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PANAMA CANAL CAPACITY ANALYSIS

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The New Panama Canal - Another Path Between the Seas
ASCE Met Section International Committee
ICE New York Local Association
New York, NY

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By Michael S. Bronzini,[1] Member, ASCE

Predicting the transit capacities of the various Panama Canal alternatives required analyzing data on present Canal operations, adapting and extending an existing computer simulation model, performing simulation runs for each of the alternatives, and using the simulation model outputs to develop capacity estimates. These activities are summarized in the succeeding sections of this paper. A more complete account may be found in the project final report (TAMS 1993). Some of the material in this paper also appeared in a previously published paper (Rosselli, Bronzini, and Weekly 1994).

Vessel Arrival and Transit Times

The principal source of data on vessel arrival patterns and transit times was the Ship Data Bank (SDB) compiled by the Panama Canal Commission (PCC). The SDB contains data on every ship transit through the Canal, including the times of passage at key control points in the system, such as the locks and the Culebra Cut. The SDB records for 13,611 vessel transits for the year 1990 were analyzed in this study. Table 1 provides a breakdown of vessels by beam, draft, and transit direction. The SDB data were supplemented by on-site data collection in Panama at the locks over a two week period in 1991.

The SDB data were used to investigate vessel arrival patterns, and to derive detailed estimates of vessel transit times, channel speeds, and locking times, for input to the Waterway Analysis Model (discussed below) and for model calibration purposes. The data collected on-site were used to assist in dividing the locking times into the specific time elements required for input to the model, and to guide the interpretation and usage of the SDB data.

Some of the principal conclusions of the data analyses conducted are as follows:

- Ship arrivals were found to be distributed randomly throughout the year; that is, there were no strong seasonal or monthly patterns evident in the data.
- The hourly pattern of ship underway times (the beginning of transit) strongly reflected the current scheduling practices used to restrict (for safety reasons)

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Table 1. Vessel Classes and Observed Frequencies (1990)

Vessel Class	Beam (ft)	Draft (ft)	No. of Ships	
			Northbound	Southbound
1	< 60	-	1371	1604
2	60 - 69	-	588	596
3	70 - 79	-	1455	1493
4	80 - 89	<= 36	587	565
5	80 - 89	> 36	40	139
6	90 - 99	<= 30	298	233
7	90 - 99	30 - 36	262	295
8	90 - 99	> 36	149	152
9	> 99	<= 30	493	381
10	> 99	30 - 36	366	384
11	> 99	36 - 38	121	177
12	> 99	> 38	282	670
13	(Passenger)	-	46	97
14	(Recreational)	-	247	393

meetings and night passage of large ships through the Culebra Cut. The pattern of underway times did not vary significantly between the rainy season and the dry season (Figures 1 and 2).

- Northbound and southbound transit times were found to be different. with an average of 12.5 hours northbound and 9.8 hours southbound. Consequently directional differences were maintained throughout the analysis. The average time in canal waters, including the time from "ready for transit" to "beginning of transit," was about 19 hours.

- The average movement time through the Canal was found to be between eight and nine hours, which is consistent with the segment travel times used by the PCC for ship scheduling. The remaining time is waiting time, primarily at the locks.

- The time interval between the arrival of a ship and its beginning of transit was also analyzed, both from the SDB records and through conversations with knowledgeable individuals in Panama. This interval, on the average, exceeded 11 hours in 1990. There are minimal operational or administrative delays during this period. Rather, most of the time is accounted for by discretionary vessel activities. and by the aforementioned scheduling practices related to

