Estimation of Delays to Boats and Vehicular Traffic Caused by Moveable Bridge Openings: An Empirical Analysis

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The paper describes an interactive and simple queuing model developed to evaluate potential delays to both vehicular and vessel traffic caused by openings and closures of a draw bridge. The queuing procedures were developed to evaluate the proposed replacement alternatives (i.e., fixed-span bridge, tunnel or moveable bridge with 55 ft (16.77 m) vertical clearance) to the existing S.E. 17th Street draw bridge across the Intracoastal Waterway (ICWW) in Ft. Lauderdale, Florida. Currently, excessive delays are experienced by vehicular and vessel traffic using the S.E. 17th Street draw bridge and the ICWW, respectively. Queues to both the vehicular and vessel traffic were estimated and analyzed using a variety of factors ranging from bridge operating characteristics and available boat holding capacity in the ICWW to forecasted vehicle and vessel traffic. The queuing procedures are demonstrated in the paper mostly via examples for the sake of simplicity in presentation. The queuing procedures presented in the paper provided useful information, such as hours of delay to vessel and vehicular traffic, which was used to evaluate the proposed replacement facilities. The queuing analysis also provided useful and appropriate guidance for changing the historical 15-min bridge opening cycle to a 30-min time-saving bridge opening scheme.

An interactive and simple queuing model developed to evaluate potential delays to both vehicular and vessel traffic caused by openings and closures of a draw bridge is described in this paper. Necessary data for the empirical analyses were collected in relation to operation of the existing S.E. 17th Street draw bridge across the Intracoastal Waterway (ICWW) in Ft. Lauderdale, Florida. The existing bascule bridge provides 25 ft (7.62 m) of vertical clearance and it is located between two signalized intersections that are less than 1 mi (1.67 km) apart.

Because of the excessive delays to both vessel and vehicular traffic, the Florida Department of Transportation (FDOT) has embarked on evaluation of the following alternatives for replacement of the existing draw bridge: (a) a high-level, fixed-span bridge; (b) a tunnel; and (c) a higher-level, moveable bridge.

For the queuing analysis presented in the paper under the moveable bridge option, both vessel and vehicle queues were analyzed on the basis of a variety of factors, from bridge operating characteristics to forecasted vessel and vehicle traffic. For the fixed-span bridge and tunnel options, it was assumed that the overall performance of the two signalized intersections would control the net traffic flow capable of traveling on S.E. 17th Street. Therefore, the number of lanes for a fixed-span bridge or a tunnel by itself, relative to the proposed improvement schemes for the two intersections, could not necessarily be an issue. It was also assumed that any queue build-up would take place before either intersection.

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VESSEL AND VEHICULAR TRAFFIC DATA

Vessel Traffic Patterns

Some information regarding the existing vessel traffic was available from the bridge tender's logs. These data showed that the bridge is opened approximately 43 times a day. This information did not provide data on the height of vessels or the duration of bridge openings—critical pieces of information needed for the analysis of different bridge height options. To provide the needed information, a vessel height survey was conducted during the peak season in April 1991. The vessel survey provided detail information on the number and height of vessels passing under or through the bridge during each opening cycle observed from 9:00 a.m. to 6:00 p.m. The survey was conducted on Tuesday, Saturday, and Sunday. The duration of the bridge opening for each cycle was also recorded.

The analysis of the boat traffic from the survey indicates that (a) the boat traffic is heavier during the weekends and has peaking characteristics similar to that of general traffic and (b) vessels that are 55 or 65 ft (16.77 or 19.82 m) high appeared to use the ICWW continuously throughout the weekend survey day. Therefore, for the fixed-span bridge option, the clearance seems to be an issue if vessels 65 ft (19.82 m) and taller are to be accommodated through the ICWW.

Boat traffic forecasts are based on the evaluation of historical data for the study area and interviews with local residents involved in the marine industry. Vessels registered in the area as well as those using the S.E. 17th Street Causeway are increasing at a rate of 5 to 6 percent per year. This rate includes boats of all sizes. The vessel type distribution from the FDOT Bridge Opening Logs for an average month in 1986 indicates that 43 percent of the vessels were motorized and the remaining 57 percent were sailing vessels. For the purpose of queuing analysis it is assumed that the number of sailing vessels, with mast heights of more than 45 ft (13.72 m), would experience a lower growth rate than that of power boats. Therefore, an annual growth rate of 3 percent seems to be reasonable, although it might result in an optimistic set of boat forecasts for 2010. Interviews with residents involved in the marine industry indicated that an annual growth rate of 1 to 3 percent is reasonable. Results of the queuing analysis presented in this paper are based on 3 percent annual growth rate in boat traffic. Year 2010 (2050) forecast of boat traffic is summarized in Table 1.

