



OFFICE OF THE SECRETARY OF TRANSPORTATION

SAFETY IMPACTS OF NEW TRAFFIC MANAGEMENT TECHNIQUES

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Executive Summary

Traffic congestion is ubiquitous in many urban areas across the United States due to the increasing traffic demand along certain corridors and limited capacity of the highways, especially during peak times of the day. Costs and environmental impacts often preclude traditional widening projects, and State DOT's are turning to alternate solutions, such as Traffic Management Techniques (TMT's) to solve the congestion problem by reducing vehicle demand. Some of the TMTs implemented in the past decade include High Occupancy Vehicle (HOV), High Occupancy Toll (HOT), Bus Rapid Transit (BRT), and Truck Only Lanes. However, due to the limited number of applications (most implementations being relatively recent), historical data on safety and traffic operations is sparse. Identifying this knowledge gap, the Office of the Secretary of Transportation issued a solicitation to conduct research to develop a methodology to assess the safety impacts of existing and proposed TMTs.

In the absence of historical crash data, traffic microsimulation models such as VISSIM hold promise in their ability to offer surrogate measures of safety based on simulation outputs. Up until now, traffic simulation models have not been built to mimic the imperfections of real world driving that might result in conflicting traffic and potential crashes. To harness the power of microsimulation models, the models' driver behavior characteristic parameters can be modified in such way that real-world human errors are generated during the simulation. The general conclusion of several previous studies is that a positive correlation exists between traffic conflicts within traffic microsimulation programs and traffic crashes in real world conditions. The simulation results can be analyzed using surrogate measures of safety to predict the relative performance of one TMT over another.

The VISSIM microscopic simulation model was calibrated using video data obtained from two freeway segments in California, under Federal Highway Administration's (FHWA) Next Generation Simulation (NGSIM) project, in an effort to make the model represent real world driving conditions with imperfect drivers. From the calibrated model, 92 building blocks were created which represent the segments of roadway between interchanges and the merge, diverge, and weave segments at interchanges for different types of TMT's (concurrent flow, physically separated, and contraflow). The microscopic simulation model was successfully calibrated to represent the California freeway segments.

Statistical models were built to estimate two traffic Measures of Effectiveness (MOE's) (vehicular throughput and vehicular speed) and one surrogate safety MOE (conflict index) for each building block. The conflict index is based on Mean Time to Collision (MTTC), a surrogate safety measure captured in this project, with a MTTC of less than 3 seconds representing a potential conflict. A statistical tool called STATA was used to build the statistical models from the results of the building block simulations. The result is specific predictive statistical equations for each series of building blocks which can be utilized to construct a model of real-world facilities to determine operational and safety impacts of different TMT's. Using inputs such as volume, free flow speed, and traffic composition, the output variables of throughputs, speeds, and MTTC can be obtained and used to determine operational and safety benefits of each scenario constructed using the building blocks.

Introduction

Most of the urban areas throughout the United States are experiencing traffic congestion due to the increasing traffic demand along certain corridors and limited capacity of the highways, especially during peak times of the day. Traditionally, congestion is addressed by adding new lanes to increase the capacity of a highway. However, the costs to widen highways, especially in urban areas, are exceedingly high and can be exorbitant. In addition, there are often numerous environmental impacts to mitigate. In addition, funding is becoming increasingly scarce for major roadway expansion and improvement projects.

Congestion is a growing problem that produces unpredictable time delay, air pollution, safety, etc. upon residents as well as business owners. For businesses, market areas might shrink due to the unpredictable and/or increased travel time resulting in added costs and inefficiency. In general, the time lost in travel delays can prove to be costly to the economic growth of the country. The impacts of growing congestion and the limitations of the conventional approach to reduce congestion created a pressing need for innovative congestion management approaches.

Many Departments of Transportation (DOTs) are relying on increased use of Intelligent Transportation Systems (ITS) technologies to improve the operational efficiency of existing facilities by deploying innovative operational control devices and providing real time traveler information. From a demand management perspective, transportation officials are using a spectrum of Traffic Management Techniques (TMTs) to influence the user demand. These approaches generally endeavor to reduce vehicular demand and increase vehicle occupancy during the peak periods, spread the peak period, and more optimally manage the demand on the available roadway network. Several TMTs promote high occupancy travel via carpools, vanpools, and transit which increases the number of people served by a facility at any given time. In addition, tolls are one strategy that can affect the composition and volume of vehicles, on highway facilities.

Government agencies all over the nation have implemented and evaluated new TMTs in the past decade to increase the efficiency of the existing transportation system in innovative manner with minimal costs. Some of the TMTs implemented in the past decade include High Occupancy Vehicles (HOV), High

Occupancy Toll (HOT), Bus Rapid Transit (BRT), and Truck Only Lanes. However, due to the fact that there have been a limited number of applications and that many of those have been relatively recent implementations, historical data on safety and traffic operations is sparse. Few studies have been conducted documenting the relative traffic operational and safety implications of these TMTs. While there is limited understanding of the operational and safety performance for the existing TMT deployments, there is almost no information on untested TMTs such as Truck Only Toll (TOT) facilities, which are at a conceptual stage. Identifying this knowledge gap, the Office of the Secretary of Transportation issued a solicitation to conduct research to develop a methodology to assess the safety impacts of existing and proposed TMTs like HOT and TOT respectively. The four TMTs (i.e., HOV, HOT, TOT, and, dedicated lane BRT) will be referred to as “selected TMTs” or “managed lane strategies” in this document.

Managed Lane Strategies

The Federal Highway Administration defines managed lanes as highway facilities or a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions. The distinction between managed lanes and other traditional forms of freeway lane management is the operating philosophy of "active management." Under this philosophy, the operating agency proactively manages demand and available capacity on the facility by applying new strategies or modifying existing strategies. The agency defines from the outset the operating objectives for the managed lanes and the kinds of actions that will be taken once pre-defined performance thresholds are met⁽¹⁾. A thorough description of the selected managed lane strategies researched in this project and locations of their successful implementation around the nation are presented in this section.

High Occupancy Vehicles (HOV) Lanes

Existing or new highway lanes are reserved for the exclusive use of vehicles with a driver and one or more passengers as shown in **Figure 1**. This TMT promotes car pools, vanpools, and transit where the number of people transported through a facility is higher for the same number of vehicles. HOV facilities have been installed in the United States and Canada for over a decade and many more are being planned. In some areas, State DOTs are expanding HOV lanes into metropolitan area-wide networks. Currently, there are over 300 HOV facilities in the US and many other facilities in planning, design, or construction phases.

Based on the available data, highest number of peak hour persons transported on the HOV lanes in the US is on NJ Route 495 Lincoln tunnel bus lane in New Jersey, with 23,500 people in the AM peak. In contrast, the HOV lanes of Interstate 5 between Northgate and South Everett in the Seattle Puget Sound region in Washington State carry their maximum number of vehicles (5,280) in the PM peak⁽²⁾.



Figure 1: A HOV facility on Highway 404 in Toronto⁽³⁾

High Occupancy Toll (HOT) Lanes

Another traffic management technique is the use of variable pricing on tolled facilities to attract motorists to lower priced off-peak times, thereby maintaining higher service level volumes during the peak periods. Combining HOV and toll pricing strategies produces a novel traffic management technique – High Occupancy Toll lanes. On HOT lanes, high occupancy vehicles have free access to the facility and the unused highway capacity is made available to single occupant vehicles through a dynamically calculated toll as shown in **Figure 2**. The lanes are managed through pricing to maintain free flow conditions even during the height of rush hour. The combined ability of HOT operations to introduce additional traffic to existing HOV facilities, while using price and other management techniques to control the number of additional motorists and maintain high service levels, renders the HOT lane concept a promising means of reducing congestion and improving service on the existing highway system.

About six (6) HOT facilities have been installed in the United States in the last decade and many more are being planned.



Figure 2: A rendering of HOT facility by WSDOT; A HOT lanes facility on SR 167 in Washington⁽⁴⁾

Bus Rapid Transit (BRT)

BRT is a high performance public transportation system where buses travel on a dedicated right-of-way coupled with enhanced infrastructure, vehicles, and scheduling to provide faster, more efficient and reliable service. An illustrative example of a BRT is shown in **Figure 3**. These systems are targeted to achieve the service quality of a light rail system while still retaining the benefits of bus transit, such as cost savings and route flexibility. BRT has been very popular with many functional forms of implementation, ranging from grade separated busways to shared usage of parking lanes in a downtown urban setting. Additional features of BRT systems include intersection bus priority, real-time bus information, and, efficient fare collection methods.



Figure 3: BRT in Cleveland, Ohio, USA⁽⁵⁾

Truck-Only Toll (TOT) Lanes

In this TMT, trucks are allowed to access the dedicated highway lanes by paying a toll. The purpose of truck-only facilities is to promote safer traffic flow, reduce congestion in the general purpose lanes and improve freight productivity⁽⁶⁾. It encourages commercial vehicles to use dedicated highway lanes with variable pricing schemes resulting in the creation of additional capacity for single and multiple occupancy passenger vehicles in general purpose lanes. Currently, only a handful of free truck-only lanes exist in the United States, but to the best of our knowledge there are no existing TOT lanes.

Project Approach

In the absence of historical crash data, traffic microsimulation models such as VISSIM hold promise in their ability to offer surrogate measures of safety based on simulation outputs. Up until now, traffic simulation models have not been built to mimic the imperfections in the real world driving (listed below) that might result in conflicting traffic.

- Driver fatigue
- Driver assessment of risks
- Driver risk taking tolerance and behavior
- Distracted driving
- Driver inexperience
- Drunk driving
- Speeding
- Weather conditions
- Road design
- Pavement conditions

To harness the power of microsimulation models, the driver behavior characteristic parameters can be modified in such a way that the human errors seen in the field are generated during the simulation. The results can then be analyzed using surrogate measures of safety to predict the relative performance of one TMT over another. This was the approach employed in this project. The specific steps in the project approach are shown in the flow chart in .

