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SECTION II SUBJECT 2
OCEAN ENGINEERING AND NAVIGATION
PART 1

COMPUTER SIMULATION AND CAPACITY EVALUATION OF PANAMA CANAL ALTERNATIVES

Albert T. Rosselli, P.E., AICP
Senior Vice President
TAMS Consultants, Inc., New York, NY 10017, USA

Michael S. Bronzini, Ph.D., P.E.
Director/Center for Transportation Analysis
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

David A. Weekly
Assistant Chief/Navigation Planning Center
U.S. Army Corps of Engineers, Huntington ,WV 25701, USA

(see pg. 1 for correct order of authors)

SUMMARY

Introduction. The Operating Characteristics and Capacity Evaluation (OCCE) Study was one of the components of a group of studies of future alternatives to the Panama Canal, sponsored by a study commission formed by the governments of Panama, the United States and Japan. The basic tool in the conduct of the study was the Waterway Analysis Model (WAM), developed originally by the U.S. Army Corps of Engineers for use on the U.S. inland waterway system and adapted under OCCE for study of Panama Canal alternatives.

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The study synthesized the many alternative plans for the Canal proposed historically into four basic groups: High-Rise Lock Canal, Low-Rise Lock Canal, Sea-Level Canal and Status Quo Canal. For economy, the sea-level cases were based on, essentially, a single-lane canal, in conjunction with the status quo canal. Hydraulic and navigation studies indicted that to achieve safe navigation, tide gates or locks would be required to control currents that would otherwise be generated by the differences in tides between the two oceans. The alternatives studied in detail are illustrated in the body of the paper.

Simulating Canal Operations. The WAM data structure was directly usable for representing the existing canal and the third locks plans. The model produced results which compared well with the actual transit times recorded in the PCC Ship Data Bank SDB. The model was modified to either preassign large vessels to use the new locks, or dynamically assign vessels to minimize vessel delays.

The alternative sea-level canal configurations require 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. This module also includes algorithms to simulate dynamic ship assignment to alternative routes, including the sea-level and status quo options.

Delay and Capacity. Operational capacity of a transportation artery is related to acceptable delay time. With ships arriving in a random fashion, average delay is a hyperbolic function of the number of transits, with delays increasing gradually at low traffic volumes and then accelerating rapidly as traffic continues to increase.

The traffic volume at the design capacity of the transportation system is obtained by selecting the maximum tolerable level of delay (i.e., the delay that is deemed to be acceptable to the shipping industry before traffic would be diverted), then reading the corresponding number of annual ship transits from the hyperbolic delay curve. Alternative delay times of six hours and ten hours were assumed as the basis of capacity.

Results and Conclusions. The resultant capacities, in terms of annual ship transits and annual tonnage are presented in Table 1 in the body of the paper.

Comparison of annual capacity with traffic forecasted by others indicates that:

- the capacity of the Status Quo Canal will be exceeded by year 2020 and new 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 to the year 2060.The decision on the most appropriate alternative to be selected will depend, therefore, on numerous factors in addition to capacity.

It was concluded that the Waterway Analysis Model was an appropriate and effective tool for analysis of the Panama Canal alternatives. The model demonstrated an adaptability for use in a variety of circumstances.

INTRODUCTION

Under the terms of the 1977 Panama Canal Treaty between the Republic of Panama and the United States, the two nations committed themselves to study the feasibility of a sea-level canal in the Republic of Panama. It was agreed subsequently that Japan would be invited as a full participant and the three nations formed the Commission for the Study of Alternatives to the Panama Canal (CAS). It was decided to evaluate not merely a sea-level canal, but a wide range of alternative concepts ranging from sea-level to the current level of the canal (+85 feet), and Routes 10 and 15 within Panama (Figure 1).

[INSERT FIGURE 1 -- 1/4 PAGE]

The Operating Characteristics and Capacity Evaluation (OCCE) Study, undertaken by TAMS Consultants, Inc. in association with Oak Ridge National Laboratory, the U.S. Army Corps of Engineers (Huntington District), and the American Bureau of Shipping, was one of the components of a group of studies of future alternatives to the Panama Canal. The basic tool of the OCCE Study was the Waterway Analysis Model, a simulation model that was developed originally by the U.S. Army Corps of Engineers for use in studies of the Mississippi River System and adapted under OCCE for the purpose of the Panama Canal studies.

