CALIBRATION AND VALIDATION OF SHAKER AND TNCC FOR DEPLOYMENT ON FLORIDA'S TURNPIKE (BD 548-25)

FINAL REPORT

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16. Abstract

The primary objective of this project was to develop TNCC and SHAKER, for use by the Florida's Turnpike Enterprise (FTE) to estimate the capacities of the toll plazas. Together, these packages have the ability to optimize the toll plaza lane configurations in terms of capacity and delays. TNCC and SHAKER were calibrated to replicate real life toll facility traffic conditions. An extensive field study on the FTE network was conducted to determine the parameters affecting toll lane capacities. Collected data included traffic characteristics, vehicle characteristics, and toll plaza characteristics. SHAKER can assist FTE engineers to design and alter FTE toll plazas' lane configuration to optimize their throughput and provide the optimized lane configuration of toll plazas in terms of capacities and delays under lane closures and maintenance activities. A secondary objective of this project was to demonstrate the practical application of the Decision Support System, which shows the bottleneck levels on all highway segments and toll plazas.

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EXECUTIVE SUMMARY

A great deal of research has been conducted on Central Florida toll roads to better understand the characteristics of tolling operations. Presently, there is no acceptable standard to compute the capacity on a highway segment in which a toll facility is located. Therefore, it is difficult for planners to design these facilities based on sudden traffic demand and for operators to respond intelligently to the changing traffic conditions at the plaza. Toll Network Capacity Calculator (TNCC) and SHAKER models were developed by the University of Central Florida (UCF) to integrate these capabilities. This project proposed two packages, TNCC and SHAKER, for use by the Florida's Turnpike Enterprise (FTE) to estimate the capacities of the toll plazas. Together, these packages have the ability to optimize the toll plaza lane configurations in terms of capacity and delays.

TNCC computes the plaza capacity and it is integrated into the SHAKER program. In this project, the use of the toll plaza queuing model SHAKER was calibrated to replicate real life toll facility traffic conditions. An extensive field study on the Florida's Turnpike Enterprise network was conducted to determine the parameters affecting toll lane capacities. Data was collected and extracted at toll locations with different configurations and pricing. Collected data includes traffic characteristics, vehicle characteristics, and toll plaza characteristics. From this data, periods of constant queuing were observed and from those periods, factors such as demand, throughput, service-time, etc. were extracted. Using the extracted parameters, SHAKER was then calibrated and validated to estimate the capacity of four different toll plazas along the Florida's Turnpike system.

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LIST OF ACRONYMS

AADT	Average Annual Daily Traffic
AAWT	Average Annual Weekday Traffic
ACM	Automatic Coin Machine
AVI	Automatic Vehicle Identification
DSS	Decision Support System
ETC	Electronic Toll Collection
FTE	Florida’s Turnpike Enterprise
HCM	Highway Capacity Manual
LOS	Level of Service
MOE	Measure of Effectiveness
NQMT	No Queue Maximum Throughput
SAIC	Science Application and International Corporation
SR	State Road
TNCC	Toll Network Capacity Calculator
TPASS	Toll Plaza Animation/Simulation System
UCF	University of Central Florida
UMass	University of Massachusetts
VPH	Vehicles per hour

1. INTRODUCTION

The major highways in Central Florida are Interstate-4, State Road (SR) 408, SR 417, SR 528, SR 429, and Florida's Turnpike. Of these major highways, all but I-4 are toll restricted facilities. The FTE states that "tolls are the most cost-effective way to directly link user fees to specific roads. These roads are self-supporting; freeing highway tax money for other needed road projects" (*1*). Through their repetitive implementation it is evident that toll collection roadways play an important role in traffic throughout Central Florida. Toll collecting roadways are unique in nature because they force a percentage of users to make periodic stops to pay tolls while the other users own electronic toll collection (ETC) devices that allow them to pay without making a complete stopping maneuver. With toll facilities, each payment type has a specific lane that the driver uses to correctly pay for his or her toll. Common lane payment types along most toll roads consist of one, or a combination of, the following: manually collected, Automatic Coin Machine (ACM), reduced speed ETC, and high speed ETC. A great deal of research has been conducted at Central Florida toll plazas to better understand the characteristics of the tolling operation. In addition, researchers have developed programs and simulation models to aid in understanding tolling elements such as the throughput, capacity, level of service, optimum lane configuration, etc. In this report, TNCC and the use of the toll plaza queuing model SHAKER (named after a shaking like process used to assign vehicles to lanes to determine optimum lane configuration) is calibrated to replicate field observed toll facility traffic conditions. TNCC calculates the capacity of the toll plaza using physics equations to be used by the SHAKER program. SHAKER was developed by the Center of Advanced Transportation Systems Simulation at the University of Central Florida (CATSS/UCF) to be used as an operational tool that specifically applies to toll plazas. SHAKER *(2)* is a macroscopic deterministic queuing model based on classical physics equations that determine a plaza's maximum hourly throughput by using the capacities calculated by TNCC and assigning vehicles to particular lane groups based on various queue conditions.

1.1. Research Purpose

In 2006, it was reported that one of the most traveled toll plazas in Central Florida exceeds an Average Annual Weekday Traffic (AAWT) greater then 125,000 vehicles (*3*). It is also estimated that during peak conditions 60 to 70% of users make use of their electronics toll collector to pay the toll. This means that 30-40% of all passing traffic at the toll plazas must make a complete stop in the middle of their travel to pay the toll. It is expected that traffic complications and backups will arise when several drivers experience this forced bottleneck. The relatively large number of drivers using the manual and automatic lanes and the increasing bottlenecks during peak hours motivates engineers and planners to look into possible countermeasures to mitigate delays, queues and high concentration of automobile emissions at toll facilities *(4)*. One such opportunity resulting from this need is the conception of traffic modeling and simulation.

In the past, it was difficult for engineers and planners to determine how particular toll plaza lane configurations would affect the traffic conditions without physically disturbing the current facility in the field. Toll plaza configuration testing in the field would be time consuming and site specific. Also, changing the toll scenarios may be confusing to daily commuters, thus causing extra delays to the motorists. In addition to increasing driver frustration, delays can potentially cause added queues and high concentrations of dangerous automobile emissions (*4*). To counter toll plaza design complications, simulation models have been developed because they have the ability to test alternative designs and plaza characteristics without the complications of actual site testing. If calibrated correctly, SHAKER is one model that potentially has this ability. Yet, before different design configurations can be modeled in SHAKER, it is important to know which factors influence toll plaza capacity to calibrate the software accordingly. The necessary calibration of any simulation model, whether macroscopic, or microscopic leads to the overall purpose of this research, which is to examine the entire calibration process of the SHAKER model. Using realistic data for calibration gives future users of the model the ability to adjust single parameters if the toll elements vary at different toll plazas or are altered during non-normal traffic situations. Therefore, upon completion of the calibration, the SHAKER results will be compared to real data so as to investigate the effectiveness and efficiency of the program's ability to replicate real life toll facility traffic conditions. Major operational benefits resulting from developing these models are to simulate and evaluate how traffic conditions will change when demand increases, when and if queues increase while a lane is closed due to maintenance or construction, the impact of constructing additional lanes, and determining whether or not the best lane type configuration is currently implemented.

1.2. Research Objectives

The objectives of the proposed project can be summarized as the following:

1. Provide a calibrated and validated tool that calculates the capacity of the toll plazas operated by Florida's Turnpike Enterprise (FTE) and accordingly estimates delays under different traffic volumes (demand).
    - Using collected 2007-2008 toll plaza data to develop default values for driver characteristics
    - Using data analysis from the previous step, calibrate the TNCC and SHAKER programs to replicate observed capacity and throughput values
    - Verify the results and performance of the SHAKER model for existing conditions and hypothetical scenarios
2. Develop an algorithm (additional function) to assist FTE engineers:
    - Design and alter FTE toll plazas' lane configuration to **optimize** their throughput
    - Provide the **optimized** lane configuration of toll plazas in terms of capacities and delays under lane closures and maintenance activities
    - Provide the **optimized** lane configuration of toll plazas in terms of capacities and delays during special events (e.g. athletic events, car races, etc.)
3. Provide a visual display, in DSS, of a portion of the FTE system, which shows the bottleneck levels on all highway segments and toll plazas.

2. LITERATURE REVIEW

This review of previous research covers multiple aspects of toll plaza operations. The first section covers previous exclusive toll plaza models and calibration techniques that have been developed to better understand toll plaza operations through the use of simulation. The second portion consists of a discussion regarding plaza capacity studies that have been conducted and their contribution to the field. The next two sections are based primarily on the SHAKER model. The first segment covers the methodology that SHAKER uses to calculate the throughput and capacity. The second segment gives a brief overview on how to use the SHAKER software and discusses some of the software's potential.

2.1. Toll Plaza Simulation Models and Calibration

2.1.1. Microsimulation Model Calibration

Traffic simulation software has become increasingly popular as a traffic analysis tool used in transportation analyses. One reason for the increase in simulation use is the need to model and analyze the operation of complex transportation systems under congested conditions. There are microscopic and macroscopic traffic flow models for simulation. Microscopic simulation models use numerous independent parameters to replicate traffic control operation and traffic flow characteristics by modeling the state (position, velocity, and sometimes additional information) of every vehicle. In contrast, macroscopic models define variables of state in terms of averages, such as the average speed, volume, and density that describe the system or parts of the system. Before using macro- and micro- simulation models they inevitably must first be calibrated before they can accurately estimate traffic conditions. Model calibration is defined as the process by which the individual components of the simulation model are adjusted or tuned so that the model will accurately represent field measured or observed traffic conditions *(5)*.

Calibration is necessary for these models because no single model can be expected to be equally accurate for all possible traffic conditions *(6)*. In general, microscopic simulation models contain default values for each variable, but they also suggest that users input a range of values for the parameters that better suit their unique condition. Changing these parameters for calibration should only be done when based on field measured conditions and all changes can be justified and are defensible by the user *(7)*. The difficulty in basing calibration on field observations is that many of the parameters used in simulation models are difficult or sometimes impossible to measure in the field, yet they can substantially impact on the model's performance. Park and Schneeberger expressed difficulty in observing particular variables, such as: start-up lost time, queue discharge rate, car-following sensitivity factors, time to complete lane changes, acceptable gaps, and driver's familiarity with the network *(7)*. Hellinga *(8)* describes the basic guidelines of a seven component calibration, but provides no direct procedure for conducting calibration and validation. The steps for calibration are listed in order as:

1. Defining study goals and objectives
2. Determining required field data
3. Choosing measures of performance
4. Establishing evaluation criteria
5. Network representation
6. Driver routing behavior
7. Evaluation of model outputs

Calibration is often referred to as an art, an inexact science, so not all calibration steps will have specific technical significance. That is why Park and Schneeberger also indicate that when using microscopic simulation models the importance of user visualization cannot be over emphasized. The goal of the microscopic simulation model is to represent field conditions as closely as possible. Therefore by nature a model cannot be considered calibrated if the animations are not visually realistic. Even if a parameter set produces statistically acceptable results but the animations are not realistic then the model cannot be considered calibrated *(7)*.

2.1.2. Exclusive Toll Plaza Models

One of the first animated toll plaza simulation software, which was designed in 1992, was the Toll Plaza Animation/Simulation System (TPASS) *(9)*. TPASS is a discrete-event toll plaza model developed by Science Application and International Corporation (SAIC). TPASS allows the user to experiment with various toll plaza configurations and traffic characteristics in order to determine the resulting queuing, wait times, and toll revenue. This model has a simulation and animation capability, which provides the user to make quantitative comparisons of experimental data sets with visual friendly animations presenting information to aide in the evaluation of the simulated scenario. It is stated that the most useful output parameter for calibration of the TPASS model is the total number of vehicles in queue *(9)*.

Toll Plaza Simulation Model (TPSIM) was developed at the University of Central Florida with the purpose of simulating toll plaza operations. TPSIM is a stochastic discrete-event microscopic simulation model that divides the toll plaza into three zones for analysis. The three zones are the approach zone, the transition zone, and the toll zone. TPSIM is a stochastic object oriented discrete-event microscopic simulation model that was coded using Microsoft Visual Basic 6.0 and interfaces with Windows98/NT. Toll plazas with up to 5 approach lanes and up to 10 toll lanes in each direction can be modeled using TPSIM. The model contains algorithms for car-following, lane-changing, and toll-lane selection and provides output for measures of effectiveness (MOE) which include throughput, average queuing delay, maximum queuing delay, and total queuing delay. The TPSIM model was calibrated with data from the Holland East Plaza in Orlando, Florida and validated for use of different toll plaza configurations and ETC lane uses *(10)*. Klodzinski et al.*(11)* verified that the TPSIM model has the capability to accordantly model any toll plaza scenario and is transferable to other toll plazas with different configurations using the following measures of effectiveness: throughput, average queuing delay, maximum queuing delay, and total queuing delay. For calibration it was found that the service time was determined to have the most significant impact on the simulation model *(11)*. Klodzinski also states that to successfully calibrate and apply TPSIM, calibration data must be chosen carefully. If multiple days are selected for calibration, they must have similar characteristics (plaza configuration) and have a service time that is not significantly statistically different *(12)*. Similar to the SHAKER model the TPSIM model is limited to simulating isolated toll plazas. It can not be used to assess an entire network consisting of several toll plazas and/or intermediate sections between each.

TOLLSIM, a stochastic simulation model developed by Wilbur Smith Associates, is used primarily to analyze the toll operation at the toll plaza approach. To be effective TOLLSIM is programmed with traffic data and lane type configuration, ramp approaches and the storage length of each lane are required. The model produces simulation analysis results in both graphical and numerical format and lists a number of measures of effectiveness, such as delay per lane, overall delay, and queue length. However, TOLLSIM does not have the capability to analyze the traffic operation downstream from the toll plaza *(13)*.

2.1.1. Adaptation of Traffic Simulation Models for Toll Plazas

In addition to using exclusive toll plaza models, microscopic simulation programs have been used to develop toll plaza models. Using Paramics, Nezamuddin *(14)* modeled a toll plaza network and Ozbay *(15)* modeled an integrated freeway and toll plaza. Nezamuddin's capacity and delay models were based on calibrating the simulation with five key parameters: queue gap distance, queuing speed, mean target headway, mean reaction time, and minimum gap. Nezamuddin determined if his simulation results were within an acceptable range of values using the GEH statistic. The GEH Statistic is used to compare observed volumes with those obtained from simulation results. The GEH statistic is a modified Chi-squared statistic that incorporates both relative and absolute differences. Ozbay et al *(15)* modeled a non-mainline toll plaza and found that the best way to fine tune calibration was with trial and error method, and fine tuning with location of sign posting.

CORSIM is a simulation model regularly used for highway corridors but it can be used in conjunction with TOLLSIM to analyze the traffic operations on ramps and local roadway systems downstream from the toll plaza. Although CORSIM can theoretically simulate operations at a toll plaza it is not a straightforward modeling effort because it requires declaration of inherent complicated operational data typically found at toll plaza *(13)*.

VISSIM is another wide-ranging simulation model that can be adapted for toll plaza performance analysis. For toll model development and calibration it requires the same input data as listed above under TOLLSIM. Similar to most traffic simulation programs, calibration is required to match existing field observed toll operations. One advantage of VISSIM is that the user can seamlessly analyze the interactions between the highway leading to the plaza, downstream from the plaza, and at the plaza *(13)*.

Ceballos *(16)* ran queue analysis models at parking exit toll plazas using the VISSIM software. Ceballos applied VISSIM because of the capabilities of the software in developing toll plaza simulations based on dynamic assignment of vehicle paths, priority rules, service time distribution, speed reduction zones, and driver behavior. Ceballos' contribution to the research comes from his analysis of the difference between using multi-server queuing models and traffic simulation techniques. The study results indicate that multi-server queuing models could be used as an initial, mostly conservative, tool in early stages of planning, but simulation should be used for advance planning, design, operation and management of toll and exit plaza facilities. This research is however limited to applications associated with toll exit plazas at airports.

In VISSIM Park et al. *(17)* calibrated and validated a microscopic simulated freeway work zone network using an eight step procedure developed for calibrating and validating microscopic simulation models. The eight step method primarily focuses on identifying key calibration sets and using genetic algorithms to optimize the parameters used to match field conditions. A genetic algorithm (GA) is a search technique used in computing to find exact or approximate solutions to optimization and search problems. Their research contributes that genetic algorithm calibration provides a more statistically significant calibrated model than does the best-guessed method or the VISSIM suggested default parameters. However, it is noted by Chitturi *(18)* that implementing this procedure requires extensive knowledge of numerous microscopic parameters, their ranges, and their significance. In addition, this method requires running several hundred simulation runs before the genetic algorithms can determine the optimal parameter set. Chitturi indicates that because of the disproportionate time and resource constraints associated with genetic algorithm design, a regular user of VISSIM may not be able to use this procedure *(18)*.

Using VISSIM Lownes and Machemehl *(19)* studied the sensitivity that the driver behavior parameters have on corridor capacity. VISSIM was calibrated to simulate the US 75/SH-190 interchange, just north of Dallas, Texas. Following initial calibration, researchers studied how capacity was affected when modifying only one parameter at a time for four levels. Statistical analyses were performed after each level to determine if the changes in capacity were statistically significant or not. The contribution of this study is the identification of parameters which could significantly affect the capacity in VISSIM. However, not addressed is the issue of how to choose the values of the parameters that had a significant effect on capacity.

While both macro and micro simulation techniques are reviewed above, it is also important to consider the comparison of the usefulness and effectiveness of each technique. Festa, et al.*(20)* conducted a comparison between two different motorway traffic models to operate a comparative evaluation of potentialities and limits in the two different approaches by applying the models on a large scale motorway network with a complete traffic data base. The two different models used were a model based on microscopic traffic theory and a macroscopic stochastic experimental model. In order to perform a comparison between these two models, they have been applied to simulate the behavior of the real system during the morning of a working day. The time was initially broken down into 15 minute periods to avoid transient periods. The mean square relative error and mean relative error were used to evaluate the differences between the observed and simulated flow rates. For this experiment the macroscopic approach resulted in smaller errors of all types than the microscopic method. Other significant findings in the literature are uncovered in terms of effectiveness of the simulation models. In terms of model time, the macroscopic approach requires few seconds to run, while the microscopic model requires more than 100 seconds per run. This time however depends upon the total number of vehicles on the extension of the network itself and the number of outputs required. The length of the computational time makes micro-simulation modeling difficult because the calibration procedure requires a very high number of simulations. In conclusion, Festa's contribution to the field is found through the comparisons of the two models. As discovered, the microscopic approach allows tracking of space-time trajectories for every vehicle from its origin to the final destination. It allows better reproduction of the traffic dynamics, but, it also imposes the necessity to calibrate a high number of parameters, causing an increase in computational times. In contrast, the macroscopic approach benefits are that it conducts to an aggregate traffic representation, and it has a very fast execution and low memory occupation *(20).*

2.1.4. Toll Plaza Capacity Studies

The 2000 Highway Capacity Manual (HCM) *(21)* defines capacity as the maximum hourly rate at which persons or vehicles can be reasonably expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions *(21)*. The 2000 HCM also states that reasonable expectancy is the basis for defining capacity. Reasonable expectancy meaning that the stated capacity for a given facility is not the absolute maximum flow rate observed at a facility, but a flow rate that can be achieved repeatedly for peak periods of sufficient demand. The HCM uses the concept of Level of Service (LOS) for all kinds of traffic facilities, but still does not provide any standard way to define LOS for toll plazas. Based on field research and data analysis, Klodzinski and Al-Deek *(22)* recommend that delay be the most credible measure of effectiveness to determine the LOS of a toll plaza. Klodzinski and Al-Deek also developed a hierarchy of LOS groups to represent different levels of delay. A vehicle arriving at the toll plaza via no queue represents the best scenario because it only experiences delay caused by the transaction time. The TPSIM computer model was used to verify with 95% accuracy the delay results that were observed in the field and used for LOS development *(23).*

Aycin *(24)* developed a manual calculation methodology to determine the capacity, queuing patterns, and delays of toll plazas by considering the approach roadway conditions and traffic demand characteristics. The goal of the research is to improve planners understanding of toll plaza operations and to provide a means of evaluating similar toll plaza simulation results.

A review of the literature of toll plaza capacity studies suggests that there is no exact capacity for any type of toll booth lane type. Three major studies, each with different results, are provided to show the uniqueness of the subject.

Pietrzyk *(25)* conducted a study of multiple types of toll lanes and found the average capacity for the different toll plaza lane types are as follows:

- Manned – 350 vph/ln
- Automatic – 500 vph/ln
- Mixed AVI(Automatic Vehicle Identification) – 700 vph/ln
- Dedicated AVI – 1,200 vph/ln
- Express AVI – 1,800 vph/ln

The average capacities for non-dedicated AVI lane types (manned and automatic) were derived from individual capacity data records provided by toll agencies including the FTE, New Jersey Turnpike, and the Dallas North Tollway. The estimated average capacities for the dedicated and express AVI lanes were based on average speeds and vehicle spacing and headways.