General Traffic Patterns

The S.E. 17th Street corridor containing the ICWW is a well-established urban area. The daily traffic volume in 1991 on S.E. 17th Street was about 42,000 annual average daily traffic (AADT). General traffic is forecasted to increase to 48,000 AADT by 2010/2050 and beyond.

QUEUING PROCEDURES AND DELAY ANALYSIS

Both vehicle and vessel queues were analyzed under the 55 ft moveable bridge replacement option for the current year and year 2010. In addition to the existing 15-min bridge opening cycle, a 30-min bridge opening option also has been considered for the queuing and delay analyses. The operation of the existing bascule bridge or any future moveable bridge has great impact on the level of service on and near the facility. The limited vessel holding capacity and the impact on traffic resulting from a bridge opening required that both vessel traffic and vehicle traffic be analyzed simultaneously. For the simple queuing analysis described here, both vessel and vehicle queues were analyzed on the basis of a variety of factors ranging from bridge operating characteristics to forecasted vessel and vehicle traffic. A discussion of the methodology and results of the queuing analysis follows.

Average vessel crossings per minute were calculated on the basis of peak hour volumes from the 1991 boat survey. An analysis of the boat survey data reveals the following characteristics of vessels passing under the S.E. 17th Street Bridge:

- Weekend boat traffic was more than three times higher than weekday traffic,
- About 10 percent of weekend and 4 percent of weekday vessels that passed under the S.E. 17th Street Bridge were more than 65 ft (19.82 m) tall, and
- About 1 percent of weekend and 1.5 percent of weekday vessels that passed under the S.E. 17th Street Bridge were more than 85 ft (25.91 m) tall.

Vessel queues were calculated on the basis of the current 15-min bridge opening scheme as well as a 30-min bridge opening option for 25-ft (7.62-m) bascule bridge and a proposed 55-ft moveable bridge. A 50-ft (15.24-m) clearance was assumed for the 55-ft (16.77-m) bridge to provide a buffer zone between the top of a vessel's mast and the bottom of the bridge structure. It was assumed that all boat or vehicular backup dissipates during every bridge opening and closure. The existing operating scheme is such that the bridge stays open until all boats in the queue pass through.

Estimation of Holding Capacity for Marine Vessels

The number of vessels that can hold safely, both north and south of the bridge, was established using various site-specific

TABLE 1 Summary of 2010 (2050) Boat Traffic Forecasts

Time of Day	WEEKEND DAY						WEEKDAY					
	Low Estimate (1% per Year)			High Estimate (3% per Year)			Low Estimate (1% per Year)			High Estimate (3% per Year)		
	<= 44' (13.4m)	>=45' (13.7m)	Total	<= 44' (13.4m)	>=45' (13.7m)	Total	<= 44' (13.4m)	>=45' (13.7m)	Total	<= 44' (13.4m)	>=45' (13.7m)	Total
9-10	17	22	39	22	29	51	5	2	7	6	3	9
10-11	16	22	38	21	29	50	6	0	6	8	0	8
11-12	26	11	37	35	14	49	11	1	12	14	2	16
12-1	24	24	48	32	32	64	8	6	14	11	8	19
1-2	18	16	34	24	21	45	17	8	25	22	11	33
2-3	38	35	73	51	46	97	13	4	17	18	5	23
3-4	43	18	61	58	24	82	7	1	8	10	2	12
4-5	20	23	43	27	30	57	8	8	16	11	11	22
5-6	11	5	16	14	6	20	0	2	2	0	3	3
Total	213	176	389	284	231	515	75	32	107	100	45	145

facts in combination with certain assumptions. Safe holding areas were established as approximately 200 ft × 1,000 ft (60.98 × 304.88 m) north of the bridge and 200 ft × 1,100 ft (60.98 × 335.37 m) south of the bridge. In order to determine the anticipated holding areas, the following factors were taken into consideration: (a) depths within the ICWW, (b) the position of the turning basin for the port area and that smaller vessels must stay clear, and (c) sight distance to the bridge (observation of the boats holding indicates that boats will stay as close to the bridge as possible while waiting).