The study was conducted in two phases. For the prescreening of alternative canal plans undertaken in Phase 1, the existing WAM was used with a range of assumptions that reflected an extension of experience with the present Panama Canal. Model runs in Phase 2 involved a modified version of the WAM, more rigorous analyses of ship arrival patterns and dynamic assignment of ships to routes. The Phase 2 runs were used to evaluate in greater detail a limited number of alternative plans selected by Commission for the Study of Alternatives to the Panama Canal (CAS) from the results of the Phase 1 capacity, engineering and economic studies.

This paper describes the project, the simulation model, the application of the model to the Panama Canal project, and the results achieved.

THE PROJECT

Alternative Plans

Over the course of over half a century, many alternatives have been proposed and studied for increasing the capacity of the 79 year old Panama Canal. These alternatives incorporated a range of different physical layouts and operating concepts, that would accommodate a range of maximum vessel sizes, extending from the present 65,000 DWT up to 250,000 DWT.

Phase 1 of the OCCE study synthesized the many alternative plans proposed historically into four basic groups: High-Rise Lock Canal (25.9m lift); Low-Rise Lock Canal (16.8m lift); Sea-Level Canal; and Status Quo (the existing canal with the authorized widening of the Culebra Cut to 192 meters completed).

After the results of the Phase 1 investigations were evaluated, the low-rise lock canal alternatives were eliminated from further consideration.

The high-rise canal alternatives would involve a new set of large locks at each end of the canal with a lift in two stages between sea-level and elevation 25.9m, that would be used in conjunction with the status quo canal (Figure 2).

[INSERT FIGURE 2 -- 1/3 PAGE]

Regarding a sea-level canal, hydraulic studies undertaken by TAMS by means of the LATIS model indicated that the currents generated in an unprotected single-lane sea-level canal by the difference in tide ranges at the Pacific and Atlantic sides of the canal (6.7 meters vs. 0.8 meters) could be as high as 5.2 knots (10.6 km/hour) and would be unsafe for the navigation of large ships. The introduction of tide gates or locks at the Pacific end would reduce the currents to a maximum of 2 knots (1.7 km/hour); therefore, only sea-level canal cases with either tide gates or locks were considered.

For economy, the sea-level cases were based on a single lane canal to the greatest extent possible, used in conjunction with the status quo canal. Because the tides at the Pacific side are diurnal (full tide cycle occurring every 12½ hours) and the tide gates would be operated only when the water level is equal at both sides of the gates, the cycle time selected for gate openings and closings was 6¼ hours. Ships would traverse the single lane segment between tide gates in convoy, at a maximum speed of 7 knots (approximately 13 km/hour). Based on the above, it was determined that the optimum spacing between tide gates would be 40 km.

The sea-level canal with locks at the Pacific side would have a longer single lane segment (about 51 km)(Figure 3). Although the operation of the locks and the convoy movements would actually be independent of the tide cycle, it was assumed for the purpose of the analysis that the convoys would operate on a 12½ hour cycle in each direction.

[INSERT FIGURE 3 -- 1/2 PAGE]

The design ship for the sea-level canal alternatives was 250,000 DWT with a beam (b) of 54m. The client established the following criteria for channel widths:

single lane - 3.0 b; double lane - 7.0 b

In Phase 2, ten alternative cases were evaluated, as listed in Table 1 and illustrated in Figures 2 and 3.

Traffic Forecasts

Traffic forecasts were prepared by others. The forecasted ship mix and number of transits varied depending on the largest allowable ship, but in broad terms, the level of traffic was forecast to be of the order of magnitude of 18,000 transits in year 2020 (50 per day), increasing to 25,000 transits in year 2060 (68 per day). The level of traffic in 1990 was roughly 11,500 transits (32 per day) not including small craft, and miscellaneous craft.

BACKGROUND OF THE WATERWAY ANALYSIS MODEL

The Waterway Analysis Model (WAM) is a system simulation model originally developed to determine the impact of tow movements on the U.S. inland waterway system. It was developed as part of the U.S. Army Corps of Engineers Inland Navigation Systems Analysis Program (INSA) for the Office of the Chief of Engineers.[1] This version was tested, modified, and calibrated by the Pittsburgh District for the Ohio River Division of the U.S. Army Corps of Engineers in 1982.[2] Later, the model was modified and its data requirements simplified by the U.S. Army Waterways Experiment Station at Vicksburg, Mississippi and the U.S. Army Corps of Engineers (Huntington District) Huntington, West Virginia. Other modifications to the model were performed subsequently.

