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INSIGHT THROUGH INNOVATION: A DYNAMIC APPROACH TO DEMAND BASED TOLL PLAZA LANE STAFFING

John Danko
Victor Gulewicz

The Port Authority Of New York & New Jersey
Management Engineering & Analysis Group
One World Trade Center, Floor 63 South
New York N.Y., 10048
Phone: 212-435-5146
Fax: 212-435-5270

ABSTRACT

For many years the operations of toll plazas have been studied to determine the optimal number of toll lanes staffed during specific times of the day. The goal in this type of analysis is to increase or decrease staffing to match peak and off-peak demand.

This paper will present a comprehensive approach to modeling toll plaza vehicle processing and evaluating alternate toll collector staffing scenarios. Utilizing a General Purpose Simulation System (GPSS) World™ simulation model, an effective tool was developed to evaluate toll plaza queuing dynamics and provide insight into their relationship to the quality of service provided.

1 PROJECT BACKGROUND

The Port Authority of New York and New Jersey (PA) is a public agency responsible for promoting and facilitating trade, commerce and transportation in the New York-New Jersey region. It is a self-supporting bi-state agency which provides, operates and maintains numerous transportation facilities in and around the New York city metropolitan area. The current demands for these facilities are especially severe on the six tunnel and bridge crossings which link New York and New Jersey at key locations within the metropolitan region.

Recently, the Interstate Transportation Department (ITD) of the Port Authority requested that the corporate Industrial Engineering unit, Management Engineering & Analysis (ME&A), assist in evaluating and updating toll lane and staffing requirements at its tunnel and bridge crossings. Historically, these efforts were accomplished using mathematically based models employing manual or computer assisted computations. Although they provide generally acceptable results, these models often failed to accurately predict toll plaza operations.

Recognizing that the traffic volumes at crossings vary over time, ITD staff were interested in developing an analytical approach which could be used to assess alternative staffing scenarios and select the most cost effective strategy for each facility.

2 STUDY OBJECTIVE AND SCOPE

To satisfy the needs identified by ITD staff, our objective was to develop an approach for determining the toll plaza lane and staffing requirements needed to provide an acceptable service level during off-peak time periods of varying levels of traffic volume and mix. The focus on the off-peak was purposeful since peak period volumes require staffing of all available toll lanes, eliminating the possibility of evaluating alternate staffing schedules.

Given the scope and complexity of the study, a phased project plan was agreed upon, beginning with a data collection program and the development and validation of the simulation model for the eight lane toll plaza at the Outerbridge Crossing (OBX). This paper will focus on the results of our Phase I effort for the OBX.

3 SERVICE LEVEL STANDARDS

In an attempt to identify any applicable standards being used in the design, evaluation and management of toll plazas, a literature search was initiated which identified a number of documents for review, including the Highway Capacity Manual. In addition, the team contacted four research organizations, 16 transportation properties and six consulting firms with transportation/traffic engineering experience.

As a result of our search, the study team found that no generally recognized/accepted service level standards existed for evaluating toll plaza performance. However, the search revealed an applicable approach used by the New Jersey Highway Authority (NJHA), which operates the Garden State Parkway (GSP). In the late 1980's, NJHA retained the services of Vollmer Associates to develop an approach for determining the number of toll booths required at each of their plazas to achieve an acceptable level of performance. Vollmer recommended the application of LOS criterion for a signalized intersection, finding very similar processing characteristics to that of a toll lane. For a signalized intersection the measure of user discomfort, and therefore LOS, is the amount of time stopped at the signal. Similarly, for a toll lane, user discomfort can be measured as the time stopped in a queue waiting to be processed.

Based on the results of our search, the team recommended and gained ITD's concurrence to apply the approach identified by Vollmer for evaluating toll plaza performance, using the LOS values in the HCM of average stopped delay per vehicle for signalized intersections (Table 1). Also, the LOS values for stopped delay were translated by the study team into the number of vehicles queued which relates well to the physical characteristics of a toll plaza, thereby providing a less abstract characterization of plaza performance.