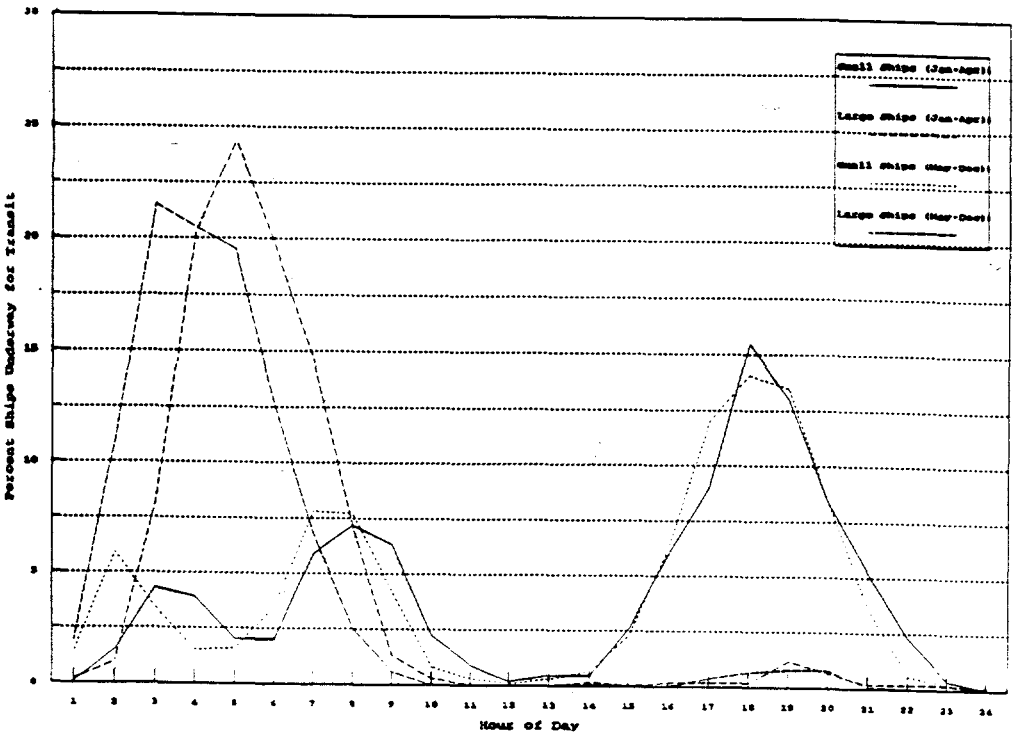

Figure 1. Northbound Underway Patterns

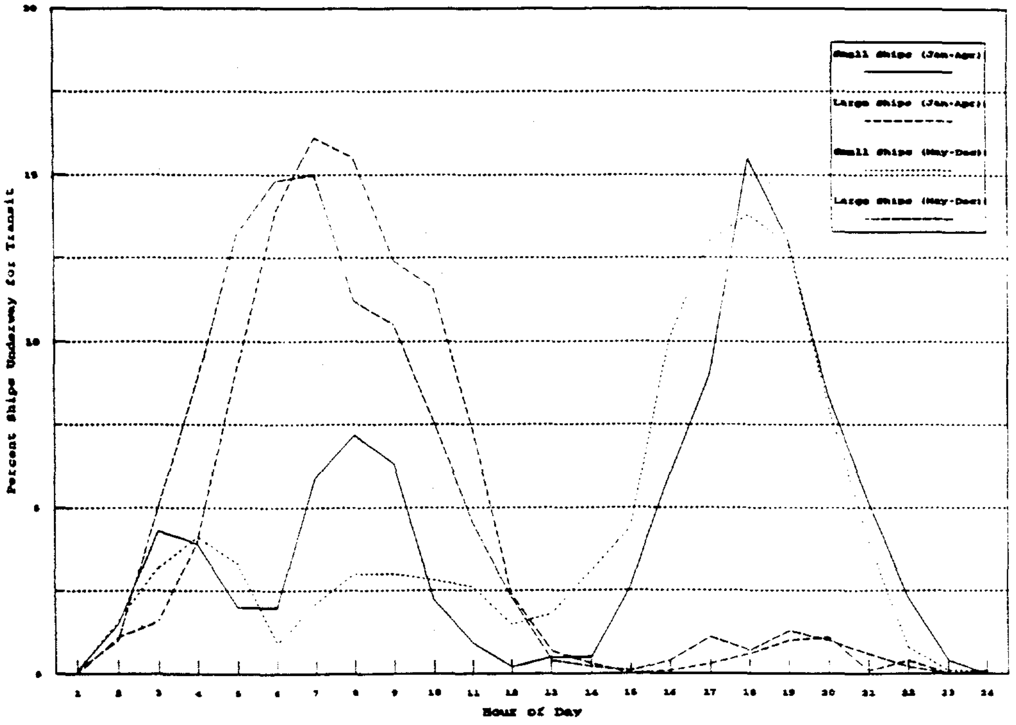

Figure 2. Southbound Underway Patterns

restrictions on passage through the Cut. The schedule delay portion of this time averaged about 8 hours in 1990.

As a result of these observations, a ship generation and scheduling program was developed to prepare vessel traffic lists for input to the Waterway Analysis Model. This program uses random underway times for future systems with the Cut restrictions lifted, or allows ship scheduling to correspond approximately to the present procedures.

The Waterway Analysis Model

The Waterway Analysis Model (WAM), which was the principal analytical tool used to estimate the capacities of the proposed alternative systems for the Panama Canal, has been in use by the U.S. Army Corps of Engineers for more than 12 years. The purpose of the WAM is to represent on a computer the operation of a waterway system in transporting waterborne cargo. The WAM is a relatively large and detailed simulation model, providing explicit representation of individual waterway facilities, cargo consignments, and vessels. The WAM was originally developed to simulate shallow draft barge traffic on the U.S. inland waterways. The model has been used extensively to simulate parallel locks, and thus was directly applicable to the multi-lane Panama Canal operations.

The basic structure of the WAM (as used for this study) is illustrated in Figure 3. The WAM requires four input files: (1) a list of shipments with the time of arrival in the system and the associated vessel requirements; (2) a description of the system, including the ports, locks, lock chambers, locking time distributions, restricted channels, vessel characteristics, and other system variables; (3) a list of lock chamber downtimes with time of occurrence, location, and duration; and (4) a run control file describing the length of the run and the types of output desired.