The basic structure of the WAM is illustrated in Figure 4. The WAM requires four input files: (1) a description of the system, including the ports, locks, lock chambers, locking time distributions, restricted channels, vessel characteristics, and other system variables; (2) a list of shipments with the time of arrival in the system and the associated vessel requirements; (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.

[INSERT FIGURE 4 -- 1/4 PAGE]

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 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; queuing statistics; and lock, port, and equipment utilization. A detailed trip report for each shipment can be created in an output called the "resource usage file" for use in post-processing.

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.

SIMULATING OPERATION OF THE PANAMA CANAL

Shipment Lists

Analysis of the distributions of vessel arrival, ready to transit, and underway times in the Panama Canal Commission Ship Data Bank 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.

WAM Modifications

The WAM was modified to simulate more directly the operation of the existing Panama Canal. Various additional 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.

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 Culebra 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.

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 locks, or dynamic assignment of vessels to minimize vessel delays, as described below. The alternative sea-level canal configurations 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. 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 fifteen lockage types for each chamber (lane) in each direction, plus distributions for multi-vessel lockages. 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.

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. This new module was programmed in Simscript and integrated with the WAM to allow simulation of combined sea-level and status quo systems.

Sea Level Convoy Formation. After a ship is assigned to the sea-level canal 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.

Before a ship gets underway, 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 ship is assigned to 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 transit 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 estimated total transit 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 Panama Canal Commission Ship Data Bank, which provided data on each canal transit for the year 1990. In all, over 13,600 ship transit records were analyzed. These data were supplemented by on-site observations made in Panama in 1991. 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 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.

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 definitive number, but is related to acceptable delay time. A higher capacity in an artery 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 in a random fashion, a plot of average delay versus the number of transits produces a hyperbolic curve, with delays increasing gradually at low traffic volumes and then accelerating rapidly as traffic continues to increase until, finally, the curve becomes asymptotic at theoretical maximum capacity.[3] The 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 plotted 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.[4]

The relationships are indicated below and on Figure 5:

$$d = \frac{Dq}{Q-q} \qquad t = T_o + d$$

where,

d = average delay = $t - T_o$ $\quad$ t = average transit time (hrs)

D = average delay at $q = Q/2$ $\quad$ q = traffic/year (ship transits or tons of cargo)

Q = annual traffic capacity (ship transits or tons of cargo) $\quad$ T_o = transit time (hrs) at $q = 0$

A more thorough understanding of the relationships of delay, capacity and 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 delay, then reading the corresponding number of annual ship transits from the curve. This point 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 the 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.

[INSERT FIGURE 5 -- 1/6 PAGE]

In systems operating on a fixed cycle, such as the sea-level canal, delay is not zero at q = 0. The delay curve equation for this case is:

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

where: T = (average transit time at q = Q/2) = T_o + D

With a third parameter to estimate, a third data point is required.

For the High-Rise Canal cases with a two-lane Culebra Cut (Cases 2 through 5) (see Table 1) the model schedules vessels to begin transit immediately upon arrival. For the single-lane Culebra Cut cases (6 and 7), however, large ships arriving at night do not start their transit until early morning. This waiting time is added to any transit delay that results from congestion, to arrive at a total delay.

For the combined sea-level and status quo alternatives (8, 9 and 10), 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 is 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 (1 through 7) and transit times of 15 hours and 19 hours for the combined sea-level/status quo cases (8, 9 and 10). Since the travel (non-delay) portion of transit time through the status quo system is approximately 9 hours, these criteria are consistent.

RESULTS OF ANALYSIS

The resultant capacities, in terms of annual ship transits and annual tonnage are presented in Table 1.

[INSERT TABLE 1 -- 1/6 PAGE]

Comparison of annual capacity with forecasted traffic indicates the following:

- the capacity of the Status Quo Canal will be exceeded by 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 year 2060.

The decision on the most appropriate alternative to be selected will depend, therefore, on numerous factors in addition to capacity, including: 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.

CONCLUSIONS

It was concluded that the Waterway Analysis Model was an appropriate and effective tool for analysis of the Panama Canal alternatives. The model demonstrated an adaptability for use in a variety of circumstances; it could also be used as a tool to assist in scheduling of ship transits.