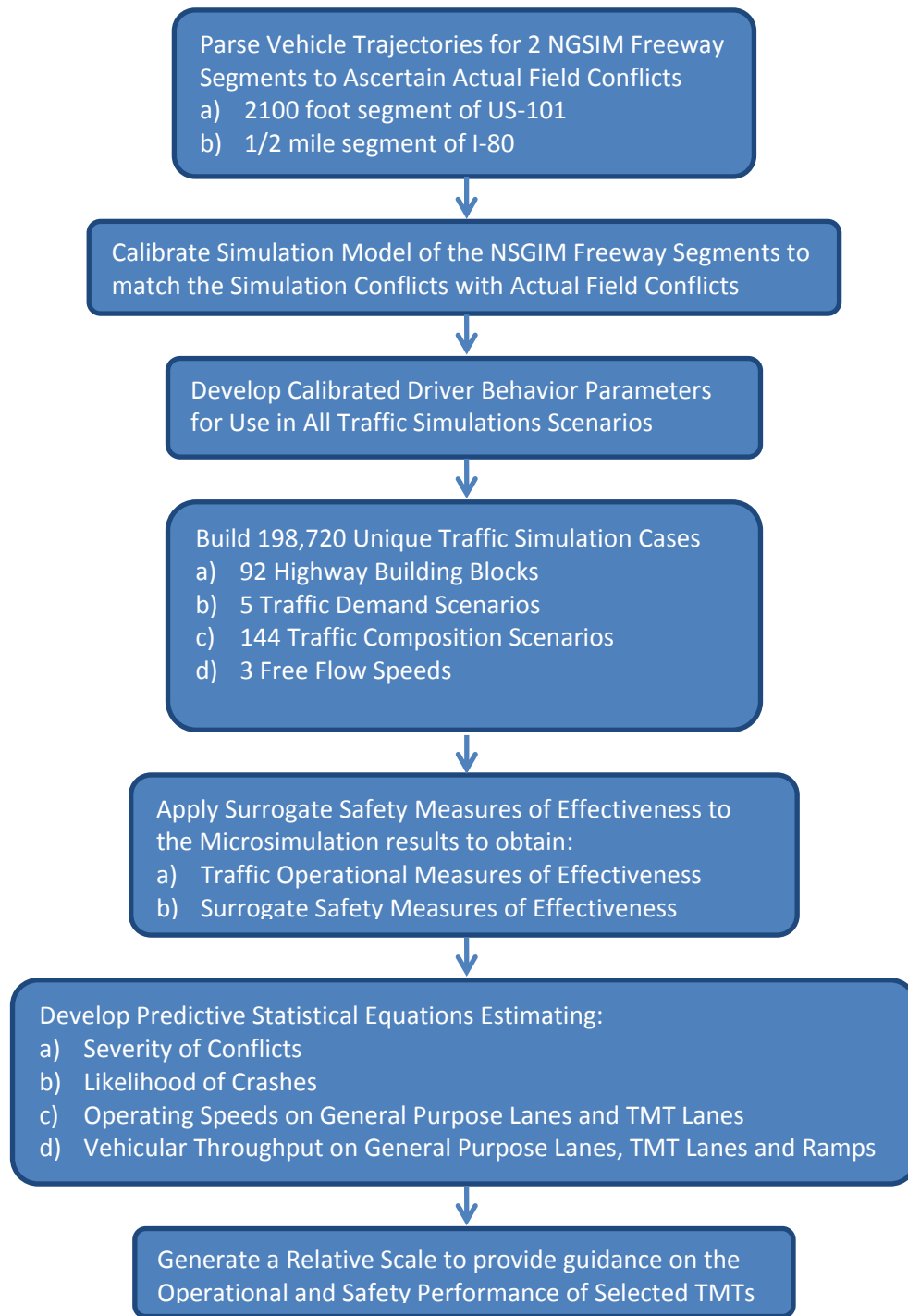


Figure 4: Research Methodology

Studies show that statistical equations which predict crashes from traffic microsimulation-generated estimates of conflicts have lower values of coefficient of determination (R^2) compared to statistical equations predicting crashes based

on vehicular volumes. Few recent studies have been conducted that compare the safety implications of some of these TMTs using surrogate measures of safety from microscopic traffic simulations. The general conclusion of these studies is that a positive correlation between traffic conflicts computed from traffic micro-simulation programs and traffic crashes. However, a recent study⁽⁷⁾ conducted for the U.S. Department of Transportation (DOT) suggests that research to date employing surrogate safety measures from traffic simulation models of new TMTs does not give any direct meaningful understanding of expected severity or number of crashes on these facilities. These limitations can be overcome by rating the TMTs relatively rather than on an absolute scale.

This research project developed meaningful insights into the relative safety performance of HOV, HOT, TOT, and BRT facilities using surrogate safety measures to help transportation officials and professionals gain insights into the safety implications of these new TMTs. The study recommends a framework that can be utilized in designing strategies that minimize safety risks under various field conditions. The intended audience of this report is the group of transportation professionals engaged in the planning, design, and operation of TMTs for highways and limited-access arterials. This report does NOT constitute a TMT selection guidebook or a definitive guide for safety and operational performance of the selected TMTs. The methodology developed in this report is a decision aid tool for transportation professionals considering the deployment of one or more of the selected TMTs on highways and limited-access arterials.

The objective of this study is not to provide technical recommendations to promote the use of TMTs; rather, it is assumed that the intended audience is already convinced of the traffic congestion relieving potential of TMTs. It is assumed that transportation agencies are familiar with elements of the existing highway infrastructure and possible potential improvements to the highway system in conjunction with the selected TMTs.

Both in theory and in practice, traffic operations and safety have a complex interrelationship; therefore, building a tool based on traffic operational and infrastructure related input parameters that would quantify the relative safety performance of different TMTs is ideally sought. The project plan describes the approach followed towards achieving this goal within the scope of the proposed project. The salient features of the project plan, some of which may be the first research application of their kind, are listed below:

- Changing “theoretically conflict-less” driver behavior in microsimulation models to replicate the “real-world” driver behavior by using driver inattention.
- Use of real world traffic conflict data from FHWA’s NGSIM project to calibrate occurrence of traffic conflicts in microsimulation models. (Please refer to Model Calibration section for information on NGSIM)
- Coverage of the four most popular TMTs, namely, HOV, HOT, TOT, and BRT facilities.
- Simulation of 198,720 Unique Traffic Simulation Cases to comprehend the complex operational and safety performance of TMTs in great detail for varied inputs of traffic demand, vehicle compositions, highway geometric sections, and operating speeds.
- Development of statistical predictive functions to estimate the operational and safety performance of selected TMTs.
- Development of guidance to transportation professionals regarding safe and efficient deployment of the selected TMTs based on research results which were not previously available.

Synthesis of Literature Review

The topic of surrogate safety measures has been of great interest to the transportation engineering community in recent times. Transportation agencies desire to use surrogate safety measures derived from microscopic simulation models for several reasons. According to Guo⁽⁸⁾, surrogate safety measures can be used to predict the level of safety of a facility which is under design or where the actual crash activity is low or crash data is unavailable. Davis, Hourdos, and Xiong⁽⁹⁾ point out that the relative rarity of crashes on a roadway segment makes surrogate safety measures desirable as a predictor of roadway safety. Although there is a large demand for this analysis method, there is much discussion at the present time over the best way to obtain field data to calibrate a simulation model, and how to apply the results to real life scenarios.

In order to obtain a more realistic model of driver behavior, Wuping, et. al.⁽¹⁰⁾ developed a method for introducing driver error and inattentiveness to a model to produce a “less than perfect driver”. Their point of view was that microscopic simulation models are capable of modeling and evaluating surrogate safety measures, but only if the model can be calibrated to accurately portray realistic driver behavior. The behavior of real world drivers is variable, with some

drivers giving greater levels of attentiveness and possessing greater levels of skill than other drivers; whereas most simulation models use constant parameters for car following, lane change gap acceptance, and other factors inherent to the operation of the simulation. The result is ideal conditions instead of actual conditions seen in the field.

The variable used in Wuping's⁽¹⁰⁾ model is the "scanning interval", which is related to driver inattention, and is specific to a particular driver at a particular location with particular traffic conditions. Their project used video data from a freeway segment in Minnesota to calibrate approximately 9 parameters, including scanning interval, maximum acceleration and deceleration rates, desired following gap time, and several others. The equations yield a variable driver reaction time based upon the instantaneous speed and density, as well as the scanning interval. The model was tested and validated against an actual data set, and the results indicate that the model can replicate both normal and un-safe driver behaviors seen in the field.

A project by Wuping, Hourdos and Michalopoulos⁽¹¹⁾ examined a collection of vehicle trajectory data, which is a necessary component of modeling "less than perfect" driver behavior and especially the trajectories of vehicles about to collide with one another. These data are necessary to calibrate and validate the microscopic simulation model, as the real data can be compared with vehicle trajectories obtained from the model results. The same Minnesota freeway segment data described above was used to obtain vehicle trajectories, with NG-VIDEO software used to extract vehicle trajectories, the same software used to obtain trajectories for the US-101 and I-80 segments in this project. Two optimization stages were used, and the goal was to minimize the difference between points projected by the simulation model and the actual vehicle trajectory obtained from the video. Their methodology should be considered for future projects involving vehicle trajectories, as it was more accurate and robust, and introduced fewer errors than the Locally Weighted Regression approach used in the past.

Feng Guo⁽⁸⁾ examined the possibility of collecting vehicle trajectory data using in-vehicle equipment. This equipment would capture the operational characteristics of the vehicle, and periods with sudden acceleration, or abnormal movement (lateral acceleration) which could be further analyzed as potential or actual crashes. It was suggested that these data would be more accurate than data collected from other sources; however, it would be more expensive and difficult to obtain, as vehicles must be outfitted with data collection devices upon

driver's consent. Also, it may be difficult to ascertain when a conflict might occur if there was no sudden evasive action taken, as determining the existence of a conflict requires trajectory data from both vehicles.

Using vehicle trajectories from a properly calibrated and validated model, one can examine surrogate safety measures to determine a roadway's relative safety. Several surrogate measures can be used, with the most common being conflicts. This measure was examined by Davis, Hourdos, and Xiong⁽⁹⁾. A conflict is defined as when two vehicles will collide if they remain on their current path and no evasive action is taken. The theory is that there should be a proportional number of crashes and conflicts in any given scenario. The basic model is a "casual model," meaning that a crash will only occur if the vehicle is incapable of avoiding the collision based on constant vehicle deceleration and reaction time. The model can be transformed into a "probabilistic casual model" if randomness is introduced to the driver's reaction, much like Wuping's⁽¹⁰⁾ project. The conclusion of the project was that when evasive action is needed at a possible conflict and the magnitude of that action (like small deceleration rate) is similar to that observed in a real-time crash, that conflict is an acceptable surrogate safety measure.

Ozbay, et. al.⁽¹²⁾, provides several other surrogate safety measures, including Time to Collision (TTC) and Possibility Index for Collision with Urgent Deceleration (PICUD). The TTC is the amount of time until a collision will occur when a conflict is presented. This would be a good surrogate safety measure; however, it is highly dependent on the individual driver's reaction time. An additional measure, called the Crash Index Density (CID) was added. This measure was loosely based on TTC, but accounted for the severity of the possible crash. The paper validated the CID theory using crash data from the New Jersey Turnpike, and the conclusion was that the CID could be used to compare alternative roadway designs to one another. However a key limitation is that the CID was not an accurate predictor of the actual crash rate, it should only be used to compare roadway segments. A modified version of TTC was developed by Gousios and Garber⁽¹³⁾, which introduced the speed of the first vehicle to the equation. In their project, a logarithmic model was used that showed a good correlation between surrogate safety measures and the number of collisions, but was highly dependent upon the threshold values chosen for TTC and the modified TTC.

The Federal Highway Administration published research on the "Surrogate Safety Assessment Model"⁽¹⁴⁾ (SSAM). This software uses a trajectory file that

can be obtained from various simulation packages, including VISSIM, AIMSUN, TEXAS, or Paramics. While highly dependent upon a well calibrated and validated source of trajectory data, the SSAM tool can be very powerful, as it automatically calculates up to 8 surrogate safety measures from the input data. The SSAM model includes a filtering mechanism, a statistical analysis tool, and tools to graphically display the results in a map format.

A study by Archer and Young⁽¹⁵⁾ indicates that VISSIM is a model often chosen for simulating surrogate safety measures. Their project examined gap acceptance at an unsignalized intersection. Acceptance and rejection data, as well as drivers' willingness to accept a gap of a particular size, were used to develop a probabilistic model. Their surrogate safety measure, which was more specific to the intersection scenario, examined the risks taken by drivers executing a turning maneuver, as well as the risk presented to a driver who may possibly have to take evasive action. This type of modeling approach to gap acceptance can also be carried to highway situations, where lane changes use a different form of gap acceptance to determine if the maneuver is safe.

Thus far, the available literature examines a wide variety of surrogate safety measures, calibration and validation techniques, and data collection methods. These topics are very important to the current FHWA project, as there is certainly a need for safety data that can be obtained from simulation models when future roadway facilities are being designed. In Kuhn's "Managed Lane Handbook"⁽¹⁶⁾, the authors point out that very few roadways are designed with managed lanes in mind in the United States. Most managed lanes are retrofitted into existing corridors where design and right-of-way constraints limit the possible designs for managed lanes. Building managed lanes on new highways is an emerging concept in the USA; however, planners typically only look at operational data with a cursory qualitative look at safety practices. A managed lane design requiring drivers to weave across general purpose lanes would intuitively be less safe than a design with direct access ramps, especially if heavy vehicles are involved. But it is very difficult to quantify this theory, much less apply quantitative results to facilities without obvious design deficiencies such as requiring weaves across general purpose lanes.

