Simulation-Based Approach to Evaluating Optimal Lane Staffing Requirements for Toll Plazas

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A comprehensive approach is presented, using a General Purpose Simulation System World simulation model, to evaluate the optimal lane staffing requirements necessary to satisfy, at an acceptable level of service, off-peak demand at a toll plaza. The approach provides an effective tool to analyze requirements, at a quantitative level, for varying levels of traffic volume and mix, thereby providing an acceptable level of service to patrons while maximizing the efficiency of the toll plaza operation. In addition, the evaluation resulted in the identification and application of a level-of-service criterion for determining toll plaza lane staffing requirements that would result in an acceptable level of performance for Port Authority toll plazas. Last, the approach allowed for modeling the toll plazas to an extremely detailed level of accuracy, which resulted in a high degree of confidence in the model's capabilities to predict plaza operations.

The Port Authority of New York and New Jersey 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 bistate agency that provides, operates, and maintains many transportation facilities. The current demands for these facilities are especially severe on the six tunnel and bridge crossings that link New York and New Jersey at key locations within the metropolitan region. These crossings are the George Washington Bridge, which connects northern New Jersey to Manhattan; the Lincoln and Holland tunnels, which link New Jersey and the Manhattan central business district; and the Outerbridge, Goethals, and Bayonne bridges, which connect Staten Island with New Jersey. Patrons traveling toward New York through each of these crossings must stop and pay a toll.

By its nature, a toll plaza can become a major congestion bottleneck that can severely impede vehicular movements in a metropolitan area. Long queues are particularly evident during the morning and evening peak travel periods, when the number of vehicles arriving sometimes greatly exceeds the tolls processing capacity at a given crossing. Conversely, during the off-peak periods, opportunities exist to maximize the efficiency of the plaza operation by determining the minimum lane staffing requirements needed to meet an acceptable service standard.

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

Recognizing that traffic volumes at crossings vary over time, ITD staff were interested in developing an analytical approach that could be used to assess alternative staffing scenarios and to select the most cost-effective strategy for each facility. Specifically, the effectiveness included vehicle queueing levels, rate of vehicle throughput, and wait time in queue. On the basis of research and past experience, ITD and ME&A staff concluded that a lane-by-lane assessment was required and could be accomplished using computer-based simulation modeling techniques.

STUDY OBJECTIVE AND SCOPE

The 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 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 alternative lane 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 the Phase 1 effort for the OBX.

SERVICE LEVEL STANDARDS

As stated previously, the operational impacts of alternative scenarios for lane and toll collector staffing must be predicted with a reasonable degree of accuracy. Furthermore, these impacts should define the performance of the toll plaza in terms of the level of service, or LOS (normally expressed as an index of discomfort), that the user experiences. As an initial step, the study team conducted research on the use of service level standards for toll plazas.

A literature search identified a number of documents for review, including the *Highway Capacity Manual* (HCM) (*1*). In addition, the team contacted four research organizations, 16 transportation properties, and six consulting firms with transportation and traffic engineering experience in an attempt to identify any applicable standards being used in the design, evaluation, and management of toll plazas.

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TABLE 1 LOS Criteria for OBX

LOS	Average Waiting Time (sec)	Average Queue (no. of veh)
A	≤ 5	≤ 1
B	≤ 15	≤ 3
C	≤ 25	≤ 5
D	≤ 40	≤ 8
E	≤ 60	≤ 11
F	> 60	> 11

As a result of the search, the study team found that generally recognized or accepted service level standards do not exist for evaluating toll plaza performance. Furthermore, for the organizations contacted, most indicated that they depend on the experience and judgment of management and operating personnel instead of formal standards for determining toll lane and staffing requirements that would result in an acceptable level of performance.