The heart of the model is the simulation module which routes each shipment from origin to destination through the different system elements. The basic mechanism involved is a simple process of scheduling simulated events and advancing a location indicator associated with the movement of each shipment through all the elements of the network (i.e., ports, locks, and channels). The appropriate processing is invoked in each network element based on the passage of simulated time. Statistics for each element and shipment are recorded as the system clock advances. The model contains shipment loading, delivery, and unloading routines for ports; a speed function, route selection, and restricted channel logic for channels; and chamber selection, lockage type determination, lockage policy routines, and lock chamber downtime processing for locks.

Output consists of tabular summaries of system performance, including travel, delay, and lockage times; queueing statistics; and lock, port, and equipment utilization. A

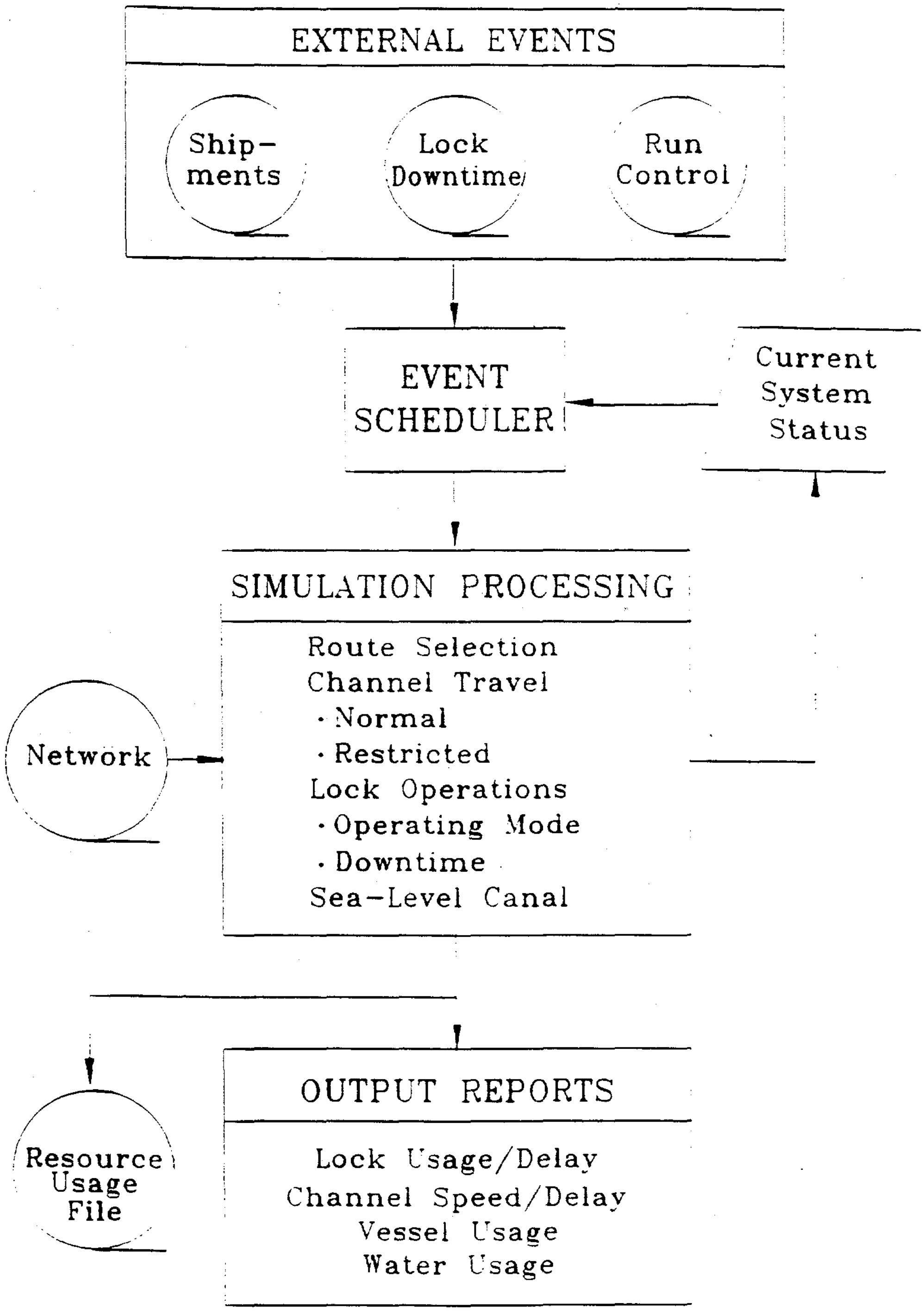

Figure 3. Organization of WAM

detailed trip report for each shipment can be created in an output called the "resource usage file" for use in post-processing.

In the U.S., the inland waterways version of the WAM has been used in investigations of restrictive channels on the Lower Tombigbee River and the Lower Cumberland River. It also has been used extensively for developing individual traffic/delay relationships at navigation locks, such as at the Winfield Locks on the Kanawha River (Bronzini, et al. 1990). These delay curves are major inputs in navigation system economic models used to justify recent inland waterway improvements at Winfield, Olmsted, McAlpine, and locks on the Monongahela River. Additionally, model output has been used as input to environmental impact models.