The "Managed Lane Handbook"⁽¹⁶⁾ lists safety as a goal of providing a managed lane facility on a highway corridor. Safety is listed as an important geometric design consideration with no advice as to how this should be accomplished. A "screening tool" is provided in the Handbook, with "minimizing traffic crashes involving large trucks" as a screening criteria. This criterion seems biased

toward truck-only managed lane facilities which would separate car and truck traffic, despite the fact that many state DOTs would like to minimize crashes involving cars and trucks anyway. The Handbook does not suggest specific design criteria that would minimize these types of crashes at facility types other than truck-only facilities. The geometric design chapter merely suggests that as many normally accepted safety features as can be incorporated into the design of managed lanes should be used.

The authors of the “Managed Lane Handbook”⁽¹⁶⁾ state that the document is a living document and was meant to be expanded. While inferences are made that incorporating standard highway safety features into managed lanes will make the managed lanes safer, there is a void of information when it comes to using safety information to screen the different types of managed lanes, and how to quantify the safety differences between various managed lane strategies. Fitzpatrick, et. al.⁽¹⁷⁾, examined the operational and design issues related to managed lanes by completing a case study of managed lane facilities in the US. While a very useful document, their methodologies relied upon a facility being constructed, and cannot be used to determine safety benefits or issues with facilities under design.

The current project seeks to incorporate realistic driver behavior into VISSIM “Managed Lane Building Blocks,” which can be used to construct a network with virtual managed lanes. The methodologies presented above can be used to calibrate the building blocks to replicate real vehicle behavior, and a properly calibrated model can yield surrogate safety measures for managed lane facilities constructed using these building blocks. The surrogate safety measures can be calculated and analyzed using a tool such as FHWA’s SSAM tool. The resulting network can then be used to determine the relative safety of one strategy over another. The network should not be used to predict the number of crashes that might occur, as that has not been sufficiently demonstrated to be accurate. Instead, the building blocks can be used to compare different strategies, with higher numbers of conflicts and other surrogate safety measures indicating a design which may be less safe than one with lesser numbers of conflicts and surrogate safety problems. The data can then be used as a planning tool to assist transportation agencies in making important, informed decisions regarding managed lanes. The end result would fill an important void in managed lane design literature.

Analyses Procedure

In this project, numerous cases of TMTs are analyzed to produce a relative scale of safety and traffic operations for various independent variables (inputs) like different highway geometries, volumes, traffic compositions, and free flow speeds. To simulate these building blocks close to reality, driver behavior data has been modified to match with the calibrated simulated models of two real-world freeway segments, 2100 feet of US-101 and ½ mile of I-80.

Model Calibration

The NGSIM project funded by FHWA collected high resolution vehicular trajectory data for two freeway and two arterial segments based on video recording of traffic data. The two freeway segments were US-101 and I-80. The NGSIM team developed a 45 minute dataset representing traffic flows on a segment of U.S. 101 (Hollywood Freeway) in the Universal City neighborhood of Los Angeles, California. The dataset represents vehicle trajectory data on a 2,100 foot, six-lane segment of southbound U.S. 101, collected on June 15th, 2005. The merge/weave section represented in the data includes the Ventura Boulevard on-ramp and the Cahuenga Boulevard off-ramp connected by an auxiliary lane. The dataset consists of detailed vehicle trajectory data, every one-tenth of a second (0.1 second), wide-area detector data and supporting data needed for behavioral algorithm research at every 100 feet of the roadway segment.

Another similar dataset representing 45 minutes of data collected during the afternoon peak period on a half mile section of eastbound I-80 in Emeryville (San Francisco), California, is also available. Three separate 15 minute periods of data collected on April 13th, 2005 are available: 1) 4:00 p.m. to 4:15 p.m.; 2) 5:00 p.m. to 5:15 p.m.; and 3) 5:15 p.m. to 5:30 p.m. The data for the 4:00 p.m. to 4:15 p.m. period primarily represents transitional traffic conditions during the build-up to congestion. The remaining two periods represent congested traffic conditions.

The research team developed two VISSIM models replicating these sections of northbound US-101 and eastbound I-80. After initial coding of the network, multiple runs of VISSIM model with varying random seeds were conducted to introduce randomness to vehicle loadings and the vehicle arrivals within the simulation environment. Specifically, the traffic volumes that were collected for the two freeway segments were modeled in VISSIM and calibrated for the following:

1. Vehicular throughput and speed by section and time period.
2. Aggregate lane changes by time period.
3. Number of conflicts.

Driver behavior inputs such as minimum headway, safety distance reduction factor, and lane change distance, were modified to achieve vehicular throughput, speed, and lane changes that were similar to field-measured values for every 100 feet of the highway. Number of conflicts was calibrated by tuning the duration and probability of temporary lack of attention. The temporary lack of attention or “sleep” parameter makes vehicles not react to a preceding vehicle (except for emergency braking) for a certain amount of time. Duration defines how long this lack of attention lasts and probability defines how often this lack of attention occurs. The project team used 0.1 second of lack of attention duration with a probability of 10 percent to match the simulation results to the field observations.

shows the measured and simulated volumes for every 100 ft of the I-80 section. **Figure 6** shows the measured and simulated speeds for the I-80 section. **Figure 7** shows the measured and simulated flows for every 100 feet of the study corridor on US-101. Similarly, **Figure 6** and **Figure 8** presents the measured and simulated speeds on the I-80 and US 101 sections.