The number of boats that can hold within the safe area was determined using the following assumptions.

First, average length for boats holding is 45 ft (13.72 m). This assumption was verified through review of the boat survey data collected in April, 1991. At this time, approximate boat lengths were recorded for all vessels passing under the bridge during an opening.

Second, "shorter" vessels such as power boats are presently passing through even when the bridge is closed.

Third, boats require at least 4 times their length and 6 times their width to stay clear of others while holding. The figures in this assumption were determined from 4 days of observation in the bridge vicinity (April 1991 boat survey) and personal experience. Note that the information from the Marina Design Standards (MDS) appeared to be inappropriate for estimation of the holding area. Use of the MDS appears to be appropriate for sizing the parking areas for the boats and not necessarily for the vessels that are temporarily holding for a bridge opening. Therefore, use of the MDS would have resulted in an unrealistically high number of boats that could not be safely held on either side of the bridge. A more conservative estimate of holding capacity for boats was used to reflect the impacts of currents and the reduction in navigation ability while the boat is sitting motionless (this is especially true for larger vessels) and to take into consideration shorter vessels passing through the queue.

Using these assumptions, the number of boats that can be safely held on either side of the bridge are as follows: for the north side of the S.E. 17th Street Bridge, 11 boats; for the south side of the S.E. 17th Street Bridge, 11 to 12 boats.

Queuing Analysis of Boat Traffic

The daily distribution of the 1991 boat survey data indicated a high concentration of boat traffic during 1 hr of either the morning or afternoon peak period. Therefore, the queuing analysis was conducted for only 1 hr instead of using blocks of time during the peak period. To compensate for any underestimation of delay due to this particular assumption, values for daily instead of peak period average service time were used. The boat survey identified a weighted (by vessels' heights) daily average service time of 0.98 min (as opposed to a peak average of 0.50 min) per vessel during the weekend and 2.45 min per vessel for the weekday.

The projected number of vessels in the average peak hour queue was multiplied by the overall daily weighted average vessel service time (estimated from the boat survey) to determine the average duration of bridge opening during the peak hour. The bridge survey identified a weighted daily average service time of 0.98 min per vessel during the weekend and 2.45 min per vessel for weekdays. These different service times probably result from the lower vessel volumes on weekdays. The same amount of time is needed to raise and lower the bridge regardless of the number of vessels passing underneath. The lower number of weekday vessels allocates this time to fewer vessels, thus increasing the average service time (minutes per vessel crossing). With only a few exceptions, the minimum bridge opening time was 5 min. To reflect actual operating characteristics in the analysis, 5 min was used as the minimum bridge opening time. Because many of the bridge openings during the weekday were to allow 5 vessels or fewer to pass underneath, this sample was not used to calculate bridge opening duration. Instead, the weekend average service time of 0.98 min per vessel was used to calculate both weekend and weekday bridge opening duration. This service time includes the time for opening and closing the bridge. Calculated bridge opening times were used when the projected vessel queues resulted in estimated bridge openings greater than 5 min.

The queuing analysis indicates that the bridge opening time is, for the most part, the same when one to five vessels pass underneath. This means that during times of low vessel traffic, such as the weekday morning peak period, the duration of each bridge opening will be the same for both the existing bridge and the 55-ft (16.77-m) bascule bridge option [i.e., no-build versus a 55-ft (16.77-m) moveable bridge]. The frequency of bridge openings would be reduced with the 55-ft (16.77-m) moveable bridge option. Data from the bridge survey indicate that currently during the morning peak hour, two vessels more than 45 ft (13.72 m) in height can be expected to pass underneath the S.E. 17th Street bridge. During the afternoon peak hour, seven vessels were counted with a height exceeding 45 ft (13.72 m).

The vessel queues during the weekday peak hours in 2010 (2050) will not reach capacity under the current 15-min operating scenario or 30-min bridge opening scheme. Weekend vessel queues are at or near capacity during the current afternoon peak operating scheme, as shown in Table 2. Weekend vessel queues would be at or near capacity for the existing 15-min bridge opening cycle in 2010 under a 55-ft (16.77-m) bridge replacement option (Table 2) using 3 percent per year growth in boat traffic. Weekend vessel queues are expected to increase by 100 percent of the existing holding area capacity under the 30-min bridge opening option both in 1991 and 2010, as demonstrated in Table 3.