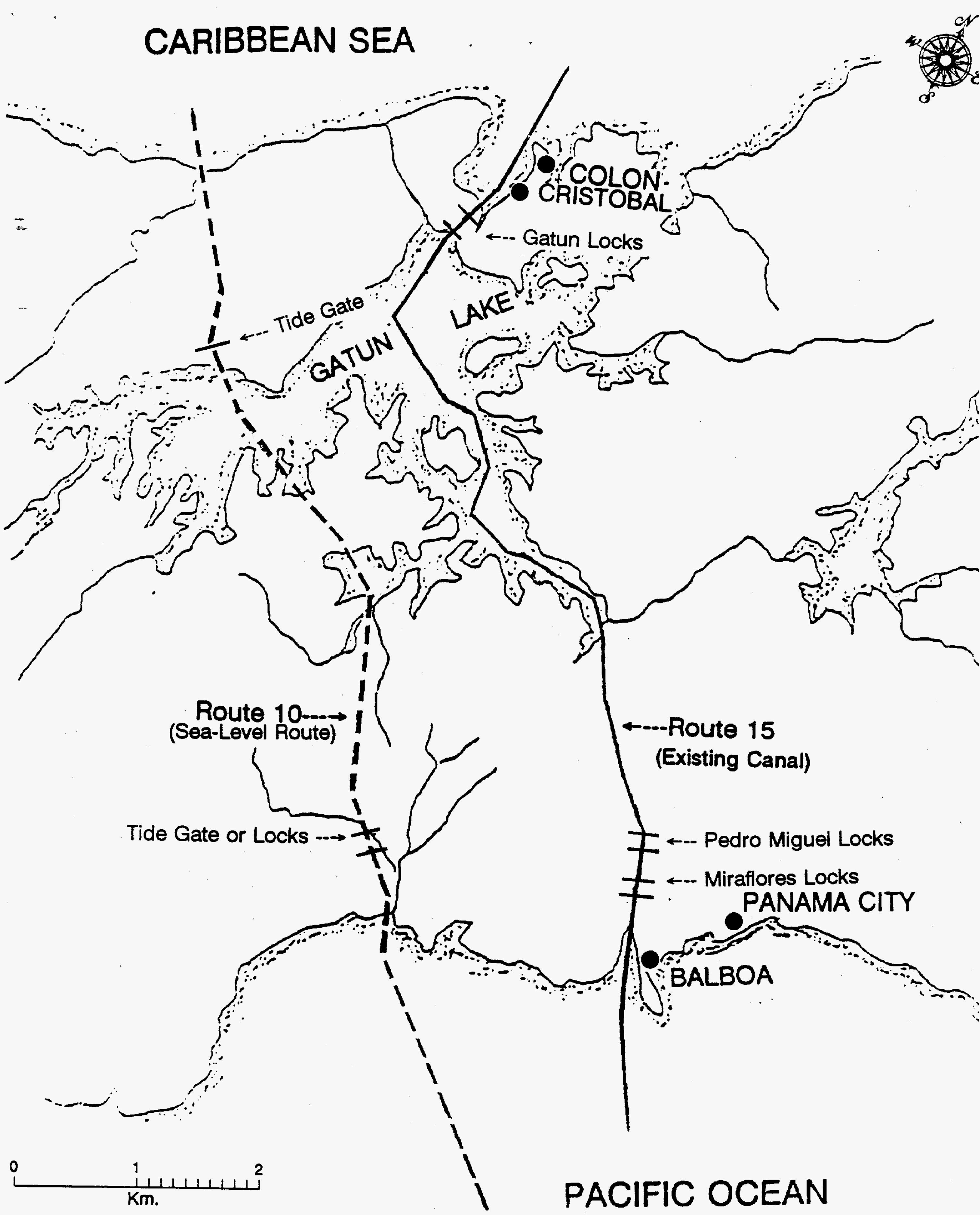
NOTES:

1. Bronzini, M. S., et al., *Inland Navigation Systems Analysis*, Vol. V, *Waterway Analysis*, CACI, Inc., Arlington, VA, for U. S. Army Corps of Engineers, Washington, D.C., July 1976.

2. U. S. Army Corps of Engineers, Pittsburgh District, *Waterway Analysis Model*, Pittsburgh, PA., January 1982; draft modifications by the Huntington District, January 1983.