A noted exception to this approach was identified for the New Jersey Highway Authority (NJHA), which operates the Garden State Parkway. In the late 1980s NJHA retained the services of Vollmer Associates to develop an approach for determining the number of toll booths required at each of its plazas to achieve an acceptable level of performance (*2*). Vollmer recommended the application of LOS criteria 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. This stopped time is equal to the total of the transaction time(s) for each vehicle in the queue ahead of that user.

On the basis of the results of the 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) (*1*). The LOS values for stopped delay were translated by the study team into the number of vehicles queued by considering the average transaction time per vehicle. The parameter of "vehicles queued" relates well to the physical characteristics of a toll plaza, thereby providing a less abstract characterization of plaza performance.

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

DATA COLLECTION APPROACH

To identify applicable time frames 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 through March and April through September were most representative of the "off-season" and "season" months, respectively. The study team then obtained daily traffic volumes for the facility from July 1991 to June 1992. Distributions of the daily vehicle volumes were calculated, and the 85th-percentile demand days given here (which have been the standard used by the transportation industry to design and evaluate facilities) were selected for each:

	Season	*Off-Season*	*Variance (%)*
Weekday	39,190	35,773	−9.5
Weekend day	42,522	38,653	−10.0

The percentage variance between the season and off-season and for each day type was then calculated; if it exceeded 5 percent, the team and facility staff concurred that this difference was attributable to seasonal aspects of traffic volume. On the basis of the percentile demand analysis, four data collection days were identified for the OBX for the weekday and weekend day scenarios during the season and off-season time frames. For each scenario, a data scanning was performed, which involved documenting at 5-min intervals the lane status (open or closed) and the vehicle queue. The vehicle queueing data for each of the eight lanes were then averaged and plotted against the number of lanes opened. An example of a scanning plot can be found in Figure 1.

Those time frames exhibiting low queue conditions and a high number of lanes open were identified as candidates for evaluating alternative lane and staffing requirements. As such, these time frames were identified for data collection:

	Season	*Off-Season*
Weekday	None	4:00 p.m.–12:00 a.m.
Weekend day	6:00–11:00 a.m.	11:00 p.m.–11:00 a.m.

MODEL STRUCTURE

The toll staffing simulation model was developed to provide the ability to analyze lane-by-lane queueing as a result of modifications to lane staffing. To achieve this level of detail, the model was devel-

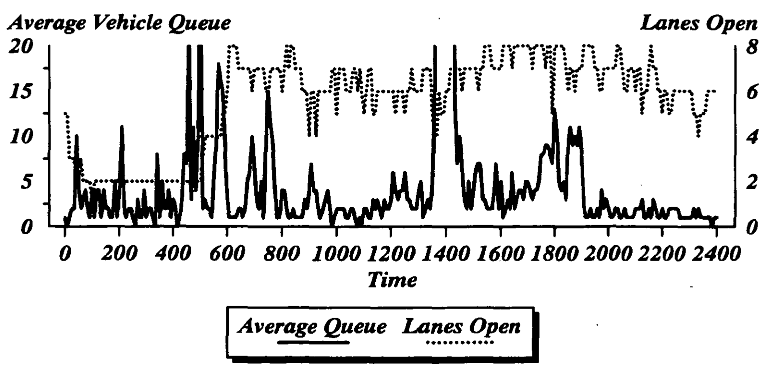

FIGURE 1 Example of OBX scanning graph.

oped using GPSS World, which is a general application simulation language run on a high-speed personal computer.

In the model, each vehicle is generated and processed individually, which allows for a greater level of accuracy. However, this level of detail resulted in the model structure containing approximately 15,000 lines of programming code, requiring that the team investigate ways to compact the model structure to keep it manageable. Through the use of several high-level GPSS World coding techniques, the structure (number and position of lanes) of the toll plaza being simulated in each model is created in memory as the model runs, rather than physically defining the plaza structure using standard coding methods. Doing this saves a substantial amount of programming lines and allows the simulation of a typical 8-hr period to run in approximately 1 min.