The model is written in the Simscript II.5 language and is maintained by the Ohio River Division's Navigation Planning Center in Huntington, West Virginia. Maintenance is on both a personal computer and a mini-computer. Model runs of 10,000 to 20,000 annual shipments for systems like the Panama Canal take up to one hour on the personal computer and 6 minutes on the mini-computer machines.

Simulating Panama Canal Operations

The WAM could be used with little or no modification to simulate the operation of the existing Panama Canal. Various program modifications were required to enable simulation of proposed future systems involving new parallel routes, such as the third locks plans and the sea-level canal.

Shipment Lists. Analysis of the distributions of vessel arrival, ready to transit, and underway times in the SDB records for 1990 showed that future vessel underway times could be generated as a Poisson process. Accordingly, a shipment list was generated for each ship transit forecast by preparing a shipment list record for each vessel transit in the forecast, randomly ordering these records, then randomly assigning the ship underway times by drawing from a negative exponential distribution with a mean equal to 365 days divided by the total number of ships.

Waterway Network. The WAM data structure was directly usable for representing the existing canal. The simulated system consisted of a port at each end, locks at Gatun, Pedro Miguel, and Miraflores, a restricted channel to represent the Culebra Cut, and the intervening channels between these elements. The restricted channel data structure was well suited for modeling the navigation restrictions in the Cut, and was configured to permit only one-way traffic for the larger classes of vessels. The locks were represented as dual chamber facilities, where each lane was considered to be a single chamber. The level of detail available in the SDB records for lock passage times did not support more detailed modeling of each level at Gatun and Miraflores (which could be represented as successive locks), and the field observations made at those locations indicated that a greater level of detail was not needed.

Configurations with a third lane of locks were represented directly as loops in the network, with the new locks located in the loops. The model supports either preassigning vessels to use the new lock, or dynamic assignment of vessels to minimize vessel delays, as described below. The alternative sea-level canal configurations generally required ships to operate in convoys, so a new logic module was created to simulate these systems. This new module was written in the Simscript language and integrated within the overall WAM structure.

Vessels. The key to representing the Panama Canal vessel fleet was to use the existing WAM commodity class and vessel type data structures to specify the ship horsepower and critical dimensions. These data are used in the model to estimate vessel speed and the space occupied in a lock chamber. The vessel classes used were initially the same as those for which average transit times are maintained separately by the Marine Bureau of the PCC for vessel scheduling purposes (see Table 1). These classes were later augmented by new classes to represent the larger ships that could transit the third locks and sea-level canal systems.

Lockage Operations. The WAM initially provided for input of processing time distributions for 15 lockage types for each chamber (lane) in each direction, plus distributions for multi-vessel lockages. The 15 distributions were intended to correspond to single, double, 3-cut, . . . , 15-cut lockages of shallow draft barge tows on the inland waterways. For Panama Canal locks, these input fields were used to specify times for the different vessel classes discussed above, and the multi-vessel locking times were used to model tandem lockages. Array dimensions were increased to allow for as many as 24 vessel classes for future systems.

The WAM was modified to schedule relay operations internally, based on queue size at the start and end of each 8-hour shift. Additionally, relay operations are started at one chamber of two chamber locks when the other chamber is down. The lock input requirements were increased to include additional time distributions and queue size variables, and model logic was added to check the current queue size.

Dynamic Routing. For alternative systems with a new third lane of high-rise locks, the model bases the routing choice on the minimum time to transit the next set of possible sectors divided by the number of available lockage lanes. A sector bias factor was added to adjust or calibrate the model, and a routing switch which can disable the dynamic routing option was also added. The estimated minimum time to transit a sector uses the following equations:

last transit time = most recent transit time - sector bias

minimum time = (ships in sector X last transit time)/lanes

minimum time = maximum of minimum time or zero

Vessels which may use either the new locks or the existing sector are assigned to the route offering the lowest estimated minimum time.

Simulating Sea-Level Canal Operations

A new logic module was created to model the formation and operation of ship convoys through the proposed sea-level canal options. This module also includes algorithms to simulate dynamic ship assignment to alternative routes, including the sea-level and status quo options. Tide gates (when required), located at each end of the single lane section, operate in concert with the tide levels of the Pacific Ocean. Convoy operation is also needed for tidal locks cases which include only a single lane channel across the Isthmus.

Sea-Level Convoy Formation. After a ship is assigned to the sea-level canal (see below), the ship travels to the appropriate anchorage area and joins the next convoy. During convoy travel each ship maintains its position relative to the ship ahead. This approach is structured to take into consideration the delays that might be experienced by the occurrence of unplanned interruptions.

Every time a ship approaches an open tide gate, it is determined whether there is enough time for the ship to completely clear the gate and enter the channel before the tide gate closes . If there is not enough time, this "last" ship becomes the "first" ship of the next convoy. This tide cycle delay is taken into consideration when making the dynamic route assignments. The entering convoy waits until the exiting convoy clears by an appropriate distance before entering the channel.