Level of Service	Average Waiting Time	Average Queue
A	≤ 5 seconds	≤ 1
B	≤ 15 seconds	≤ 3
C	≤ 25 seconds	≤ 5
D	≤ 40 seconds	≤ 8
E	≤ 60 seconds	≤ 11
F	> 60 seconds	> 11

Table 1: Level of Service Criteria for The OBX

After considering this research, ITD management decided that the range of service level "C" to "D" would be their operating goal.

4 DATA COLLECTION APPROACH

To identify applicable timeframes for toll lane and staffing analyses and obtain the required data for model development, the study team developed and conducted an aggressive data collection program. An initial step in this evaluation was obtaining a definition of seasonality of traffic demand for the facility. It was determined that October thru March and April thru September, were most representative of the "off-season" and "season" months, respectively. The study team then obtained daily traffic volumes for the facility during the period July, 1991 to June, 1992. Using the Statgraphics™ statistical software program, distributions of the daily vehicle volumes were calculated and 85th percentile demand days listed below (which has been the standard used by the transportation industry to design and evaluate facilities) were selected for each.

85th Percentile Demand Vehicle Volumes

	Season	Off-Season	Variance
Weekday	39,190	35,773	-9.5%
Weekend Day	42,522	38,653	-10.0%

The percent of variance between the season and off-season and for each day type was then calculated, and if it exceeded 5%, the team and facility staff concurred, that this difference was attributable to seasonal aspects of traffic volume. Based on the percentile demand analysis, four data collection days were identified for the OBX for

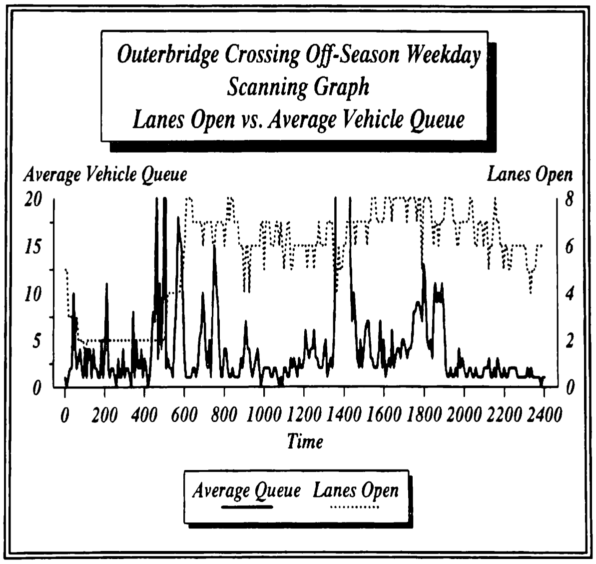

Figure 1: Example of an OBX Scanning Graph

the weekday and weekend day scenarios during the season and off-season timeframes. For each scenario, a "data scanning" was performed which involved documenting at five minute intervals the lane status (open or closed) and the vehicle queue. The vehicle queuing data for each of the eight lanes was then averaged and plotted against the number of lanes opened. An example of a scanning plot can be found in Figure 1.

Those timeframes exhibiting low queue conditions and a high number of lanes open were identified as candidates for evaluating alternative lane/staffing requirements. As such, these timeframes which are summarized below, were identified for data collection.

Timeframes Identified For Lane Staffing Evaluation

	Season	Off-Season
Weekday	None	16:00-24:00
Weekend Day	6:00-11:00	23:00-11:00

5 MODEL STRUCTURE

The Toll Staffing Simulation Model was developed to provide the ability to analyze lane-by-lane queuing as a result of modifications to lane staffing. In order to achieve this level of detail, the model was developed using GPSS World™, which is a general application simulation language.

For model input, vehicle interarrival data was collected independently for each arrival lane and by vehicle type (car, bus, light truck and heavy truck). The data was then fed into two statistical software packages to determine if the arrivals "fit" a standard theoretical distribution (pattern) of arrivals. The first statistical package, BestFit™, was used to determine of 18 distributions, which pattern fits the closest to the field data. Once the best distribution was identified, the data was fed into StatGraphics™ to determine if it passed the Kolmogorov-Smirnov (KS) test. Different arrival distributions were created (fit) for each half hour time period to allow for changes in the volume of each vehicle type arriving at different times during the day.