Average vessel delay and total vessel delay for the peak hour was calculated on the basis of the existing 15-min bridge opening cycle, a 30-min bridge opening option, the vessel queue, and the service rate. Results for 1991 and 2010 (2050) under a 55-ft (16.77-m) bridge replacement option are summarized in Tables 2 and 3.

Queuing Analysis of Vehicle Traffic

The existing vehicle queues are about 1,000 to 1,500 (304.88 to 457.32 m) ft behind the two intersections during the peak hour. Vehicle queues were calculated based on the existing and forecasted length of bridge openings. One result of using a minimum opening time was that vehicle queues per bridge opening for the 25-ft and 55-ft (7.622-m and 16.77-m) bridge

TABLE 2 Peak Season Vessel Delay Analysis (15-min Bridge Opening Scenario)

Year	15-Minute Bridge Operating Scheme	Vessel Queue	Total Vessel Delay (in minutes)	Peak "Hour" Delay 15 min. Cycle X 4 (in minutes)	Daily Vessel Delay (in hours)
25' (7.6m) Bridge					
1991	Weekday	3	27	108	9
1991	Weekend	11**	131	524	34
2010 (2050)	Weekday	5	45	180	15
2010 (2050)	Weekend	20*	476	1904	92
55' (16.7m) Bridge (With 45-Foot (13.73m) Effective Clearance)					
2010 (2050)	Weekday	3	27	108	9
2010 (2050)	Weekend	11**	131	524	34

* Exceeds maximum vessel holding capacity.

** Vessel queue at holding capacity.

Note: Daily delay was calculated by converting four 15-minute bridge cycles into an hourly volume, taking into account the bridge opening duration, and then dividing by the peak hour factor of .15 derived from the boat survey data.

during the weekday a.m. and p.m. peak hours were identical, even though vessel volumes were not. The actual number of bridge openings during the peak hour will be less for the 55-ft (16.77-m) bridge, especially during the morning peak hour. Data from the bridge survey indicate that currently during the weekday a.m. peak hour, one vessel more than 50 ft (15.24 m) high can be expected to pass S.E. 17th Street. During the weekday p.m. peak hour, four vessels taller than 55 ft (16.77 m) were counted.

Actual 1991 and forecasted 2010 peak hour traffic was converted to vehicle arrivals per minute to determine the length of the vehicle queue on the basis of the estimated duration of the bridge opening. The base year 1991 and 2010 (2050) p.m. peak hour traffic volumes were used to determine peak hour vehicle traffic crossing the bridge. Both vessel and vehicle queues for 1991 and 2010 (2050) during the weekday p.m. peak hour and the weekend p.m. peak hour are presented in Tables 4 and 5 for the 15-min and 30-min bridge opening cycles, respectively.

Because the weekday peak hour bridge opening duration is the same for both the existing bridge and the 55-ft bridge, the vehicle queues per bridge opening would be the same for either option. The frequency of bridge openings and the associated vehicle queues will be reduced with the 55-ft bridge.

Average and total vehicle delay were calculated for the different bridge options on the basis of the length of the bridge

TABLE 3 Peak Season Vessel Delay Analysis (30-min Bridge Opening Scenario)

Year	30-Minute Bridge Operating Scheme	Vessel Queue	Total Vessel Delay (in minutes)	Peak "Hour" Delay 30 min. Cycle X 2 (in minutes)	Daily Vessel Delay (in hours)
25' (7.6m) Bridge					
1991	Weekday	6	102	204	19
1991	Weekend	22*	546	1092	71
2010 (2050)	Weekday	11**	214	428	35
2010 (2050)	Weekend	41*	1399	2798	133
55' (16.7m) Bridge (With 45-Foot (13.73m) Effective Clearance)					
2010 (2050)	Weekday	6	102	204	19
2010 (2050)	Weekend	22*	546	1092	71

* Exceeds maximum vessel holding capacity.

** Vessel queue at holding capacity.

Note: Daily delay was calculated by converting two 30-minute bridge cycles into an hourly volume, taking into account the bridge opening duration, and then dividing by the peak hour factor of .15 derived from the boat survey data.