Dynamic Ship Assignment. Ship assignments to routes are based on the answer to the following question: How long will it take for a ship to traverse the canal using each of the alternative routes under their present conditions? Given a ship type, the module determines whether it is a large ship which must use the sea-level canal route. If it is, this ship will proceed to join a convoy as described above. If it is not, then the following procedure is followed:

a. Calculate a base time for the ship to travel the sea-level channel, unimpeded. Calculate (update) the expected waiting time, defined as the delay due to the ships ahead in the convoy (number and type) but not yet in the single lane channel. If the tide gate is closed, the waiting time also takes into account the delay until the gate opens. Add the expected waiting time and the base time to obtain the ship's total travel time.

b. Estimate the transit time that the ship would experience if it were to use the "lock" option (status quo system). This estimate is based on the most recent transit time of a vessel through the status quo system.

c. The ship is assigned to that route offering the shortest estimated transit time.

Model Calibration

Inputs for the existing Panama Canal were estimated from the PCC Ship Data Bank and by on-site observations, as described earlier. The modified WAM was run with an input file representing the existing system, and with shipment inputs representing the actual 1990 traffic. The model produced an estimated average Canal transit time, exclusive of pre-transit delay, of 11.8 hours, which compared rather well with the actual transit time of 11.1 hours recorded in the Ship Data Bank. Various other, more detailed model outputs also exhibited a close agreement with the observed or recorded operating characteristics of the existing canal. Thus, the model was deemed to be accurate enough to proceed with using it to simulate the alternative conceptual plans.

Simulating the Panama Canal Alternatives

Given the calibrated Waterway Analysis Model and the results of analyzing the SDB records, a series of further data analyses and assumptions were made to prepare the inputs needed to simulate the performance of the alternative conceptual plans for the Panama Canal under different future vessel traffic levels. These data and analyses include the future mix of vessel traffic, vessel characteristics, and lock sizes and operating times for the new locks plans.

Vessel mix forecasts for the years 2020 and 2060, for maximum vessel sizes of 65,000, 150,000, and 250,000 dead weight tons (DWT) were obtained from the vessel traffic forecasts prepared by the commodity traffic projections contractor for the study. The vessel mix for the 200,000 DWT maximum vessel size was interpolated from the 150,000 and 250,000 DWT vessel size projections. Considering all of these cases, the number of ship transits forecast for the Canal range from about 18,000 ships to 25,000 ships.

Vessel characteristics, including length, beam, maximum draft, and engine power, were obtained by reviewing the designs of commercial ships built worldwide in recent years. For the larger ship sizes introduced for the third locks and sea-level canal plans, observations of ship designs were augmented by data on ship stopping behavior obtained from ship trial runs and from computer simulation. These latter sources also provided data on minimum ship stopping times, which were used to develop input data on minimum ship separations for the sea-level canal WAM simulations.

Lock chamber sizes for the proposed new locks were developed by considering the minimum clearances between the ship and the lock chamber required for efficient operations. Locking times were then estimated by considering the operations in the existing locks which feature similar vessel-to-lock clearances.

Simulation runs for each of the conceptual alternatives were made by preparing an input vessel traffic list with the requisite number of ships, using the vessel traffic mix for the appropriate year (usually 2060) and maximum vessel size, and configuring the network and downtime input files to represent the appropriate system. Simulation runs were made for two different traffic levels for the third locks plans, and for three traffic levels for the sea-level canal options. In all cases, the new systems were run in parallel with the status quo system, and vessel traffic was dynamically assigned to the alternative routes based on current simulated operating conditions over each route.

Delay and Capacity

The Waterway Analysis Model produced estimates of average delay and transit time as a function of the annual number of ship transits. The next step was to compute capacity from the output of the model.

Operational capacity of a transportation artery is not a single number, but is related to acceptable delay time. A higher operational capacity, in terms of the number of vehicles accommodated, can be achieved at a cost of greater congestion and longer delays.

In the Canal, the level of delay time is related to the rate of ship arrivals, compared with the rate at which ships can transit the Canal. With ships arriving randomly, a plot of average delay versus the number of transits produces a hyperbolic curve, with delays increasing gradually at low traffic volumes and then increasing rapidly as traffic continues to increase until, finally, the curve becomes asymptotic to the theoretical maximum capacity (Davidson 1966). This theoretical maximum level of capacity, as a practical matter, is not achievable, because levels of congestion and delays would be excessive. As that level is approached, a slight increase in the number of transits produces a large increase in delay time.

Research based on simulation analysis indicates that the delay curve may be estimated from as few as two data points, with the best results achieved if one point is on the flat portion of the curve and the other on the steep portion or the bend of the curve (Bronzini 1984).