The lane selection data, which describes how vehicles choose which toll lane to enter was also collected for each scenario at the OBX. To collect the lane selection data, a random sample of vehicles entering the toll plaza was observed. For each observed vehicle, the bridge arrival lane (left or right), queue in each of the eight toll lanes (#2 through #16, numbered evenly), and the destination toll lane was recorded. Four general driving habits were observed:

1. Most drivers enter a toll lane on the same side of the toll plaza from which they exited the span.
2. Most drivers, once they have selected which half of the plaza to enter, select the lane with the shortest queue on that side.
3. Some drivers were observed entering the lane with the shortest queue, even though an empty lane was available. It was believed that these patrons focused on only the other vehicles in the plaza and not on the signals above the toll lanes. This caused them to believe that the empty lanes were closed.
4. A small percentage of drivers appeared to randomly choose a toll lane.

These driving habits were replicated in the simulation model by using percentages to create a Lane Selection Algorithm, developed by the study team, which determines the probability of any vehicle entering any lane in the toll plaza based on the level of queuing. An example of the Lane Selection Algorithm used in the model is shown in Figure 2.

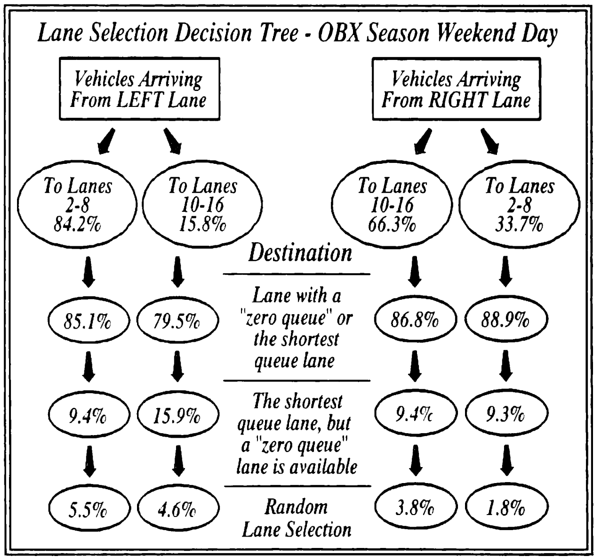

Figure 2: Lane Selection Algorithm

The processing rate data is composed of both the "move time" (the time required for the next vehicle to move into and out of the toll booth) and the "transaction time" (the time required for the patron to pay the toll).

Empirical distributions were developed for the move time for each of the four vehicle classes and transaction times for three possible payment types (using cash with change returned, exact change, or a pass/ticket).

The OBX Toll Relief and Meal Record, which is the staffing plan (schedule) for the facility, was used to simulate minute-by-minute when each toll lane was scheduled to be open, accounting for personal breaks, meal breaks or lane closures.

6 MODEL VALIDATION

A simulation model is only beneficial if its results are known to be accurate. Because of the significant impacts of the results of the Tolls Staffing simulation model, the study team decided to validate the model using two different variables, vehicle queue and throughput.