For model input, vehicle interarrival data were collected independently for each arrival lane and by vehicle type (car, bus, light truck, and heavy truck). The data were then fed into a statistical software package to determine if the arrivals "fit" a standard theoretical distribution (pattern) of arrivals. The package, CurveFit, was used to determine which standard distribution fits the closest to the field data. The software selects the distribution on the basis of the "shape" of the arrival pattern and whether it passed both the Kolmogorov-Smirnov and Anderson-Darling tests. By passing these tests, the data are confirmed to be a good fit. Use of the standard theoretical distributions in the model was preferred because it accounts for all possibilities of randomness in that pattern and eliminates the statistical anomalies that occur in raw data, which is the case for when the actual empirical distributions are used. Different arrival distributions were created (fit) for each 1/2-hr period to allow for changes in the volume of vehicles that arrive at different times during the day.

The lane selection data, which describe how vehicles choose which toll lane to enter, were also collected for each scenario at the OBX. To collect these 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 (even Numbers 2 through 16), and the destination toll lane were recorded. The OBX toll plaza layout can be found in Figure 2.

From the recorded data, 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 choose a toll lane randomly.

These driving habits were replicated in the simulation model by using percentages to create a lane selection algorithm, developed by the study team, that determines the probability of any vehicle's entering any lane in the toll plaza based on the level of queueing. An example of the lane selection algorithm used in the model is shown in Figure 3. This algorithm for the OBX season weekend day revealed that drivers tend to stay on the same side of the toll plaza from which they arrived, with 84.2 percent of the drivers arriving from the left lane choosing Lanes 2 through 8 (left side) and 66.3 percent of the drivers arriving from the right lane choosing lanes 10 through 16 (right side). The 33.7 percent that arrived from the right lane and moved to the left side was higher than the 15.8 percent moving from the left to the right side. The study team observed that this is caused by trucks that dominate the right arrival lane. Cars arriving in the right lane tend to move more to the left to avoid the truck queueing on the right side of the toll plaza.

The processing rate data are 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, and lane closures.

MODEL VALIDATION

A simulation model is beneficial only if its results are known to be accurate. Because of the significant impacts of the results of the toll

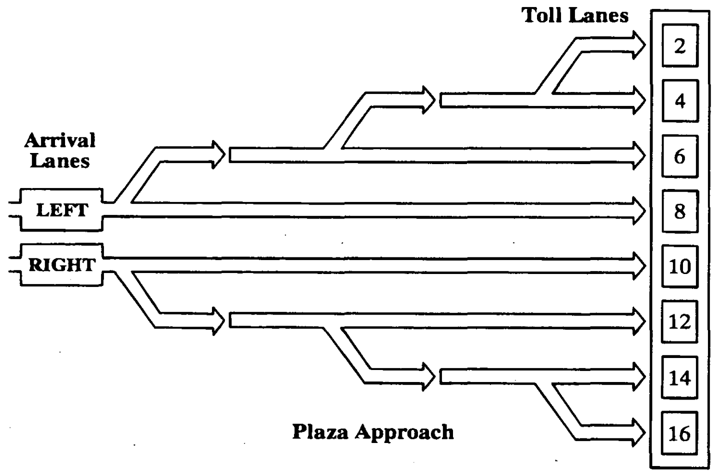

FIGURE 2 OBX toll plaza layout (not to scale).