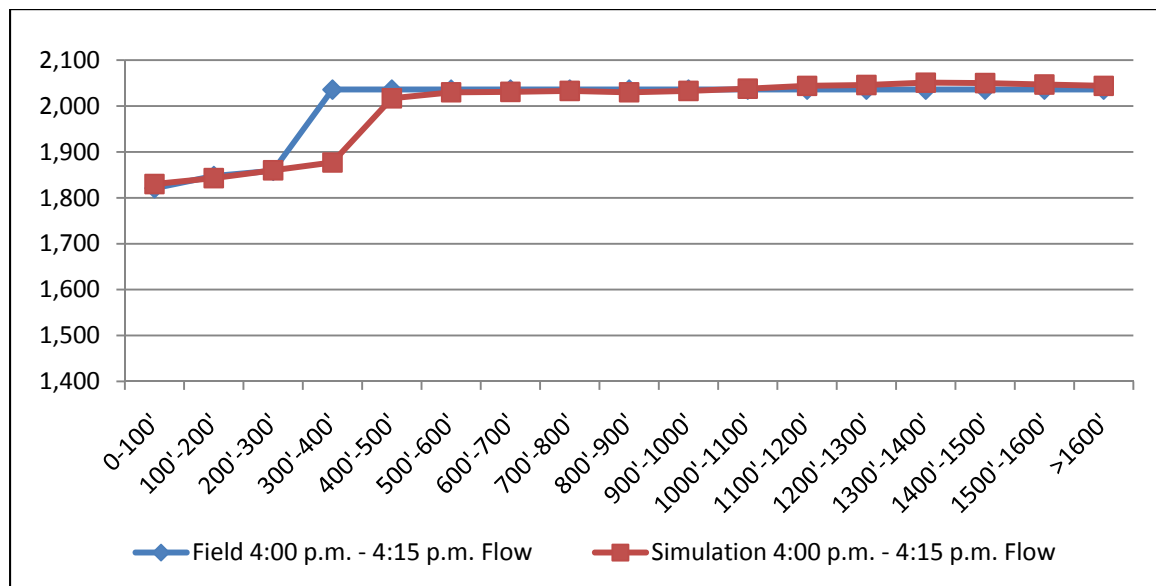


Figure 5: Volume throughputs from the field and microsimulation along I-80

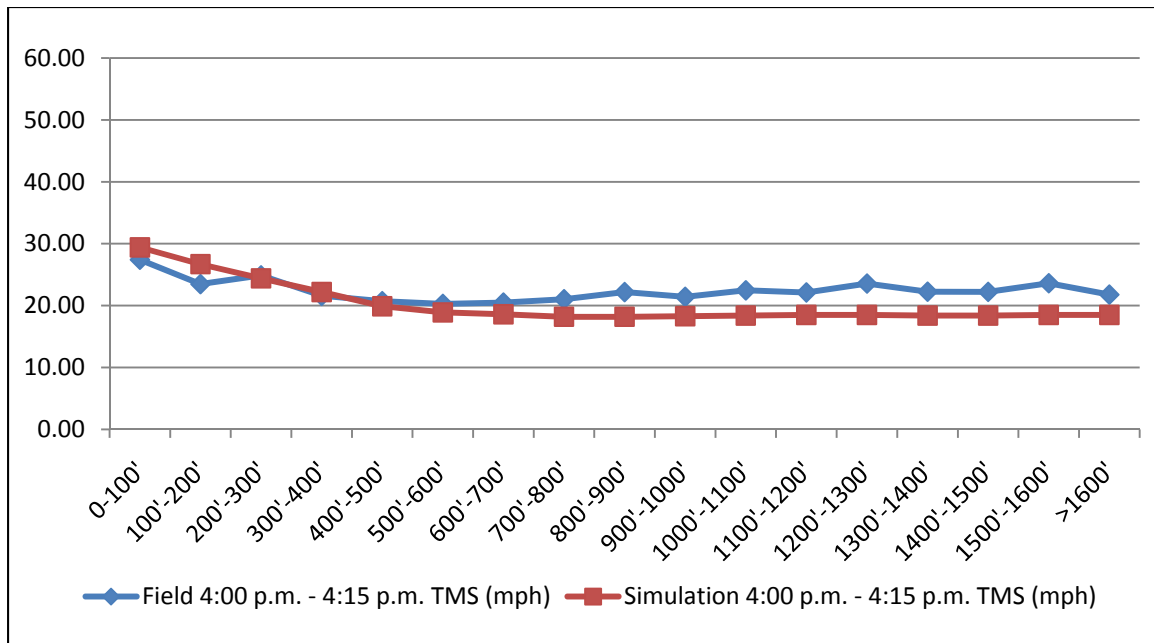


Figure 6: vehicular speeds along I-80

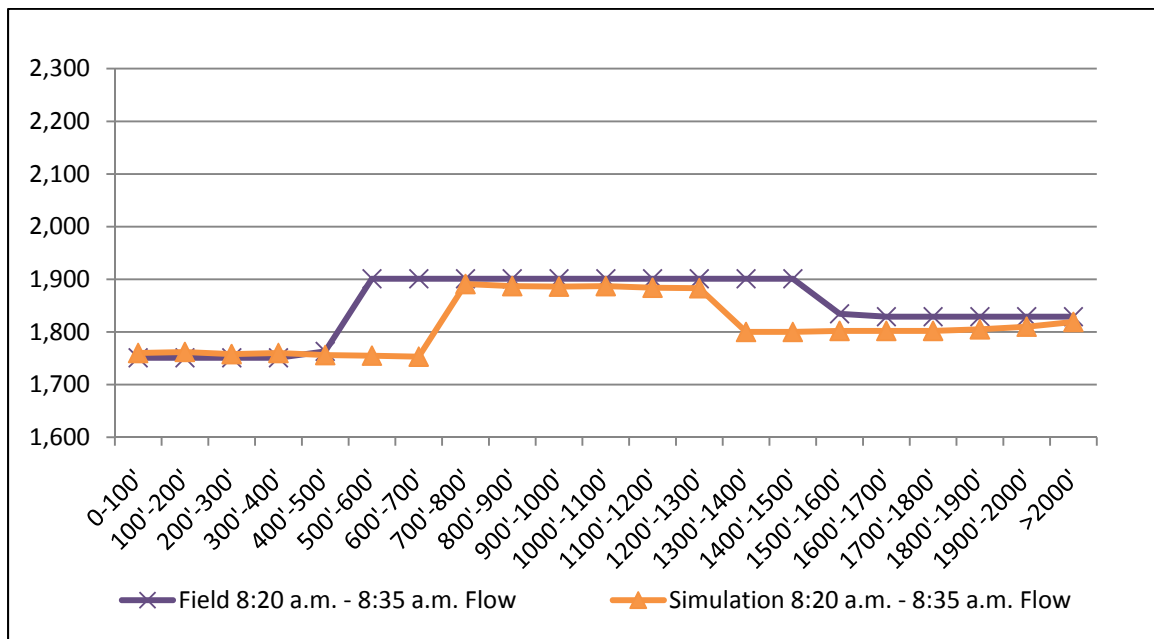


Figure 7: Volume throughputs from the field and microsimulation along US 101

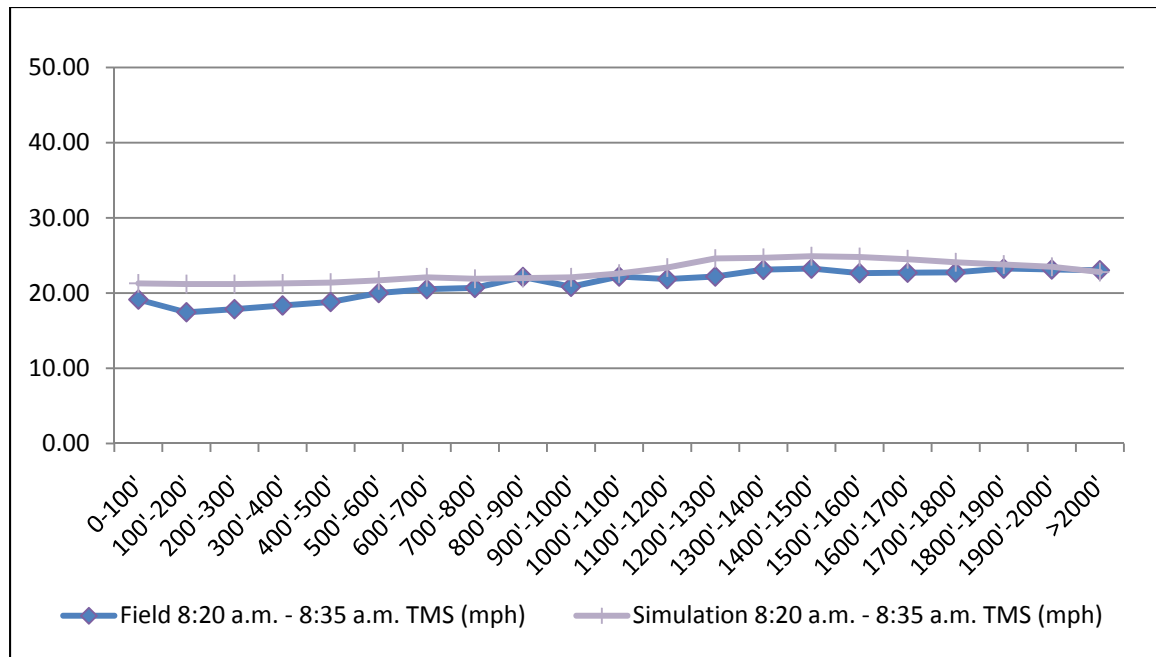


Figure 8: vehicular speeds along US 101

The number of lane changes observed in the microsimulation and in the field match closely as shown in

Table 1. To create the necessary congestion during the AM and PM peak periods, reduced speed zones were placed downstream of the study area. The calibration process required many iterations to accurately reflect the field conditions. Each model run was conducted using a 30-minute seeding period followed by a 1-hour simulation for I-80 and a 45-minute simulation period for US-101.

Table 1: Lane changes with 0.1 seconds of lack of attention and 10% probability

I-80 Lane Change Comparison	Field	VISSIM
4:00 - 4:15 PM	1,002	1,087
5:00 - 5:15 PM	904	945
5:15 - 5:30 PM	905	856
Total	2,811	2,888
US-101 Lane Change Comparison	Field	VISSIM
7:50 - 8:05 AM	986	880
8:05 - 8:20 AM	656	765
8:20 - 8:35 AM	645	584
Total	2,287	2,229

TMTs Simulation

As the US-101 and Interstate 80 case studies demonstrated, changing the driver behavior parameters can bring the simulation very close to reality, so both operational and safety performance became reliable for evaluating the existing TMT, a broader range of freeway configurations are desired to estimate the performance of the selected TMTs.

To model “real-world” driver behavior, modified driver behavior inputs obtained from the calibrated models of US-101 and I-80 were used in the simulation cases for various TMTs. There were more than 216,000 unique simulation scenarios for the selected TMTs under various traffic demands, speeds, lane geometries, and vehicle compositions. The flowchart in shows the key steps in the building block analysis procedure. Each unique lane geometry is referred to as a building block in this report.

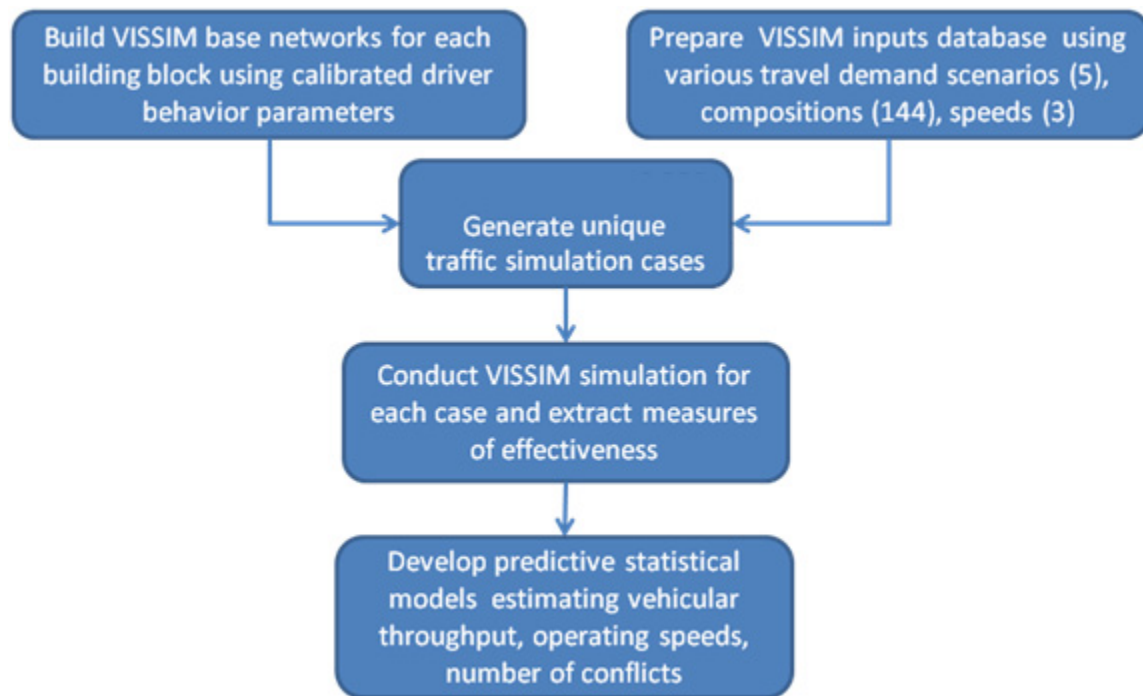


Figure 9: A graphical representation of building block analysis procedure

Building Blocks

The two major building blocks of a highway system are interchanges and highway sections between the interchanges. Interchange areas can be further classified into:

1. Merge Section
2. Diverge Section
3. Weave Section

From a traffic operational standpoint, all highway TMTs can be subdivided into highway sections having characteristic geometric design features and traffic control devices with associated traffic volumes. In order to understand the operational and safety performance of the selected TMTs in a highway system, it is important to understand the equivalent operational performance of the TMTs in the individual highway building blocks constituting the entire length of the freeway section. A total of 92 building blocks shown in **Table 2** were identified with different combinations of number of freeway and TMT lanes, type of freeway section (merge, diverge, weave or basic) and implementation style of TMTs.

Implementation styles of TMTs can be mainly classified into three categories:

1. Demarcated or Concurrent Flow Lanes: Separation of general purpose lanes and managed lanes by pavement markings.
2. Physically Separated: Separation of general purpose lanes and managed lanes by some form of physical barrier. Separated lanes will also include reversible lanes, elevated lanes and bypass lanes.
3. Contraflow: Separation of general purpose lanes and managed lanes travelling in opposite directions by pavement markings. Contraflow lane TMTs are not widely prevalent in the United States, except for at a few locations (e.g., Houston and Atlanta). However, they have been included to understand the potential impacts and severities of head-on collisions between travelling vehicles in adjacent lanes separated by pavement markings

A base network was coded in VISSIM for each building block shown in **Table 2** representing the proposed highway geometric section, including basic, merge or diverge type, demarcated or physically separated, number of lanes (general purpose lanes, TMT lanes, on-ramp lane, and off-ramp lane), segment length (upstream, downstream, two-sided weave segment), distance from on-ramp lane

entrance to TMT lanes entrance (if applicable), and distance from TMT lanes exit to off-ramp lane exit (if applicable).

For the building blocks that have entrance or exit terminals (building blocks 1-84), the research team had to prepare a unique base network for each operating speed for each building block scenario. The main reason was that different design speeds have different taper lengths and acceleration or deceleration lengths. The AASHTO Green Book (*A Policy on Geometric Design of Highways and Streets*) was used as a guidance to determine the segment length around on-ramp and off-ramp.

Table 2: 92 unique building blocks

Highway Building Blocks	Type of Highway Segment	TMT Separation Technique	Number of General Purpose Lanes	Number of TMT lanes	Length of Upstream Segment (miles)	Length of Downstream Segment (miles)	Number of On-Ramp Lanes	Number of Off-Ramp Lanes	Distance from On-Ramp Lane Entrance to TMT Lane(s) Entrance (feet)	Distance from TMT Lane(s) Exit to Off-Ramp Lane Exit (feet)	Length of Two-Sided Weave Segment	Position of Ramp Lane(s) relative to highway lanes
Section 1: Merge with Pavement Demarcated(PD) TMT Lanes												
1	Merge	PD	2	1	1	2	1	NA	NA	NA	NA	Right
2	Merge	PD	3	1	1	2	1	NA	NA	NA	NA	Right
3	Merge	PD	4	1	1	2	1	NA	NA	NA	NA	Right
4	Merge	PD	3	2	1	2	1	NA	NA	NA	NA	Right
5	Merge	PD	4	2	1	2	1	NA	NA	NA	NA	Right
6	Merge	PD	5	2	1	2	1	NA	NA	NA	NA	Right
7	Merge	PD	4	3	1	2	1	NA	NA	NA	NA	Right
8	Merge	PD	5	3	1	2	1	NA	NA	NA	NA	Right
Section 2: Merge with Physically Separated(PS) TMT Lanes												
9	Merge	PS	2	1	1	2	1	NA	1000	NA	NA	Right
10	Merge	PS	2	1	1	2	1	NA	2000	NA	NA	Right
11	Merge	PS	3	1	1	2	1	NA	1500	NA	NA	Right
12	Merge	PS	3	1	1	2	1	NA	3000	NA	NA	Right
13	Merge	PS	4	1	1	2	1	NA	2000	NA	NA	Right
14	Merge	PS	4	1	1	2	1	NA	4000	NA	NA	Right
15	Merge	PS	3	2	1	2	1	NA	1500	NA	NA	Right
16	Merge	PS	3	2	1	2	1	NA	3000	NA	NA	Right
17	Merge	PS	4	2	1	2	1	NA	2000	NA	NA	Right
18	Merge	PS	4	2	1	2	1	NA	4000	NA	NA	Right
19	Merge	PS	5	2	1	2	1	NA	2500	NA	NA	Right
20	Merge	PS	5	2	1	2	1	NA	5000	NA	NA	Right
21	Merge	PS	4	3	1	2	1	NA	2000	NA	NA	Right
22	Merge	PS	4	3	1	2	1	NA	4000	NA	NA	Right
23	Merge	PS	5	3	1	2	1	NA	2500	NA	NA	Right
24	Merge	PS	5	3	1	2	1	NA	5000	NA	NA	Right