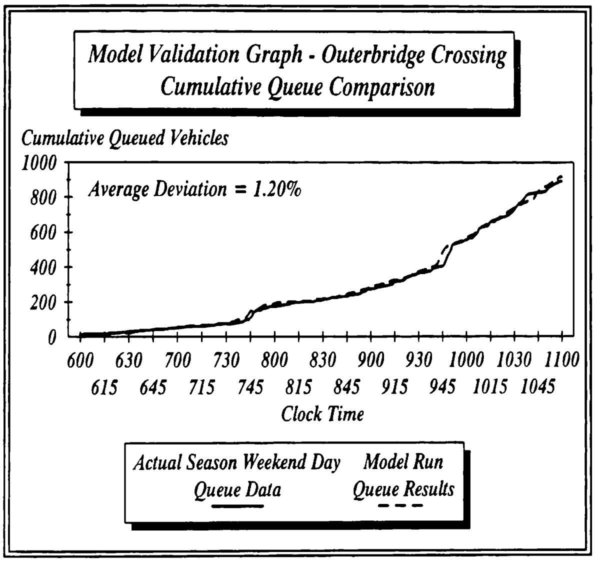

Figure 3: OBX Validation Queue Graph

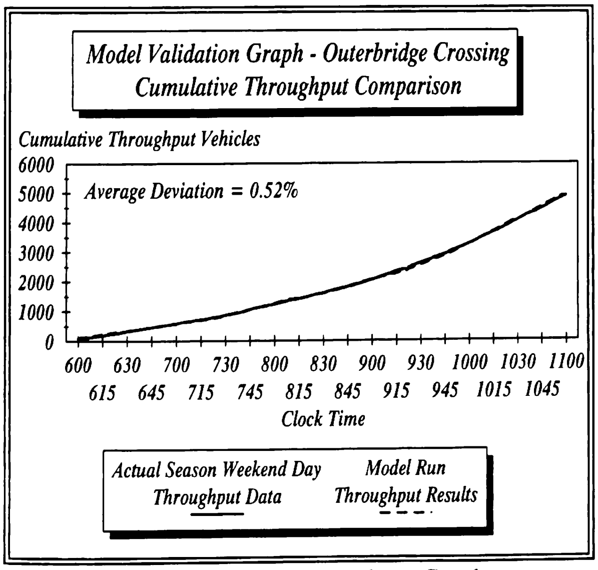

Figure 4: OBX Validation Throughput Graph

For the OBX, the Season Weekend scenario was selected for validation. During the data collection on Sunday, August 30, 1992, the vehicle queue in each lane and the total vehicle throughput were recorded at one minute intervals from 6:00 a.m. to 11:00 a.m. Additionally, all lanes were recorded as being open (green light) or closed (red light) at one minute intervals.

The OBX model was configured based on the data recorded on August 30, 1992, and was then programmed to tabulate the individual lane queue and total toll plaza throughput at one minute intervals to match the field data collection method. The results of the queue validation can be seen in Figure 3. In addition to the close visual comparison, the study team felt it was necessary to create one value which will indicate the level of the models accuracy. So in addition to the visual comparison, the absolute differentials in average vehicle queue between the field measured data and the models calculated value were tabulated at one minute intervals. The average for the scenario timeframe (6:00-11:00) was then calculated for this variance, which the study team defined as the "Average Deviation" (average error) value for the model. For the OBX validation, the Average Deviation in queuing was 1.2%. This can be translated as the model having an average of 1.2% error in estimating vehicle queue, or conversely, the model being 98.8% accurate in predicting vehicle queue, which is evidence that the model capabilities are confirmed. In addition, the throughput graph (Figure 4) reveals similar results with an Average Deviation in vehicle throughput of 0.52%.

Based on the results of the validation, the study team was confident that the models capabilities are accurate in predicting vehicle processing at the OBX.

7 MODEL SCENARIOS

Based on the four OBX scanning scenarios mentioned in the Data Collection Approach section, the study team determined that three scannings, Off-Season Weekday (abbreviated as OSWD), Season Weekend Day (SSS) and Off-Season Weekend Day (OSSS), offered the potential for schedule modification.

For each scenario, the OBX model structure was modified to simulate the vehicle arrival, lane selection and processing rate patterns based on the data collected for each. Once the structures were developed, a batch of ten (10) model runs using varying random number streams was conducted for each to create the "typical" demand during that timeframe at the facility. The results of the 10 runs were then averaged, creating the "typical" day results.

8 RESULTS

For each of the scenarios, the base condition model was run first to determine the "baseline" results. The base condition models simulate toll plaza operations using the existing OBX toll collector staffing plan. The Average Vehicle Queue per lane was tracked for each run throughout the scenario timeframe. This variable was chosen by the team because it is a good indicator of the overall operating condition of the toll plaza. In addition, the waiting time in the queue was tracked for each vehicle in the model run and distributions were created showing the delay pattern for that scenario.