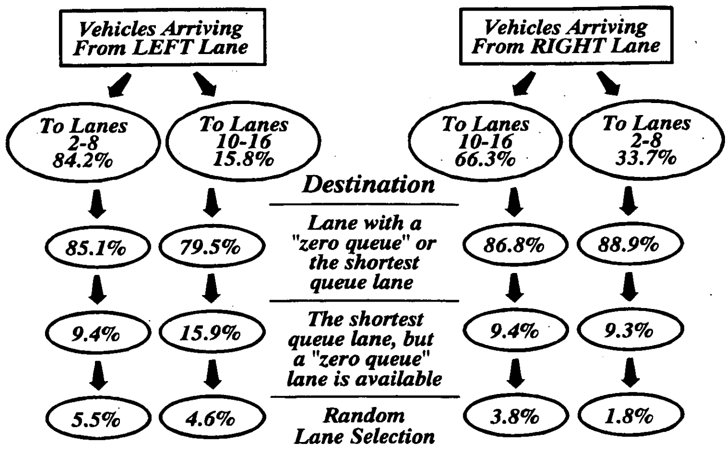

FIGURE 3 Lane selection algorithm.

staffing simulation model, the study team decided to validate the model using two variables: vehicle queue and throughput.

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 1-min intervals from 6:00 to 11:00 a.m. Additionally, all lanes were recorded as being open (green light) or closed (red light) at 1-min intervals.

The OBX model was configured on the basis of data recorded on August 30, 1992, and was then programmed to tabulate the individual lane queue and total toll plaza throughput at 1-min intervals to match the field data collection method. The results of the queue validation can be seen in Figure 4. The study team thought that it was necessary to create one value that would indicate the level of the model's accuracy. So in addition to the visual comparison, the absolute differentials in average vehicle queue between the field-measured data and the model's calculated value were tabulated at 1-min intervals. The average for the scenario time frame (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 queueing was 1.2 percent. This can be translated as the model having an average of 1.2 percent error in estimating vehicle queue or, conversely, the model being 98.8 percent accurate in predicting vehicle queue, which is evidence that the model capabilities are confirmed. In addition, the throughput graph (Figure 5) reveals similar results, with an average deviation in vehicle throughput of 0.52 percent.

From the results of the validation, the study team was confident that the model can accurately predict vehicle processing at the OBX.

MODEL SCENARIOS

Using the four OBX scanning scenarios mentioned earlier, the study team determined that three scannings, off-season weekday, season weekend day, and off-season weekend day, offered the potential for modifying lane staffing requirements.

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 10 model runs using varying random number streams was conducted for each to create the "typical" demand during that time frame at the facility. The results of the 10 runs were then averaged, creating the typical day results.

RESULTS

For each of the scenarios, the base condition model was run first to determine the baseline results. The base condition models simulate

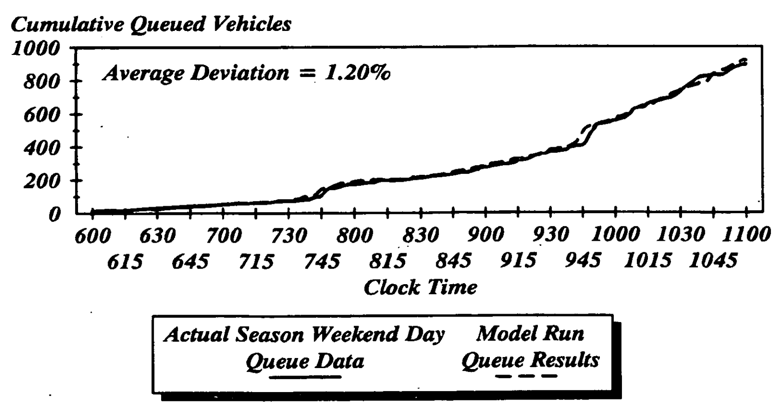

FIGURE 4 OBX validation queue graph.