Zarrillo et al. *(26)* collected field data that showed processing rates for different customer-groups at the Holland East Plaza, located on SR-408 in Orlando Florida, and Interchange 11A, located on the Massachusetts Turnpike 90. The results propose that on OOCEA toll facilities:

- Manual service (M) can process 8.3±0.8 veh/min (498±48 vph)
- Automatic Coin-Machine (ACM) Service lanes (no semi-trucks permitted and no gate present), can process 10.3±0.5 veh/min (618 ± 30 vph)
- Truck Manual (T) service consisting of derives of semi-trucks can process 2.3+1.3 veh/min (138 ± 78 vph)
- ETC Service (E15) using AVI technology to automatically record the toll amount and drivers are limited to speed limits of 15 mph, can process 15.0±2.0 veh/min (900 ± 120 vph)
- ETC Service (E35) with drivers limited to speed limits of 35 mph, can process 23.0±2.0 veh/min (1,380 ± 120 vph)
- ETC Service (E55) with drivers limited to speed limits of 55 mph, can process 32.0±2.0 veh/min (1,920 ± 120 vph)

Woo and Hoel *(27)* conducted a study on the Richmond-Petersburg Turnpike in Virginia using synchronized video cameras to determine the service times and capacity of 4 different toll plazas. They determined the service time for trucks ranged from 12.87 to 14.88 seconds for trucks, and from 5.11 to 5.47 seconds for automobiles. They make no distinction between the service time for manned booths versus ACM booths because according to their study ACM service time is shorter or exhibit little or no difference than manned booths. Their capacity study uses an automobile equivalent for trucks that ranges from 2.39 to 2.91 passenger cars per truck. The results of their research are as follows:

- A general toll booth capacity ranges from 650 to 705 passenger cars per hour
- An exact change toll booth without a lifting barrier is between 645 and 665 passenger cars per hour
- An exact change toll booth with a lifting barrier has a capacity of 600 passenger cars per hour

The dissimilar capacity results published in multiple literatures suggests that there is no one value recommended for all toll plazas and there appears to be no general agreement among traffic engineers as to its precise value. Table 1 below summarizes different toll plaza studies and the capacities discovered in each.

Table 1: Summary of Toll Plaza Capacity Research Results

	Differing Capacities in Research, by Author (veh per hour per lane)		
Lane Type	**Pietrzyk***	**Zarrillo****	**Woo*****
Manned	350	498	675
ACM	500	618	655
Truck	--	138	--
ETC (35 mph)	1200	1380	--
ETC (high speed)	1800	1920	--

* New Jersey Turnpike, Florida Turnpike, and the Dallas North Tollway
**Holland East Plaza, located on SR-408 in Orlando Florida, and Interchange 11A, located on the Massachusetts Turnpike 90
***Richmond-Petersburg Turnpike in Virginia

Other factors that may contribute to a varying capacity are that under light traffic, the toll collector's performance may be reduced due to the lack of need to work fast as the case when pressured with a queue. When toll collectors are under greater pressure from a growing queue, they tend to process transactions faster *(27)*. Service times have a strong influence in the toll plaza capacity. They are important parameters to consider in the design of these facilities. They are also essential information for operational decisions that involve the definition of work shifts and number of opened booths *(28)*. Service time per vehicle is greatly affected by the number of bills and/or coins that must be processed by the toll booth collector or ACM. Astarita et al. suggests that every toll booth type is characterized by its own service time distribution, with an average value and a standard deviation *(29)*. In the same literature it was determined that drivers' behavior variability is stochastic by nature, while other elements of the toll booth traffic are generally deterministic. Manned toll booths charging exact bill amounts tend to have higher capacities than ones that do not. ACM booths capacity decreases with the increase of number of coins needed to make payment. Other factors that have the potential to influence the processing time are the experience and pace of the toll collectors, the use of toll gates, the methods of toll collection, and the presence of drivers with exact fee amounts. The FTE uses gates on its ACM lanes to indicate when the payment is fully received by the machine. According to Pietrzyk *(25)*, who compared the Florida's Turnpike system to the Tampa Crosstown Expressway, the New Jersey Turnpike, and Dallas North Tollway, the average capacities of ACM lanes with gates are typically reduced by 10 to 20 percent of that of un-gated lanes. The traffic distribution can also affect the plaza capacity as manual booths with high truck percentages typically have lower service volumes than those that server primarily automobiles.

Traffic congestion levels also affect the service time per vehicle for the reason that while waiting in queues motorists experience extra time to search for money before they make their final stop in the queue to pay the toll transaction *(27)*. Oliveira also discovered that a joint analysis of the maximum and minimum times model shows that the variability between maximum and minimum service times decreases as flows increase at the toll plazas. Thus, the system becomes more stable at high traffic flows *(28)*. When traffic congestion occurs at plazas with insufficient queue storage lengths there exists the potential for the capacity of the plaza to be drastically reduced. The plaza dimensions and layout upstream of the toll booths is thus another factor that governs the plaza's overall capacity. According to Astarita et al. "When the vehicle arrival rate exceeds the corresponding service rate, slowed vehicles directed towards over-saturated booths (usually the manual ones) can cause a cut-off in the flow of other vehicles, which are destined to a non-congested booth" *(29)*.

While there are numerous studies that focus on the calibration process of simulation models and as many studies that focus on determining the capacity of a toll plaza, there is no evidence in the literature of a study using plaza capacity to calibrate both a deterministic and stochastic toll plaza model with research objectives rooted in the evaluation of the efficiency and exactness of each models ability to match such an extensive field data collection study.

3. SHAKER REVIEW

Zarrillo and Schmitt *(2, 30, 31, 32, 33)* completed extensive research in developing the SHAKER tool to simulate vehicle queuing behavior at toll plazas. TNCC calculates the capacity of the toll plaza and SHAKER is a deterministic queuing model based on classical physics equations that determines a plaza's maximum hourly throughput by assigning vehicles to lanes based on toll lane queuing conditions *(2)*. The following sections are provided to elaborate on the methodologies used in the SHAKER software, examine previously conducted calibration attempts, and lastly a section showing screen shots and how to use the SHAKER software is provided.

3.1. General SHAKER Methodology

In SHAKER, hourly throughput for a lane under queuing conditions is calculated using the linear equations of motion. However, the lane-percentages or the relative frequency of occurrence must be known and used as input to these equations. Therefore, a method for distributing the approaching traffic into the available lanes is required. Thus, the shaking method is incorporated. The shaking process moves around vehicles from one lane to another until a correct distribution is established. The determination of the correct distribution is based on the stability of an outcome measure, such as hourly throughput, queue length or delay. The shaking process has a set of conditions, constraints or rules that must be obeyed; for instance, the model only allows vehicles to be placed, shook or queued in a lane in which their category has available service. If there is more than one lane available as a possible choice, then SHAKER uses one of four types of criteria upon which drivers may base their decision:

1. Drivers may prefer lanes that have the smallest number of remaining vehicles in the queue
2. Drivers may prefer lanes that have the smallest remaining queue length
3. Drivers may prefer lanes that have the shortest wait time in the remaining queue
4. Drivers may prefer lanes that have the fastest moving remaining queue

Criteria 1 and 2 appear very similar because both are rooted in the queue length but they differ because of the potential varying length of vehicles in the queue. For instance, the difference is better understood in the example of a driver approaching a toll plaza where one lane has three vehicles in one lane and one 18-wheeler in the other. Due to their respective lengths the remaining queue may be similar lengths but there is a different amount of remaining vehicles in each queue. Criteria 3 and 4 are correlated because the calculation for the determination of each is the inverse of the other. In Criteria 3 and 4 SHAKER can determine a plaza's throughput by assuming drivers are quite skilled and choose a lane that provides their required service but minimizes their waiting-time-in-the-queue.

The shaking process continues as long as the output measure changes in value. Once stability is reached the shaking process stops. SHAKER uses steady state equilibrium assumptions to obtain the maximum throughput for a toll plaza and estimate the optimal booth configuration. SHAKER's throughput calibration is accomplished by adjusting the vehicle-properties for five categories so that the model's output for the hourly throughput matches those measured in the field. The five parameters to be adjusted are:

1. Vehicle length
2. Acceleration
3. Deceleration
4. Driver reaction time
5. Processing time

After modeling the queuing at toll collection facilities in SHAKER, the throughput of the entire plaza may be predicted.

SHAKER ultimately takes the demand and forces the vehicles to pass through the toll plaza using a basis of equilibrium to find capacity. An equilibrium methodology has some drawbacks that are addressed in the model. For example, to account for vehicle types such as trucks using lane types unconventional to design, SHAKER splits up the ETC category into two groups; ETC trucks and non-ETC trucks. The model can more accurately reflect the policy that trucks are prohibited from using the ACM lanes. The SHAKER tool categorizes vehicles by their payment method and lane type they choose. This study has adopted the use of initials that represent the different lane type choices; they are:

E_p = Two wheel vehicle who chooses Electronic Toll Collection lane
E_T = Truck that chooses the Electronic Toll Collection lane
A = Two axle vehicle choosing the Automatic Coin Machine lane
M = Two axle vehicle choosing the manned toll booth lane
T = Truck that chooses the manned toll booth lane

3.2. SHAKER Methodology to Calculate Lane Throughput

This section elaborates on the methodology used by SHAKER *(2, 30, 31, 32, 33)* to compute the capacity and throughput of toll plaza's lanes. SHAKER can determine the number of processed vehicles per unit time at toll collection facilities given the total number of vehicles arriving at the plaza and their traffic characteristics. This is identical to knowing the number of vehicles of each customer type arriving at the plaza" *(2)*. In this model, car-following theory is used to derive a model for mixed lanes. To describe the SHAKER methodology further it is more convenient to break up the procedure into two parts:

1. The determination of the traffic characteristics in each lane of the plaza.
2. The determination of the maximal throughput of each lane knowing the traffic characteristics in each lane.

Each procedure requires the other as an input before it can be solved. Therefore, the model is an iterative feedback algorithm simultaneously adhering to these two processes. There are numerous equations used to determine the maximum throughput for lanes in which drivers have to stop to pay tolls and lanes in which drivers only slow down to pass as their ETC transponder takes care of the toll, and a mixed lane used to simulate vehicles that own ETC transponder but choose to drive the non-dedicated ETC lanes. In the SHAKER methodology these lanes are designated as pure lanes for stopping vehicles, pure lanes for non-stopping vehicles, and mixed lanes for stopping and non-stopping vehicles. Pure lane is defined as the lane servicing a particular customer type. For example, capacity of a manned pure lane is calculated using the basic properties (default values) of the manned customer type (M). Initially SHAKER finds the probability of finding trains of each vehicle type in each lane type to create the traffic composition. Next SHAKER determines the overall throughput (maximum number of vehicles a lane can process per unit time dependent upon the traffic characteristics in this lane) of each lane by referencing the vehicle characteristics of each vehicle type. To explain the methodology of the algorithm the following steps are followed:

1. The user is asked for the traffic characteristics which includes the percentages of arriving vehicles to the plaza that belong to each of the traffic categories or customer types
   - P_T, the percentage of arrivals that pay their toll manually and are categorized as trucks.
   - P_A, the percentage of arrivals that pay their toll via an automatic coin machine and are categorized as non-trucks.
   - P_{EP}, the percentage of arrivals that pay their toll electronically and are categorized as non-trucks.
   - P_{ET}, the percentage of arrivals that pay their toll electronically and are categorized as trucks.

Then the percentage of arrivals that are manual users and categorized as non-trucks is computed as the remaining percentage, $P_M = (1- P_T + P_A + P_{EP} + P_{ET})$.

2. The user is asked for the total volume of approaching vehicles in one hour. The number of vehicles of each category or customer type is then calculated as the product of this volume and the percentages from step one.
3. The number of arriving vehicles is initially distributed in the lanes obeying the constraint that only certain customer types are allowed in certain lanes. For instance, the mixed lane MTE_PE_T, only allows categories M, T, E_P and E_T. And mixed lane AE_PE_T only allows categories A, E_P and E_T. Each lane that allows a specific category of traffic is distributed the same number of vehicles in that category. Thus, the program now knows how many vehicles are in each of the lanes and of what category they belong. Therefore, the program knows the percentages of each category are in each lane. These individual lane-percentages are necessary for the next step because they are input to the equations used to calculate each lane's throughput.
4. The throughput in vehicles per hour, vph, is calculated for each lane individually based on equations (1), (2), (3), (4), (5), (6) and (7) shown below.

- If the user chooses the decision criterion #1 (explained in section 3.1), then one vehicle for a particular category in the lane with the longest remaining-queue-number is moved to the lane with the shortest remaining-queue-number. The remaining-queue-number is the difference between the queue-number and the throughput for a specific lane. After moving one vehicle, the initial distribution has been changed slightly by one vehicle in each of two lanes. The new queue-numbers and new percentages in each of the lanes can be calculated and used again in the equations to calculate the new throughput for each of the individual lanes. The new remaining-queue-number in each of the lanes is determined by subtracting the new throughput from the queue-number. Again, one vehicle in the lane with the longest remaining-queue-number is moved to the lane with the shortest remaining-queue-number. And again, the new percentages in each of the lanes is calculated and used in the equations to calculate the throughput for each of the individual lanes. This process repeats again and again until stability in the remaining-queue-number occurs in all lanes.
- If the user chooses the decision pattern #2 (explained in section 3.1), then one vehicle for a particular category in the lane with the longest remaining-queue-length is moved to the lane with the shortest remaining-queue-length. Remaining-queue-length is the number of remaining vehicles or the remaining-queue-number multiplied by their spacing. Spacing is the length of the vehicle and the distance between the vehicles, (l_x+b_x), both chosen as input by the user. The X represents the category of traffic, A, M, T, E_T and E_P. SHAKER suggests default values for these inputs. After moving one vehicle, the initial distribution has been changed slightly by one vehicle in each of two lanes. The new queue-number and new percentages in each of the lanes is calculated and used in the equations to calculate the new throughput for each of the individual lanes. The new remaining-queue-length in each of the lanes is again determined. Again, one vehicle is moved. This process repeats until stability in remaining-queue-length occurs in all lanes.
- If the user chooses the decision pattern #3 (explained in section 3.1), then one vehicle for a particular category in the lane with the largest average waiting time is moved to the lane with the shortest average waiting time. Average waiting time is the remaining-queue-number in a lane divided by the throughput for that lane. After moving one vehicle, the initial distribution has been changed slightly by one vehicle in each of two lanes. The new queue-numbers and new percentages in each of the lanes is calculated and used in the equations to calculate the new throughput for each of the individual lanes. The new throughput is subtracted from the queue-number to get the remaining-queue-number and this is divided again by the throughput to determine the average waiting time. Again, after comparison of the average waiting time, one vehicle is moved from one lane to another. This process repeats until stability in the average waiting time occurs in all lanes.
- If the user chooses the decision pattern #4 (explained in section 3.1), then one vehicle for a particular category in the lane with the slowest average-vehicle-speed is moved to the lane with the fastest average-vehicle-speed. The average-vehicle-speed is proportional to the throughput. Faster processing of the vehicles in a lane means that the vehicles are moving faster in their lane. After one vehicle is moved, the new percentages in each of the lanes is calculated and used in the equations to calculate

the new throughput for each of the individual lanes. Again, one vehicle is moved after comparison of the new average-vehicle-speed. This process repeats until stability in the average-vehicle-speed occurs in all lanes.

5. Throughput in units of vehicles per hour for the entire plaza is the sum of the individual lanes' throughputs.

3.3. TNCC and SHAKER's Equations to compute Lane Capacity and Throughput of a Toll Collection Facility

Equation (1) describes the throughput in vph for a dedicated ETC lane, where $\mathrm{v}_{\mathrm{limit}}$ is in units of ft/second, such that typical speeds of 35.00 mph corresponds to 51.63 ft/s. Using this equation, values of capacity in a dedicated ETC lane under queuing conditions at 35 mph speed limits compute to 1697 vph, when there are P_{ET} = 0% trucks and P_{EP} = 100% non-trucks. If there is a 10% truck then the capacity is reduced to 1602 vph.

$$\mathrm{S}^{\text{dedicated-ETC -lane}} = \frac{1}{\left(\mathrm{P}_{\mathrm{E_P}}\left(t_R \mathrm{v}_{\mathrm{limit}} + l_{\mathrm{E_P}}\right) \Big/ \mathrm{v}_{\mathrm{limit}}\right) + \left(\mathrm{P}_{\mathrm{E_T}}\left(t_R \mathrm{v}_{\mathrm{limit}} + l_{\mathrm{E_T}}\right) \Big/ \mathrm{v}_{\mathrm{limit}}\right)} \times 3600 \frac{s}{hr} \tag{1}$$

where,
S = Capacity of the lane in vph
P_{EP} and P_{ET}= Percentage of ETC Non-Trucks and ETC Trucks respectively
t_R = Driver reaction time in seconds
l= Average Vehicle length in feet

Equation (2) describes the capacity in vph for a lane other than a dedicated ETC lane. It is the inverse of the average time it takes to process a vehicle in a lane.

$$\mathrm{S}^{\text{any other Lane-Type}} = \mathit{Maximum}\ \text{Capacity for one lane (vph)} = \frac{1}{H + J + K + L + M} \times 3600 \frac{s}{hr} \tag{2}$$

where,
H = Average time in sec/veh, weighted by the probability of their occurrence, to process all M, T and A vehicles that approach the plaza and are not followed by a train of ETC vehicles.
J = Average time in sec/veh, weighted by the probability of their occurrence, to process short trains of ETC vehicles that are not trucks following a slower vehicle.
L = Average time in sec/veh, weighted by the probability of their occurrence, to process longer trains of ETC vehicles that are not trucks following a slower vehicle.
K = Average time in sec/veh, weighted by the probability of their occurrence, to process short trains of ETC vehicles that are trucks and follow a slower vehicle.

M = Average time in sec/veh, weighted by the probability of their occurrence, to process longer trains of ETC vehicles that are trucks and follow a slower vehicle.