8.1 OBX Off-Season Weekday Results

For the OBX Off-Season Weekday scenario, the analysis time frame based on the results of the scanning was identified as 16:00 - 24:00. The results for all vehicles in the base condition (no staffing changes) can be found in Figure 5 and Table 2.

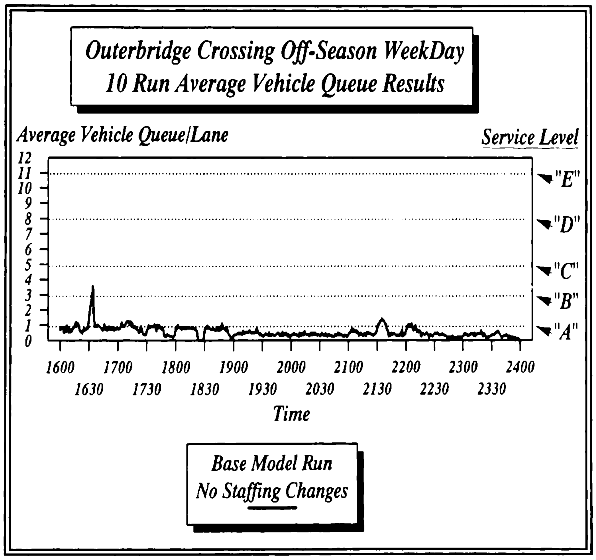

Figure 5: OBX OSWD Base Condition Queue Graph

For the Base Condition, the maximum average queue was 4.8 vehicles. This was equivalent to LOS C, which was the lowest level resulting from the existing staffing plan. For a majority of the timeframe, the plaza was operating in LOS A. Additionally, the average and maximum wait time in the queue was 11.3 seconds and 300 seconds, respectively.

For all of the scenarios, the study team decided that the lane which was "open" for the longest time during the analysis timeframe would always the first to be closed to determine the queuing impacts. This was done to represent the "worst case" possibility, since it will create the largest change in lane availability. For the OBX Off-Season Weekday, the first lane to be closed was lane 14. With lane 14 closed from 16:00-24:00, the

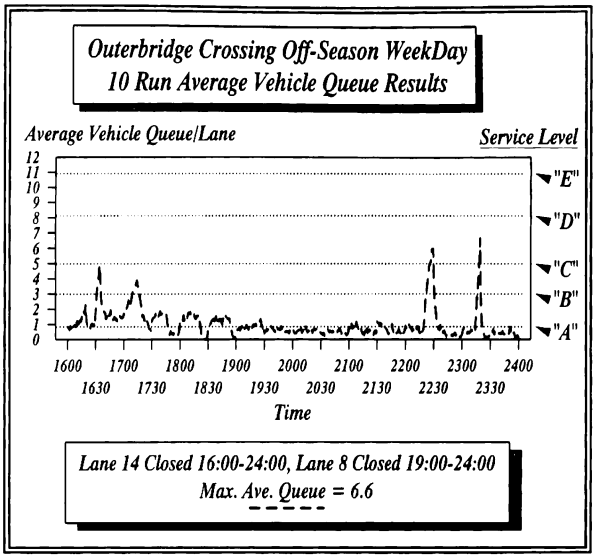

Figure 6: OBX OSWD Modified Lane Staffing Queue Graph

OBX Off-Season Weekday Results

OBX Off-Season Weekday	Base Staffing Results	Lane 14 Closed	Lane 14 & 8 Closed
Max. Avg. Vehicle Queue	4.8 Vehicles	4.9 Vehicles	6.6 Vehicles
Lowest LOS	C	C	D
Avg. Time In Queue	11.3 Seconds	13.2 Seconds	14.2 Seconds
Max. Time In Queue	300 Seconds	313 Seconds	313 Seconds
% Vehicles With No Wait	25%	21%	20%
% 60+ Second Wait	1.0%	1.3%	2.1%

Table 2: OBX Modified Lane Staffing Results, Off-Season Weekday

simulated 10 run results indicated minimal change in queuing from the base condition, with an average maximum queue of 4.9 vehicles (see Table 2), which was within the LOS C target.