The mathematical relationships are indicated below and on Figure 4.

t = transit time (average, hours)
q = traffic (ships or tons) per year
T_0 = transit time at $q = 0$
d = average delay = $t - T_0$
Q = annual traffic capacity
D = average delay at $q = Q/2$
T = $T_0 + D$

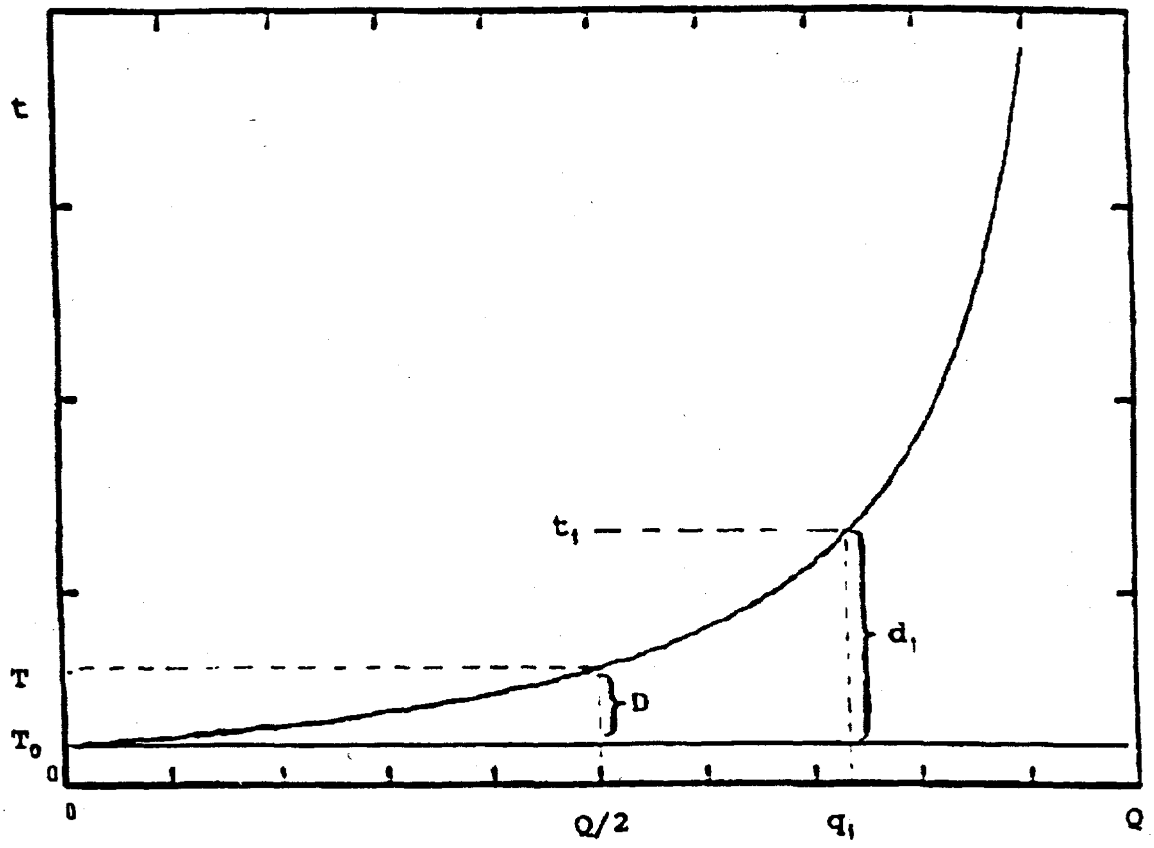

Figure 4. Delay Curve

$$d = \frac{Dq}{Q-q} \tag{1}$$

$$t = T_0+d \tag{2}$$

In systems operating on a fixed cycle, "delay" is not zero at q = 0. Thus, referring to Figure 4, the variables of interest are t_i, T, and T_0 rather than d_i and D. The delay curve equation for this case is:

$$t = T_0+\frac{q(T-T_0)}{Q-q} \tag{3}$$

With three parameters to estimate, at least three data points are required.

A more thorough understanding of the relationships of delay, capacity, and the level of service provided to vessel operators is gained by viewing the entire delay curve. The traffic volume at the design capacity of the transportation system is obtained by selecting the maximum tolerable level of average delay, then reading the corresponding number of annual ship transits from the curve. This value may be considered the maximum practicable capacity. The position of this point on the curve shows the effect of small changes in traffic on the expected average delay and, consequently, the stability of operations in this range of the curve. A preferred design capacity is the point of transition from the curved section to the upper, steep portion of the curve.

For the high-rise canal cases with a two-lane Culebra Cut, the model schedules vessels to begin transit immediately upon arrival. For the single-lane Culebra Cut cases, however, large ships arriving at night do not start their transit until early morning. This waiting time was added to any transit delay due to congestion, to arrive at the total delay time.

For the combined sea-level and status quo alternatives, because actual travel times differ along the two routes, it was more appropriate to use transit time (travel plus delay) as a measure, rather than delay time alone. This was also compatible with the dynamic route assignment logic in the model, which attempts to equalize transit time on the two routes.

Alternative delay times of six hours and ten hours were assumed as the basis of capacity for the high-rise canal cases, and transit times of 15 hours and 19 hours for the combined sea-level/status quo cases. Since the travel (non-delay) portion of transit time through the status quo system is approximately 9 hours, these criteria are consistent.

Because of the different operating procedures for the sea-level canal, as compared with the status quo canal and the third locks plans, it was not possible to develop composite delay or transit time curves for these systems. The principal reason is that the cyclic convoy operations of the single-lane sea-level channels impose a minimum average delay of several hours, even at very low traffic levels. Consequently, the following strategy was used to develop meaningful estimates of operational capacity for these cases:

- The sea-level canal version of the WAM was used to simulate operation of the combined sea-level and status quo canals, including dynamic assignment of ships to the two channels. Runs were made at three traffic levels selected to span the knee of the capacity curve and a transit time versus traffic level capacity curve for the sea-level canal only was developed.