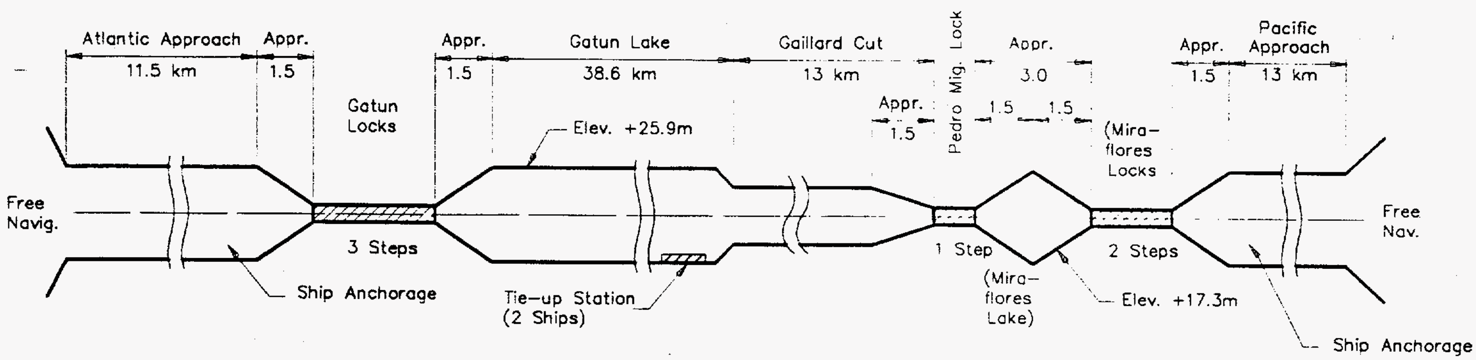
3. Davidson, K.B. (1966). *A Flow-Travel Time Relationship for Use in Transportation Planning.* Proceedings, Australian Road Research Board, Melbourne, v.3, 183-194.

4. Bronzini, M.S. (1984). *Simulation-Based Estimates of Delays at Navigation Locks.* Proceedings, Transportation Research Forum, v.25, n.1, 420-428.