Highway Building Blocks	Type of Highway Segment	TMT Separation Technique	Number of General Purpose Lanes	Number of TMT lanes	Length of Upstream Segment (miles)	Length of Downstream Segment (miles)	Number of On-Ramp Lanes	Number of Off-Ramp Lanes	Distance from On-Ramp Lane Entrance to TMT Lane(s) Entrance (feet)	Distance from TMT Lane(s) Exit to Off-Ramp Lane Exit (feet)	Length of Two-Sided Weave Segment	Position of Ramp Lane(s) relative to highway lanes
Section 3: Diverge with Pavement Demarcated(PD) TMT Lanes												
25	Diverge	PD	2	1	2	1	NA	1	NA	1000	NA	Right
26	Diverge	PD	3	1	2	1	NA	1	NA	1500	NA	Right
27	Diverge	PD	4	1	2	1	NA	1	NA	2000	NA	Right
28	Diverge	PD	3	2	2	1	NA	1	NA	1500	NA	Right
29	Diverge	PD	4	2	2	1	NA	1	NA	2000	NA	Right
30	Diverge	PD	5	2	2	1	NA	1	NA	2500	NA	Right
31	Diverge	PD	4	3	2	1	NA	1	NA	2000	NA	Right
32	Diverge	PD	5	3	2	1	NA	1	NA	2500	NA	Right
Section 4: Diverge with Physically Separated(PS) TMT Lanes												
33	Diverge	PS	2	1	2	1	NA	1	NA	1000	NA	Right
34	Diverge	PS	2	1	2	1	NA	1	NA	2000	NA	Right
35	Diverge	PS	3	1	2	1	NA	1	NA	1500	NA	Right
36	Diverge	PS	3	1	2	1	NA	1	NA	3000	NA	Right
37	Diverge	PS	4	1	2	1	NA	1	NA	2000	NA	Right
38	Diverge	PS	4	1	2	1	NA	1	NA	4000	NA	Right
39	Diverge	PS	3	2	2	1	NA	1	NA	1500	NA	Right
40	Diverge	PS	3	2	2	1	NA	1	NA	3000	NA	Right
41	Diverge	PS	4	2	2	1	NA	1	NA	2000	NA	Right
42	Diverge	PS	4	2	2	1	NA	1	NA	4000	NA	Right
43	Diverge	PS	5	2	2	1	NA	1	NA	2500	NA	Right
44	Diverge	PS	5	2	2	1	NA	1	NA	5000	NA	Right
45	Diverge	PS	4	3	2	1	NA	1	NA	2000	NA	Right
46	Diverge	PS	4	3	2	1	NA	1	NA	4000	NA	Right
47	Diverge	PS	5	3	2	1	NA	1	NA	2500	NA	Right
48	Diverge	PS	5	3	2	1	NA	1	NA	5000	NA	Right

Highway Building Blocks	Type of Highway Segment	TMT Separation Technique	Number of General Purpose Lanes	Number of TMT lanes	Length of Upstream Segment (miles)	Length of Downstream Segment (miles)	Number of On-Ramp Lanes	Number of Off-Ramp Lanes	Distance from On-Ramp Lane Entrance to TMT Lane(s) Entrance (feet)	Distance from TMT Lane(s) Exit to Off-Ramp Lane Exit (feet)	Length of Two-Sided Weave Segment	Position of Ramp Lane(s) relative to highway lanes
Section 5: Two-Sided Weave Section with Pavement Demarcated(PD) TMT Lanes												
49	Weave	PD	2	1	1	2	1	1	1000	1000	NA	Right
50	Weave	PD	2	1	1	2	1	1	2000	2000	NA	Right
51	Weave	PD	3	1	1	2	1	1	1500	1500	NA	Right
52	Weave	PD	3	1	1	2	1	1	3000	3000	NA	Right
53	Weave	PD	4	1	1	2	1	1	2000	2000	NA	Right
54	Weave	PD	4	1	1	2	1	1	4000	4000	NA	Right
55	Weave	PD	5	1	1	2	1	1	2500	2500	NA	Right
56	Weave	PD	5	1	1	2	1	1	5000	5000	NA	Right
57	Weave	PD	3	2	1	2	1	1	1500	1500	NA	Right
58	Weave	PD	3	2	1	2	1	1	3000	3000	NA	Right
59	Weave	PD	4	2	1	2	1	1	2000	2000	NA	Right
60	Weave	PD	4	2	1	2	1	1	4000	4000	NA	Right
61	Weave	PD	5	2	1	2	1	1	2500	2500	NA	Right
62	Weave	PD	5	2	1	2	1	1	5000	5000	NA	Right
63	Weave	PD	4	3	1	2	1	1	2000	2000	NA	Right
64	Weave	PD	4	3	1	2	1	1	4000	4000	NA	Right
65	Weave	PD	5	3	1	2	1	1	2500	2500	NA	Right
66	Weave	PD	5	3	1	2	1	1	5000	5000	NA	Right

Highway Building Blocks	Type of Highway Segment	TMT Separation Technique	Number of General Purpose Lanes	Number of TMT lanes	Length of Upstream Segment (miles)	Length of Downstream Segment (miles)	Number of On-Ramp Lanes	Number of Off-Ramp Lanes	Distance from On-Ramp Lane Entrance to TMT Lane(s) Entrance (feet)	Distance from TMT Lane(s) Exit to Off-Ramp Lane Exit (feet)	Length of Two-Sided Weave Segment	Position of Ramp Lane(s) relative to highway lanes
Section 6: Two-Sided Weave Section with Physically Separated(PS) TMT Lanes												
67	Weave	PS	2	1	1	2	1	1	1000	1000	NA	Right
68	Weave	PS	2	1	1	2	1	1	2000	2000	NA	Right
69	Weave	PS	3	1	1	2	1	1	1500	1500	NA	Right
70	Weave	PS	3	1	1	2	1	1	3000	3000	NA	Right
71	Weave	PS	4	1	1	2	1	1	2000	2000	NA	Right
72	Weave	PS	4	1	1	2	1	1	4000	4000	NA	Right
73	Weave	PS	5	1	1	2	1	1	2500	2500	NA	Right
74	Weave	PS	5	1	1	2	1	1	5000	5000	NA	Right
75	Weave	PS	3	2	1	2	1	1	1500	1500	NA	Right
76	Weave	PS	3	2	1	2	1	1	3000	3000	NA	Right
77	Weave	PS	4	2	1	2	1	1	2000	2000	NA	Right
78	Weave	PS	4	2	1	2	1	1	4000	4000	NA	Right
79	Weave	PS	5	2	1	2	1	1	2500	2500	NA	Right
80	Weave	PS	5	2	1	2	1	1	5000	5000	NA	Right
81	Weave	PS	4	3	1	2	1	1	2000	2000	NA	Right
82	Weave	PS	4	3	1	2	1	1	4000	4000	NA	Right
83	Weave	PS	5	3	1	2	1	1	2500	2500	NA	Right
84	Weave	PS	5	3	1	2	1	1	5000	5000	NA	Right

Highway Building Blocks	Type of Highway Segment	TMT Separation Technique	Number of General Purpose Lanes	Number of TMT lanes	Length of Highway Segment (miles)
Section 7: Basic Highway Section with Pavement Demarcated(PD) TMT Lanes					
85	Basic	PD	2	1	5
86	Basic	PD	3	1	5
87	Basic	PD	4	1	5
88	Basic	PD	3	2	5
89	Basic	PD	4	2	5
90	Basic	PD	5	2	5
91	Basic	PD	4	3	5
92	Basic	PD	5	3	5

These building blocks were then simulated for a subset of traffic compositions, volumes, and highway speeds. A list of assumed values were temporarily coded for origin-destination volumes and speeds in the base networks, which were replaced later by the real values in the inputs database described in the following section. Measures of effectiveness and simulation parameters were also included in the base networks.

Finally, in order to model appropriate driving behavior and lane change maneuvers on general purpose lanes and TMT lanes, lane closure technique was commonly applied when building the VISSIM base networks. Vehicles in all the base networks were coded separately in to various categories like General Purpose (GP) car, GP truck, GP bus, TMT car, TMT truck, and TMT bus for collecting detailed measures of effectiveness, better display during simulation, and easy review of the models.

[Inputs Preparation](#)

This section explains the VISSIM inputs preparation procedure for building blocks in great detail.

Free Flow Speed (FFS) and Posted Speed Limits

FFSs and posted speed limits have direct impacts on the traffic operational and safety performance of any transportation system. Given the potential of deploying the selected TMTs on arterial corridors which typically have lower posted speed limits compared to highways, three different highway FFSs were modeled for each building block. For each highway speed, on and off-ramp speeds were altered as shown in **Table 3**.

Table 3: Free-flow speeds used in this analysis

FFS (mph)	1	2	3
Highway	50	65	80
On-Ramp	25	25	25
Off-Ramp	30	35	35

Vehicle Types and Traffic Composition

To model various TMTs, the research team defined three classification categories of vehicles for simplicity listed below:

- Passenger Cars and other Two-Axle, four-Tire Single Unit Vehicles
- Buses
- Trucks (Single Unit Trucks and Combination Trucks)

Based on the discussion with DOT project staff, the research team simulated the following traffic compositions for all three vehicle types (cars, trucks and buses) covering the four most popular TMTs – HOV, HOT, TOT, and BRT. There are 16 traffic compositions identified for general purpose lanes and 9 traffic compositions for TMT lanes shown in **Tables 4** and **5** respectively, for every geometric design alternative. In other words, 144 unique traffic composition combinations in total were modeled for each building block.

Table 4: Traffic compositions for General Purpose Lanes

Traffic Composition Index	Cars	Trucks	Buses
1	100%	0%	0%
2	95%	0%	5%
3	90%	0%	10%
4	80%	0%	20%
5	95%	5%	0%
6	90%	5%	5%
7	85%	5%	10%
8	75%	5%	20%
9	90%	10%	0%
10	85%	10%	5%
11	80%	10%	10%
12	70%	10%	20%
13	80%	20%	0%
14	75%	20%	5%
15	70%	20%	10%
16	60%	20%	20%

Table 5: Traffic compositions for TMT Lanes

Traffic Composition Index	Cars	Trucks	Buses	TMT Type
1	0%	100%	0%	Truck Only
2	0%	0%	100%	Bus Only
3	0%	90%	10%	Truck/Bus Only
4	0%	10%	90%	Truck/Bus Only
5	90%	5%	5%	HOV/HOT
6	85%	10%	5%	HOV/HOT
7	70%	5%	25%	HOV/HOT
8	100%	0%	0%	HOV/HOT
9	85%	0%	15%	HOV/HOT

Traffic Volumes and Maximum Throughput

For a single isolated highway lane with a fixed posted speed limit/FFS, roadway grade, unlimited traffic demand, and absence of downstream or upstream bottlenecks, the maximum throughput is primarily dependent upon the traffic composition of entering traffic volumes. The research team identified the traffic output for the maximum throughput of cars, trucks, and buses for a given operating speed listed above and developed the passenger car equivalency for trucks and buses as shown in **Table 6**. Then the maximum vehicular throughput for each building block was calculated using number of highway travel lanes and the derived passenger car equivalencies based on traffic composition and operating speed.

Table 6: Maximum throughput presented in car equivalents

FFS	100% Cars	100% Trucks	Car Equivalency	100% Buses	Car Equivalency
Highway Segment					
35 mph	2,031	1,533	1.33	1,351	1.50
50 mph	2,213	1,512	1.46	1,486	1.49
65 mph	2,334	1,464	1.59	1,396	1.67
80 mph	2,327	1,451	1.60	1,357	1.71
Ramp Segment					
15 mph	1,065	756	1.41	692	1.54
25 mph	1,705	1,232	1.38	1,091	1.56
30 mph	1,884	1,396	1.35	1,223	1.54
35 mph	2,031	1,533	1.33	1,351	1.50

For example, vehicle composition index 2 from **Table 4** is comprised of 95% cars and 5% buses. Using the car equivalencies provided in **Table 6**, the maximum throughput on highway segment for a FFS of 80mph = $2327 \times 95\% \text{ cars} + (2327/1.71) \times 5\% \text{ buses} = 2278.69 = 2279 \text{ vehicles/hour/lane}$

Demand scenario

After establishing the maximum vehicular throughput for a given combination of highway geometry, FFSs, and traffic composition, the research team modeled the following five traffic demand sets. The demands shown in **Table 7** are fractions or multiples of the ascertained maximum throughput to cover the range of under saturated and oversaturated traffic conditions.