The value of H is described by equation (3) in units of seconds per vehicle. It computes the average time, weighted by the probability of their occurrence, to process all M, T and A vehicles that approach the plaza and are not followed by a train of ETC vehicles. Here it is assumed that the vehicles accelerate throughout half the spacing $(b_x + l_x)$ and decelerate throughout the other half. Substitution of the driver/vehicle properties (listed in step three) conclude that a queued lane containing only M vehicles has a processing time of H = 7.23 seconds and thus a processing rate of S^M = 498 vph. Similarly, for A and T vehicles, calculations produce processing times of 4.62 and 26.07 seconds, respectively, and processing rates of 779 and 138 vph. Additional calibration can be carried out with the manipulation of the property values listed in step three.

$$H = \sum_{\mathrm{X=M,T,A}} \mathrm{P_X} \left[t_R + t_{stop\,\mathrm{X}} + \sqrt{\frac{(\mathrm{b_X} + l_\mathrm{X})}{\mathrm{a_X}}} + \sqrt{\frac{(\mathrm{b_X} + l_\mathrm{X})}{\mathrm{d_X}}} \right] \qquad (3)$$

where,
b = Distance between vehicles in feet
a = Vehicle acceleration in ft/sec^2
d = Vehicle deceleration in ft/sec^2

The value of J is described by equation (4) in units of seconds per vehicle. It computes the average time, weighted by the probability of their occurrence, to process short trains of ETC vehicles following a slower vehicle. Here, trains do not contain trucks using ETC. For 35 mph speed limits, typical values of n_{speed} in equation (4) are 5 or 6 vehicles. This implies that trains of more than five E_P vehicles following one non-ETC vehicle would probably reach the speed limit of 35 mph while passing through the toll facility. Processing times for longer trains use equation (5), which computes values for L.

$$J = \sum_{n=1}^{n_{speed}} \left\{ \mathrm{P_E}^n (1 - \mathrm{P_E}) \left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}} \right)^n \left[t_R + \frac{1}{n} \sqrt{\frac{2n\,(\mathrm{b_{E_P}} + l_{\mathrm{E_P}})}{\mathrm{a_{E_P}}}} \right] \right\} \qquad (4)$$

where, $n_{speed} = \dfrac{\mathrm{v_{limit}}^2}{2\mathrm{a_{E_P}}(\mathrm{b_{E_P}} + l_{\mathrm{E_P}})}$ and $\mathrm{P_E} = \mathrm{P_{E_P}} + \mathrm{P_{E_T}}$

$$L = \sum_{n=1+n_{speed}}^{\infty} \left\{ \mathrm{P_E}^n (1 - \mathrm{P_E}) \left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}} \right)^n \left[t_R + \frac{\mathrm{v_{limit}}}{n\mathrm{a_{E_P}}} + \frac{1}{\mathrm{v_{limit}}} \left((\mathrm{b_{E_P}} + l_{\mathrm{E_P}}) - \left(\frac{\mathrm{v_{limit}}^2}{2n\mathrm{a_{E_P}}} \right) \right) \right] \right\} \qquad (5)$$

where, n_{speed} = Number of vehicles in the train following one non-ETC vehicle reaching the speed limit of 35 mph

The value of K is described by equation (6) in units of seconds per vehicle. It computes the average time, weighted by the probability of their occurrence, to process short trains of ETC vehicles that are trucks and follow a slower vehicle. For 35 mph speed limits, typical values of $n_{speed\ \mathrm{T}}$ in equation (6) are 22 or 23 vehicles using a 50% ETC usage rate with 10% of those being trucks and 90% being passenger cars. This implies that trains of more than twenty-two E_T vehicles following one non-ETC vehicle would probably reach the speed limit of 35 mph while passing through the toll facility. Processing times for longer trains use equation (7), which computes values for M.

$$K = \sum_{n=1}^{n_{speed\ \mathrm{T}}} \left\{ \mathrm{P_E}^{\,n}\left(1-\mathrm{P_E}\right)\left(1-\left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}}\right)^{n}\right)\left[t_R + \frac{1}{n}\sqrt{\frac{2n\left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}}\left(\mathrm{b_{E_P}} + l_{\mathrm{E_P}}\right) + \frac{\mathrm{P_{E_T}}}{\mathrm{P_E}}\left(\mathrm{b_{E_T}} + l_{\mathrm{E_T}}\right)\right)}{\mathrm{a_{E_T}}}}\right]\right\} \tag{6}$$

where, $n_{speed\ \mathrm{T}} = \dfrac{\mathrm{v_{limit}}^{2}}{2\mathrm{a_{E_T}}\left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}}\left(\mathrm{b_{E_P}} + l_{\mathrm{E_P}}\right) + \frac{\mathrm{P_{E_T}}}{\mathrm{P_E}}\left(\mathrm{b_{E_T}} + l_{\mathrm{E_T}}\right)\right)}$

$$M = \sum_{n=1+n_{speed\ \mathrm{T}}}^{\infty} \left\{ \mathrm{P_E}^{\,n}\left(1-\mathrm{P_E}\right)\left(1-\left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}}\right)^{n}\right)\left[t_R + \frac{\mathrm{v_{limit}}}{n\mathrm{a_{E_T}}} + \frac{1}{\mathrm{v_{limit}}}\left(\left(\frac{\mathrm{P_{E_P}}}{\mathrm{P_E}}\left(\mathrm{b_{E_P}} + l_{\mathrm{E_P}}\right) + \frac{\mathrm{P_{E_T}}}{\mathrm{P_E}}\left(\mathrm{b_{E_T}} + l_{\mathrm{E_T}}\right)\right) - \left(\frac{\mathrm{v_{limit}}^{2}}{2n\mathrm{a_{E_T}}}\right)\right)\right]\right\} \tag{7}$$

3.4. Previously Calibrated Version of TNCC and SHAKER

During calibration SHAKER uses the single service lane processing rates for different categories, S_M, S_T, S_A, and S_E, given by observed field data values listed in Table 2 *(30)*. In other words, except for the ETC category, input of 100% into SHAKER's capacity equations of any one of SHAKER's categories will result in lane throughput values that are equal to the processing rates listed in Table 2. For the case of the dedicated ETC lanes in which a speed limit of 35 mph is enforced, SHAKER is calibrated using a value of 1698 vph for the processing rate of ETC vehicles that are passenger cars and 1060 vph for ETC vehicles that are not passenger cars.

Table 2: Field Measured Processing Rates for the Traffic Categories used in Calibration

Type of Toll Service	X	S^X (vph)
Manual for passenger cars	M	$S^M = 498 \pm 48$
Automatic Coin Machine Users	A	$S^A = 618 \pm 30$
Manual for vehicles other than passenger cars	T	$S^T = 138 \pm 78$
Mixture of ETC passenger cars and semi-trucks traveling at 35mph	E_P and E_T	$S^E = 1560 \pm 120$

In order to achieve calibration such that the throughput equations accurately reflect field values of the processing rates, it was necessary to manipulate the driver/vehicle property values listed in Table 3 *(2)*. These property values vary from region to region anyway. For instance, in a community with a large population of senior citizens, the driver reaction time property, T_R, may have a value of 2.1 rather than 1.8 seconds. In addition, stop time values to pay the toll may be 2.0 rather than 1.5 seconds. These property values, once inserted into the throughput equations, would result in higher values for the processing times for this community. This would compute to smaller throughputs and would accurately reflect the smaller corresponding processing rates measured in the field.

Table 3: SHAKER's Default Properties of the Traffic Categories at the Toll Facilities Table

	M	**T**	**A**	**E_P**	**E_T**
l_X =Average vehicle Length (meters)	5.8	21	5.8	5.8	21
b_X = Distance between vehicles (meters)	2.0	3.0	2.0	2.0	3.0
a_X = Vehicles' Acceleration (meters/second^2)	2.0	0.25	2.0	2.0	0.25
d_X =Vehicles' Deceleration (meters/second^2)	2.0	0.25	2.0	2.0	0.25
T_R = Drivers' reaction Time (seconds)	1.8	1.8	1.8	1.8	1.8
$t_{stop\ X}$ = Stop–Time at payment (seconds)	1.5	4.7	0.075	0.0	0.0

3.5. Using the SHAKER Software

The developments of the SHAKER model have occurred fairly recently and the program is not yet as globally distributed as the VISSIM software is; therefore the procedure on how to use SHAKER is also relatively new and seldom used before. This section is provided to show the essential steps in obtaining research goals, toll plaza capacities and throughputs, by means of the SHAKER software.

The SHAKER plaza calculator finds the best configuration for the given lane and the lane properties and finds the throughput of all the configurations and displays the throughput of the best configuration. Nonspecific input values are used for the purpose of this section and are only used for software introduction. When SHAKER is first opened the user is presented with a window such as the one provided in Figure 1. Before moving on, the user is to choose whether to allow the SHAKER software to automatically calculate the best lane type configuration by checking the Automatic tab (first choice in Figure 1) or enter each of the number and type of lanes manually by checking the Manual tab (the second choice in Figure 1).

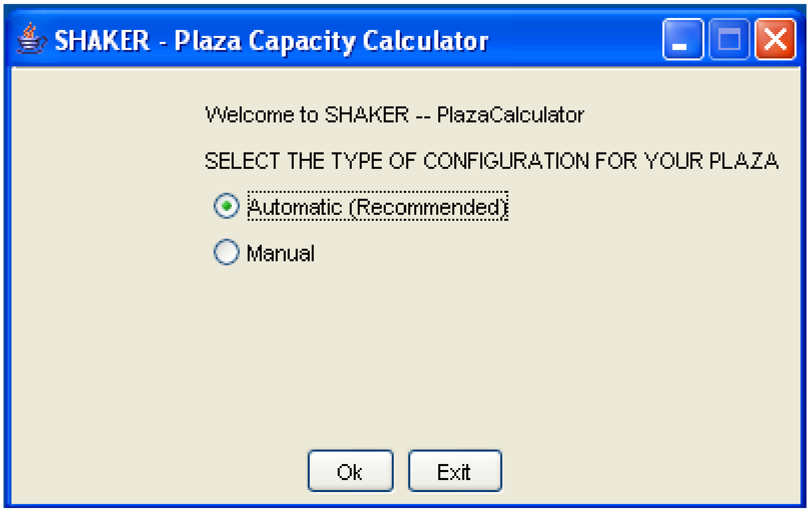

Figure 1: SHAKER Opening Screen

When using the Automatic option, which is the only portion of SHAKER used for this research, the user is taken to an input screen where has the option to enter the following (as also shown in Figure 2):

1. The number of lanes
2. Toll Value – Each toll value has different stop times for calculating capacity
3. Select if open road tolling or not. This is for the ETC lanes only
4. Enter the total number of arriving vehicles
5. Percentage of users in each of the following categories:

a. (E_p) two axle vehicles using ETC lanes
b. (E_t) 2+ axle vehicles (trucks) using ETC lanes
c. (A) ACM vehicles
d. (M) Two axle vehicles using manned lanes
e. (T) 2+ axle vehicles (trucks) using manned lanes

Here it is assumed that E-lanes can allow Ep and Et vehicles, A-lanes allow Ep, Et and Auto vehicles, M-lanes allow all type of vehicles. Percentage of Trucks (T) vehicles does not include the percentage of Sun Pass Truck vehicles (Et).

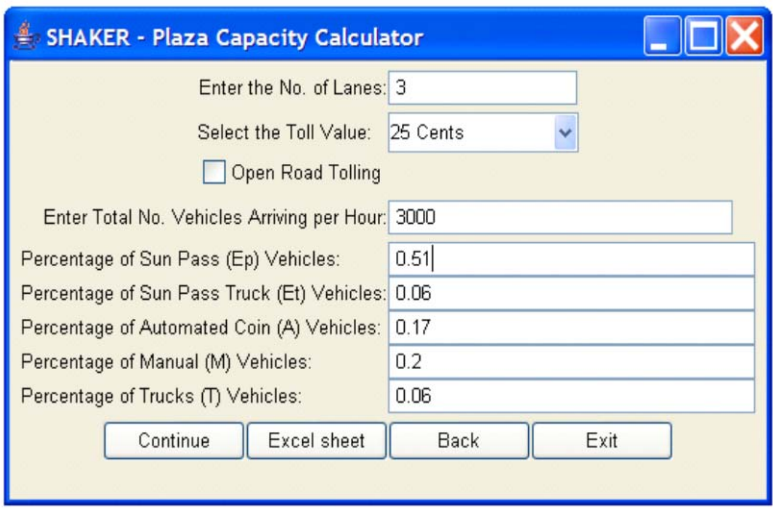

Figure 2: SHAKER Automatic Plaza Configuration Input Screen

After entering these values and when the user clicks Continue, the plaza calculator performs its simulation by finding all the possible configurations for the number of lanes entered and the user now is presented with an iconic representation of volumes and capacity per lane (as provided in Figure 3). In this step SHAKER calculates the throughput of all these configurations and compares them to find the best configuration and displays the results for the best configuration. The user can change the number of arriving vehicles or vehicle percentages in this window and press *Get Throughput* button. This will give the best configuration for updated values. The throughput and capacity is displayed in the *Best Configuration* section located in the lower left section of the window. The throughput, capacity, and queue length of each individual lane is displayed when the mouse is hovered over each lane icon, as shown in Figure 4. The throughputs for each vehicle class and payment type are color coded in this dropdown menu. The throughput for manual paying passenger cars is displayed in yellow and manual paying trucks is displayed in black. The capacity of that particular toll booth is displayed in green and all other overall toll plaza characteristics, such as queue length and time to dissipate queue, are listed below that.

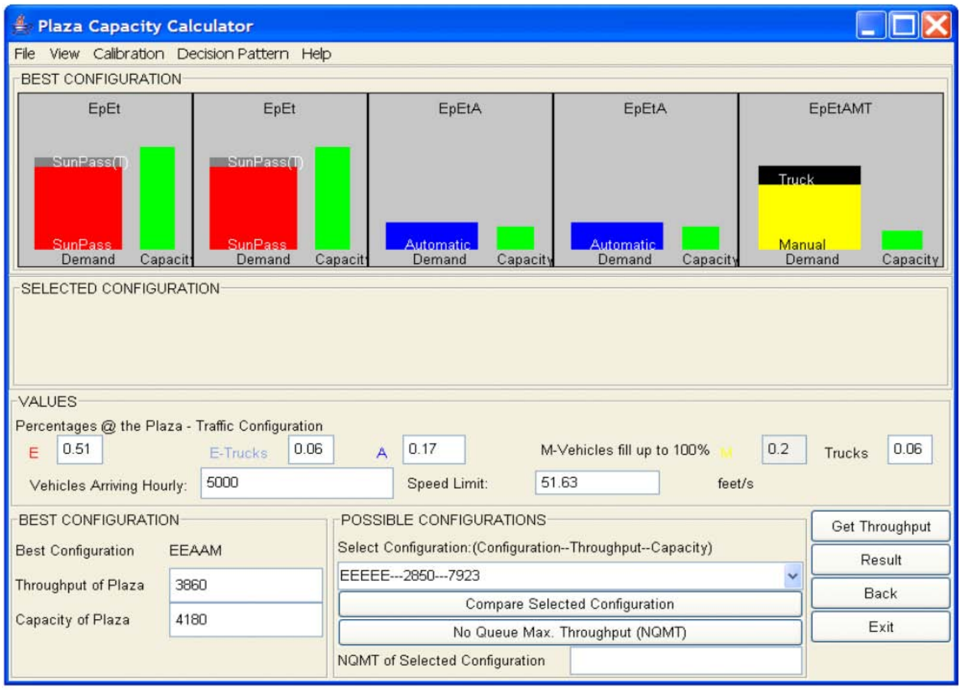

Figure 3: SHAKER Best Configuration Window

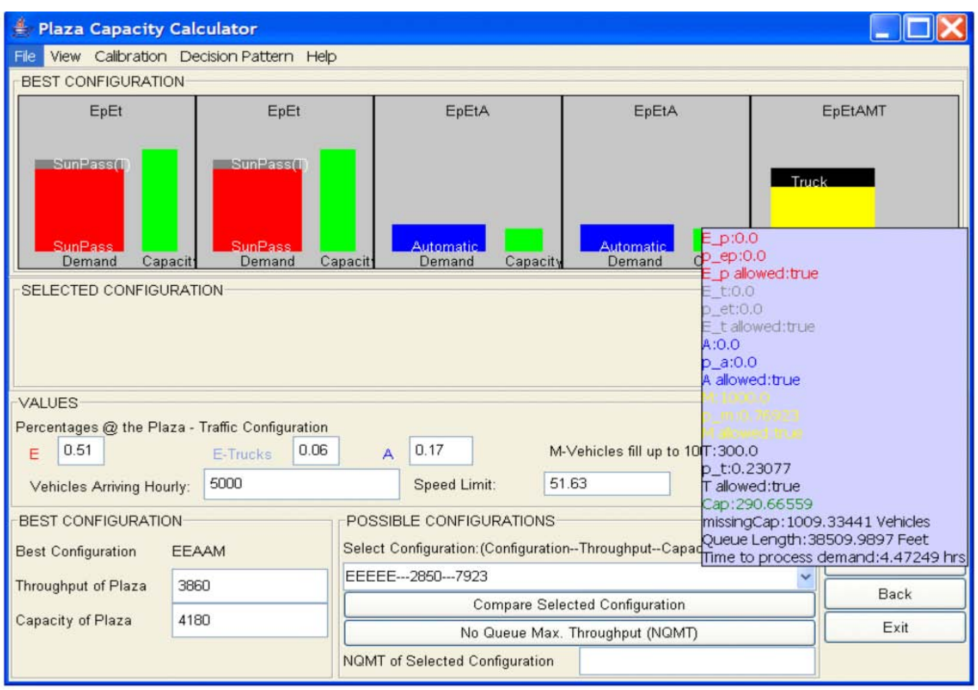

Figure 4: Individual Lane Analysis

To check all possible configurations of the toll plaza the user can select any configuration of lanes from the *Select Configuration* pull down menu. Once the new configuration is selected SHAKER displays the throughput and capacity of each configuration. The user is given the option to compare the original and new configuration by graphical representation of both the best and the selected configurations so that the user can compare the two simultaneously. An example of one such comparison is shown in Figure 5.

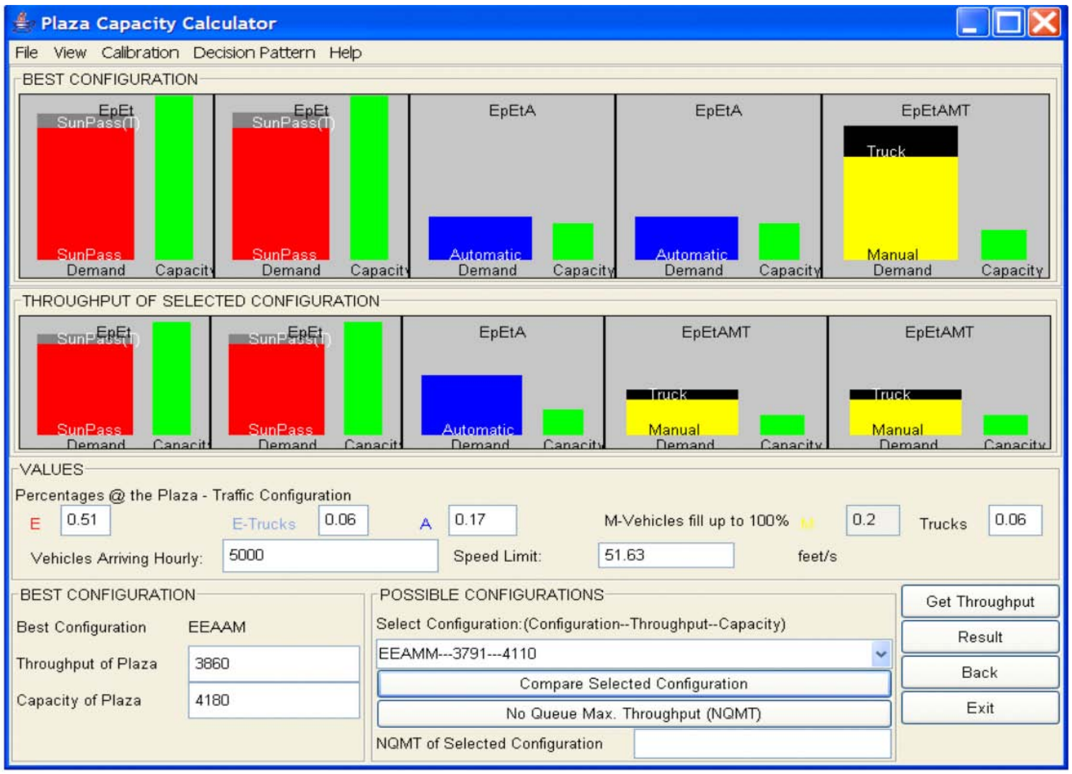

Figure 5: SHAKER - Comparing Configurations Example

The SHAKER model also provides the user with the option to conduct the following list of commands:

- No Queue Maximum Throughput (NQMT) is defined as the maximum possible arrival volume in which all vehicles arriving can be processed in an hour such that no queues exist in any of the lanes at the end of the hour i.e. maximum throughput of the plaza until a queue is formed in at least one lane. Click on *No Queue Max. Throughput* button to show the NQMT of the selected configuration in the text box next to 'NQMT of Selected Configuration' text and the bar representation is shown in selected configuration box. To get the NQMT, the selected configuration should have at least one lane to service each customer type.
- Calibrate- Calibration is changing the basic properties to meet observed/desired throughput rates of pure lanes. Sets of basic properties can be saved and opened with save

Calibration and open Calibration in the Calibration menu in both manual and automatic configurations.

To change basic properties of the calibration the user can alter any number of the provided parameters in this window. Under the sub menu item Customer Type, the user can choose a particular customer type, after which a dialog box appears. The text fields are filled with default values which the user has the option to change. Figure 6 is provided to show this window.

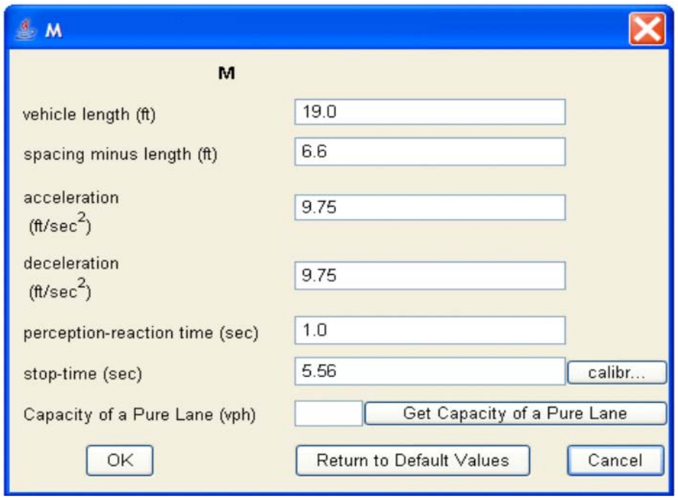

Figure 6: SHAKER - Calibration Window Example

The customer type dialog box also helps the user calibrating the basic properties to meet observed/desired throughput rates of pure lanes. The *Get Capacity of a pure lane* button calculates the capacity of a pure lane using the calibration parameters defined on the frame and writes it in the capacity text field beside. Users may change this value according to their field measurements of the processing rates (vehicles processed per hour) in their region. The calibrate button next to stop-time search for a reasonable value of a particular basic property such that the calculated capacity of a pure lane (vph) matches the capacity placed in the capacity text field. All other basic properties stay constant. In the case of a pure A lane or pure M lane or pure T lane, calibrate buttons appear next to stop-time parameter. Because the other basic properties influence the mixed lane behavior it is recommended to make each parameter consistent with the basic properties of the corresponding non ETC customer types.