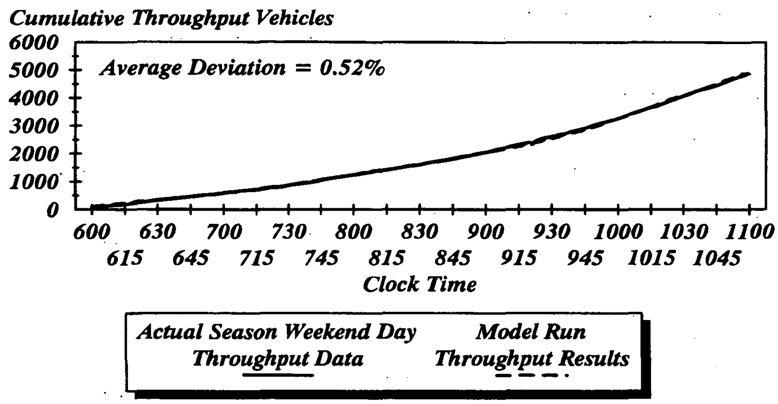

FIGURE 5 OBX validation throughput graph.

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 time frame. This variable was chosen by the team because it is a good indicator of the overall operating condition of the toll plaza.

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 4:00 p.m. through 12:00 a.m. The results for all vehicles in the base condition (no staffing changes) can be found in Figure 6.

For the base condition, over the time frame being analyzed, the plaza was operating within LOS A. The lowest level resulting from the existing staffing plan was LOS C, albeit for a very short duration.

For all of the scenarios, the study team decided that the lane that was open for the longest time during the analysis time frame would always be the first to be closed to determine the queueing impacts. This was done to represent the worst-case possibility, since it would 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 4:00 p.m. to midnight, the simulated results indicated minimal change in queueing from the base condition.

The next step was to determine the impact of closing an additional lane. Lane 8 was open the next longest in the time frame, so it was the next to be closed from 4:00 p.m. to midnight. Preliminary runs with Lane 8 closed revealed that severe queueing occurred between 4:00 and 7:00 p.m., resulting in LOS F, but for the rest of the time frame, only two small spikes into LOS D were the worst queueing obtained. From these results, the team decided that Lane 8 could be closed only from 7:00 p.m. to midnight. With Lanes 14 and 8 closed, LOS A or B was maintained throughout most of the time frame (Figure 7). Since the two small spikes created by closing Lane 8 moved beyond the maximum LOS C into LOS D for only a total of about 5 min, 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 queueing would result.

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 to 11:00 a.m. For the base condition, operating conditions during most of the time frame were within LOS A. The results for all vehicles in the base condition (no staffing changes) can be found in Figure 8.

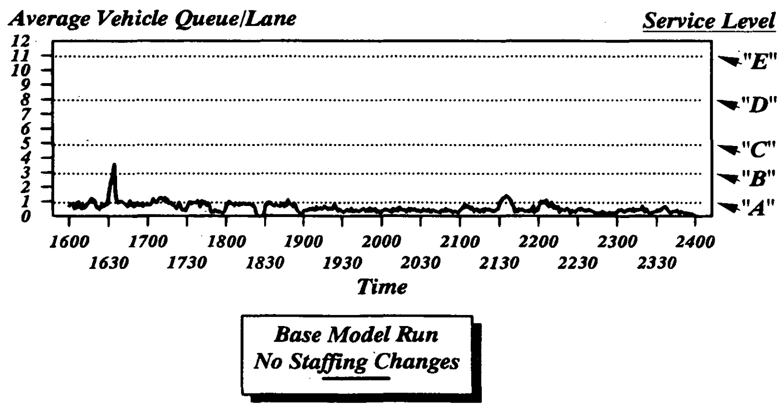

FIGURE 6 OBX base condition queue graph, off-season weekday.

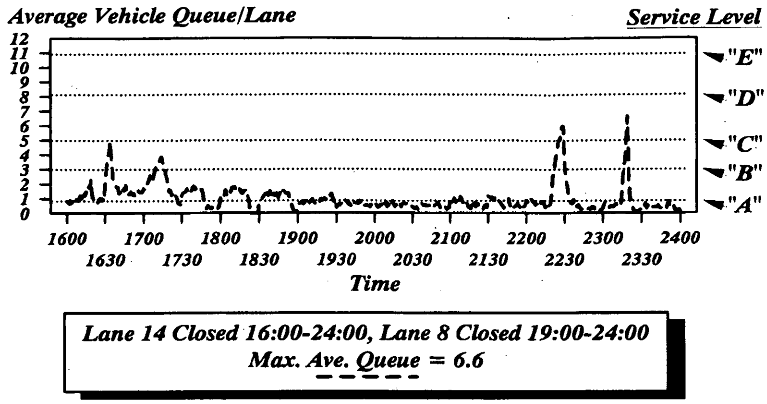

FIGURE 7 OBX modified lane staffing queue graph, off-season weekday.