TABLE 4 Peak Season Vessel and Vehicle Queues (15-min Bridge Opening Scenario)

Year	15-Minute Bridge Operating Scheme	Vessel Queue	Vehicle Queue	
			Westbound	Eastbound
25' (7.6m) Bridge				
1991	Weekday	3	88	69
1991	Weekend	11**	176	139
2010 (2050)	Weekday	5	98	78
2010 (2050)	Weekend	20*	358	283
55' (16.7m) Bridge (With 45-Foot (13.73m) Effective Clearance)				
2010 (2050)	Weekday	3	98	78
2010 (2050)	Weekend	8	143	113

* Exceeds maximum vessel holding capacity.

** Vessel queue at holding capacity.

opening (which is determined by the vessel queue) and the time it takes for the vehicle queue to dissipate. The delay associated with the vehicle queue was calculated on the basis of the length of the vehicle queue, the speed of the roadway, and the capacity of the roadway.

For the purpose of illustrating the method used to determine vessel and vehicle queues and delays, the following example shows the calculations step by step:

Calculation of Queues and Delays

The queue and delay procedures are summarized in the following steps:

1. Calculate vessel queue;
2. Determine bridge opening time required to clear vessel queue;
3. Calculate vehicle queue on the basis of hourly traffic and duration of bridge opening;
4. Calculate vessel delay on the basis of bridge cycle length and time required to clear the queue; and
5. Calculate total vehicle delay on the basis of duration of bridge opening and time required to clear the queue, including queue dissipation.

Example of Queue Length Estimation

Step 1

The vessel queue is determined by the bridge cycle length, currently 15 min between openings, and average hourly vessel traffic. For the base year (1991), the weekend p.m. peak vessel traffic during the hour from 2 to 3 p.m. was 45 vessels per hour. This translates to 0.75 vessels per minute arriving

TABLE 5 Peak Season Vessel and Vehicle Queues (30-min Bridge Opening Scenario)

Year	30-Minute Bridge Operating Scheme	Vessel Queue	Vehicle Queue	
			Westbound	Eastbound
25' (7.6m) Bridge				
1991	Weekday	6	103	81
1991	Weekend	22**	352	299
2010 (2050)	Weekday	11**	212	167
2010 (2050)	Weekend	41**	733	579
55' (16.7m) Bridge (With 45-Foot (13.73m) Effective Clearance)				
2010 (2050)	Weekday	5	98	78
2010 (2050)	Weekend	17**	286	226

* Exceeds maximum vessel holding capacity.

** Vessel queue at holding capacity.

at the S.E. 17th Street Bridge. A 15-min bridge cycle forces 11 vessels to queue up before the next bridge opening.

Step 2

The vessel survey indicated that the weighted average vessel service flow rate (duration of bridge opening divided by number of vessels that pass underneath) was 0.98 min per vessel for the weekend. A queue of 11 vessels would then result in a bridge opening duration of 10.8 min.

Step 3

The number of westbound and eastbound 1991 p.m. peak hour vehicles traveling on the S.E. 17th Street Bridge are 2,103 and 1,661, respectively. This weekday peak hour traffic estimate was converted to weekend peak hour estimate using a factor (the weekend p.m. peak is 0.93 of the weekday p.m. peak) derived from a comparison of the weekday and weekend peak hour bridge counts conducted in March 1991. The resulting weekend p.m. peak hour (2 to 3 p.m.) vehicle traffic estimates used in this example are as follows: westbound 1,956 and eastbound 1,545. Similar weekend volumes for 2010 (2050) are as follows: westbound 2,190 (i.e., 2,355 × .93) and eastbound 1,730 (i.e., 1,860 × .93).

1991 peak hour (weekend) vehicle traffic is then converted to vehicle arrivals per minute. The vehicle queue is calculated as the number of vehicles arriving at the bridge per minute multiplied by the duration of the bridge opening.