4. EXPERIMENTAL DESIGN PROCEDURE

Before any efforts towards model calibration can begin the user must define a complete, beginning to end, experimental procedure. To develop a simulation model calibration and validation process two well recognized methods have been combined, taking the strengths of each, and are slightly adapted to simulate isolated toll plaza operations. General microsimulation calibration techniques are followed to calibrate SHAKER because there is no literature specific to calibrating a deterministic model versus a stochastic model. According to the FHWA Traffic Analysis Toolbox, Volume 3 *(6)* the overall process for developing and applying a microsimulation model to a specific traffic analysis situation consists of seven major tasks (also shown in Figure 7):

1. Identification of Study Purpose, Scope, and Approach
2. Data Collection and Preparation
3. Base Model Development
4. Basic Model Error Checking/Initial Evaluation
5. Calibration of model
6. Alternatives Analysis
7. Final Report and Technical Documentation

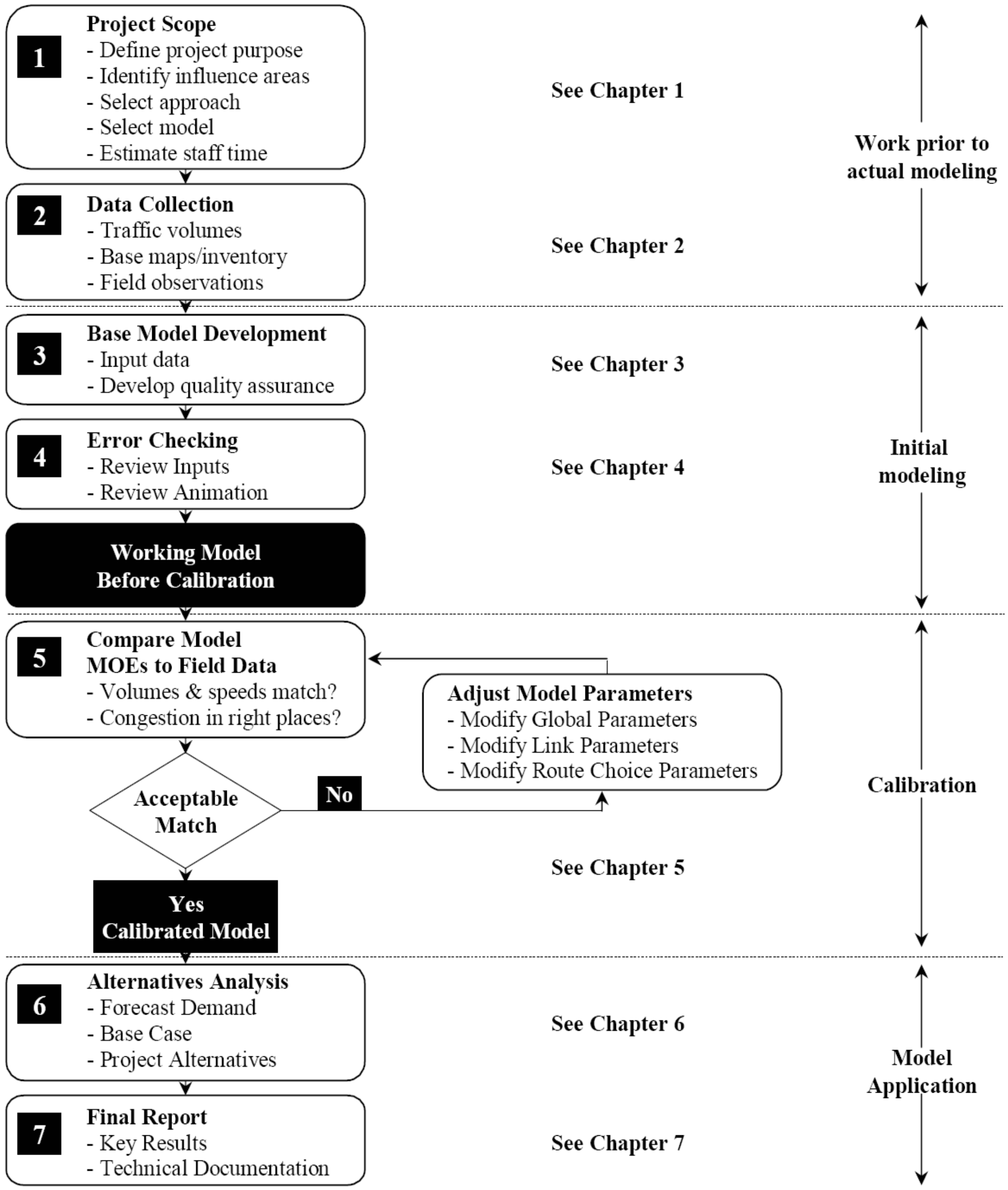

Figure 7: FHWA Calibration Flow Chart (7)

Steps 6 and 7 of this model will not be directly addressed in this research because they are included in the FHWA documentation for clients who wish to use the methodology specifically for planning purposes. The calibration model described by the FHWA follows a sound process in calibrating a microsimulation model, but fails to mention any steps pertaining to model feasibility and validation. To make up for this vacancy, the calibration model proposed by Park and Qi is adopted for its extensive validation procedure *(7)*. The final two calibration steps adopted for this study are: i) the evaluation of final calibrated parameter set and, ii) ensuring statistical and visual validation of calibrated model. The combination of these two calibration procedures results in a more complete experimental design process for calibrating a microsimulation model. It is noted that the calibration process can not continue to the next step unless the previous step in this process is first satisfied. In some cases where the step's objectives are not possible, the user may have to reconsider the activity in a previous step in order to move on or in extreme cases restart the entire experiment from step one. Each step is briefly described in the following sections.

4.1. Step 1 Identification of Study Purpose, Scope, and Approach

This step includes how and why the study is to be conducted. In addition, this step includes choosing which sites to use for data collection and which software will be used for model development and evaluation. Step one was partially addressed in the early stages of this paper in the introduction, purpose, and literature review sections. The next phase of the experiment outline consists of defining a particular data collection procedure. The data collection aims at analyzing toll lanes processing times (or service time) and all other the factors affecting the latter. If a better understanding of toll plazas' operation/ processing time is established, results may be used for simulation models' calibration.

4.2. Step 2 Data Collection and Preparation

To effectively calibrate any simulation model site data must be used to compare simulation results for model validity. Information collected in the field typically consists of three types of data: site geometries, traffic characteristics, and vehicle distributions. Calibration data commonly consists of one or more traffic characteristics, such as: capacity, demand, travel time, queue length, delay, etc. To avoid collecting useless field data researchers should choose which measures of effectiveness will be used for model evaluation and calibration. For this research a one day pilot study was conducted at a randomly selected toll plaza to test data collection equipment, data collection procedures, investigate site details, and visually observe traffic patterns. A rehearsal data extraction activity was also conducted to gain experience in the process, practice extraction techniques, and learn the limitations of the field collected data. The preparation of the final data is just as important as the collection process. The raw data collected in the field has to be extracted so that it represents the data needed to satisfy the goal of the collection. The data must also be checked for consistency at this step. It is important that field collected data is complete and targets a specific traffic condition. For example, field collected capacities may be checked against the HCM analysis to ensure there is not a large variation. If there is skeptical variation of any classification it is recommended that the data be reevaluated to confirm differences are genuine.

4.3. Step 3 Base Model Development

The goal of the base model development is to accurately recreate the traffic organization, operation, and driver behaviors that existed at the field data collection site. This step provides verification that the software is compatible to the uniqueness of each site. Because the SHAKER model was designed strictly for toll plazas there is little to no initial model development required. In order to build a toll plaza configuration, the SHAKER model simply requires the user to input number of lanes, vehicle distributions, and demand volumes. The specifics on how to develop the model to replicate the field conditions is well described in program's user manual, thus these steps will serve as the primary reference for building the initial model. An extensive review of how the model is developed is provided later in the paper.

4.4. Step 4 Basic Model Error Checking/Initial Evaluation

Error checking and initial evaluations of the simulated model should be completed before calibration takes place. If a traffic or network related error is detected after calibration it can potentially cause the entire calibration process to be deemed obsolete. One aspect of basic error checking is visually observing the base case animation model to ensure that general traffic behaviors are observed. The importance of manual visualization checks can not be overlooked because as powerful as the computer is, it does not have the judgment and reasoning skills of the human mind. The computer will undoubtedly produce the optimum model but, without correct user defined parameters, it does so without meaningful knowledge if the simulation specifics are realistic. At this point in the procedure is a good step to check that input distributions are functioning as intended. Initial checks may consist of categorizing the throughput results by vehicle type to ensure that the same inputted vehicle distributions were used for the simulation or recording all toll plaza dwell times and comparing them against the programmed dwell time distribution to ensure that the model recreates the intended activity. The later portion of this step is to initially evaluate the base model to check its ability to simulate field conditions. Statistical tests should be conducted to determine if the simulated measure of effectiveness (MOE) are within an acceptable range of the target values. Therefore, a well acceptable range of error must be defined. If the software can initially predict MOEs based on default values alone then there is no need to calibrate the model any further.

4.5. Step 5 Model Calibration

The next step of the experimental design is the actual calibration procedure. According to the FHWA Guidelines for Applying Traffic Microsimulation Modeling Software *(6):*

> Calibration is the adjustment of model parameters to improve the model's ability to reproduce local driver behavior and traffic performance characteristics. Calibration is necessary because no single model can be expected to be equally accurate for all possible traffic conditions. Even the most detailed microsimulation model still contains only a portion of all of the variables that affect real-world traffic conditions. Since no single model can include the whole universe of variables, every model must be adapted to local conditions.

Before any calibration can take place it is important to determine which MOE will be used for as a surrogate measure to match the model. Next, influencing parameters must be classified as either directly affecting the MOE or not affecting the MOE. Only simulation parameters that affect the MOE should be reviewed and adjusted in order to reach the optimum parameter configuration. When possible, the parameters in which field data is available should be implemented before any parameters are adjusted because measured values represent justifiable alterations to the base model. Remaining parameters can be used for model calibration in a series of logical, sequential steps. Each time a parameter is adjusted the new model should be evaluated for performance measures and then compared to field conditions. Checking the model results for similarity to the field measured conditions requires use of statistical analysis to improve reliability. The differences between the predicted model outputs, when compared to field measured values, are called the residuals and are used to evaluate the usefulness of the model. Root mean square error, analysis of variance (ANOVA), and/or student t-tests are a few variations of statistical tests used in such analysis *(34)*. Unlike stochastic models, deterministic models will always produce the same results when repetitions are preformed with the same input data. Therefore, there is no need to calculate how many runs are required when using this type of simulation.

4.6. Step 6 Evaluation of Calibrated Parameter Set

The evaluation of the calibrated parameter set step is to compare the original default parameters versus the calibrated parameters found in the previous step. It is important to compare the results to ensure that the calibrated parameters are justifiable and not just the values that force the calibration to match field conditions.

4.7. Step 7 Validation

The final model calibration step consists of two verification sub steps that are intended to finalize the model and approve of its functionality. The first of the two validation steps requires that the simulation model be visually evaluated for reasonability and that ensure the model functions realistically. Visualization checks are important because the computer will always produce optimal models but sometimes does so without knowing if the simulation specifics are realistic by human drivers. The second of the verification steps is to statistically verify that the calibrated model estimates, within range, similar results when compared to an additional untried data set. Usually this is done so using data collected at the same site but for a different day or using data collected at a similar site but different location. For this research the validation data will be extracted from the same site but from a different day and to ensure validation, an additional parameter to the original will be examined. These last two steps are very simple compared to the calibration techniques previously discussed, but prove to be extremely important in ensuring that the simulation model compromise a useful model.

5. IMPLEMENTING THE EXPERIMENTAL DESIGN PROCEDURE

To complete the objectives of this research, the described methodology had to be implemented specifically for use with the SHAKER program. The organization of the experimental design portion of this research follows a systematic sequence of events that if altered could potentially impact the calibration results. The following sections provide information on how each step was implemented. Steps 1 and 2 are independent of the SHAKER model or any simulation model so they are introduced first and then after is a section pertaining specifically to the calibration of the SHAKER model.

5.1. Step 1 Identification of Study Purpose, Scope, and Approach

The benefits of simulation models led to the purpose of this study, which was to examine the effectiveness of two toll modeling programs that are similar in purpose but vary in approach and methodology. SHAKER has the potential to work as a tool that can estimate the maximum throughput and capacity of toll plazas. Some major benefits from using this model are examining how traffic conditions will change when a lane is closed due to maintenance or construction, or how adding more lanes would improve the plaza operations. Since the population in the Central Florida area continues to grow rapidly simulation will prove to be useful in order to adjust for future traffic demands. In summary, the objective of this study is to develop, calibrate, and analyze the SHAKER toll plaza simulation models. To conduct this research necessary data had to be collected at multiple toll plazas along the FTE network in Central Florida. Ultimately, the research process consists of using data collected in the field to serve as the principal dataset in which later developed simulation results will be calibrated.

5.2. Step 2 Data Collection and Preparation

In an effort to correctly calibrate the SHAKER toll plaza tool, field data was collected at four Florida's Turnpike operated toll facilities located in Central Florida. Each site differed from the others in terms of the number of lanes, lane configuration, toll base fee, highway location, traffic demand, and vehicle type percentage. The sites chosen for data collection were: the Lake Jesup Mainline Plaza along the Seminole Expressway (SR-417), the Beachline West Expressway Toll Plaza (SR-528), the Daniel Webster Western Beltway Plaza (SR-429), and the Leesburg Toll Plaza along the Florida's Turnpike Mainline (SR-91).

Table 4 presents the different elements at each of the toll plaza faculties. Unless noted in the table, it can be assumed that opposing directions share similar characteristics. Figure 8 shows a pictorial of a typical toll plaza configuration and how lanes along the Florida's Turnpike system are configured and shows how each payment type follows a color coordinated scheme. Figure 9 shows all 5 toll plaza configurations with number of lanes and shows how lane configurations split from original travel lanes to multiple toll plaza service lanes.

Table 4: Field Data Site Locations - Toll Plaza Characteristics

	base toll fee (two axel)	# of total lanes	# of high speed ETC lanes	# of non high speed ETC lanes	# of manual pay lanes	# of exact change coin lanes	gate regulated lanes
Lake Jesup SR-417	$2.00	4	0	2	2	0	Yes
Beachline Eastbound SR-528	$0.75	6	0	2	2	2	Yes
Beachline Westbound SR-528	$0.75	5	0	2	2	1	Yes
Western Beltway SR -429	$1.00	4	2	1	1	0	Yes
Leesburg Plaza SR-91	$2.50	5	0	1	4	0	Yes

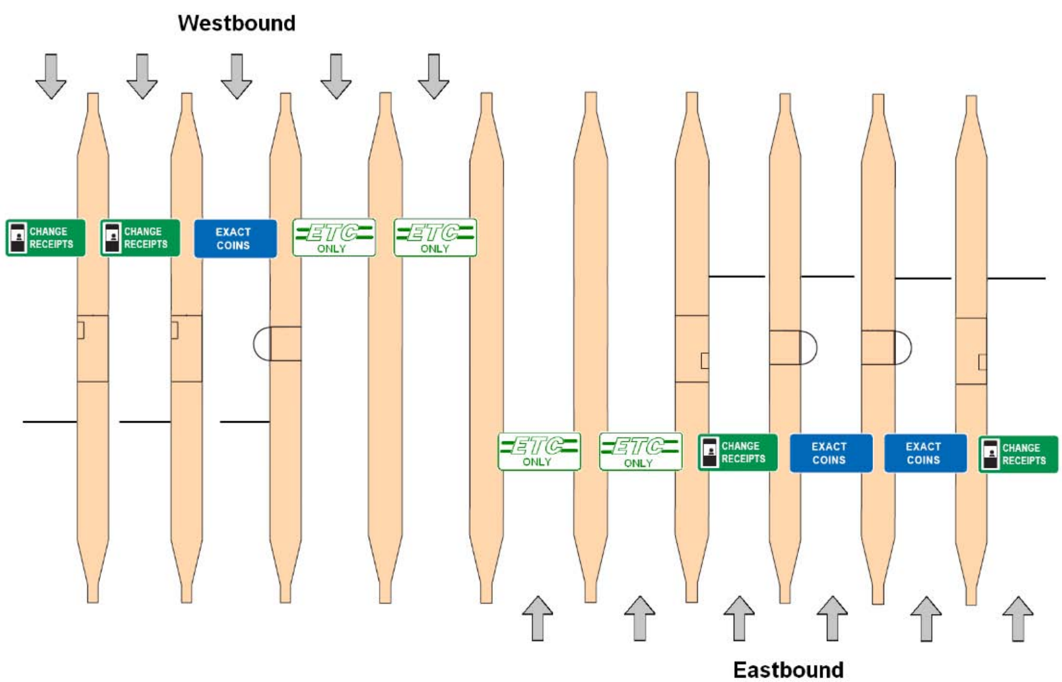

Figure 8: SR-528 Beachline West Toll Plaza Configuration

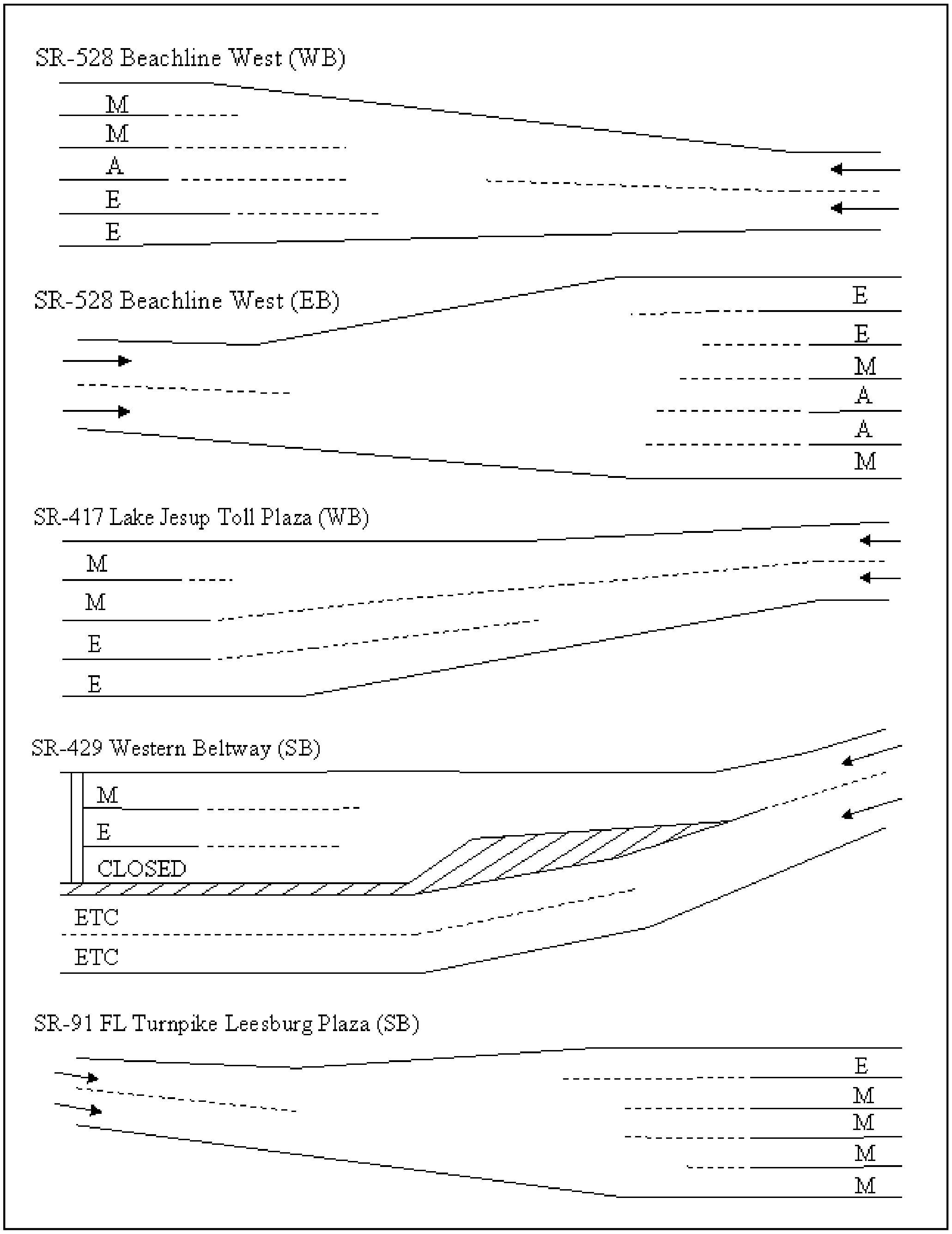

Figure 9: Toll Plaza Configurations.

Field data collected was categorized into three major categories: traffic characteristics, vehicle distributions, and toll plaza characteristics. The traffic data collected at each plaza was volume, demand, throughput, and queue lengths. The individual vehicle data collected was vehicle type, lane choice, processing time, payment type, whether the vehicle arrived during a queue or not, arrival time, departure time, and inter-arrival time between vehicles. The toll plaza data recorded consisted of the number of lanes, number of each type of lane, whether the direction of travel was into or out of the metropolitan area, and whether the plaza was observed during the AM or PM. Table 5 is provided to show an inventory of the video data recorded and the amount of lane-hours at each of the toll plaza sites.