Table 7: Five demand scenarios

Index	Percentage
1	0.5
2	0.75
3	0.9
4	1
5	1.2

The research team performed a large number of traffic simulations to ascertain the operational and safety performance of TMTs under very diverse operating conditions. The total number of simulations performed by the research team = 92 building blocks $\times$ 144 traffic compositions $\times$ 5 traffic demands $\times$ 3 FFSs, which is approximately 198,720 individual simulation cases.

Due to the large scale of the simulation assignment, the research team built a base network in VISSIM for each building block scenario and then deployed an automation procedure in Microsoft Office Access to generate the base network variations using all combinations of input variable values. Each simulation run was conducted using a 30-minute (0-1800 seconds) seeding period followed by 1-hour (1800 seconds - 5400 seconds) simulation period.

Measures of Effectiveness (MOE)

The research team collected three traffic operational MOEs and one surrogate safety MOE from each traffic simulation case.

- Data collection points were placed on the appropriate lanes in the end of the network to collect vehicle throughputs and speeds on GP highway segments, TMT highway segments, and ramps.
- ‘Lane changes’ output provided data as to when and where lane changes of vehicles took place. This data is further condensed into total number of lane change maneuvers in each scenario.
- ‘Vehicle record’ output has desired vehicle parameters such as location, speed, acceleration, etc., for individual vehicles at user-defined time steps within the desired time interval. A representative fifteen minutes of data (3600-4500 seconds) was used given the size of this MOE (several gigabits) due to the huge amount of data recorded. This data was used to develop Modified Time To Collision (MTTC) by incorporating the velocity of the leading vehicle, the velocity of the following vehicle, distance between the two vehicles, their respective accelerations and 0.1 seconds of reaction time.

$$MTTC = \frac{D_{(l-f)}}{(V_f + 0.1 \times A_f) - (V_l + 0.1 \times A_l)}$$

$D_{(l-f)}$ - Distance between the leading and following vehicle

V_f - Velocity of the following vehicle

A_f - Acceleration of the following vehicle

V_l - Velocity of the leading vehicle

A_l - Acceleration of the leading vehicle

Model Run Execution

The simulation run time varies mainly with the number of vehicles being processed in the network as every vehicle produces a vehicle trajectory file recording its speed, acceleration, and position at regular time intervals. A building block with more lanes requires more computing power than a similar building block configuration with fewer lanes. Simulation run time also increases with the demand. For example, a demand of 1.2 times the capacity takes much longer than a scenario with under-saturated conditions.

Statistical Analysis

The MOEs obtained from VISSIM models including general purpose throughput and speed, TMT throughput and speed, and MTTC data are statistically analyzed to generate equations that could closely predict the MOEs given the

input values. The conflict index is a summation of all occurrences in the simulation within the simulation period where MTTC does not exceed 3.0 seconds reported in conflicts/mile. Negative binomial distribution has been used for statistical analysis in this project as the variance of the data exceeds the mean. Such data is generally said to be 'overdispersed' and negative binomial regression models show such data with better accuracy⁽¹⁸⁾.

Simulation cases were grouped into sections based upon geometry and TMT implementation style. All the simulation cases under each section were analyzed together, producing more usable and informative results. Based on this analysis, a relative scale was developed for each section in terms of traffic operations and safety.

The building blocks are classified into seven sections listed below. **Table 2** shows the building blocks under each section.

1. Merge Section with Demarcated TMT Lanes.
2. Merge Section with Physically Separated TMT Lanes.
3. Diverge Section with Demarcated TMT Lanes.
4. Diverge Section with Physically Separated TMT Lanes.
5. Two-Sided Weave Section with Demarcated TMT Lanes.
6. Two-Sided Weave Section with Physically Separated TMT Lanes.
7. Basic Highway Section with Demarcated TMT Lanes.

The variables of interest are the throughputs, speeds, and MTTC. While throughput and speed act as a barometer for the traffic operations, conflict index will gauge the number of conflicts that in turn indicates the safety of a scenario. The variables of interest will be referred to as dependent variables and the models inputs like volume inputs, traffic composition, Free Flow Speed, and demand are independent variables in this analysis.

The general functional form of the model assumed for this analysis is shown in **Equation 1**.

$$DV = \exp (\alpha + \beta_1 \times IV_1 + \beta_2 \times IV_2 + \dots + \beta_N \times IV_N) \quad (1)$$

Where,

DV = Dependent Variable

α and $\beta_1 - \beta_N$ = constant and coefficients estimated in the statistical analysis

$IV_1 - IV_N$ = Independent variables (inputs) included in the model

Input variables were added or removed in the process of modeling if it resulted in the following conditions:

- Significantly improved the accuracy of the model.
- The effect of the variable was intuitive (e.g., speed of the vehicles in general purpose lanes decreases with the volume that enters the facility denoted by gpinput)

To model the dependent variable gpspeed, various independent variables like gpinput, gpspeedinput, gpcar, gp trucks, gplane, and onrampinput were used as shown in .

<pre> 1 . use "\\vavna\Projects\38022.00 USDOT Traffic Analysis\tech\VISSIM Building Block > s\StatisticalModel\BB1-8MasterFile.dta" </pre>						
Negative binomial regression			Number of obs		=	17277
			LR chi2(6)		=	28654.37
Dispersion = mean			Prob > chi2		=	0.0000
Log likelihood = -51530.411			Pseudo R2		=	0.2175
gpspeed	Coef.	Std. Err.	z	P> z	[95% Conf. Interval]	
gpinput	-5.15e-06	1.31e-06	-3.92	0.000	-7.73e-06	-2.57e-06
gpspeedinput	.0149952	.0000824	182.07	0.000	.0148338	.0151566
gpcar	.1888641	.0138526	13.63	0.000	.1617135	.2160148
gp trucks	.1140758	.019034	5.99	0.000	.0767699	.1513818
gplane	.0173111	.0025862	6.69	0.000	.0122421	.02238
onrampinput	-.0000331	7.54e-06	-4.38	0.000	-.0000478	-.0000183
_cons	2.930241	.0181764	161.21	0.000	2.894616	2.965866
/lnalpha	-19.88639	20.11396			-59.30902	19.53624

Figure 10: Negative binomial model for general purpose speed from STATA

The independent variables entered the model form as adjustments to the base value of α in **Equation 1**. The parameter values (β 's) indicate the magnitude and direction of the adjustment to the base α value. Using the values in , general purpose (gp) speed for section 1, merge section with demarcated TMT Lanes (building blocks 1-8) can be predicted using **Equation 2**.

$$\text{gpspeed} = \exp(2.93 - 5.15 \times 10^{-6} \times \text{gpinput} + 0.149 \times \text{gpspeedinput} + 0.188 \times \text{gpcar} + 0.114 \times \text{gp trucks} + 0.017 \times \text{gplane} - 3.31 \times 10^{-5} \times \text{onrampinput}) \quad (2)$$

Results and Findings

Predictive Statistical Models

The results from VISSIM for the various building blocks were analyzed using a statistical tool called STATA. The general procedure used for the analysis is described in detail earlier in Statistical Analysis section. This section of the report presents the equations generated for each type of facility to predict the GP throughput, TMT throughput, GP speed, and TMT speed based on inputs such as vehicular input, speed limit, traffic composition, and lane configuration. A general note is that the coefficient of determination (R^2) values for conflict index are low for all the building blocks analyzed and appropriate caution should be exercised in using the estimated values of conflict index as a safety surrogate for guiding transportation policy decisions.

Section 1: Merge Section with Demarcated TMT Lanes

Equations for section 1 were derived based on the simulation results from building blocks 1 to 8.

$$\text{GP Throughput} = \exp (7.344433 + (0.0000751 \times \text{gp input}) + (0.0001941 \times \text{on-ramp input}) + (0.0003443 \times \text{gp speed input}) + (0.1193892 \times \text{gp car}) - (0.0456766 \times \text{gp trucks}) + (0.1379866 \times \text{gp lanes}))$$
$$\text{GP speed} = \exp (2.930241 - (0.00000515 \times \text{gp input}) - (0.0000331 \times \text{on-ramp input}) + (0.0149952 \times \text{gp speed input}) + (0.1888641 \times \text{gp car}) + (0.1140758 \times \text{gp trucks}) + (0.0173111 \times \text{gp lanes}))$$
$$\text{TMT throughput} = \exp (6.339845 + (0.0000522 \times \text{TMT input}) + (0.0003686 \times \text{on-ramp input}) + (0.2714367 \times \text{TMT car}) + (0.0093113 \times \text{TMT trucks}) + (0.4254007 \times \text{TMT lanes}))$$
$$\text{TMT speed} = \exp (3.040779 - (0.0000128 \times \text{TMT input}) + (0.0139507 \times \text{TMT speed input}) + (0.0679383 \times \text{TMT car}) + (0.0247892 \times \text{TMT trucks}) + (0.0432345 \times \text{TMT lanes}))$$
$$\begin{aligned} \text{Conflict Index} = & \exp (15.533300 + (0.0012245 \times \text{gp input}) + (0.0034568 \times \text{on-ramp input}) \\ & + (0.0011456 \times \text{gp speed input}) + (0.1788890 \times \text{gp car}) - (0.125689 \times \text{gp trucks}) \\ & + (0.1577734 \times \text{gp lanes})) + (0.0011568 \times \text{TMT input}) + (0.120009 \times \text{TMT car}) \\ & + (0.0187776 \times \text{TMT trucks}) + (0.07257008 \times \text{TMT lanes})) \end{aligned}$$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed and Conflict Index were 0.90, 0.96, 0.94, 0.92 and 0.57, respectively. This means that the statistical model for GP Throughput explains 90% of the variation in the data given the input values of gp input, on-ramp input, gp speed, gp car percentage, gp truck percentage, and number of gp lanes.

Section 2: Merge Section with Physically Separated TMT Lanes

Equations for section 2 were derived based on the simulation results from building blocks 9 to 24.

$$\text{GP Throughput} = \exp (7.005342 + (0.0000789 \times \text{gp input}) + (0.0002162 \times \text{on-ramp input}) + (0.0004577 \times \text{gp speed input}) + (0.2105656 \times \text{gp car}) - (0.0340895 \times \text{gp trucks}) + (0.1887237 \times \text{gp lanes}))$$

$$\text{GP speed} = \exp (2.889498 - (0.0000114 \times \text{gp input}) + (0.0148123 \times \text{gp speed input}) + (0.2020417 \times \text{gp car}) + (0.1217119 \times \text{gp trucks}) + (0.0296725 \times \text{gp lanes}))$$

$$\text{TMT throughput} = \exp (6.759833 + (0.0002596 \times \text{TMT input}) + (0.2277858 \times \text{TMT car}) + (0.0120461 \times \text{TMT trucks}) + (0.137664 \times \text{TMT lanes}))$$

$$\text{TMT speed} = \exp (3.081612 + (0.0138346 \times \text{TMT speed input}) + (0.0362642 \times \text{TMT car}) + (0.0192662 \times \text{TMT trucks}) + (0.0226781 \times \text{TMT lanes}))$$

$$\begin{aligned} \text{Conflict Index} = \exp (15.33560 + (0.0013235 \times \text{gp input}) + (0.004567 \times \text{on-ramp input}) + (0.0012356 \times \text{gp speed input}) + (0.153566 \times \text{gp car}) - (0.134455 \times \text{gp trucks}) \\ + (0.147789 \times \text{gp lanes})) + (0.00324555 \times \text{TMT input}) + (0.4111222 \times \text{TMT car}) + (0.0186678 \times \text{TMT trucks}) + (0.6957018 \times \text{TMT lanes})) \end{aligned}$$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed and Conflict Index were 0.93, 0.96, 0.88, 0.92 and 0.64, respectively.