In this example, the queue length for 1991 westbound weekend traffic is calculated as follows (see Table 4):

32.6 vehicles per minute × 10.8 min (5 min for weekday)

= 352 vehicles, or 176 per lane

The queue length for 1991 eastbound weekend traffic is calculated as follows (see Table 4):

25.8 vehicles per minute × 10.8 min (5 min for weekday)

= 278 vehicles, or 139 per lane

Example of Delay Estimation

Step 4: Vessel Delay per Bridge Opening Cycle

Vessel delay is a function of time waiting for the bridge to open and the time spent clearing the queue. Assuming vessels arrive randomly at the bridge, the average vessel delay as a result of the bridge cycle would be one-half of the cycle length, or, in this case, 7.5 min. The average vessel delay resulting from the vessel queue would be one-half of the duration of the bridge opening, or 5.4 min per vessel [2.5 min. per vessels for weekday (5.0 × 0.5)] minus the time it would normally take to pass under the bridge (.98 min). Total vessel delay per bridge cycle is calculated as the sum of the bridge opening cycle and queue delays multiplied by the number of vessels in the queue.

[(Bridge opening cycle delay × # of boats per cycle)

+ (queue clearance delay × # of boats per cycle)]

= total boat delay per bridge cycle

For a 1991 weekend, vessel delay is calculated as follows (see Table 2):

(7.5 min × 11 boats)

+ [(5.4 min − .98 min) × 11 boats] = 131 boat min

For a 1991 weekday, vessel delay is calculated as follows (see Table 2):

(7.5 min 3 boats)

+ [(2.5 min − .98 min) × 3 boats] = 27 boat min

Step 5: Total Vehicle Delay

Vehicle delay was estimated by applying a bottleneck concept developed by Adolf May (*1*). A bottleneck (in this case, a draw bridge) on a roadway may be represented by the behavior of a queue during one cycle of a traffic signal. This method assumes that vehicles arrive randomly at the bridge in spite of being interrupted by the two intersections at either end of the bridge. This seems to be a reasonable assumption because the bridge opening cycle was so much greater than the cycle at the intersections. When the bridge is open, it probably does not matter whether the arriving vehicles would stop at the intersections or at the bridge because the intersections are not far from the bridge.

May's bottleneck model is formulated as follows:

- q = average arrival rate of traffic (vehicle per minute) upstream of the bottleneck;
- s = saturation flow rate or capacity [vehicle per minute—1,850 vehicles per hour per lane (*2*)] of uninterrupted flow;
- sr = flow rate (vehicles per minute) at bottleneck during blockade (zero when bridge is open to boat traffic);
- r = duration of blockade (bridge opening time in minutes);
- to = time for queue to dissipate after the blockade is removed (in minutes); and
- tq = total elapsed time from start of blockade (bridge opening) until free flow resumes [$r + to$ (minutes)].

The duration of the queue is calculated in Equation 1:

$$tq = r\,(s - sr)\,/\,(s - q) \tag{1}$$

The number of vehicles affected is calculated in Equation 2:

$$N = q \times tq \tag{2}$$

The average number of minutes of vehicle delay is calculated in Equation 3:

$$d = r\,(q - sr)\,/\,2q \tag{3}$$

Total vehicle minutes of delay are calculated in Equation 4:

$$D = r \times N / 2 \quad (4)$$

These equations have been used to estimate total vehicle delays. For example, for 2010 p.m. peak weekend operation under a 15-min bridge opening scheme, queue duration, average vehicle delay, and total vehicle delay are calculated as follows.

For queue duration in minutes, Equation 1 is used. The following equations are for 2010 westbound weekend traffic:

$$s = 1{,}850 \times 2 \text{ (lanes)} / 60 = 61.7 \text{ vehicles/minute}$$

$$q = 2{,}355 \text{ (weekday vph)} \times .93 = 2{,}190 \text{ vph, or}$$

$$q = 2{,}190 / 60 = 36.5 \text{ vehicles/minute}$$

$$r = 8 \text{ vessel queue} \times .98 \text{ min service time} = 7.84 \text{ min (5 for weekday operation)}$$

$$tq = 7.84\,(61.7 - 0) / (61.7 - 36.5) = 19.20 \text{ min of queue duration}$$

The duration of queue for bridge opening is 7.84 min. The amount of time necessary to dissipate the entire queue is 19.20 − 7.84 = 11.36 min.

The following equations are for 2010 eastbound weekend traffic:

$$q = 1{,}728 / 60 = 28.8 \text{ vehicles/minute}$$

$$tq = 7.84\,(61.7 - 0) / (61.7 - 28.8) = 14.70 \text{ min of queue duration}$$

The duration of queue for bridge opening is 7.84 min. The amount of time necessary to dissipate the entire queue is 14.70 − 7.84 = 6.86 min.