For this scenario, the first lane to be closed was Lane 12. With Lane 12 closed, the results indicated minimal change in queueing from the base condition.

Since Lane 8 was opened the second 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 to 8:30 a.m. with a maximum average queue of 29.3 vehicles (Figure 9). Otherwise, LOS C or better was maintained. Since Lanes 12 and 8 will be closed in the modified staffing plan, the existing relief toll collectors will have fewer lanes to cover. If the relief schedule is modified so that relief toll collectors open Lane 8 between 7:45 and 8:30 p.m., the queueing pattern will revert to LOS B during these 45 min, which was observed during the previous run. Thus, the team determined that Lane 8 could be closed (with some minor shifting of breaks) from 6:00 to 11:00 a.m. with no detrimental customer impacts. Further lane closures were not possible, as additional runs revealed excessive queueing to LOS F.

OBX Off-Season Weekend Results

For the OBX off-season weekend scenario, the analysis time frame was identified as 11:00 p.m. to 11:00 a.m. For the base condition, the average queue was within LOS A or B for almost the entire time. The results for all vehicles in the base condition (no staffing changes) can be found in Figure 10.

For this scenario, the first lane to be closed was Lane 12. With Lane 12 closed, the results indicated no change in queueing from the base condition.

Lane 8, being open the second longest, was then closed. Preliminary runs with Lane 8 closed revealed that the queue spiked into LOS F from 11:00 p.m. to midnight, 8:00 to 8:30 a.m., and 10:00 to 11:00 a.m. Otherwise, the queue levels maintained LOS C or better. If Lane 8 were not closed until midnight and adjustments could be made for relief toll collectors to open Lane 8 from 8:00 to 8:30 a.m. and 10:00 to 11:00 a.m., the queueing would, at its worst point, revert to LOS C. The team determined that Lane 8 could be closed from midnight to 11:00 a.m. (Figure 11). Further lane closures were not possible, as additional runs revealed that substantial queueing would result in LOS F.

CONCLUSIONS

On the basis of the results of the modified lane staffing simulation analyses, the team recommended that the current lane staffing plan for the OBX be modified as described in this paper.

The lane modifications can be phased into the current staffing plan by not back-filling the lanes indicated to be closed in the event of an unexpected schedule vacancy (e.g., when a toll collector calls in sick or requests a day off). In this way, monitoring of the queue-

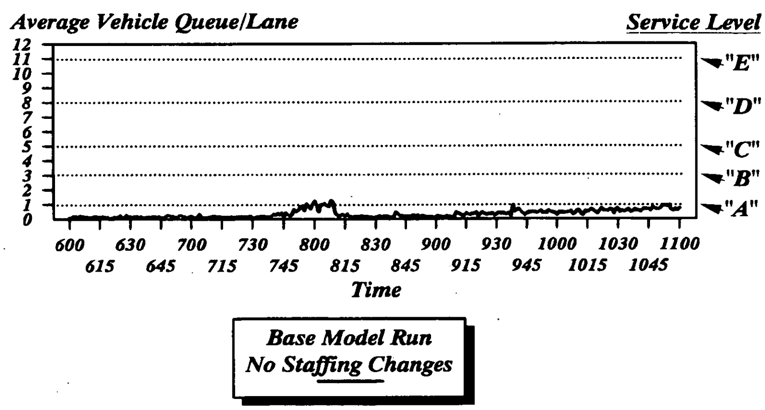

FIGURE 8 OBX base condition queue graph, season weekend day.