The next step was to determine the impact of closing an additional lane. Lane 8 was open the next longest in the timeframe so it was the next to be closed from 16:00-24:00. Preliminary runs with lane 8 closed revealed that severe queuing occurred between 16:00-19:00, resulting in LOS F, but for the remainder of the time frame, only two small spikes into LOS D were the worst queuing obtained. Based on these results, the team decided that lane 8 could only be closed from 19:00 - 24:00. With lane 14 and 8 closed, only a minimal increase to an average vehicle queue of 6.6 vehicles was found (see Figure 6 and Table 2). Since the two small spikes created by closing lane 8 moved beyond the maximum LOS C into LOS D for only a total of approximately five (5) minutes, and no other significant change was found, the team concluded that closing lane 8 would be acceptable. Further lane closures were not possible, as additional runs revealed that severe queuing would be the result.

8.2 OBX Season Weekend Results

For the OBX Season Weekend scenario, the analysis time frame based on the results of the scanning was identified as 6:00 - 11:00. For the Base Condition, the maximum average queue was 1.3 vehicles, which was equivalent to LOS B, which was the lowest level obtained.

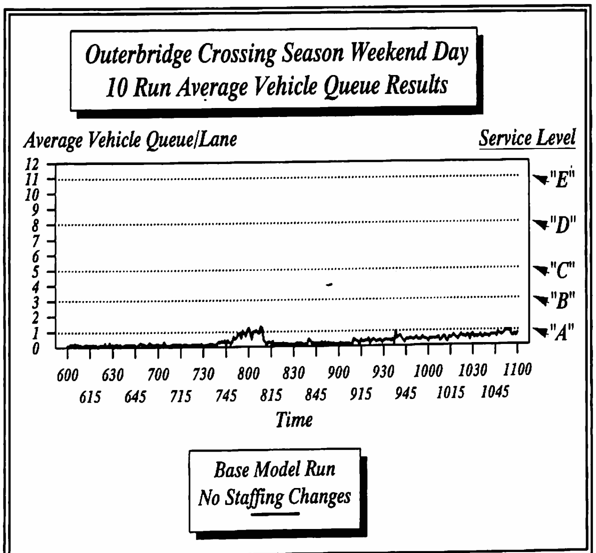

Figure 7: OBX SSS Base Condition Queue Graph

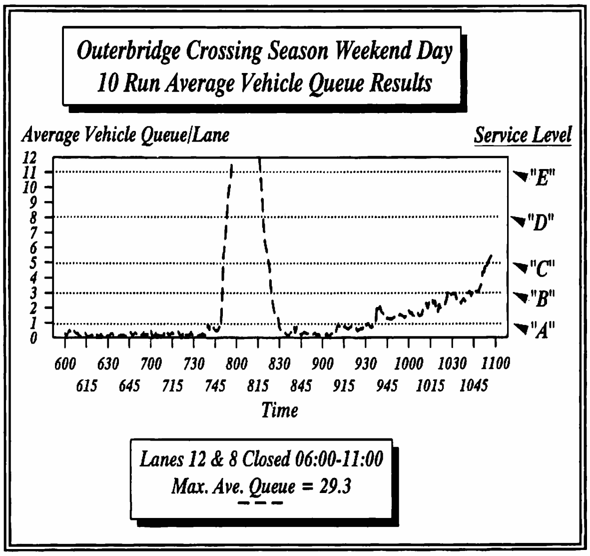

Figure 8: OBX SSS Modified Lane Staffing Queue Graph

OBX Season Weekend Day Results

OBX Season Weekend	Base Staffing Results	Lane 12 & 8 Closed	With Relief
Max. Avg. Vehicle Queue	1.3 Vehicles	29.3 Vehicles	4.8 Vehicles
Lowest LOS	B	F	C
Avg. Time In Queue	10.2 Seconds	49.3 Seconds	36.1 Seconds
Max. Time In Queue	150 Seconds	898 Seconds	892 Seconds
% Vehicles With No Wait	35%	20%	23%
% 60+ Second Wait	0.8%	23%	16%

Table 3: OBX Modified Lane Staffing Results, Season Weekend Day

Operating conditions during most of the timeframe were within LOS A. Additionally, the average and maximum wait time in the queue was 10.2 and 150 seconds, respectively. The results for all vehicles in the base condition (no staffing changes) can be found in Figure 7 and Table 3.