The average vehicle delay in minutes is calculated using Equation 3:

$$d = 7.84 / 2 = 3.92 \text{ min}$$

because $sr = 0$ for both westbound and eastbound (2.5 for weekday).

The total number of vehicles affected is calculated using Equation 2. The following equation shows the number of vehicles for westbound weekend traffic:

$$36.5 \times 19.20 = 701 \text{ vehicles}$$

The following is the equation for eastbound weekend traffic:

$$28.8 \times 14.7 = 423 \text{ vehicles}$$

Total vehicle delay is calculated using Equation 4. For 2010 westbound weekend traffic, the delay is as follows:

$$7.84 \times 701 / 2 = 2{,}748 \text{ min}$$

For 2010 eastbound weekend traffic, the delay is as follows:

$$7.84 \times 423 / 2 = 1{,}658 \text{ min}$$

The calculation of queue duration indicated that under most circumstances the queue will dissipate during the required 15-min bridge cycle.

SUMMARY FINDINGS AND CONCLUSIONS

The queuing procedures presented in this paper provided useful information for evaluation of the proposed replacement facilities for the existing 25-ft (7.62-m) moveable bridge from the traffic operation standpoint. Obviously, if the elimination of delays to vehicular and vessel traffic is the only criterion by which to judge the proposed replacement facilities, the tunnel would be the superior option. Comparably, an 85-ft (25.91-m), fixed-span bridge would be a viable option if ves-

TABLE 6 Total Daily Delay Comparison Analysis for Average Peak Season Weekday (Delay Due to Bridge Openings)

Alternative	Cycle	1991 Vehicle Hours	1991 Vessel Hours	2010/2050 Vehicle Hours	2010/2050 Vessel Hours
55' (16.77m) Bascule Bridge	15-min	na	na	1,196	9
	30-min	na	na	933	19
25' (7.62m) Bascule Bridge	15-min	946	9	1,196	15
	30-min	724	19	2,710	35*
Tunnel	15-min	na	na	0	0
	30-min	na	na	0	0
Fixed-Span Bridge (65' or 85') (19.82m or 25.91m)	15-min	na	na	na	na
	30-min	na	na	na	na

* Under this scenario the vessel queue would be at holding capacity.
na = not applicable

TABLE 7 Total Daily Delay Comparison Analysis for Average Peak Season Weekend Day (Delay Due to Bridge Openings)

Alternative	Cycle	1991 Vehicle Hours	1991 Vessel Hours	2010/2050 Vehicle Hours	2010/2050 Vessel Hours
55' (16.77m) Bascule Bridge	15-min	na	na	3,636	34*
	30-min	na	na	8,582	71**
25' (7.62m) Bascule Bridge	15-min	2,865	34*	8,970	92**
	30-min	6,656	71**	18,577	133**
Tunnel	15-min	na	na	0	0
	30-min	na	na	0	0
Fixed-Span Bridge (65' or 85') (19.82m or 25.91m)	15-min	na	na	na	na
	30-min	na	na	na	na

* Under this scenario the vessel queue would be at holding capacity.
** Under this scenario the vessel holding capacity would be exceeded.
na = not applicable

sels with mast heights of 85 ft (25.91-m) were eliminated. The existing and projected daily boat traffic mast height distributions indicate that about 1 percent of the boats using the ICWW require more than 85 ft (25.91 m) of clearance during the weekends. On weekdays, about 1.5 percent of the boats appear to require this amount clearance.

Summary findings from the queuing and delay analysis are presented in Tables 6 and 7 for an average weekday and weekend day operation, respectively. Hours of delay to vessel and vehicular traffic were used in the economic analysis to rank the proposed replacement facilities to the existing moveable bridge. Furthermore, the analysis provided useful guidance for a more efficient operation of the existing bridge. As shown in Tables 6 and 7, a reduction of about 22 percent in vehicular traffic delays is expected under the 30-min bridge opening scheme for the weekdays relative to the 15-min scheme. The existing bridge operation was recently changed from the 15-min opening cycle to a 30-min scheme. Initial observations appear to confirm the findings from the queuing analysis.

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