- The capacity curve for the status quo canal operating by itself was used to represent its operating characteristics in these combined systems.

- The capacity for the sea-level canal component was then added to the capacity of the status quo canal to arrive at the total capacity of the combined system.

Typical capacity curves obtained from the methods described above, for the status quo, a high-rise locks case, and a sea-level canal case, are shown in figures 5, 6, and 7.

Results of Capacity Analysis

The estimated capacities of the Panama Canal alternatives, in terms of both annual ship transits and annual freight tonnage, are presented in Table 2. Comparison of annual capacity with the forecasted traffic levels indicates the following:

- the capacity of the status quo canal will be exceeded by the year 2020 and expanded facilities will be required to accommodate the traffic demands by that date;

- all of the improvement scenarios would have adequate capacity to meet forecasted needs by the year 2060.

Both the third locks plans and a sea-level canal are able to provide the requisite capacity if they are operated in parallel with the existing system, which would continue to serve ships up to 65,000 DWT. Of course, an operating plan would be

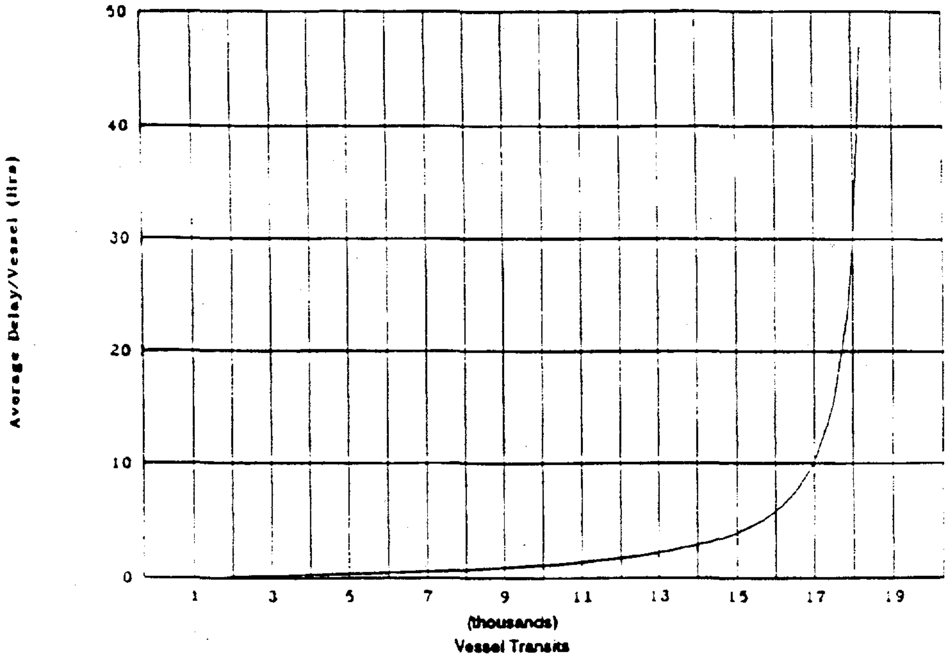

Figure 5. Delay Curve for Status Quo, 65,000 DWT

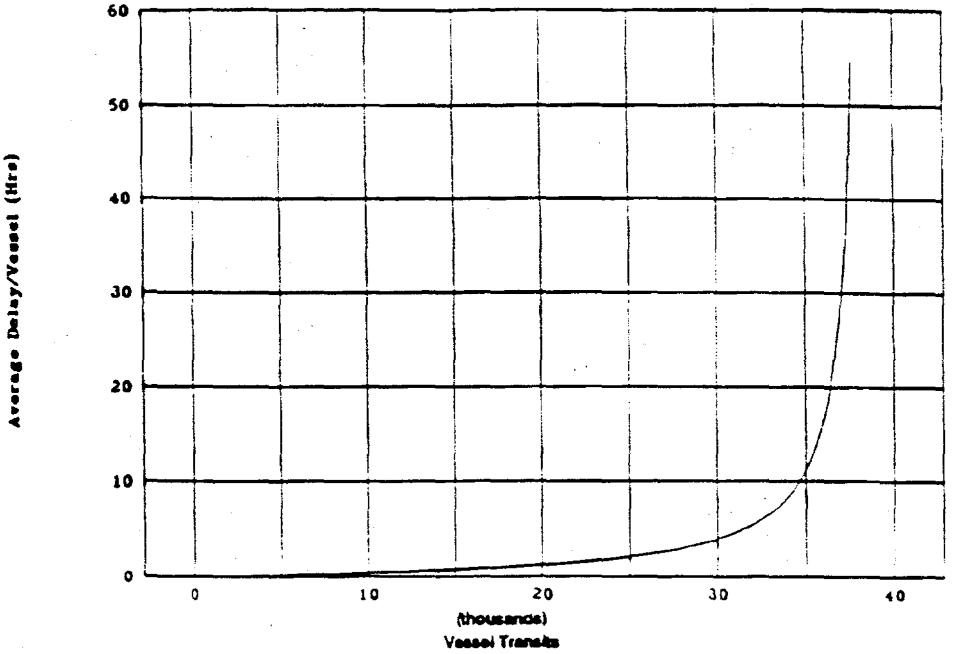

Figure 6. Delay Curve for High-Rise Locks, 150,000 DWT

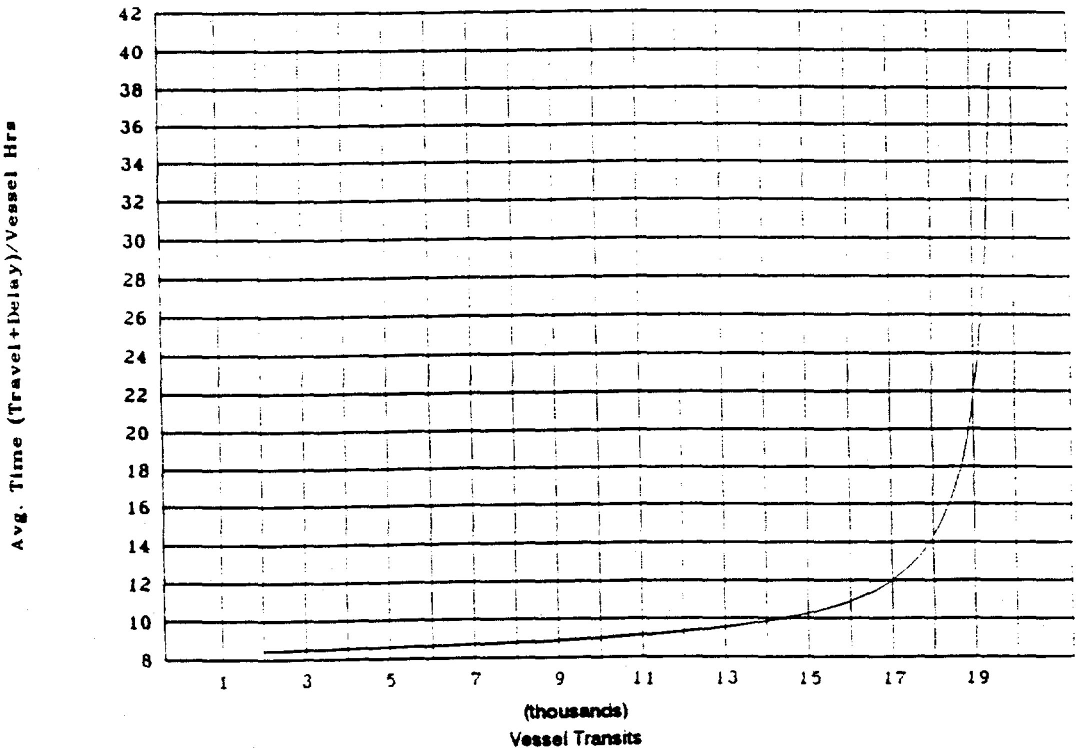

Figure 7. Delay Curve for Sea-Level Canal with Tide Gates

Table 2. Estimated Capacity