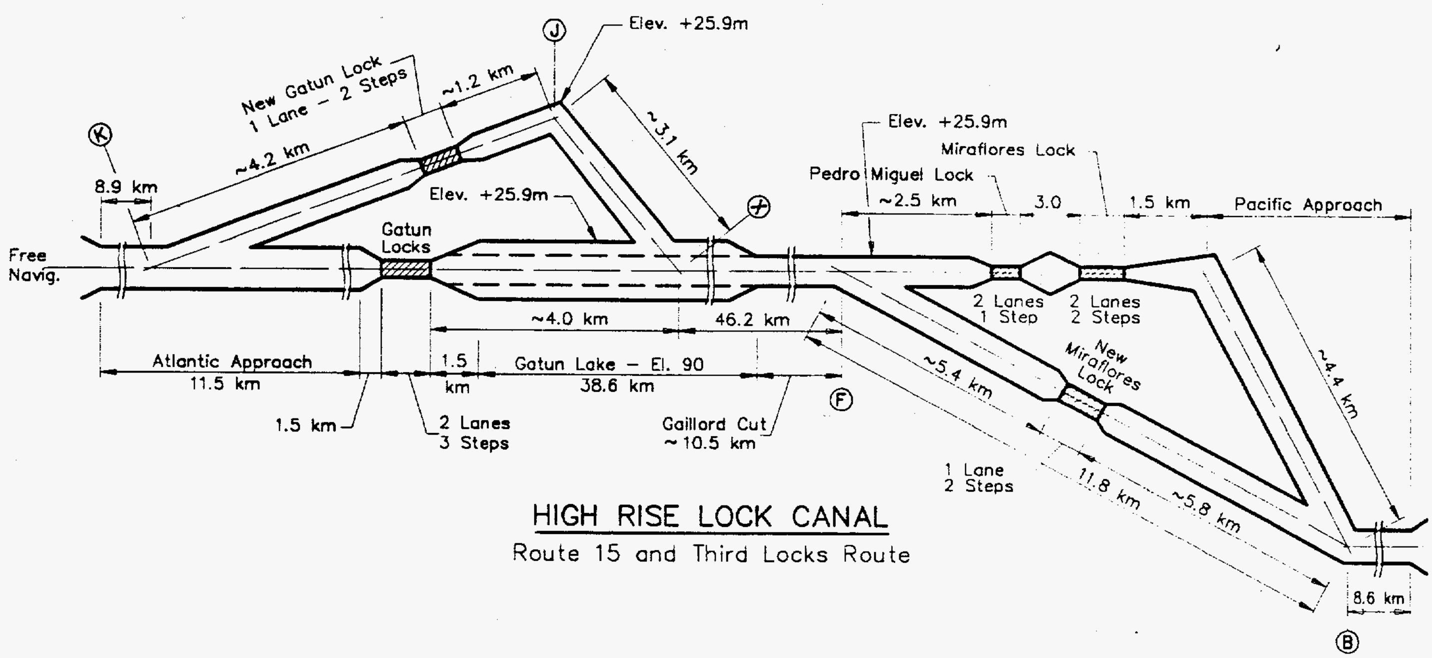


ALTERNATIVE CANAL ROUTES

Figure



EXISTING PANAMA CANAL (ROUTE 15)