Section 3: Diverge Section with Demarcated TMT Lanes

Equations for section 3 were derived based on the simulation results from building blocks 25 to 32.

$$\text{GP Throughput} = \exp (6.560748 + (0.000082 \times \text{gp input}) + (0.0003398 \times \text{off-ramp input}) - (0.0043354 \times \text{gp speed input}) + (0.20277 \times \text{gp car}) - (0.080046 \times \text{gp trucks}) + (0.2901621 \times \text{gp lanes}))$$

$$\text{GP speed} = \exp (3.041545 - (0.0000215 \times \text{gp input}) + (0.0134595 \times \text{gp speed input}) + (0.1442662 \times \text{gp car}) + (0.0409929 \times \text{gp lanes}))$$

$$\text{TMT throughput} = \exp (6.433743 + (0.0005427 \times \text{TMT input}) - (0.0014471 \times \text{TMT speed input}) + (0.1388437 \times \text{TMT car}) + (0.033115 \times \text{TMT trucks}) - (0.02369 \times \text{TMT lanes}))$$

$$\text{TMT speed} = \exp (3.100351 + (0.0139135 \times \text{TMT speed input}) + (0.0354165 \times \text{TMT car}))$$

$$\text{Conflict Index} = \exp (14.116720 + (0.00112999 \times \text{gp input}) + (0.004567 \times \text{off-ramp input}) + (0.0010009 \times \text{gp speed input}) + (0.167790 \times \text{gp car}) - (0.109889 \times \text{gp trucks}) + (0.1676123 \times \text{gp lanes})) + (0.00106778 \times \text{TMT input}) + (0.400223 \times \text{TMT car}) + (0.0198900 \times \text{TMT trucks}) + (0.708887 \times \text{TMT lanes}))$$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed and Conflict Index were 0.92, 0.89, 0.70, 0.89 and 0.55, respectively.

Section 4: Diverge Section with Physically Separated TMT Lanes

Equations for section 3 were derived based on the simulation results from building blocks 33 to 48.

$$\text{GP Throughput} = \exp (6.780723 + (0.000097 \times \text{gp input}) + (0.0003577 \times \text{off-ramp input}) - (0.004002 \times \text{gp speed input}) + (0.20200 \times \text{gp car}) - (0.079912 \times \text{gp trucks}) + (0.3001234 \times \text{gp lanes}))$$

$$\text{GP speed} = \exp (3.052127 - (0.0000220 \times \text{gp input}) + (0.014325 \times \text{gp speed input}) + (0.144433 \times \text{gp car}) + (0.0410034 \times \text{gp lanes}))$$

$$\text{TMT throughput} = \exp (6.517352 + (0.0005512 \times \text{TMT input}) - (0.0014523 \times \text{TMT speed input}) + (0.139126 \times \text{TMT car}) + (0.034222 \times \text{TMT trucks}) + (0.2402 \times \text{TMT lanes}))$$

$$\text{TMT speed} = \exp (3.10245 + (0.0139567 \times \text{TMT speed input}) + (0.0360007 \times \text{TMT car}) + (0.0642688 \times \text{TMT lanes}))$$

$$\text{Conflict Index} = \exp (14.00910 + (0.0014007 \times \text{gp input}) + (0.0020917 \times \text{off-ramp input}) + (0.0011002 \times \text{gp speed input}) + (0.45899 \times \text{gp car}) - (0.122451 \times \text{gp trucks}))$$

$$+ (0.598984 \times \text{gp lanes})) + (0.0020094 \times \text{TMT input}) + (0.488922 \times \text{TMT car}) + (0.0100612 \times \text{TMT trucks}) + (0.6456023 \times \text{TMT lanes}))$$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed, and Conflict Index were 0.91, 0.92, 0.74, 0.90 and 0.51, respectively.

Section 5: Two-Sided Weave Section with Demarcated TMT Lanes

Equations for section 3 were derived based on the simulation results from building blocks 49 to 66.

$$\text{GP Throughput} = \exp (7.78889 + (0.0001661 \times \text{gp input}) + (0.0010008 \times \text{on-ramp input}) + (0.0003213 \times \text{off-ramp input}) + (0.0006521 \times \text{gp speed input}) + (0.110006 \times \text{gp car}) - (0.0422234 \times \text{gp trucks}) + (0.1350076 \times \text{gp lanes}))$$

$$\text{GP speed} = \exp (2.980004 - (0.00001009 \times \text{gp input}) - (0.0000887 \times \text{on-ramp input}) - (0.0000787 \times \text{off-ramp input}) + (0.0148887 \times \text{gp speed input}) + (0.1889998 \times \text{gp car}) + (0.112356 \times \text{gp trucks}) + (0.0179111 \times \text{gp lanes}))$$

$$\text{TMT throughput} = \exp (6.37834 + (0.0001003 \times \text{TMT input}) + (0.0003876 \times \text{on-ramp input}) + (0.0000106 \times \text{off-ramp input}) + (0.2714289 \times \text{TMT car}) + (0.0093299 \times \text{TMT trucks}) + (0.1355432 \times \text{TMT lanes}))$$

$$\text{TMT speed} = \exp (3.05112 - (0.0000787 \times \text{TMT input}) + (0.0140005 \times \text{TMT speed input}) + (0.0681003 \times \text{TMT car}) + (0.0251234 \times \text{TMT trucks}) + (0.0433445 \times \text{TMT lanes}))$$

$$\text{Conflict Index} = \exp (14.000891 + (0.0015556 \times \text{gp input}) + (0.007778 \times \text{on-ramp input}) + (0.048890 \times \text{off-ramp input}) + (0.0013357 \times \text{gp speed input}) + (0.123766 \times \text{gp car}) - (0.167889 \times \text{gp trucks}) + (0.167778 \times \text{gp lanes})) + (0.0056678 \times \text{TMT input}) + (0.4008987 \times \text{TMT car}) + (0.0167612 \times \text{TMT trucks}) + (0.1677682 \times \text{TMT lanes}))$$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed and Conflict Index were 0.88, 0.91, 0.75, 0.88 and 0.50, respectively.

Section 6: Two-Sided Weave Section with Physically Separated TMT Lanes

Equations for section 3 were derived based on the simulation results from building blocks 67 to 84.

$$\text{GP Throughput} = \exp (7.80041 + (0.0001902 \times \text{gp input}) + (0.0010033 \times \text{on-ramp input}) + (0.0003452 \times \text{off-ramp input}) + (0.0004567 \times \text{gp speed input}) + (0.110321 \times \text{gp car}) - (0.0420007 \times \text{gp trucks}) + (0.4350004 \times \text{gp lanes}))$$

$$\text{GP speed} = \exp (2.991002 - (0.00000899 \times \text{gp input}) - (0.0000991 \times \text{on-ramp input}) - (0.0000504 \times \text{off-ramp input}) + (0.0148337 \times \text{gp speed input}) + (0.1888767 \times \text{gp car}) + (0.112512 \times \text{gp trucks}) + (0.0175341 \times \text{gp lanes}))$$

$$\text{TMT throughput} = \exp (6.5678 + (0.0001231 \times \text{TMT input}) + (0.2712234 \times \text{TMT car}) + (0.0094010 \times \text{TMT trucks}) + (0.4353788 \times \text{TMT lanes}))$$

$$\text{TMT speed} = \exp (3.07781 - (0.0001009 \times \text{TMT input}) + (0.0140034 \times \text{TMT speed input}) + (0.065009 \times \text{TMT car}) + (0.0250017 \times \text{TMT trucks}) + (0.0433765 \times \text{TMT lanes}))$$

$$\text{Conflict Index} = \exp (14.000203 + (0.0016568 \times \text{gp input}) + (0.006654 \times \text{on-ramp input}) + (0.030099 \times \text{off-ramp input}) + (0.0012322 \times \text{gp speed input}) + (0.100044 \times \text{gp car}) - (0.164789 \times \text{gp trucks}) + (0.134555 \times \text{gp lanes}) + (0.0043415 \times \text{TMT input}) + (0.3944561 \times \text{TMT car}) + (0.0143135 \times \text{TMT trucks}) + (0.0998914 \times \text{TMT lanes}))$$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed and Conflict Index were 0.89, 0.93, 0.72, 0.89 and 0.49, respectively.

Section 7: Basic Highway Section with Demarcated TMT Lanes

Equations for section 3 were derived based on the simulation results from building blocks 85 to 92.

$$\text{GP Throughput} = \exp (7.485626 + (0.0001677 \times \text{gp input}) - (0.0603546 \times \text{gp trucks}) + (0.0407882 \times \text{gp lanes}))$$

$$\text{GP speed} = \exp (2.843833 - (0.000016 \times \text{gp input}) + (0.0153684 \times \text{gp speed input}) + (0.2067352 \times \text{gp car}) + (0.1384142 \times \text{gp trucks}) + (0.0391858 \times \text{gp lanes}))$$

$$\text{TMT throughput} = \exp (6.601387 + (0.0004082 \times \text{TMT input}) + (0.0648832 \times \text{TMT car}) + (0.0394483 \times \text{TMT lanes}))$$

$$\text{TMT speed} = \exp (3.010196 - (0.0000227 \times \text{TMT input}) + (0.0142639 \times \text{TMT speed input}) + (0.0625485 \times \text{TMT car}) + (0.0284007 \times \text{TMT trucks}) + (0.0660769 \times \text{TMT lanes}))$$

Conflict Index = $\exp (12.17878 + (0.0010088 \times \text{gp input}) + (0.0000884 \times \text{gp speed input}) + (0.103445 \times \text{gp car}) - (0.134551 \times \text{gp trucks}) + (0.104343 \times \text{gp lanes}) + (0.0013441 \times \text{TMT input}) + (0.1142261 \times \text{TMT car}) + (0.009983 \times \text{TMT trucks}) + (0.0766641 \times \text{TMT lanes}))$

The coefficient of determination (R^2) for GP Throughput, GP speed, TMT throughput, TMT speed, and Conflict Index are 0.83, 0.88, 0.77, 0.85 and 0.67, respectively.

Application of Equations

In this section, specific examples are provided to illustrate the process of applying statistical equations that have been listed in the previous section.

Background

A transportation agency has a freeway section with four general purpose lanes and is investigating the consequences of converting the left-most general purpose lane to a pavement-demarcated managed lane. The TMT strategies under consideration are HOV, BRT and TOT. Given the roadway geometrics, two freeway sections are analyzed below:

- a) Closed segment with Demarcated TMT Lanes of 2.0 mile length
- b) Merge Section with Demarcated TMT Lanes of 1.5 mile length

The traffic volumes and compositions for each of the alternatives that been held constant. However, appropriate assumptions have been made to redistribute traffic between the GP lanes and managed lanes for the TMT strategies.