For this scenario, the first lane to be closed was lane 12. With lane 12 closed, the results indicated minimal change in queuing from the base condition with an average maximum queue of 2.2 vehicles.

Since lane 8 was opened the 2nd longest amount of time, it was the next to be closed. Preliminary runs with lane 8 closed revealed that the queue spiked into LOS F from 7:45-8:30, with an maximum average vehicle queue of 29.3 vehicles (see Figure 8 and Table 3). Otherwise, LOS C or better was maintained. Since lanes 12 & 8 will be closed in the modified staffing plan, the existing relief toll collectors will have less lanes to cover. If the relief schedule is modified so that relief toll collectors open lane 8 between 7:45-8:30, the queuing pattern would revert back to the LOS B during this 45 minute time frame, which was observed during the previous run. The average vehicle queue with relief coverage dropped to 4.8 vehicles, which is within the LOS C guideline (see Table 3). Based on these results, the team determined that lane 8 could be closed (with some minor shifting of breaks) from 6:00-11:00, with no detrimental customer impacts. Further lane closures were not possible, as additional runs revealed excessive queuing to LOS F.

8.3 OBX Off-Season Weekend Results

For the OBX Off-Season Weekend scenario, the analysis time frame was identified as 23:00 - 11:00. For the Base Condition, the maximum average queue was 3.5 vehicles, which was equivalent to LOS C, which is the lowest level provided in the existing staffing plan.

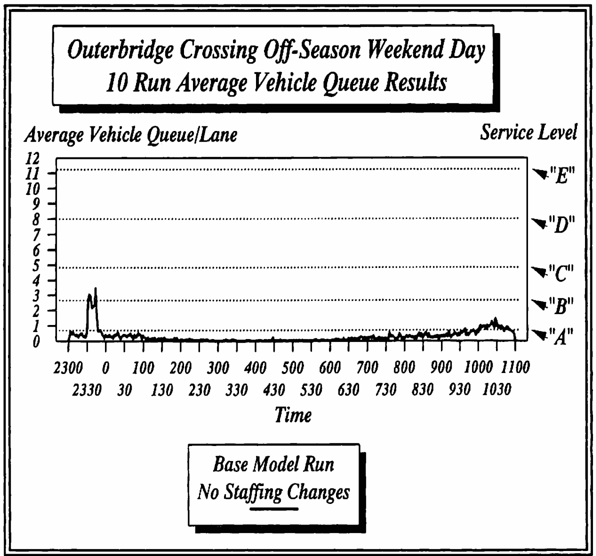

Figure 9: OBX OSSS Base Condition Queue Graph

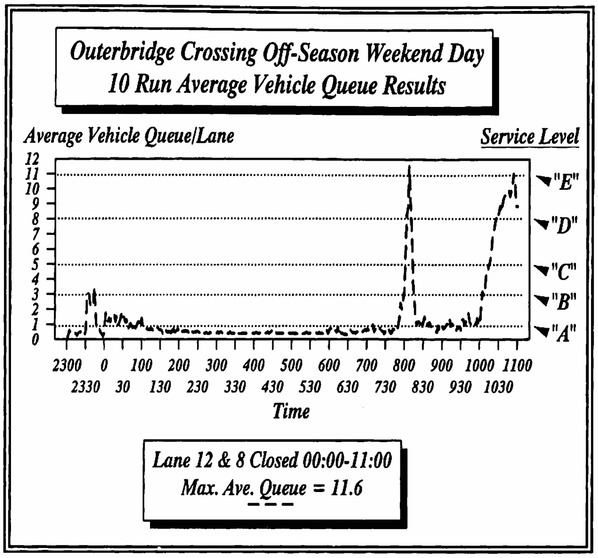

Figure 10: OBX OSSS Modified Lane Staffing Queue Graph

OBX Off-Season Weekend Day Results

OBX Off-Season Weekend Day	Base Staffing Results	Lane 12 & 8 Closed	With Relief
Max. Avg. Vehicle Queue	3.5 Vehicles	11.6 Vehicles	5.9 Vehicles
Lowest LOS	C	F	C
Avg. Time In Queue	8.8 Seconds	38.5 Seconds	12.6 Seconds
Max. Time In Queue	603 Seconds	702 Seconds	620 Seconds
% Vehicles With No Wait	42%	31%	34%
% 60+ Second Wait	0.9%	13%	2.7%