As shown in Table 5, different lane-hours totals were collected for each data collection site. This total varies because each plaza's effective role towards the research goal differed and because of data collection feasibility limitations. Several more lane hours were collected at the Beachline West and Lake Jesup because these sites utilized all possible lane types, they experienced the most diverse vehicle and payment type percentages, and were selected as the plazas to use for primary calibration purposes. Calibration requires several additional hours of data to ensure that enough data points are collected to make an accurate estimate of driver behaviors. Data collected from the Lake Jesup, Western Beltway, and Leesburg Plazas were primarily used for verification purposes so not as many hours of data were needed. After preliminary analysis of the Lake Jesup plaza, it was determined that for model verification the amount of lane-hours required for the Western Beltway and Leesburg plazas could be reduced.

Table 5: Video Data Inventory

Toll Plaza Site	Direction of Travel	Peak Period	Days Collected	Lane-Hours Collected
Lake Jesup SR-417	Northbound	AM	6	24
Sept. 4-6 2007		PM	6	24
	Southbound	AM	6	24
		PM	6	24
Beachline West SR-528	Eastbound	AM	5	25
Nov 13-15, 2007		PM	6	30
Feb. 20 & 25, 2008	Westbound	AM	5	25
		PM	6	30
Western Beltway SR-429	Northbound	PM	1	6
April 16, 2008	Southbound	PM	1	6
Leesburg Plaza SR-91	Southbound	AM	1	10
April 2 & 8, 2008		PM	1	10

5.2.1. Data Collection Equipment Configuration

At each site four cameras are used to capture operations at and upstream of the toll plaza facility. All four of the cameras were started simultaneously and each captures a different condition. Two of the four cameras were used to capture one approach and the other two are simultaneously capturing the opposing direction. Figure 10 shows an aerial view of the Lake Jesup Toll Plaza and is provided to show an example of how the cameras were configured at each site. One camera (Figure 10: NB & SB Camera 1) in each direction was primarily used to capture the throughput, processing times, inter-arrival time, vehicle type, and payment type for each lane.

The second camera (Figure 10: NB & SB Camera 2) in each direction was set to capture the demand and queue conditions. A still frame image of the video provides an example of both camera set ups in Figure 11 and Figure 12. Similar placed camera arrangements were implemented at the other data collection locations, but exact locations were ultimately restricted by right of way and safety considerations. The video image collection process for each site took place over multiple days and captured two hours during the morning (7-9AM) and afternoon (4-6PM) rush hour peaks.

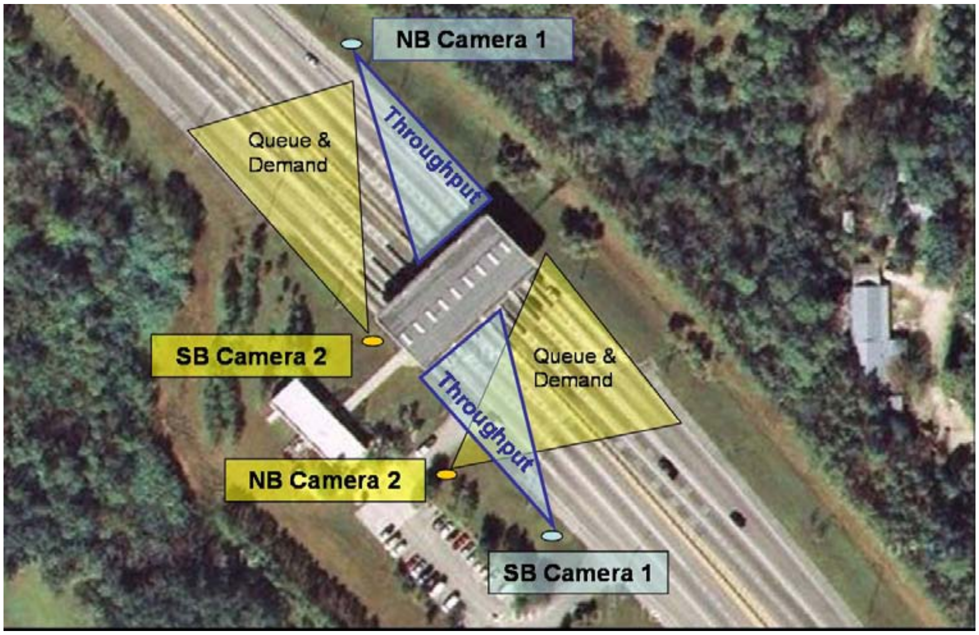

Figure 10: Camera Setup Configuration Example

Figure 11: Video Image Example of Camera 1 (Throughput and Processing time)

Figure 12: Video Image Example of Camera 2 (Demand and Queue Length)

5.2.2. Data Extraction Procedure

Once the digital videos were transferred from the camera to the computer, the software Adobe Premier Professional was used to view the files. This program allows the user to study videos to the accuracy of 30 frames per second. Traffic characteristics such as demand, throughput, processing rates, and queue lengths of different toll categories were extracted from the digital video. The throughput was recorded as the number of vehicles that pass through the toll per 15 minutes. The demand is the throughput plus the length of the queue, if present, and is also measured every 15 minutes. In addition, the lane choice and vehicle type (passenger car or truck) was recorded. The following descriptions explain each variable and how it was collected:

- Throughput – recorded as the number of vehicles that pass through the toll plaza within a period of time. Each vehicle is classified by an arrival time and departure time. Recording specific arrival times allows for throughput to be determined for any time frame desired.
- Demand – is the throughput plus the length of the queue, if present. This was measured by counting the number of vehicles in the queue at any given time and adding that value to the throughput for the same period.
- Processing Time – is the calculated difference between the arrival and departure time. The arrival time is the instant that the vehicle makes a complete stop within the toll collectors range. It was observed that a number of drivers attempt to offer their payment to the toll collector while their vehicle is still slowly crawling. In this case the arrival time is classified as the instant the individual begins the transaction with the toll collector. The departure time is recorded upon the onset of acceleration following the payment. The processing times can be very short so it is important to be as precise as possible; therefore, the arrival and departure times are extracted from the video with $1/30^{th}$ of a second accuracy.

- Move-ahead-time – The elapsed time between the lead vehicle departure time and following vehicles arrival time. The Move-ahead time is calculated as the time elapsed difference between the Inter-arrival time and the Processing time.
- Queue Length – is measured as the number of vehicles building up in each lane who are waiting to be served by the toll attendant. Queue length was measured by simply counting the number of vehicles in the queue. Through the benefits of video review this can be recorded at any point in time.
- Arrival on Queue – When a vehicle approaches the toll plaza it is either faced with a queue resulting from previous toll plaza delay or is faced with no queue. For this research arriving during a queue means they are at least the third vehicle in line. A vehicle arriving as the first or second vehicle at the toll plaza is not considered arriving during queue.
- Vehicle Type –two categories of vehicles were recorded, either a vehicle was recorded as a passenger car or a truck. A truck is considered any vehicle having or towing more than two axles touching the pavement.
- Lane Type – 4 types of lanes were observed. They are Electronic Toll Collection lanes (ETC), High Speed ETC, Manual Attendant Mixed lanes and Automatic Coin Machine Mixed lanes.
- AM/PM – Video analysis of periods occurring in the morning peak (7-9AM) were classified as AM and periods occurring in the afternoon peak (4-6PM) were classified as PM.

Each vehicle passing the toll plaza during the analysis period was considered one data point. Every non ETC vehicle was observed for above criteria and data was recorded in a table that exceeded 20,000 entries. Vehicles using the ETC lanes were only observed for vehicle type, demand, and throughput. By design, ETC vehicles do not stop so in their case the other parameters proved no practical significance. An example of the individual vehicle data extraction table is provided in Table 6. All vehicles not using the ETC lane use either the ACM or manned lanes. These vehicles are subject to all extraction information data. An additional table is used to organize all vehicle extraction data for volumes, demands, queue lengths and, vehicle type percentages. An example of that table is shown in Table 7 below. All vehicles not using the ETC use either the ACM or manual lanes and they were subject to all processing information data. The number of non-ETC vehicles and lane-hours analyzed for each toll plaza location is listed below in Table 8.

Table 6: Example of Individual Vehicle Data Extraction Table

Veh ID	site	Lane #	Time AM(0), PM(1)	metro out(0) into(1)	lane type m(0) a(1)	Vehicle Type (M or T)	Arrival Time Min	Arrival Time Second	Arrival Time Frame	Departure Time Second	Departure Time Frame	Processing Time (sec)	inter-arrival time (sec)	queue present(1), no queue(0)	volume (veh/15min)
1	6	1	1	1	0	M	0	0	0	7	17	7.57	4.33	1	84
2	6	1	1	1	0	M	0	11	10	12	15	1.17	3.77	1	84
3	6	1	1	1	0	M	0	16	6	18	22	2.53	3.70	1	84
4	6	1	1	1	0	M	0	22	25	26	18	3.77	4.10	1	84
5	6	1	1	1	0	M	0	31	13	44	10	12.90	4.83	1	84
6	6	1	1	1	0	T	0	47	11	57	29	10.60	3.03	1	84
7	6	1	1	1	0	M	1	4	2	9	21	5.63	6.10	1	84
8	6	1	1	1	0	M	1	13	23	16	10	2.57	4.07	1	84
9	6	1	1	1	0	M	1	20	14	23	16	3.07	4.13	1	84
10	6	1	1	1	0	M	1	28	15	30	19	2.13	4.97	1	84
11	6	1	1	1	0	M	1	35	8	40	14	5.20	4.63	1	84
12	6	1	1	1	0	M	1	45	14	47	14	2.00	5.00	1	84
13	6	1	1	1	0	M	1	49	14	52	13	2.97	2.00	1	84
14	6	1	1	1	0	M	1	56	16	58	15	1.97	4.10	1	84
15	6	1	1	1	0	M	2	2	8	6	1	3.77	3.77	1	84
16	6	1	1	1	0	M	2	8	22	11	12	2.67	2.70	1	84
17	6	1	1	1	0	M	2	15	7	19	0	3.77	3.83	1	84
18	6	1	1	1	0	M	2	22	28	24	24	1.87	3.93	1	84
19	6	1	1	1	0	M	2	27	23	36	2	8.30	2.97	1	84
20	6	1	1	1	0	M	2	40	28	43	6	2.27	4.87	1	84
21	6	1	1	1	0	M	2	47	21	50	13	2.73	4.50	1	84
22	6	1	1	1	0	M	2	55	0	57	4	2.13	4.57	1	84
23	6	1	1	1	0	M	2	59	24	64	29	5.17	2.67	1	84
24	6	1	1	1	0	M	3	8	27	13	8	4.37	3.93	1	84
25	6	1	1	1	0	M	3	16	14	21	9	4.83	3.20	1	84
26	6	1	1	1	0	M	3	25	1	28	22	3.70	3.73	1	84
27	6	1	1	1	0	M	3	33	8	37	12	4.13	4.53	1	84
28	6	1	1	1	0	M	3	42	18	44	24	2.20	5.20	1	84

Table 7: Example of Traffic Data Extraction Table

Date/Time	15 min period	Passenger Car Throughput veh/per lane (from out to inner lane)					Truck Throughput veh/per lane (from out to inner lane)					Through-put Total	Que Length (per 15 min)			Demand (veh/hr)
		M	M	A	E_p	E_p	T	T	A	E_T	E_T		M	M	A	
2/25/2007	0-15	87	95	93	113	132	4	0	0	17	4	545	10	12	8	575
4:00 -5:00 PM	15-30	87	88	89	137	144	2	2	0	6	3	558	1	2	2	563
	30-45	77	86	82	118	158	4	1	0	6	4	536	0	2	0	538
	45-60	75	88	74	141	149	1	0	0	12	3	543	15	10	15	583
Hourly Total		326	357	338	509	583	5	1	0	18	7	2182	-	-	-	2222

Table 8: Data Analysis Inventory

Data Acquisition Location	Vehicles Procesed	Lane-Hours Analyzed
Lake Jesup SR-417		
Northbound	3,297	16
Southbound	3,904	16
Beachline West SR-528		
Eastbound	5,404	24
Westbound	5,619	19.5
Western Beltway SR-429		
Northbound	219	2
Southbound	313	2
Leesburg Plaza SR-91		
Southbound	1,694	16
Total	20,450	95.5

5.2.3. Data Investigation

To calibrate the SHAKER model the capacity was selected as the measure of effectiveness to evaluate first, hence field observed capacity was compared to the model estimated capacity. To measure capacity in the field, the FHWA recommends observing locations where queues persist for at least 15 consecutive minutes and then measure the flow rate at the point where the queue discharges. The resulting flow rate is the field-measured capacity *(6)*. Therefore, only periods under queuing conditions were used in the calibration and validation process. The following tables (Table 9 and Table 10) show the data used for calibration and validation of the SHAKER model. Each of the periods listed was under constant queuing during the data extraction period. The calibration periods of both the manned and ACM lanes was observed along the Westbound Beachline West SR-528 toll plaza on Feb 25, 2008. The verification data is compromised of a mixture of data from the same toll plaza but from the Westbound approach on Feb. 25, 2008 and the Eastbound and Westbound approach on Nov. 13, 2007.

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Table 9: SR 528 Data for Calibration and Validation of Manned and ACM Lanes

		Period	Demand (vphpl)	Capacity (vphpl)	Queue Length (vehpl)	% Trucks	% non Trucks
Manned Lanes	Calibration Data	1	339	336	3	0.036	0.964
		2	374	364	10	0.044	0.956
		3	357	356	1	0.022	0.978
		4	402	344	58	0.012	0.988
		5	415	332	83	0.036	0.964
		6	435	352	83	0.034	0.966
		7	351	348	3	0.011	0.989
		8	392	380	12	0.000	1.000
		9	362	360	2	0.022	0.978
		10	350	348	2	0.011	0.989
		11	362	352	10	0.000	1.000
		12	438	380	58	0.000	1.000
		13	435	352	83	0.011	0.989
		14	451	368	83	0.011	0.989
	Validation Data	15	372	364	8	0.033	0.967
		16	366	364	2	0.022	0.978
		17	329	328	1	0.101	0.899
		18	374	364	10	0.032	0.968
		19	385	376	9	0.031	0.969
		20	395	388	7	0.020	0.980
		21	382	380	2	0.021	0.979
ACM Lanes	Calibration Data	1	388	376	12	0.0	1.0
		2	380	372	8	0.0	1.0
		3	358	356	2	0.0	1.0
		4	338	328	10	0.0	1.0
		5	370	312	58	0.0	1.0
	Validation Data	6	369	364	5	0.0	1.0
		7	333	328	5	0.0	1.0
		8	319	316	3	0.0	1.0
		9	369	364	5	0.0	1.0
		10	345	340	5	0.0	1.0
		11	379	376	3	0.0	1.0
		12	394	392	2	0.0	1.0

Table 10: SR-417, SR-429, FL Turnpike Queuing Periods

Additional Toll Site Data Used for Validation of Calibration technique

	Period	Capacity (vphpl)	% Trucks	% non trucks
SR 417 Manned Lanes	1	360	0.000	1.000
	2	376	0.000	1.000
	3	342	0.018	0.982
	4	360	0.033	0.967
	5	384	0.000	1.000
	6	372	0.000	1.000
	7	344	0.012	0.988
	8	388	0.031	0.969
	9	348	0.046	0.954
	10	342	0.035	0.965
SR 429 Manned Lanes	1	420	0.0	1.000
	2	380	0.0	1.000
FL Turnpike Manned Lanes	1	204	0.0	1.000
	2	200	0.0	0.970

To determine the capacity it was also important to filter the data to eliminate potentially unfavorable traffic conditions. The test to run on the data was to determine if any of the saturated periods are performing statistically different than any of the other periods is described. To test this, the individual vehicle's processing time and inter-arrival time from each group was statistically compared to the same parameters in the other group by use of ANOVA statistics. The importance of this check is to determine if there were any unaccountable errors in the traffic makeup that were not detectable from simple observation. Also, in order to investigate different periods, the service times must not be significantly different; otherwise the periods will not have analytical value as a data test set to be used for calibration *(8)*. If the processing times are significantly different from one group to another it suggests that the period at question experiences unique conditions that could be attributed by factors other then the traffic; for example, the speed of toll plaza operator, a slower release gate, congestion downstream, etc. If the inter-arrival time distribution of one period was statistically different from the next period it suggests that there is not as constant of a queue as expected, thus capacity is not reached. When a queue is present the spacing of vehicles is assumed to be generally the same distance thus the inter-arrival time should be generally consistent.

The statistics used for this test was an Analysis of Variance (ANOVA). ANOVA is similar to regression in that it is used to investigate and model the relationship between a response variable and one or more predictor variables. However, analysis of variance differs from regression in two ways: the predictor variables are qualitative (categorical), and no assumption is made about the nature of the relationship (that is, the model does not include coefficients for variables). In effect, analysis of variance extends the two-sample t-test for testing the equality of two population means to a more general null hypothesis of comparing the equality of more than two means, versus them not all being equal.

The output from an ANOVA study is arranged in the tables below (Table 11). The table consists of the sources of variation, their degrees of freedom, the total sum of squares, and the mean squares. The ANOVA table also includes the F-statistics and p-values. These values were used to determine whether the predictors or factors are significantly related to the response.

The following describes the statistical test:

Null Hypothesis (Ho): the lanes data are not significantly different
Alternative Hypothesis (Ha): the lanes data are significantly different
Test Statistic: (p-value) significance of 95%

The following is a list of the components of the ANOVA tables (Table 11):

- Source - indicates the source of variation, either from the factor, the interaction, or the error. The total is a sum of all the sources.
- DF - degrees of freedom from each source. If a factor has three levels, the degree of freedom is 2 (n-1)
- SS - sum of squares between groups (factor) and the sum of squares within groups (error)
- MS - mean squares are found by dividing the sum of squares by the degrees of freedom.
- F - Calculated by dividing the factor MS by the error MS; one can compare this ratio against a critical F found in a table or use the p-value to determine whether a factor is significant.
- P - used to determine whether a factor is significant; typically compared against an alpha value of 0.05. If the p-value is lower than 0.05, then the factor is significant.

From Table 11 the p-value of the processing times and inter-arrival times for each period are p=0.974 and p = 0.108 respectively. P-values greater then 0.05 leads to failing to reject the null hypothesis and suggests that there is not enough statistical evidence to disprove that there is statistical difference between each period's processing times and inter-arrival times. The conclusion that can be drawn for this analysis is that even though the throughputs per hour in each time frame varies from 328 to 388 vehicles per hour per lane there is no indication that the capacity is affected by exterior elements. Because these two tests show no significant differences they are suitable to serve as the primary targets used for simulation calibration. If a statistical difference did occur in one of the time frames it would suggest that this time frame does not follow one of the constraints of determining capacity, which is that results should be repeatable under common conditions.

Table 11: ANOVA Table SR-528 Processing Times and Inter-Arrival Times of Calibration and Verification Data

One-way ANOVA: Processing Time versus Period

Source	***DF***	***SS***	***MS***	***F***	***P***
Period	20	334.6	16.7	0.48	0.974
Error	1844	64085.5	34.8		
Total	1864	64420.2			

One-way ANOVA: Inter-arrival Time versus Period

Source	***DF***	***SS***	***MS***	***F***	***P***
Period	20	52.0	2.6	1.41	0.108
Error	1841	3401.2	1.85		
Total	1861	3453.1			

Individual Period Results

		Processing Time		***Inter-arrival Time***	
Level	***N***	***Mean***	***StDev***	***Mean***	***StDev***
1	336	6.41	11.87	4.10	1.14
3	364	5.55	3.82	4.13	1.09
4	356	5.70	4.48	4.17	1.24
7	344	6.08	5.40	4.26	1.96
8	332	5.87	5.42	4.30	1.21
9	352	5.31	5.58	4.14	0.78
11	348	5.15	4.61	4.59	1.05
13	380	5.02	4.02	4.42	1.11
14	360	5.46	3.74	4.54	1.07
15	348	5.77	4.33	4.43	1.26
16	352	5.73	3.84	4.45	1.15
17	380	5.30	4.22	4.23	0.83
18	352	5.86	5.31	4.33	1.00
19	368	5.49	5.58	4.20	0.93
42	364	5.02	3.93	4.64	1.50
44	364	5.62	10.75	4.25	1.18
45	328	6.64	5.47	4.38	2.55
48	364	5.43	5.56	4.62	1.56
50	376	5.01	6.07	4.61	1.75
51	388	5.62	7.28	4.28	0.99
52	380	5.10	5.09	4.36	1.90

6. CALIBRATING THE SHAKER MODEL

6.1. Step 3 SHAKER Model Development

As mentioned previously, calibration of simulation models is necessary if the initial default parameters of the model being used do not result in verifiable traffic measure. However, because even the most detailed model still contains only a portion of all of the variables that affect real-world traffic conditions almost every model will require some form of calibration. Also, since no single software can realistically include each and every variable, every model must be adapted to fulfill the objectives of the study. The objective of the calibration process is to find a set of parameter values for the model that best reproduces local traffic conditions *(6)*. The objective of the calibration of SHAKER is to find a set of parameter values that best reproduces the capacity of the non-ETC payment lanes at toll plazas.