Data Elements for Freeway Section A:

Scenario - All GP Lanes

Number of GP Lanes – 4

GP Lanes Truck Percentage – 4%

GP Lanes Bus Percentage – 6%

GP Lanes Car Percentage – 90%

GP Lanes Input Volume – 7000 veh/hr

GP Lanes Posted Speed Limit – 55 mph

Scenario - HOV Lanes

Number of GP Lanes – 3

GP Lanes Truck Percentage – 5%
GP Lanes Bus Percentage – 0%
GP Lanes Car Percentage – 95%
GP Lanes Input Volume – 5980 veh/hr
GP Lanes Posted Speed Limit – 55 mph
Number of HOV Lanes – 1
HOV Lanes Truck Percentage – 0%
HOV Lanes Bus Percentage – 41%
HOV Lanes Car Percentage – 59%
HOV Lanes Input Volume – 1020 veh/hr
HOV Lanes Posted Speed Limit – 55 mph

Scenario - BRT Lanes

Number of GP Lanes – 3
GP Lanes Truck Percentage – 4%
GP Lanes Bus Percentage – 0%
GP Lanes Car Percentage – 96%
GP Lanes Input Volume – 6580 veh/hr
GP Lanes Posted Speed Limit – 55 mph
Number of BRT Lanes – 1
BRT Lanes Truck Percentage – 0%
BRT Lanes Bus Percentage – 100%
BRT Lanes Car Percentage – 0%
BRT Lanes Input Volume – 420 veh/hr
BRT Lanes Posted Speed Limit – 55 mph

Scenario - TOT Lanes

Number of GP Lanes – 3
GP Lanes Truck Percentage – 0%
GP Lanes Bus Percentage – 6%
GP Lanes Car Percentage – 94%
GP Lanes Input Volume – 6720 veh/hr
GP Lanes Posted Speed Limit – 55 mph
Number of TOT Lanes – 1
TOT Lanes Truck Percentage – 100%
TOT Lanes Bus Percentage – 0%
TOT Lanes Car Percentage – 0%
TOT Lanes Input Volume – 280 veh/hr
TOT Lanes Posted Speed Limit – 55 mph

Model Results for Freeway Section A:

Using the statistical equations from Section 7 (Basic Highway Section with Demarcated TMT Lanes), we get the following results:

Scenario - All GP Lanes

GP Thruput – 6770 veh/hr

GP Speed – 50.7 mph

CI = 377,972,674 conflicts/mile

Scenario - HOV Lanes

GP Thruput – 5703 veh/hr

GP Speed – 52.1 mph

HOV Thruput – 1020 veh/hr

HOV Speed – 48.2 mph

Total Thruput = 6723 veh/hr

CI = 556,086,435 conflicts/mile

Scenario - BRT Lanes

GP Thruput – 6309 veh/hr

GP Speed – 51.6 mph

HOV Thruput – 420 veh/hr

HOV Speed – 47.0 mph

Total Thruput = 6729 veh/hr

CI = 425,628,991 conflicts/mile

Scenario - TOT Lanes

GP Thruput – 6475 veh/hr

GP Speed – 51.0 mph

TOT Thruput – 280 veh/hr

TOT Speed – 48.6 mph

Total Thruput = 6755 veh/hr

CI = 407,600,786 conflicts/mile

Interpretation of Results for Freeway Section A

For Section A of the freeway, all four strategies perform similarly in terms of vehicular throughput and vehicular travel speeds. However, the estimated number of conflicts is higher for the three TMTs when compared to the alternative with GP lanes only. One explanation for this result could be the friction between vehicular types in the GP lanes and managed lanes for the TMT

strategies, given the fact that the separation is only based on pavement demarcation. Among the three TMTs, the TOT strategy has the lowest conflict index. This may be due to the low truck volume in the managed lane for the TOT strategy versus higher vehicular volumes in the managed lanes for the HOV and BRT strategies.

Data Elements for Freeway Section B:

Scenario - All GP Lanes

Number of GP Lanes – 4
GP Lanes Truck Percentage – 4%
GP Lanes Bus Percentage – 6%
GP Lanes Car Percentage – 90%
GP Lanes Input Volume – 7000 veh/hr
GP Lanes Posted Speed Limit – 55 mph
On-Ramp Input Volume – 500 veh/hr

Scenario - HOV Lanes

Number of GP Lanes – 3
GP Lanes Truck Percentage – 5%
GP Lanes Bus Percentage – 0%
GP Lanes Car Percentage – 95%
GP Lanes Input Volume – 5980 veh/hr
GP Lanes Posted Speed Limit – 55 mph
Number of HOV Lanes – 1
HOV Lanes Truck Percentage – 0%
HOV Lanes Bus Percentage – 41%
HOV Lanes Car Percentage – 59%
HOV Lanes Input Volume – 1020 veh/hr
HOV Lanes Posted Speed Limit – 55 mph
On-Ramp Input Volume – 500 veh/hr

Scenario - BRT Lanes

Number of GP Lanes – 3
GP Lanes Truck Percentage – 4%
GP Lanes Bus Percentage – 0%
GP Lanes Car Percentage – 96%
GP Lanes Input Volume – 6580 veh/hr
GP Lanes Posted Speed Limit – 55 mph
Number of BRT Lanes – 1

BRT Lanes Truck Percentage – 0%
BRT Lanes Bus Percentage – 100%
BRT Lanes Car Percentage – 0%
BRT Lanes Input Volume – 420 veh/hr
BRT Lanes Posted Speed Limit – 55 mph
On-Ramp Input Volume – 500 veh/hr

Scenario - TOT Lanes

Number of GP Lanes – 3
GP Lanes Truck Percentage – 0%
GP Lanes Bus Percentage – 6%
GP Lanes Car Percentage – 94%
GP Lanes Input Volume – 6720 veh/hr
GP Lanes Posted Speed Limit – 55 mph
Number of TOT Lanes – 1
TOT Lanes Truck Percentage – 100%
TOT Lanes Bus Percentage – 0%
TOT Lanes Car Percentage – 0%
TOT Lanes Input Volume – 280 veh/hr
TOT Lanes Posted Speed Limit – 55 mph
On-Ramp Input Volume – 500 veh/hr

Model Results for Freeway Section B:

Using the statistical equations from Section 2 (Merge Section with Demarcated TMT Lanes), we get the following results:

Scenario - All GP Lanes

GP Thruput – 5674 veh/hr
GP Speed – 51.7 mph
CI = 387,613,342,599 conflicts/mile

Scenario - HOV Lanes

GP Thruput – 4606 veh/hr
GP Speed – 51.7 mph
HOV Thruput – 1020 veh/hr
HOV Speed – 48.33 mph
Total Thruput = 5626 veh/hr
CI = 95,765,278,879 conflicts/mile

Scenario - BRT Lanes

GP Thruput – 4822 veh/hr

GP Speed – 51.5 mph

HOV Thruput – 420 veh/hr

HOV Speed – 46.8 mph

Total Thruput = 5242 veh/hr

CI = 199,916,663,483 conflicts/mile

Scenario - TOT Lanes

GP Thruput – 4871 veh/hr

GP Speed – 51.1 mph

TOT Thruput – 280 veh/hr

TOT Speed – 48.1 mph

Total Thruput = 5151 veh/hr

CI = 237,724,110,228 conflicts/mile

Interpretation of Results for Freeway Section B

For Section B of the freeway, GP lanes only and HOV strategies perform better than TOT and BRT strategies in terms of vehicular throughput. This seems intuitive since the number of vehicles on the managed lanes is much lower for BRT and TOT strategies compared to the number of vehicles on the managed lanes for HOV strategy and the number of equivalent vehicles on the GP lanes for the GP lanes only strategy. Given the lower vehicular volume on the managed lanes for TOT and BRT strategies, there is higher vehicular volume redistributed on the GP lanes for the TOT and BRT strategies. Because of the higher volumes on the GP lanes for the TOT and BRT strategies, there is significant friction with the on-ramp merging traffic leading to a drop in vehicular throughput when compared with the vehicular throughput for the HOV strategy.

The HOV strategy has the lowest number of conflicts, followed by BRT, TOT and GP lanes only strategies. Because the HOV strategy has better vehicular distribution between the managed lanes and GP lanes, there is less friction with the merging of on-ramp traffic from the right onto the GP lanes. With the TOT and BRT strategies, majority of the on-ramp traffic have to merge with the relatively higher traffic volumes on existing GP lanes. This creates added friction when compared to the HOV strategy. In case of the GP lanes only strategy, all the on-ramp traffic merges with the existing traffic on all four lanes creating major friction. This may explain the reason behind the highest value of conflict index noted for the GP lanes only strategy when compared to other TMTs.

General Guidance on Interpretation of Results

The statistical models developed are expected to help transportation engineers and planners analyze and understand the operational performance and relative level of safety on different freeway sections under varying traffic volume conditions. Secondly, the conflict index is only an estimate of the aggregate number of conflicts predicted for each of the strategies. In the scope of this project, no co-relation has been established between the conflict index and resultant crashes. Additionally, the conflicts have not been segregated based on the level of severity of the conflict (e.g., intuitively, the collision of a car and truck may seem to have a higher probability of severity than a crash involving two cars with all other parameters being the same). Therefore, the conflict index is limited to the number of possible conflicts estimated between the different strategies being analyzed and may not offer a direct co-relation to the relative crash safety of the underlying strategies. The authors suggest appropriate caution be exercised in using the estimated values of conflict index.

Recommendations for Future Research

In many aspects, this research study has been a pioneer in the field of using microscopic simulation analysis to predict relative safety performance of different TMTs. This study was the first attempt to analyze the utility of microscopic traffic simulation models in modeling vehicular conflicts and to use that information to formulate statistical prediction models that can be used by practitioners for better decision making. Some important assumptions used in this study are listed in this section to expose weakness in the current models developed, identify knowledge gaps and provide direction for future research efforts.

Freeway Building Blocks

- A simplistic assumption was made that a freeway can be broken down into its constituting parts and thereby analyzed in smaller sections called building blocks. Detailed description on construction of building blocks can be found in the sub-section “Building Blocks” under section “TMTs Simulation”. The limitation of this approach is the fact that continuity of the freeway system is not taken into account by breaking it into parts. Specifically, if one section of the freeway will experience heavy congestion

resulting in significant reduction in vehicular throughputs, those effects are not transferred to the adjacent building block sections on the freeway.

- All on-ramps and off-ramps have been assumed to enter or exit on the right side of the freeway. Left-side ramp entries and exits were not modeled and evaluated.
- All on-ramps and off-ramps were modeled as single-lane ramps. The impacts of alternate ramp configurations (e.g. dual-lane ramps) should be investigated in future research.
- All the building blocks in the freeway sections did not have any major changes to the horizontal roadway profile. In other words, curved roadway sections and resultant impacts were not modeled.
- Values for many geometric features within building blocks (e.g., length of acceleration lane, etc.) were assumed to be constant and accordingly analyzed. This limits the relevancy of results to freeway sections with building blocks having geometric characteristics similar to what was analyzed.

Microscopic Simulation

- The microscopic simulation assumed absence of cross-entry and cross-exit (i.e., shuffling between the GP lanes and managed lanes) between vehicles in the managed lanes and GP lanes on closed freeway sections with pavement demarcation. This may be contrary to real-world experience where cross-entry and cross-exit do occur between managed lanes and GP lanes on closed freeway sections with pavement demarcation.
- As part of this research, calibration of only one parameter “vehicular inattention” in VISSIM was used to attempt to capture the effects of driver errors in real-world environments and reproduce them in rigid microscopic simulation environments. In future, multiple parameters with better accuracy in VISSIM and/or other microscopic simulation software may be available to accurately capture the effects of driver errors in real-world environments and reproduce them in rigid microscopic simulation environments.
- The default vehicular characteristics in VISSIM (e.g., power, acceleration, etc.) were used in the analysis. Future research may be helpful to analyze the sensitivity of results to changes in vehicular characteristics.
- All simulation cases were run for 3,600 seconds after seeding them for 1,800 seconds. Future research may be helpful to analyze the sensitivity of analysis results to simulation times beyond 3,600 seconds.

Statistical Modeling

- Though this study had a large sample size for development of statistical models, future research may be helpful in expanding the sample size of simulation cases in developing statistical models.
- The goodness of fit for statistical models predicting conflict index could be improved with future research.
- Future statistical models could investigate the inclusion of conflict severity as part of the conflict index.
- Future statistical models could investigate the relationship of conflicts and conflict severity to actual crashes.

Summary and Conclusions

Along with quantifying operational performance, this research study has for the first time quantified the safety performance of different Traffic Management Techniques relative to each other through the variable conflict index. One of the key features of the analysis methodology is its foundation in microscopic traffic simulation. Compared to a foundation based on theoretical traffic flow theory equations, that foundation is superior in its ability to be sensitive to changes in traffic demand and other geometric and operational parameters. Agencies can use regularly available traffic input data to estimate the relative operational performance and safety impacts of different TMTs.

As stated earlier, each managed lane strategy is intrinsically defined by the traffic volumes and vehicular compositions. In other words, the difference between the HOT and HOV strategies are fundamentally defined by the traffic volumes and vehicular compositions in those strategies. The value of statistical equations comparing managed lanes to non-managed lanes is fully harnessed by providing reasonable traffic and geometric inputs. No overarching generalization in trends of different TMTs were visible in the scope of this research. Each case is unique and has to be individually analyzed to understand the estimated implications. The estimates of conflict index may help add a safety perspective along with traffic operations in evaluating potential managed lane strategies and comparing managed lanes with non-managed lane strategies. This study has established a potential framework for future studies in the domain of surrogate safety modeling and analysis using microscopic simulation.

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