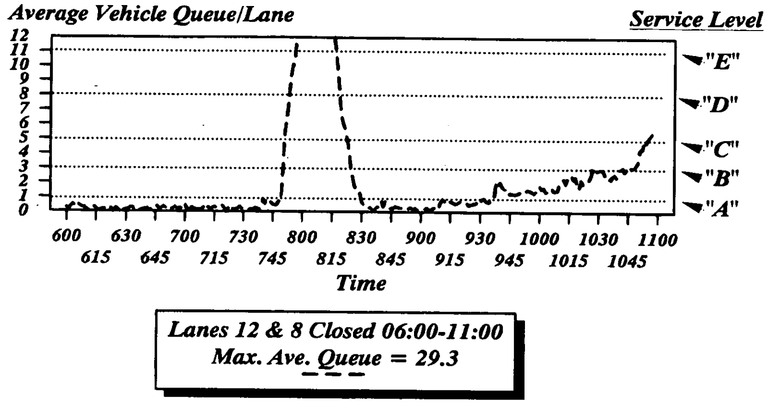

FIGURE 9 **OBX modified lane staffing queue graph, season weekend day.**

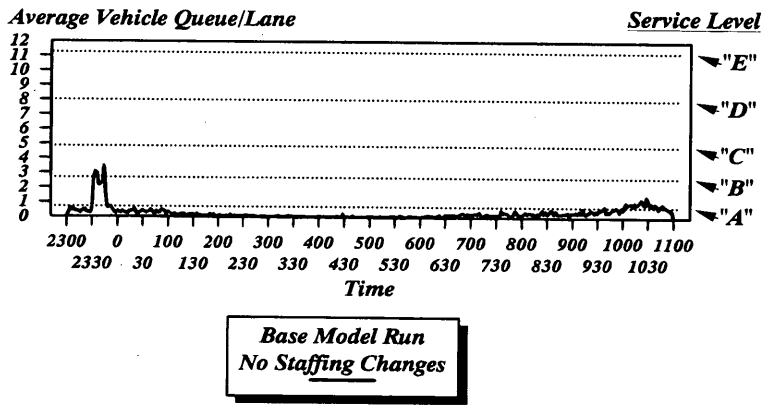

FIGURE 10 **OBX base condition queue graph, off-season weekend day.**

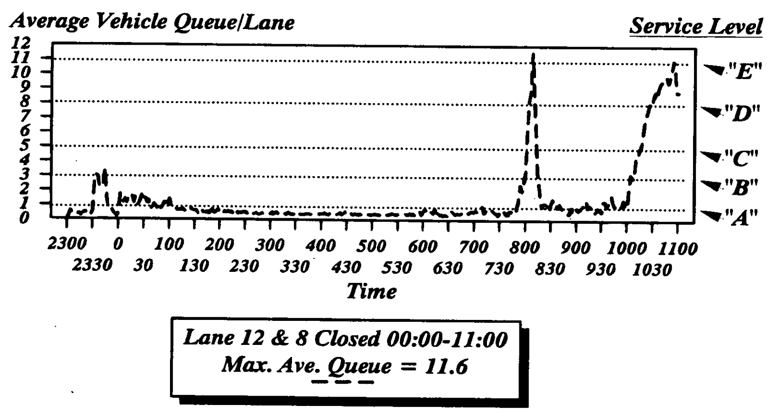

FIGURE 11 **OBX modified lane staffing queue graph, off-season weekend day.**

ing impacts of lane closures as vacancies occur, before full implementation, can further field-validate the schedule changes at the facility.

The recommended plan will reduce toll lane staffing hours by 5.8 percent a year, resulting in an annual cost savings of $114,000. 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 systemwide service improvement plan can be developed and implemented.

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