6.2. SHAKER Calibration Steps

The calibration of SHAKER was divided into several steps. First, a particular toll plaza was coded in SHAKER and a measure of effectiveness (MOE) was selected to serve as the index of comparison. Second, an initial evaluation was conducted with SHAKER's default parameter values. Third, if the selected measure of effectiveness was different in simulated and real conditions, an examination of the key parameters was conducted and calibration parameters were determined. Multiple runs with different values of the key parameters were run by trial and error until the calibration part is completed. Fourth, as for the validation part, different toll plazas were coded in SHAKER and the field observed MOE was compared to the simulation MOE.

The overriding assumption for calibrating models is based on simplifying fixed parameters as much as possible. Fixing parameters and/or constraining them to certain intervals helps address the calibration process. Usually the average length of a vehicle type and distance between standing vehicles can be measured rather simply and precisely so that they can be assumed constant in the calibration process. Furthermore, it is a reasonable assumption that manual vehicles, M, and passenger cars with transponders using the manned booth lane, E_P, have the same acceleration, a, and deceleration, d, properties, average length, l, and distance between standing vehicles, b. The same is true for trucks, T, and trucks with transponders using the manned lanes, E_T. The driver's reaction time, t_R, is assumed equal for all customer types. Electronically paying vehicles have no time to pay, $t_{stop} = 0$. ACM users, A, should have the same properties as manuals, M, except the time to pay, $t_{stop}A$, varies *(2)*. SHAKER was initially calibrated and validated on the OOCEA network and the resulting key calibration parameters are presented in Table 12 and are used by SHAKER as default values.

Table 12: Initial Calibration Parameters of SHAKER (31)

	M	T	A	E_P	E_T
l_X =Average vehicle Length (meters)	5.8	21	5.8	5.8	21
b_X = Distance between vehicles (meters)	2.0	3.0	2.0	2.0	3.0
a_X = Vehicles' Acceleration (meters/second^2)	2.0	0.25	2.0	2.0	0.25
d_X =Vehicles' Deceleration (meters/second^2)	2.0	0.25	2.0	2.0	0.25
T_R = Drivers' reaction Time (seconds)	1.8	1.8	1.8	1.8	1.8
$t_{stop\ X}$ = Stop–Time at payment (seconds)	1.5	4.7	0.075	0.0	0.0

To calibrate SHAKER, first the capacity was selected as the measure of effectiveness of the model, hence field observed capacity was compared to the model estimated capacity. To measure capacity in the field, the FHWA recommends observing locations where queues persist for at least 15 consecutive minutes and then measure the flow rate at the point where the queue discharges. The resulting flow rate is the field-measured capacity *(6)*. Therefore, only periods under queuing conditions were used in the calibration and validation process (see Table 9 and Table 10).

6.2.1. Step 4 Initial Evaluation of SHAKER

Second, since the SR-528 toll plaza had all possible lane types in use the initial evaluation of SHAKER was implemented using SR-528 toll plaza, shown in Figure 1. Next, SR-528 was coded in SHAKER, the simulation was run and the simulated toll plaza capacity was determined. The default key parameters used in the first run are shown in Table 12. Field observed capacities were determined for 14 periods (15 minute-intervals) for the manual pay lanes and 5 periods (15 minute-intervals) for the ACM lanes (see Table 9). As shown in Table 14, the initial simulated capacities and the field observed capacities are significantly different (manual lane *p*-value=4.9E-17, ACM *p*-value=2.7E-05).

6.2.2. Step 5 & 6 SHAKER Calibration and Error Checking

After investigating key parameters of SHAKER, it was determined that the model bases the capacity of a lane on the combination of 5 parameters; they are: vehicle length, spacing, acceleration and deceleration, perception-reaction time, and stop-time. In agreement with literature it was determined that of the possible parameters the stop-time was the variable that would vary the most from toll plaza to toll plaza. Therefore, to calibrate the SHAKER model all variables except the stop-time were preset from location to location for each lane group. It should be noted that when using the field data for parameter estimation only the values from the selected periods of queuing should be used for calibration. To obtain the calibration parameters for stop-time, the stop-time mean and mode of only queuing periods were calculated. The approach to use these statistics was based on that the stop-time mode is related to planning evaluation and the stop-time mean is related to operational analysis. Run2 and Run3 were conducted with adjusting stop time (or processing time) while keeping all other parameters fixed. Table 13 shows the parameter values used in each run. For Run2, where the stop time parameter was adjusted using the average field measured stop time, the difference between the modeled and field observed capacities for the manual and ACM lanes were still statistically significant (*p*-value=2.3E-11, *p*-value=0.09 respectively, see Table 14. In Run3, where the mode field measured stop-time was used, the difference between the modeled and field observed capacities for the manual and ACM lanes were not statistically significant (*p*-value=0.315, *p*-value=0.181 respectively; see Table 14). However, also shown in Table 14, the mean relative errors were 2.91% and 6.35% for the manual and ACM lanes in that order.

It was then determined that not only the stop-time parameter, but all 5 parameters should be reevaluated with the extracted data. In earlier calibrations of SHAKER *(2)* all parameters were fixed and estimated capacities were calibrated by forcing the stop-time to result in capacities that matched field data observed by Zarrillo in 1998 *(30)*. It was then proposed to use field data for not only capacities, but for stop-time, reaction times, acceleration and decelerations. First, erroneous decimals in the averages spacing and vehicle lengths were rounded to the nearest whole number to ease future use. The code was originally written with metric units and when converted to SI units superfluous decimals were uncovered. The driver-reaction time was then reconsidered. By nature, the reaction time is difficult to precisely measure, but based on video observation analysis the reaction time was estimated to average 1 second instead of the preprogrammed default of 1.8 seconds. Next, new acceleration and deceleration values were calculated using the field observed inter-arrival times. To determine the time needed for acceleration and deceleration the SHAKER code assumes that the driver accelerates for half the spacing distance and then decelerates for the remaining half. In the field collected data the inter-arrival time was used in conjunction with the linear equation of motion under uniform acceleration to determine an appropriate value (distance traveled equals one half the acceleration times elapsed time squared, $d=\frac{1}{2}\alpha \Delta t^2$) and solved for acceleration, *a*. To use this equation the average inter-arrival time was found. Next, the reaction time was subtracted from the inter-arrival time to give the time when the vehicle is actually moving. This time was then divided by 2 to account for the half acceleration and half deceleration spacing assumption. Next, the linear motion equation was used to calculate the acceleration and deceleration needed to traverse the average vehicle spacing. It was noted that to successfully drive the distance created by the vehicle length and spacing the acceleration and deceleration had to be increased from 6.6 to 9.75 ft/s^2 for passenger cars and from 0.825 to 3.95 ft/s^2 for trucks. Table 13 summarizes the adjusted parameters in Run 4.

Table 13: SHAKER Calibration Parameter Inventory

Run Number	SHAKER Calibration Parameter	Automatic Coin Machine	PC Manual Pay	Truck Manual Pay
Run 1 (Non Calibrated SHAKER)	vehicle length (ft.)	19.14	19.14	69.3
	vehicle spacing (ft.)	6.6	6.6	9.9
	vehicle acceleration, (ft/sec^2)	6.6	6.6	0.825
	vehicle declaration, (ft/sec^2)	6.6	6.6	0.825
	driver reaction-time, (sec.)	1.8	1.8	1.8
	toll stop-time, (sec.)	0.075	1.475	4.68
Run 2 (Average Stop-time)	vehicle length (ft.)	19.14	19.14	69.3
	vehicle spacing (ft.)	6.6	6.6	9.9
	vehicle acceleration, (ft/sec^2)	6.6	6.6	0.825
	vehicle declaration, (ft/sec^2)	6.6	6.6	0.825
	driver reaction-time, (sec.)	1.8	1.8	1.8
	toll stop-time, (sec.)	5.48	5.78	17.58
Run 3 (Mode Stop-time)	vehicle length (ft.)	19.14	19.14	69.3
	vehicle spacing (ft.)	6.6	6.6	9.9
	vehicle acceleration, (ft/sec^2)	6.6	6.6	0.825
	vehicle declaration, (ft/sec^2)	6.6	6.6	0.825
	driver reaction-time, (sec.)	1.8	1.8	1.8
	toll stop-time, (sec.)	3.50	3.00	11.00
Run 4 (All Measured Field Data)	vehicle length (ft.)	19	19	70
	vehicle spacing (ft.)	6	6	10
	vehicle acceleration, (ft/sec^2)	9.75	9.75	3.95
	vehicle deceleration, (ft/sec^2)	9.75	9.75	3.95
	driver reaction-time, (sec)	1	1	1
	toll stop-time, (sec)	5.80	5.56	11.00

In Run 4, the key parameters were adjusted once again. The resulting difference between the modeled and field observed capacities for the manual and ACM lanes were not statistically significant (p-value=0.467, p-value=0.860 respectively; see Table 14). Moreover, also as shown in Table 14, the mean relative errors decreased to 1.03% and 3.76% for the manual and ACM lanes in that order, which are acceptable errors in simulation (< 5%).

Table 14: Calibration and Verification Statistical Results

Calibration: Errors in SHAKER's Estimation of Toll Lane Capacity										
	Manned Lane					**ACM Lane**				
	Observed Capacity (vph)	**Modeled Capacity (vph)**	***Average Errors*** [1]		**T test Statistic**	**Observed Capacity (vph)**	**Modeled Capacity (vph)**	***Average Errors*** [2]		**T test Statistic**
			% Error	***RMSE***				***% Error***	***RMSE***	
Run 1 (Non Calibrated SHAKER)	355	476	34.22	14,922	4.9E-17	361	618	73.12	73,092	2.7E-05
Run 2 (Mean Stop-time)	355	300	-15.55	3,234	2.3E-11	361	321	10.10	1,396	0.090
Run 3 (Mode Stop-time)	355	365	2.91	959	0.315	361	360	3.37	477	0.181
Run 4 (All Measured Values)	355	358	1.03	158	0.467	361	360	0.85	360	0.860
Validation: Errors in SHAKER's Estimation of Toll Lane Capacity										
	Manned Lane Analysis					**ACM Lane Analysis**				
	Observed Capacity (vph)	**Modeled Capacity (vph)**	***Average Errors*** [1]		**T test Statistic**	**Observed Capacity (vph)**	**Modeled Capacity (vph)**	***Average Errors*** [2]		**T test Statistic**
			% Error	***RMSE***				***% Error***	***RMSE***	
SR 528 Validation Group	366	355	-2.88	549	0.169	354	360	1.26	667	0.5986
SR 417 Validation Group	362	367	1.78	268	0.366	--	--	--	--	--
SR 429 Validation Group	400	414	3.76	596	0.611	--	--	--	--	--
SR 91 Validation Group	202	208	3.22	43	0.131	--	--	--	--	--

[1,2] Although very similar, mean relative Average Errors are calculated by first taking the errors associated with each individual test period then calculating the run average, it is not the error in final Capacity Averages

-- ACM lanes were not in use at these locations

6.2.3. Step 7 SHAKER Validation

Next, for the validation process, SR-528, SR-417, SR-429, and SR-91 were coded in SHAKER. The stop time for each toll-lane at each toll plaza was observed in the field and adjusted in SHAKER accordingly. Table 15 summarizes the final field observed stopping time values for each toll plaza, per lane type, and per vehicle type.

As shown previously in Table 14, there were no statistically significant differences between the observed capacities and the simulated capacities for the manned and automatic lanes (SR-528 Manual lane p-value=0.169, ACM p-value=0.5986; SR417 p-value=0.336, SR429 p-value=0.611, SR91 p-value=0.131). Table 14 also shows that the errors are in acceptable ranges (SR528=-2.88%, SR417=1.78%, SR429=3.76%, SR91=3.22%).

Table 15: Stop Times Used for Validation

		Payment Type		
Validation Data Site Location	**SHAKER Calibration Parameter**	**Automatic Coin Machine**	**PC Manual Pay**	**Truck Manual Pay**
SR-528, EB	toll stop-time, (sec.)	5.8	5.56	11.0
SR-417, NB & SB	toll stop-time, (sec.)	*	5.12	12.9
SR-91 FL TPK, SB	toll stop-time, (sec.)	*	12.50	19.0
SR-429, NB & SB	toll stop-time, (sec)	*	4.49	11.0

* ACM lanes were not utilized at these locations

7. APPLICATIONS AND COMPARISONS OF TOLL PLAZA MODELS

This section is dedicated to the uses and developments of each of the two evaluated simulation models. First, a case study focusing on a new application within the SHAKER model is observed. Next, SHAKER models are coded to represent a lane closure so as to evaluate their strengths in simulating a special case scenario. Lastly, to establish model efficiency, the two model's results were compared to the initial field observed capacities and queue lengths.

7.1. SHAKER Best Configuration Optimization Case Study

A new application was added to SHAKER that has the ability to automatically select the best configuration of a toll plaza given that the lane-user remains unchanged. After inputting data extracted from observed volumes into SHAKER and running the model, this application, using same input data, generates the optimum lane configuration. The optimum lane configuration was based on increasing capacity, reducing queue lengths, but still providing the lanes required to service all payment and vehicle types. Using data from the SR-528 Eastbound approach, an example of the best configuration outputs is generated and shown in Figure 13. The top row displays the best lane configuration; the bottom row represents the current lane configuration, and below both is where the input data is defined. In the display throughputs and capacities are represented by vertical bars, similar to that of a bar chart. The green color bar denotes the capacity of each lane and the red, blue, and yellow denote the throughputs for the ETC, automatic, and manual respectively. Within this application, SHAKER is not limited to providing the results from the best configuration, but also automatically calculates the capacity, throughput, and queue lengths for every possible lane configuration. The pull down menu under POSSIBLE CONFIGURATIONS allows the user to select from any of the lane configurations and visually examine the results of each.

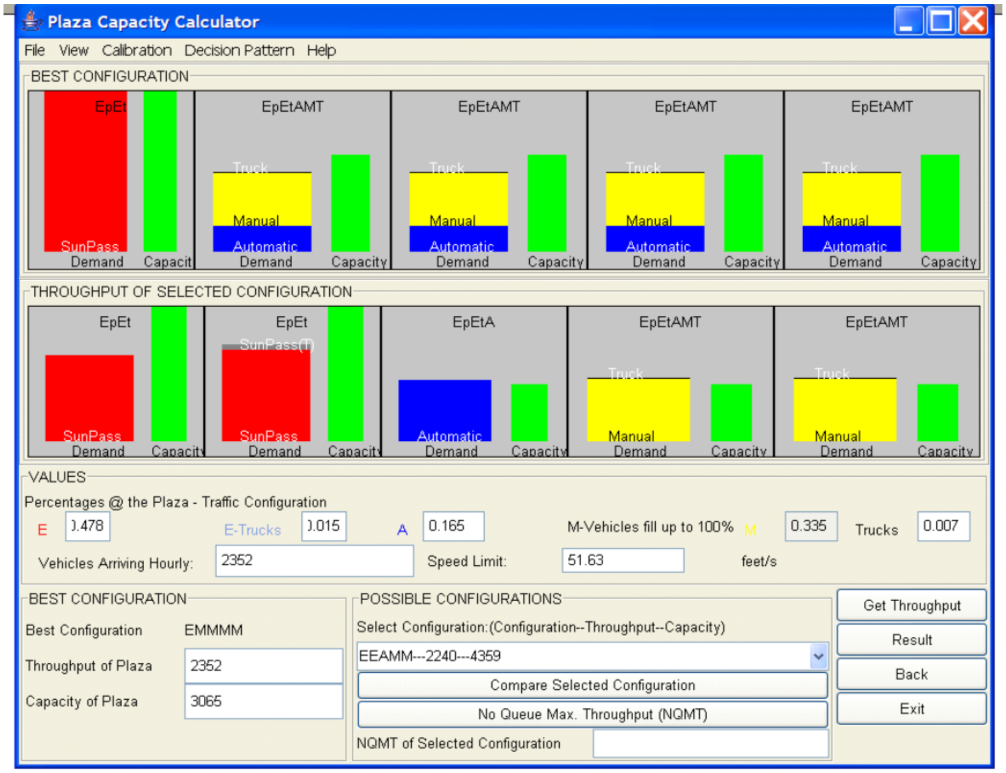


Figure 13: SHAKER Screenshot for Current versus Best Configuration of SR-528 EB

All four toll plazas (six different configurations) were coded in SHAKER and the new SHAKER application was run to determine the optimal toll plaza configuration that increases capacity and reduces queues in the manual and automatic lanes. The data used for demand values and vehicle percentages are randomly selected from the capacity periods that were previously identified in this research. The traffic data inputted for this case study are provided in Table 16. Case study results are shown below, as Table 17 summarizes the current and the optimal configurations of the six configurations. For instance, for SR 528 WB, the existing configuration consists of two ETC lanes, one ACM lane, and two Man. lanes and the optimal selected SHAKER configuration is two ETC lanes, zero ACM lanes, and three Man. lanes. The best configuration of this toll plaza would result is a queue reduction of 119 vph. As shown in Table 18, in order to increase capacity and reduce queuing SHAKER recommended changing the configuration of all toll plazas except for the FL Turnpike toll plaza.

Table 16: Input Data for Best Configuration Case Study

Site Location	Passenger Car Demand veh/hr/per lane type			Truck Demand veh/hr/per lane type			Demand Total (veh/hr)	Queue Length veh/per lane			Vehicle Type Percentages				
	M	A	E_p	M_T	A	E_T		M	A	E	E_p	E_T	M	A	M_T
528 WB	788	388	1124	16	0	36	2352	88	32	0	0.478	0.015	0.335	0.165	0.007
528 EB	636	728	2000	16	0	52	3432	20	20	0	0.583	0.015	0.185	0.212	0.005
528 EB 2	695	776	2000	5	0	52	3528	20	20	0	0.567	0.015	0.197	0.220	0.001
417 NB	708	-	1412	12	-	80	2212	56	-	0	0.638	0.036	0.320	0.000	0.005
417 SB	752	-	2128	0	-	76	2956	36	-	0	0.720	0.026	0.254	0	0
FL TPK	816	-	500	0	-	115	1431	6	-	0	0.349	0.080	0.570	0	0
429 NB	420	-	428	0	-	20	868	20	-	0	0.493	0.023	0.484	0	0

Table 17: SHAKER Selected Optimal Configurations

	Current Configuration			**Best Configuration**			***Total Queue Reduction (vph)***
	Lane Type (count)			***Lane Type (count)***			
Toll Plaza Site	***ETC***	***ACM***	***Man.***	***ETC***	***ACM***	***Man.***	
SR 528 WB	2	1	2	2	0	3	119
SR 528 EB	2	2	2	1	3	2	20
SR 417 NB	2	0	2	1	0	3	14
SR 417 SB	2	0	2	1	0	3	31
FL TPK	1	0	4	1	0	4	0
SR 429 NB	2	0	1	1	0	2	6

7.2. Simulated Lane Closure– Comparison of Special Scenario Case Study

An important element of traffic simulation models is rooted in their ability to adhere to special situations. Due to special events such as: heavy demands, emergency situations, crashes, lane closures, and unexpected maintenance, traffic often deviates from the expected. A simulation model should have the ability to do so also. To test the model's ability to adjust to special situations a lane closure will be coded into the base network and results are collected. A lane closure was chosen as the most advantageous scenario to test because it applies to traffic situations on multiple levels. Obviously, a lane closure represents the situation of actually closing a lane due to maintenance or accident at the toll plaza. In addition, if the same input volume is used a lane closure also estimates the effects of an increased traffic demand per lane. Instead of running another simulation to test increased demand, the lane closure forces the same situation upon the model. This procedure will also provide results on whether or not the SHAKER model produces similar toll plaza results to that of the widely used microsimulation VISSIM software *(35)*. The procedure followed for this investigation starts with first using SHAKER to find the best configuration of the toll plaza with a lane closed and recording results on capacity, throughput, and queue lengths. Next, the network built in VISSIM is adjusted to replicate the SHAKER recommended configuration (See Figure 15 and Figure 16). The throughput and queue length results from multiple VISSIM runs will then be compared to the SHAKER outputs.

Using the same demand volumes as in the best configuration case study (Table 16) SHAKER was run with a lane closed. Figure 14 is provided to show an example of the best configuration generated by SHAKER using SR-528 Eastbound Data. After each of the six configurations are run the best one lane closed configurations results are tabulated in Table 18. As shown in the table below, SHAKER suggested that sacrificing an ETC (keeping all other types available) in most of the cases results less queues at the toll plaza compared to closing any other type of lanes. However, for the FTE toll plaza SHAKER suggested closing a manual lane since this toll plaza consists of one ETC lane.

