8774	11451	30.5%	7886	-10.1%
GPL		27140	28618	5.4%	24236	-10.7%
US 50		12402	13505	8.9%	11145	-10.1%
US 29		8734	9345	7.0%	8022	-8.2%
Total		57050	62919	10.3%	51289	-10.1%
Revenue		$9,878	$23,690	139.8%	$6,116	-38.1%

M1a: -20% of High Occupancy Vehicles and +10% of overall travel demand
M1b: -20% of High Occupancy Vehicles and -10% of overall travel demand