Table 4: OBX Modified Lane Staffing Results

Additionally, the average and maximum wait time in the queue was 8.8 and 603 seconds, respectively. The results for all vehicles in the base condition (no staffing changes) can be found in Figure 9 and Table 4.

For this scenario, the first lane to be closed was lane

12. With lane 12 closed, the results indicated no change in queuing from the base condition with an average maximum queue of 3.5 vehicles.

Lane 8 being open the 2nd longest was then closed. Preliminary runs with lane 8 closed revealed that the queue spiked into LOS F from 23:00-24:00, 8:00-8:30, and again from 10:00-11:00, resulting in a maximum average vehicle queue of 11.6 vehicles (see Figure 10 and Table 4). Otherwise, the queue levels maintained LOS C or better. If lane 8 were not closed until 24:00 and adjustments can be made for relief toll collectors to open lane 8 from 8:00-8:30 and 10:00-11:00, the queuing would, at its worst point, revert back to LOS C for the scenario. The average vehicle queue with this configuration dropped to 5.9 vehicles (see Table 4). Based on these results, the team determined that lane 8 could be closed from 24:00-11:00. Further lane closures were not possible, as additional runs revealed that substantial queuing would result in LOS F.

9 CONCLUSIONS

Based on the results of the modified lane staffing simulation analyses, the team recommended that the current lane staffing plan for the OBX be modified to include the following lane staffing changes:

For the Off-Season Weekday
(Monday through Friday, October through March) -

1) Close Lane 14 from 16:00 to 24:00
2) Close Lane 8 from 19:00 to 24:00

For the Season Weekend
(Saturday & Sunday, April through September) -

1) Close Lane 12 from 6:00 to 11:00
2) Close Lane 8 from 6:00 to 11:00
3) Modify relief schedule so that Lane 8 is open between 7:45-8:30.

For the Off-Season Weekend
(Saturday & Sunday, October through March) -

1) Close Lane 12 from 23:00 to 11:00
2) Close Lane 8 from 23:00 to 11:00
3) Modify relief schedule so that Lane 8 is open between 8:00-8:30 and 10:00-11:00.

These lane modifications can be phased into the current staffing plan by not back-filling those lanes that we have indicated to be closed in the event of an unexpected schedule vacancy (e.g., when a toll collector calls in sick or requests a personal day off). In this way, the schedule changes can be further "field" validated at the facility by monitoring the queuing impacts of the lane closures as vacancies occur, prior to full implementation.

The recommended toll collector schedule plan based on the results of this analysis for the OBX will represent an annual reduction of 5.8% in toll lane staffing hours, resulting in a cost savings of $106,000 annually. The next step for the study team will be to continue the analysis at the remaining Port Authority tunnel and bridge facilities so that a system wide service improvement plan can be developed and implemented.

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AUTHOR BIOGRAPHIES

JOHN P. DANKO is a Senior Simulation Consultant with the Port Authority Of New York & New Jersey and holds a Bachelor Of Science degree in Industrial Engineering from the New Jersey Institute Of Technology. He designs and conducts simulation studies in a wide variety of transportation, vehicle and patron systems which improve the flow through major aviation, tunnel and bridge facilities in the New York City metropolitan region. John is also a Senior Member of the Institute Of Industrial Engineers Operations Research Division and a member of the Society For Computer Simulation.

VICTOR J. GULEWICZ is a Principal Management Engineer in the Port Authority Of New York & New Jersey. In addition to toll plaza modeling, he has managed and performed various simulation studies related to airport terminal design evaluations. Victor is an Associate Member of the Transportation Research Board.

KEY WORDS

Modeling Methodology, Toll Plaza Simulation, Toll Collector Scheduling.