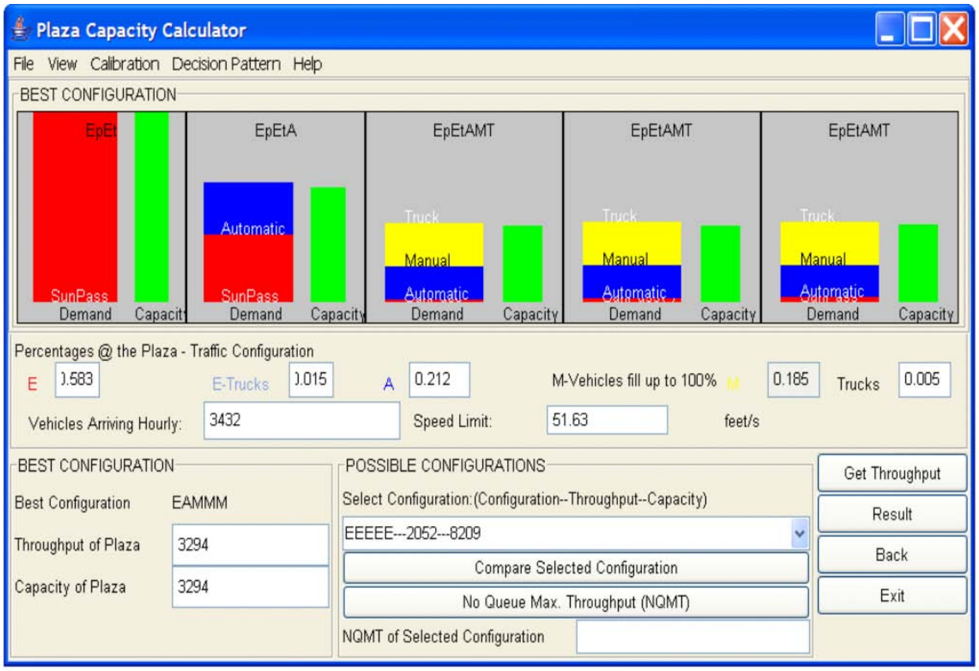


Figure 14: Best One Lane Closed Configuration Example - SR 528 Eastbound

Table 18: Best Configuration in Case of Lane Closure

	Current Configuration			**One Lane Closed Configuration**		
	Lane Type (count)			***Lane Type (count)***		
Toll Plaza Site	***ETC***	***ACM***	***Man.***	***ETC***	***ACM***	***Man.***
SR 528 WB	2	1	2	1	1	2
SR 528 EB	2	2	2	1	1	3
SR 417 NB	2	0	2	1	0	2
SR 417 SB	2	0	2	2	0	1
FL TPK	1	0	4	1	0	3
SR 429 NB	2	0	1	1	0	1

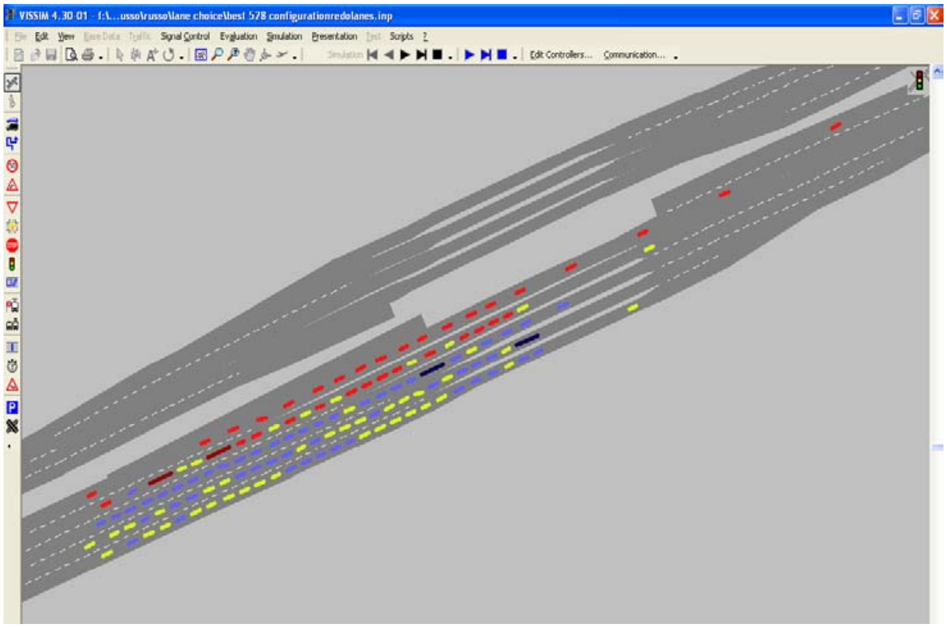


Figure 15: Two Dimensional Model of VISSIM Network with Lane Closure

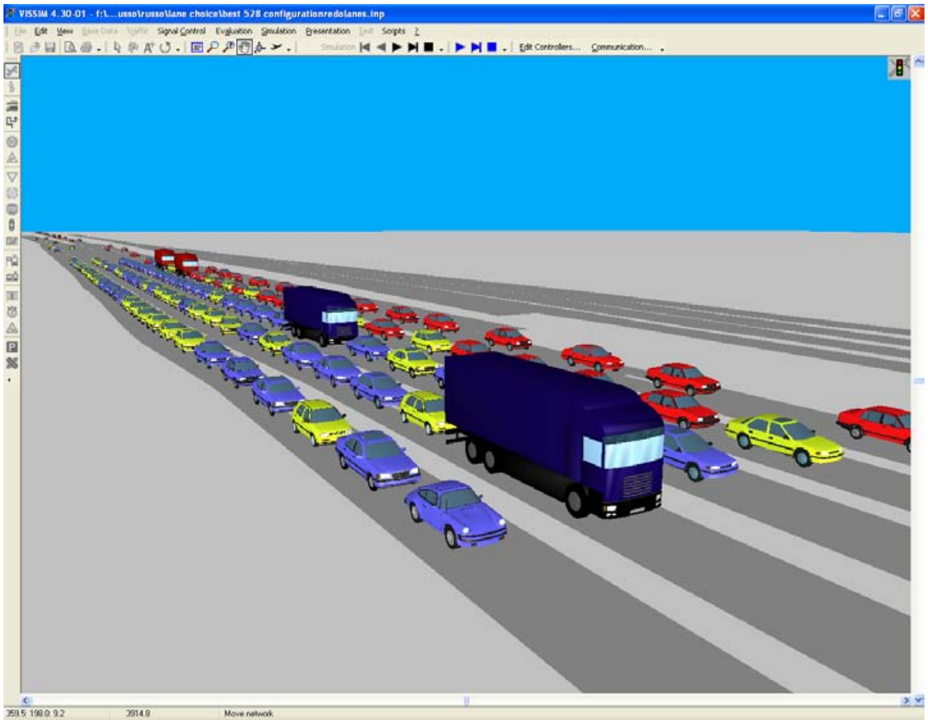


Figure 16: Three Dimensional Model of VISSIM Network with Lane Closure

Next the best one lane close configuration was coded into the VISSIM networks. This was easily done by simply deleting one of the connector nodes from one of the networks previously built for model calibration. One additional change to the network that must be done before realistic results are noticed was that ETC vehicles should be allowed to use any lane, which they will if the queues are short enough, and there needs to be more variation for ACM users to be willing to use manned lanes. This was accomplished by redrawing the route choices so that every vehicle was available to use any lane type; except that cash users can not use ETC lanes. Each approach from the SR-528 plaza and SR-417 plaza was used for this evaluation in VISSIM. Other sites were neglected for this procedure if there was no decision on which lane type to close. For instance, there is only one ETC lane and four manned lanes at the Florida Turnpike Mainline Plaza so in order to maintain the correct services to drivers it is unavoidable that only a manned lane be closed. The opposite holds true for the SR-429 plaza where two ETC lanes and one manned lane are currently in operation. It is also unavoidable that if a lane is to be closed it must be the ETC lane.

The results of the VISSIM generated throughput and queue lengths are provided in Table 19. SHAKER results were consistent and independent of when and how the results are obtained. On the other hand, VISSIM results were dependant on the seed number that corresponds to that simulation run. Therefore, VISSIM results originate from 10 different seed numbers. The error calculated is the fractional difference between the VISSIM model (base case) and the SHAKER Model (comparison case) divided by the base case results. The results indicate that SHAKER model estimates an accurate throughput of the toll plaza within 5% error for each of the VISSIM simulated toll plazas. Also, according to the GEH statistic, the SHAKER model and VISSIM model agree on similar queue length estimation. The GEH statistic is used here because percent error would be skewed by the small values associated with the queue lengths and results would not be indicative of the actual strength of model estimation *(14)*. When evaluating the GEH statistic any result less than five indicates a suitable match between modeled and observed conditions; a result between five and ten warrants further investigation of the data; and any value greater than ten is not a suitable match and indicates there is no match between the two data groups.

Table 19: One Lane Closed Configuration Evaluation

SR-528 Eastbound	Comparison of Simulated Throughput (vph)							Comparison of Simulated Queue Length (Veh)						
	E	A	MA	MA	MA	Total	Error*	E	A	MA	MA	MA	Total	GEH***
VISSIM**	1493	778	378	373	374	3396		8	18	26	26	27	105	
SHAKER	1636	551	361	372	373	3293	0.03	24	29	25	29	31	138	2.994

SR-528 Westbound	E	A	M	M	Total	Error*	E	A	M	M	Total	GEH***
VISSIM**	1092	352	351	344	2139		0	28	41	41	110	
SHAKER	1159	369	352	352	2232	-0.043	0	19	50	50	119	0.841

SR-417 Northbound	E	M	M	Total	Error*	E	M	M	Total	GEH***
VISSIM**	1494	352	252	2098		2	13	14	29	
SHAKER	1491	354	354	2199	-0.048	0	7	7	14	3.235

SR-417 Southbound	E	E	M	Total	Error*	E	E	M	Total	GEH***
VISSIM**	1073	1274	354	2701		0	0	387	387	
SHAKER	1102	1103	360	2565	0.05	0	0	390	390	0.152

* Error calculated as percent error in simulation variation using VISSIM as base case and SHAKER as test case

** VISSIM results are averages of 10 simulation runs, each run referencing a different seed number

*** GEH Statistic = square_root[(2(m-c)^2)/(m+c)], where m is modeled value and c is orignal value
a value less than 5 is considered a suitable match between observed and modeled values (19)

7.3 Simulated Values – Comparison of Estimated Values to Observed Values

An additional step in verifying the uses of the SHAKER model was to compare the results to that of a toll plaza model simulated in microsimulation program VISSIM to evaluate the effectiveness of each to determine which better estimates volumes and capacity closest to that of the observed conditions. Each of the two models has been calibrated and statistically verified to match the observed capacity but no evaluation has been conducted to determine the precision of each. The queue lengths cannot be fully evaluated from model to model in this step because the queue is the average of the difference between the demand and throughput and in the field the queue length is dependant on unpredictable conditions and varies from day to day. Table 20 is provided to show the comparison of the observed and simulated capacities from SHAKER and VISSIM. It is extracted from the table that there is no clear indication of which model better estimates capacity. In each of the sites tested the observed capacity fell between the SHAKER and VISSIM simulated capacity. This made it difficult to determine which model better estimates the capacity. However, when evaluating calibration results from Table 20 it was determined that based on t-test values there is no significant difference between the SHAKER and VISSIM model when compared to the observed conditions. The differences between the simulated capacities do show a slight trend that for each manned lane SHAKER slightly over estimates capacity and VISSIM slightly underestimates capacity, but this trend is considered insignificant to make any sound conclusions from. In either situation or lane type the slight variation is small enough to not completely hinder the performance of the toll plaza. A trend is however observed in the ETC lane capacity as SHAKER estimates a larger capacity than does the VISSIM simulation. The capacities of the ETC lanes were determined from the simulation models but not through observation. It was not possible to observe ETC lane capacity in the field because there was never a period of time where queuing was present for any substantial amount of time. From this analysis there is no clear indication which simulation model better estimates capacity but there is evidence that for manned lanes the SHAKER model is the less conservative approach because the capacity is larger thus meaning the resulting queues and delays will be shorter.

Table 20: Comparing Toll Plaza Simulation Models

Toll Plaza	Data Category		
Manned Lanes	**Observed**	**SHAKER**	**VISSIM***
SR 528			
Average Capacity, vph	355	358	352
% error in capacity		-0.85	0.85
T-Test on capacity		0.467	0.222
SR 417			
Average Capacity, vph	361	367	358
% error in capacity		-1.66	0.83
T-Test on capacity		0.366	0.720
SR 429			
Average Capacity, vph	400	414	395
% error in capacity		-3.50	1.25
T-Test on capacity		0.611	0.444
SR 91 FL TPK			
Average Capacity, vph	202	208	206
% error in capacity		-2.97	-1.98
T-Test on capacity		0.131	0.934
ACM Lanes SR-528			
Average Capacity, vph	360	352	365
% error in capacity		0.85	-1.11
T-Test on capacity		0.222	0.440
ETC Lanes SR-528			
Estimated Capacity, vph	N/A**	1587	1559

* VISSIM Test Run 6 is used for this analysis
**Not available. Queues were never present in field observations but through simulation capacities can be obtained

When comparing the uses of two models results it is also equally important to consider the additional costs in using each. The first element to be compared is the set up and simulation time. The SHAKER model setup takes mere seconds in order to create a network and input vehicle characteristics, another few seconds to calibrate driving parameters, and roughly ten or so additional seconds for simulation to run its course and to report analysis. Conversely, setting up the VISSIM model, even for the most experienced user, can take several hours because the roadway and traffic must be created and defined before any simulation can take place. Also, when using VISSIM the report analysis time can take several more hours as its accuracy is dependant on the number of required simulation runs and complexity of the network. Because of VISSIM's stochastic nature of assigning unique characteristics to each vehicle one by one the simulation time required for VISSIM is exponentially higher than the time needed for SHAKER.

The major benefit to having quick programming and reporting times is that in times of unpredicted conditions SHAKER can be setup and run in a matter of minutes; thus allowing decision makers to take quick action when needed. VISSIM on the other hand would take hours to run particular scenarios.

In addition to long set up times, data reporting in VISSIM is also more complicated than in SHAKER. In order to observe capacity results in VISSIM a file type requesting the software to record particular data for each lane and vehicle time must first be created. Then the user must exit VISSIM and open up a text file where results are recorded. In constant, because SHAKER is dedicated for the uses of toll plaza queuing, the capacity and queue reporting is simplistic, available immediately, and no programming of file types is necessary to obtain results. Unlike VISSIM, SHAKER reports capacity and queues in a visually pleasing graphical manner assisting the users understanding of the traffic situation without having to look at specific numbers. This element is beneficial for multiple reasons. For instance, when reporting results to unfamiliar persons the graphical file is quickly understood even with no previous knowledge. Also, its simplicity allows for a user of any SHAKER experience or transportation expertise to quickly grasp how to use the software and what the results mean.

8. DECISION SUPPORT SYSTEM

A Decision Support System (DSS) is an interactive computer software designed to assess the performance of a toll network by quantifying both the number and type (or severity) of bottlenecks on the toll network. The DSS server is up and running at http://134.88.50.42. DSS can be used as a tool to assist engineers and operators make decisions concerning the operations of toll roads and plazas. This includes assisting in the design of lane configuration patterns at the toll plazas to maximize operational efficiency. It also includes assisting in the planning and construction of maintenance schedules during low traffic demand. In addition, operators will be able to plan for special scheduled events in which traffic volumes are known to surge. A DSS may predict the effect of additional interchanges on toll plazas and thus assist engineers in identifying the best location for a new interchange on the network. They could also predict the effect of adding additional lanes to busy highway segments.

A dynamic real-time DSS, rather than static, collect data continuously and would provide operators with on-line tools that could assist with their hour-to-hour decisions as well as their day-to-day decisions. Road network operators could determine the effects of an unexpected incident on tolling operations. Other unscheduled lane closings could also be simulated.
A DSS-server for a portion of the FTE, SR-528 Beachline West Toll Plaza is completed in coding. This system provides visual display of bottleneck conditions on the network in this region.

University of Massachusetts (UMass) Dartmouth has completed the following tasks:

1. Installed the donated ArcGIS 9.2 software in two UMass Dartmouth campus computers and constructed ArcGIS maps displaying individual highway segments on the Turnpike. Instead of using TransCAD, ArcMap was used. And although a license of TransCAD was purchased and installed in the UMass Dartmouth campus computers, this software was found to be unnecessary due to the new applications on the latest version of ArcGIS software. See Figure 17, Figure 18, Figure 19, Figure 20, and Figure 21 for operating DSS.

2. Generated a database of parameters associated with the attributes of the polygons in ArcIMS. The ArcGIS 9.2 software was donated by the UMass, Dartmouth. Some of the parameters are changeable by the website user and are listed below.

- Interchange densities or interchanges per mile, IPM
- Number of traffic lanes on the segment, N
- Ideal Free Flow Speed, FFSideal
- Lateral Clearance factor, FLC
- Lane Width factor, FLW
- Percentage of approaching vehicles to the plaza that are trucks, PT, automatic coin machine users, PA, EPass users that are trucks, PET, and EPass users that are vehicles other than trucks, PEP

- Passenger car equivalents on extended general highway segments taken to be ~2.0, somewhere between Level and Rolling type of terrain, ET
- Population factor, FP
- Approach traffic volumes, V, in vehicles per hour, VPH

3. Other parameters will automatically be computed once the website user makes these changes. The following parameters can be computed:

- Interchange density factor, Fid = 5*IPM – 2.5
- Lane number factor, Fn, = 7.5 – 1.5*N
- Free Flow Speed, FFS, in miles per hour, MPH = FFSideal * Fid * Fn * FLC * FLW
- Maximum Service Flow, MSF for minimum LOS E, in units of pcphpl, MSF = 10*FFS + 1700
- Percentage of approaching vehicles to the plaza that are not trucks and that use the manual toll collection service, PM = 100% – (PT + PA + PEP + PET)
- Heavy vehicle factor, FHV = (1 / (1 + PT *(ET – 1)))
- Service Flow rate, SF, for LOS E, in units of VPH, SF = MSF*N*FHV*FP