Study Case	Conceptual Alternative	Maximum Ship Size 000s DWT	No. of New Lanes		Capacity-Annual Transits No. of Ships		Capacity M Tons	
			Channel	Lock	6 Hr. Delay	10 Hr. Delay	6 Hr. Delay	10 Hr. Delay
1	Status Quo	65	-	-	16,100	17,000	374	395
2	High-Rise Locks (85ft)	150	2	1	32,500	34,600	978	1,041
3	High-Rise Locks (85ft)	150	2	2	48,300	51,300	1,455	1,545
4	High-Rise Locks (85ft)	200	2	1	33,200	35,300	999	1,062
5	High-Rise Locks (85ft)	200	2	2	51,100	54,300	1,559	1,657
6	High-Rise Locks (85ft) Culebra Cut single-lane	150	2	1	31,200	34,400	941	1,038
7	High-Rise Locks (85ft) Culebra Cut single-lane	200	2	1	31,600	34,600	963	1,055
8	Route 10 Tide Gates & Status Quo	250	1	**	42,500*	44,000*	1,318	1,364
9	Route 10, 3 Pacific Locks & Status Quo	250	1	3	33,300*	41,700*	1,032	1,273
10	Route 10, 4 Pacific Locks & Status Quo	250	1	4	37,000*	47,500*	1,147	1,472

NOTE: Culebra Cut is two lanes, unless noted otherwise.
* Capacity based on transit times of 15 and 19 hours.
** Tide Gates

devised to balance traffic and delays between the old and new portions of the expanded Panama Canal system. Even though the allocation of traffic might not be exactly the same as that implemented in the simulations, the delay results are likely to be similar.

The decision on the most appropriate alternative to be selected will depend on numerous factors in addition to capacity. These include costs, benefits to Panama and international navigation, environmental impacts, safety, reliability, disruption of operations during construction, time of construction, financial feasibility, and institutional arrangements required for construction and operation.

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