Figure 17: Homepage of the Decision Support System for the FTE

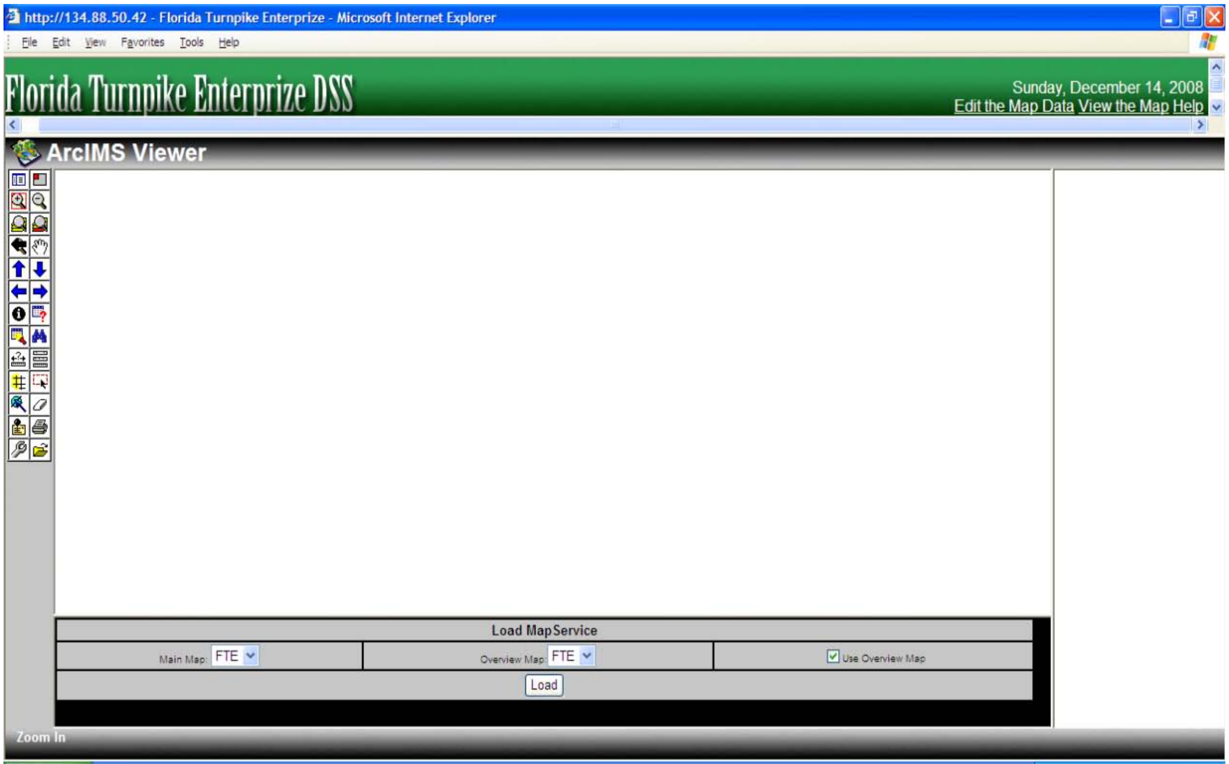


Figure 18: ArcIMS Viewer

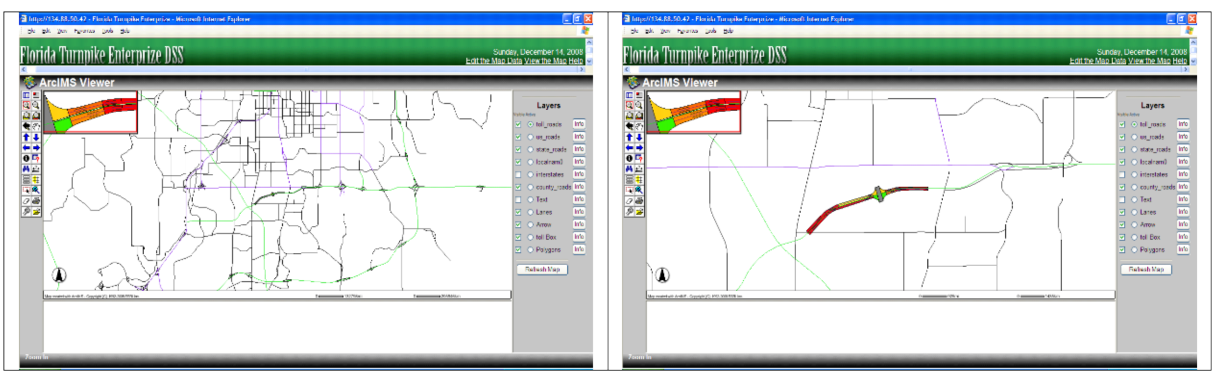
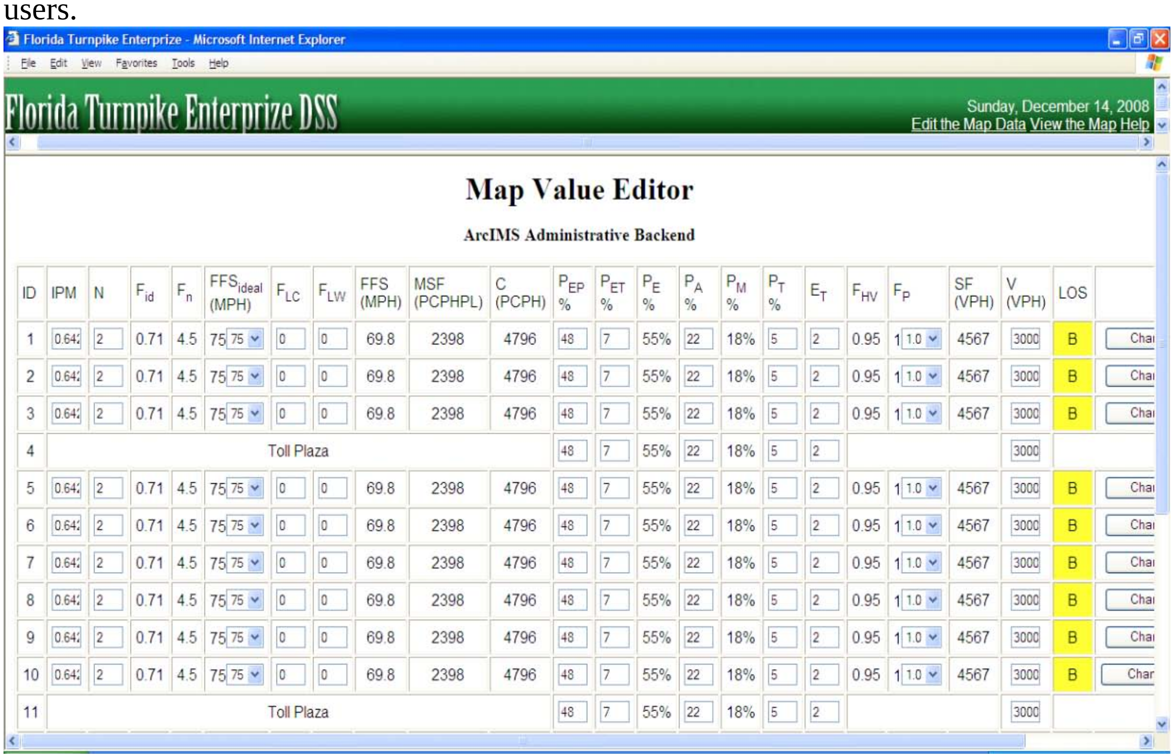


Figure 19: Polygons of Highway Segments- Click Load Map

Figure 20: Beachline West Toll Plaza and Highway Segments on 528

The "Edit the Map" button directs users to the database; each row represents parameters for one highway segment polygon. Parameters that are in blocks with an outlined box are changeable by users.



ID	IPM	N	F_{id}	F_n	FFS_{ideal} (MPH)	F_{LC}	F_{LW}	FFS (MPH)	MSF (PCPHPL)	C (PCPH)	P_{EP} %	P_{ET} %	P_E %	P_A %	P_M %	P_T %	E_T	F_{HV}	F_P	SF (VPH)	V (VPH)	LOS	
1	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
2	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
3	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
4	Toll Plaza										48	7	55%	22	18%	5	2				3000		
5	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
6	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
7	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
8	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
9	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Chai
10	0.642	2	0.71	4.5	75 75	0	0	69.8	2398	4796	48	7	55%	22	18%	5	2	0.95	1 1.0	4567	3000	B	Char
11	Toll Plaza										48	7	55%	22	18%	5	2				3000		

Figure 21: Edit Window of DSS

Procedure for Implementation of ArcIMS DSS server:

- Installed Apache HTTP server (freeware)
- Installed PHP server side scripting
- Installed MySql (database)
- Installed TomCat (java servlet)
- Installed ArcIMS (displays maps)
- Drew polygons in ArcGIS
- Inserted values into two MySql databases (Master/default and edits/changes)
- Assembled (~20) polygons into maps using Google Maps and ArcMap (two of the polygons are the Beachline West Toll Plaza)
- Authored and integrated the map and the database using ArcIMS author
- Created administrative backend using PHP which will change the edits/changes database
- Created administrative logins with PHP MySql
- Published server and make sure Port 80 is available to traffic off campus

Supplemental Feature: Server determines best lane configuration using SHAKER repetitively and test out Beachline West Toll Plaza.

9. SUMMARY AND CONCLUSIONS

This research focused on the development and calibration of SHAKER, a deterministic queuing model for vehicles utilizing toll collection facilities. The benefits of simulation models led to the purpose of this report, which was to examine the calibration of this model. SHAKER has the potential to work as a tool that can estimate the maximum throughput and capacity of toll plazas so that planners and engineers can better develop traffic plans for toll plaza design.

The efforts involved in developing a data collection procedure and calibrating a toll plaza capacity model of multiple Florida Turnpike toll plazas is described in this report. The lane capacity was chosen as the parameter to calibrate the SHAKER model with. Obtaining capacity estimates is in fact a timely manner. In total 248 lane-hours of video were recorded, but as shown in only 95.5 lane-hours were analyzed. In addition, because toll plaza queuing was not continuously present for all periods of study only a percentage (47/95.5=49%) of the analyzed 95.5 lane-hours could be used for capacity estimation. Even though the capacity is difficult to observe its importance is unmistakable because the efficiency of the SHAKER model is largely dependant on the assumption that the toll plaza faces queuing conditions. The final calibrated model of SHAKER is able to accurately calculate, within 5% error, the capacity of multiple toll lane types. The calibration procedure proved that when using observed field data, instead of best guessed estimates, to make up the default parameter set the SHAKER model performs most efficiently. It is very important that the correct vehicle percentage and stop-time be known before using the model because out of all the vehicle parameters these two have the potential to vary most for each toll plaza and toll amount. From the calibration process it was confirmed that toll plazas with even value fee amounts, such as SR-429 and SR-417 charging $1.00 and $2.00 respectively, had smaller stop-times than did the toll plazas which charged uneven amounts; SR-528 and SR-91 charged $0.75 and $2.50. As it would be assumed, smaller stop-times and lanes with smaller percentages of trucks resulted in higher capacities.

The calibrated and validated SHAKER model can be used as a tool in the traffic operations and planning fields. In the operations field SHAKER can determine the different effects that a varying demand has on the toll plaza capacity, queue lengths, and delays.

Unlike more complicated micro simulation programs, in SHAKER the user can close or add a lane with just one click of the mouse. This option proves to be useful for quick on the go simulation to learn the affects of having to close down a booth due to construction, maintenance, or in the case of a traffic incident. Additionally important to determining the affects of these conditions is simulation speed. Unlike complicated micro-simulation software that require extensive programming knowledge and time, the SHAKER model setup takes mere seconds in order to create a network and input vehicles, another few seconds to calibrate driving parameters, and roughly 10 or so additional seconds for simulation to run its course and to report analysis. Another benefit that SHAKER has over other models is its simplicity. SHAKER reports capacity and queues in a visually pleasing graphical manner assisting the users understanding of the traffic situation without having to understand specific values. This element is beneficial when reporting results to unfamiliar persons as the graphical file is quickly understood even with no previous knowledge. Also, its simplicity allows for a user of any SHAKER experience or transportation expertise to quickly grasp how to use the software and what the results indicate. One of SHAKER's many befits to the planning field is that it can be used to determine the configuration of toll lane types that will result in the most proficient operations.

All in all, the extensive field study provided valuable processing time and demand data that was used to establish capacities based on lane type, payment type, payment amount, and vehicle type. The capacities resolved were used as the primary measure in calibrating and validating simulation modes. Much attention was put on using the field measured values in as many instances in calibration as possible. It is quite possible the SHAKER model could be forced to replicate field results without using field conditions but the methodology would contribute nothing to the field for future research. The best configuration application in SHAKER was demonstrated and proven to be effective in suggesting a better configuration of current plaza configurations. The best configuration application was also applied to test the effects that closing a lane or increasing demand has on a toll plaza.

To further knowledge on the topic of isolated toll plaza simulation models future research is recommended to instantaneously run multiple SHAKER models, each representing a different toll plaza configuration and traffic demand along a network. Instead of having to simulate each toll plaza separately this model would be able to automatically adjust for varying inputs to the network from on ramps and reduction in downstream demand due to network departures. This model would serve promising when modeling the effects that special event conditions such as a sporting event, accident, or lane closure have on the entire network. For instance, in the current model a lane closure increases the queue at that particular toll plaza, but it is unknown if special conditions also have a profound effect the operations at plazas downstream.

9.1. Strengths and Limitations of the SHAKER Model

As mentioned multiple times in this research traffic is sometimes unpredictable. However, SHAKER assumes equilibrium amongst lane choice and queuing. SHAKER does not show the simulation of individual vehicles but it is known that it assumes equal headways and arrival rates throughout the analysis time period. Also, in SHAKER the user must enter one processing time that is applied to all vehicles within that lane group and payment type. As shown in the calibration steps in this research the processing time distribution does not follow a normal curve nor is there one distinct processing rate that prevails over the others. Allowing for a distribution of processing rates determines the presence and magnitude of queues.

Even though limitations are inevitable, it is important that the simulation model capacity is accurately simulated and can be used to benefit operational situations related to toll plaza traffic conditions. While the benefits of the SHAKER model are important, it is also just as important to identify any limitations of the models. The SHAKER model strictly has the potential to model an isolated toll plaza. If queue lengths are longer than the queue storage bays upstream of the toll plaza then queues may back up into un-congested ETC lanes; thus reducing the capacity of those lanes. Without any network visualization it is difficult to identify if this situation is occurring. A limitation also lies within the distribution methodology in the SHAKER model. When SHAKER faces demands in excess of the lane plaza capacity the program assumes that the queue vehicles follow the same distribution as the throughput distributions entered. However, this limitation can easily be avoided if the overall demand accounts for the make up of vehicles types within the queue. Another limitation of SHAKER that has already been addressed is its deterministic approach to modeling. SHAKER modeling assumes equal headways and processing times. However, field observations show that queuing is more localized and dependant on the arrival rate and heavily dependant on processing times. For instance, one particular vehicle could require over one minute to complete their transaction and during that time multiple vehicles will undoubtedly queue up temporarily until favorable conditions return.

It should be noted that all four toll plazas evaluated for this research are managed and operated by the FTE. Toll plazas managed by different entities could result in different procedures that could influence lane capacity. The capacities and processing times are limited to toll plazas that utilize gates to indicate when proper payments are received. If toll plazas are installed without gates the processing time is expected to be reduced and capacity is expected to increase. If future research is to be conducted in this topic, it is recommended that a toll plaza that experiences queues in the ETC lanes as well as cash payments lanes be evaluated so as to develop a capacity value for all lanes at once.

9.2. Decision Support System Capabilities

The DSS developed in this project can serve as a viable tool for planning, operation, and management activities. Planners and operators are able to assess the current performance of the toll facility in terms of capacity, throughput, queue building, and bottlenecks. They can apply "what if?" type scenarios to evaluate the system performance due to increased demand, road construction, lane blockage, and unexpected incidents. Expansion to the network through adding lanes or interchanges can also be assessed. The graphical representation of the network performance supported by tabular statistics makes the system friendly and versatile.

LIST OF REFERENCES

1. Florida Turnpike - Frequently Asked Questions, Florida Turnpike Enterprise, Florida Department of Transportation, http://www.floridasturnpike.com/about_faqs.cfm, Accessed Jan. 31, 2008.

2. Schmitt, D. T., "Modeling Toll Plaza Performance – Decision Support System for Operatiors – SHAKER", Thesis, University of Massachusetts Dartmouth, 2003.

3. Orlando Orange County Expressway Authority System's Traffic Data & Statistical Manual-Mainline Plaza Characteristics, Orlando Orange County Expressway Authority, http://www.oocea.com/trafficstatistics/historicaltraffic, Accessed Jan. 31, 2008.

4. Klodzinski, J. G., Al-Deek, H. M. and Radwan, A. E., "Evaluation of Vehicle Emissions at an Electronic Toll Collection Plaza", Presented at the 77th Annual Meeting of the Transportation Research Board, Washington, D.C. 1998.

5. Milam, R. T., "Recommended Guidelines for the Calibration and Validation of Traffic Simulation Models", Richard T. Milam. Fehr & Peers Associates, Inc., http://www.fehrandpeers.com/publications/traff_simulation_m.html , Last viewed March 2002.

6. "Traffic Analysis Toolbox- Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software", Federal Highway Administration - United States Department of Transportation, Development, and Technology Turner-Fairbank Highway Research Center, 2004.

7. Park, B and Schneeberger, J. D., "Microscopic Simulation Model Calibration and Validation: A Case Study of VISSIM for a Coordinated Actuated Signal System", Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C. 2003.

8. Hellinga, B. R., "Requirements for the Calibration of Traffic Simulation Models", Department of Civil Engineering, University of Waterloo, http://www.civil.uwaterloo.ca/bhellinga/Publications%20Page/Publications/CSCE-1998-Calibration.pdf , Last viewed August 2008.

9. Redding, R. T. and Andrew J. J., "TPASS: Dynamic, Discrete-event Simulation and Animation of a Toll Plaza", Proceedings of the 24th Conference on Winter Simulation, Arlington, Virginia, United States, December 13-16, 1992, pp. 1292-1295.

10. Al-Deek, H. M., Mohamed, A. A. and Malone, L., "A New Stochastic Discrete-Event Micro Simulation Model for Evaluating Traffic Operations at Electronic Toll Collection

Plazas", Journal of Intelligent Transportation Systems; Oct-Dec2005, Vol. 9 Issue 4, p205-219, 15p.

11. Klodzinski, J. G. and Al-Deek, H. M., "Transferability of a Stochastic Toll Plaza Computer Model", Journal of the Transportation Research Board, No. 1811, December 2002, pp.40-49.

12. Klodzinski, J., Gordin, E. and Al-Deek, H. M., "Evaluation of Impacts from Deployment of an Open Road Tolling Concept for a Mainline Toll Plaza", Journal of the Transportation Research Board, No. 2012, pp. 72-83, October 2007

13. Smith, R. F. and et al., "State of the Practice and Traffic Control Strategies at Toll Plazas: Best Practices", Manual of Uniform Traffic Control Devices, Federal Highway Administration, Federal Highway Administration, June 2006.

14. Nezamuddin, N. and Al-Deek, H., "Developing a Microscopic Toll Plaza and Toll Road Corridor Model Using PARAMICS", Journal of the Transportation Research Board, No. 2047, pp. 100-110, October 2008.

15. Ozbay, K., Sandeep, M. and Bekir, B., "Development and Calibration of an Integrated Freeway and Toll Plaza Model for New Jersey Turnpike using Paramics Microscopic Simulation Tool", Proceedings of the 8th International IEEE Conference on Intelligent Transportation Systems, Vienna, Austria, September 13-16, 2005.

16. Ceballos, G. and Owen, C., "Queue Analysis at Toll and Parking Exit Plazas: A Comparison between Multi-server Queuing Models and Traffic Simulation", VISSIM Library.

17. Park, B. and Qi, H., "Microscopic Simulation Model Calibration and Validation for Freeway Work Zone Network – A Case Study of VISSIM", Virginia Transportation Research Council and Federal Highway Administration, March 20, 2006.

18. Chitturi, V. and Rahim F., "Calibration of VISSIM for Freeways", Presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

19. Lownes, N. E. and Machemehl R. B., "Sensitivity of Simulated Capacity to VISSIM Driver Behavior Parameter Modification", Presented at the 85th Annual Meeting of the Transportation Research Board, Washington D.C., 2006.

20. Festa, D., et.al., "Experimental Analysis of Different Simulation Models for Motorway Traffic Flow", Proceedings from 2001 IEEE Intelligent Transportation Systems Conference, 25-29 Aug. 2001, Oakland, CA, USA.

21. "Highway Capacity Manual", TRB, National Research Council, Washington, D.C., 2000.

22. Klodzinski, J. G. and Al-Deek, H. M., "New Methodology for Determined Level of Service at Toll Plazas", Journal of Transportation Engineering, March 2002, Vol.128, No. 2, pp.1-9.

23. Klodzinski, J. G. and Al-Deek, H. M., "Proposed Level of Service Methodology for Toll Plazas", Presented at the 81st Annual Meeting of the Transportation Research Board, Washington, D.C., 2002.

24. Aycin, M. F., "Simple Methodology for Evaluating Toll Plaza Operations", Transportation Research Record: Journal of the Transportation Research Board, No. 1988, Washington, D.C., 2006, pp. 92-101.

25. Pietrzyk, M. C., "Electronic Toll Collection Systems", Transportation Research Board Special Report 242, Curbing Gridlock, National Research Council, Washington, D.C., 1994, Vol. 2, pp. 464-501.

26. Zarrillo, M. L., Radwan A. E. and Dowd, J. H., "Toll Network Capacity Calculator: Operations Management and Assessment Tool for Toll Network Operators", Transportation Research Record 1781, TRB, National Research Council, Washington, D.C., 2002.

27. Woo, T. H. and Lester, A. H., "Toll Plaza Capacity and Level of Service", Transportation Research Record: Journal of the Transportation Research Board 1320, Transportation Research Board, National Research Council, Washington, D.C., 1991, pp. 119-127.

28. Oliveira, M., Cybis, H. and Beatriz, B., "An Artificial Neural Network Model for Evaluating Workers' Performance at Tollbooths", 1st International Symposium on Freeway and Tollway Operations, Athens, Greece, June 2006. Available at SSRN: http://ssrn.com/abstract=962730

29. Astarita, V., Michael, F. and Giuseppe, M., "A Microscopic Traffic Simulation Model for the Evaluation of Toll Station Systems", IEEE Intelligent Transportation Systems Conference Proceedings, 2001. Oakland, CA, August 25-19, 2001, pp. 692- 697.

30. Zarrillo, M. L., "Development and Applications of TPModel: A Queuing Model Describing Traffic Operations During Electronic Toll Collection (ETC)", Ph.D. Dissertation, University of Central Florida, Orlando, FL, 1998.

31. Zarrillo, M. L., Radwan, A. E. and Dowd, J. H., "Toll Network Capacity Calculator: Operations Management and Assessment Tool For Toll Network Operators", Transportation Research Board Journal, Record Number 1181, May 2002.

32. Zarrillo, M. and Radwan, A. E., "Identification of Bottlenecks on a Toll network of Highways", 7th International ASCE Specialty Conference on Applications of Advance Technology in Transportation, August 2002, Boston, Massachusetts.

33. Zarrillo, M. L., Radwan, A. E. and Al-Deek, H. M., “Modeling Traffic Operations at Electronic Toll Collection and Traffic Management Systems”, The International Journal on Computers and Industrial Engineering, December 1997, Volume 33, Numbers 3-4, pp. 857-860.

34. Mendenhall, W. and Terry, S., “Statistics for Engineers and the Sciences”, 5^{th} ed. Upper Saddle River: Prentice Hall, 2006.

35. “VISSIM User Manual: Version 4.30.”, P. T. V. AG., Karlsruhe, Germany, 2007.