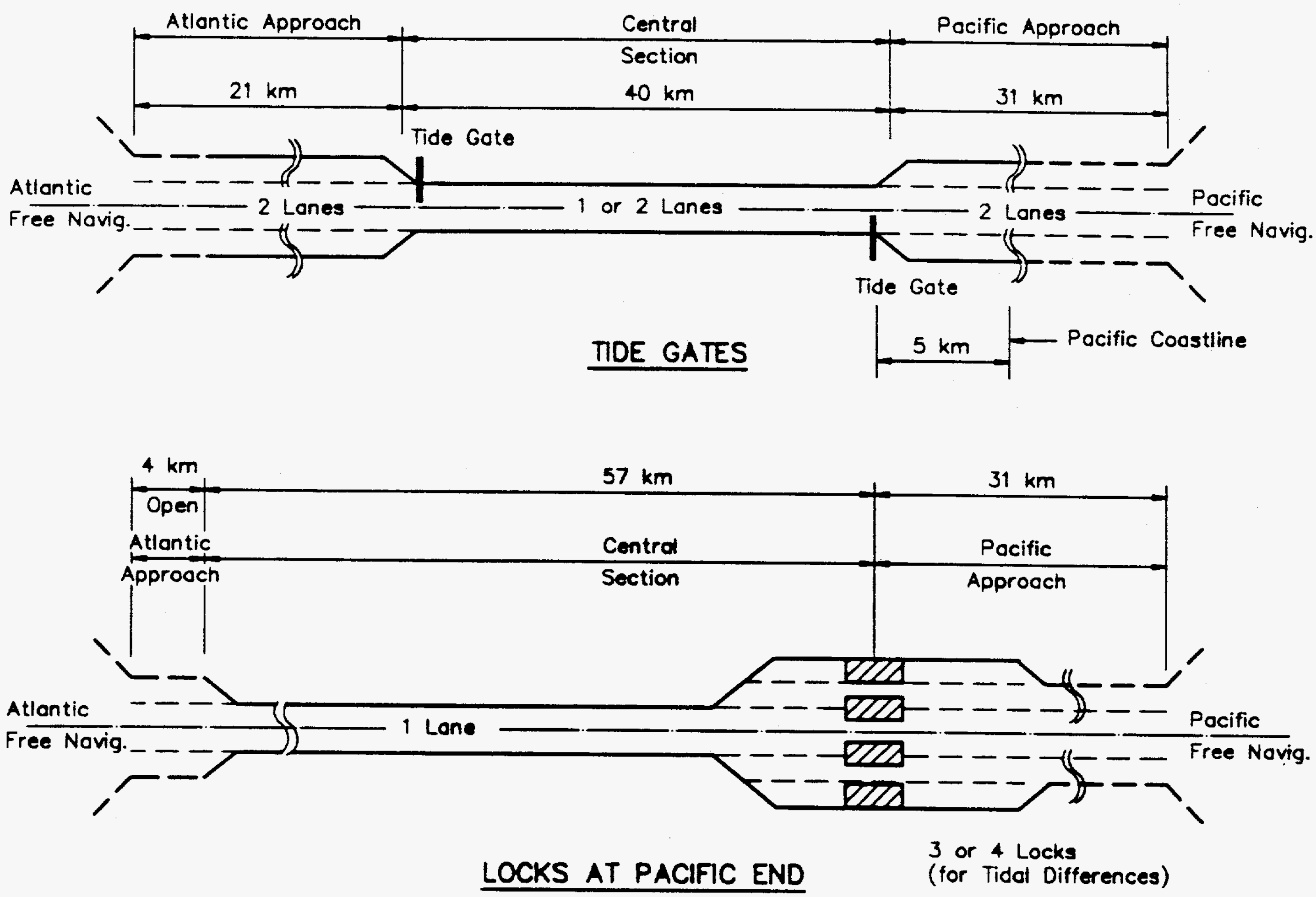


HIGH RISE LOCK CANAL

Route 15 and Third Locks Route

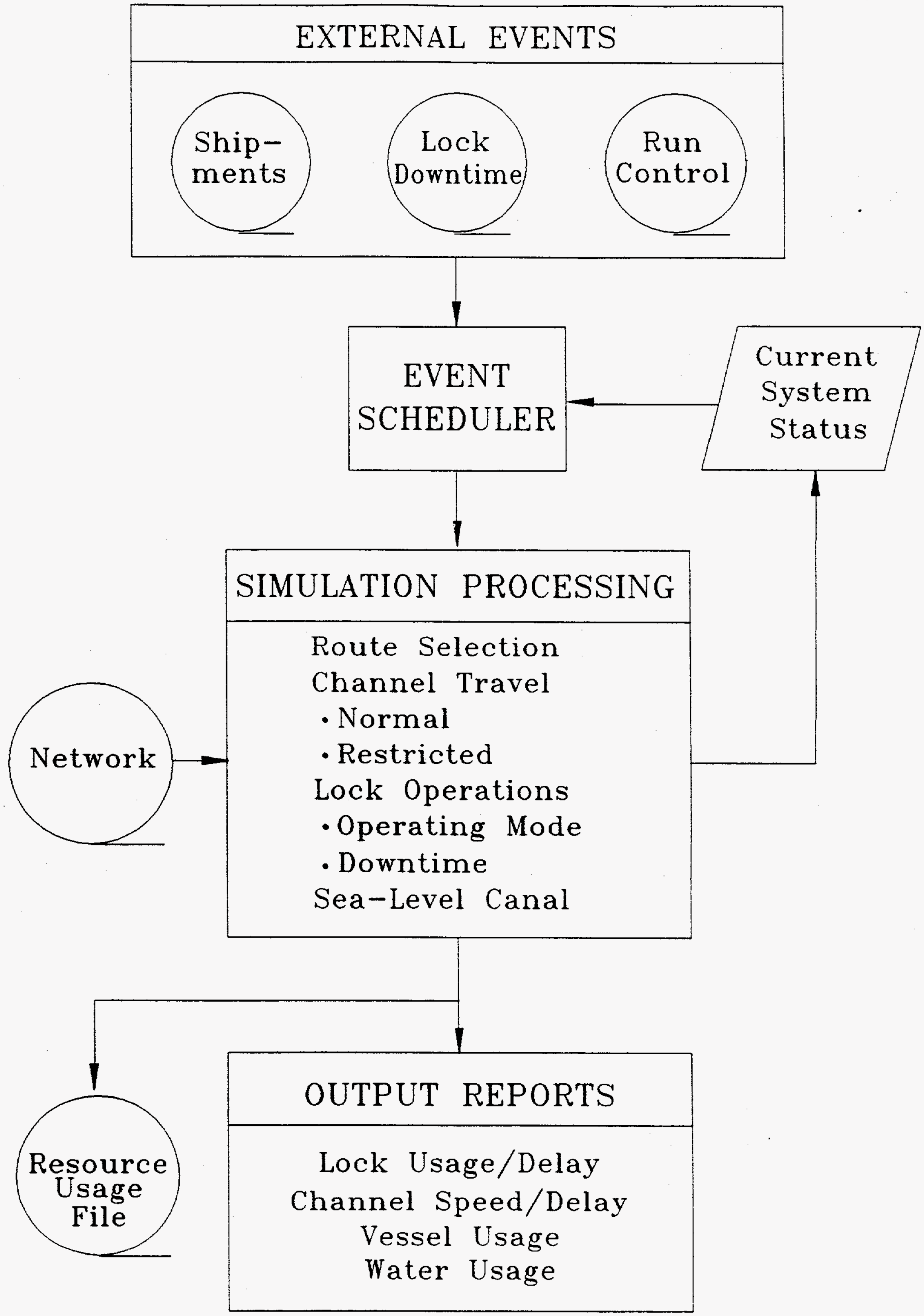
SCHEMATICS OF ALTERNATIVE LOCK PLANS

Figure 2

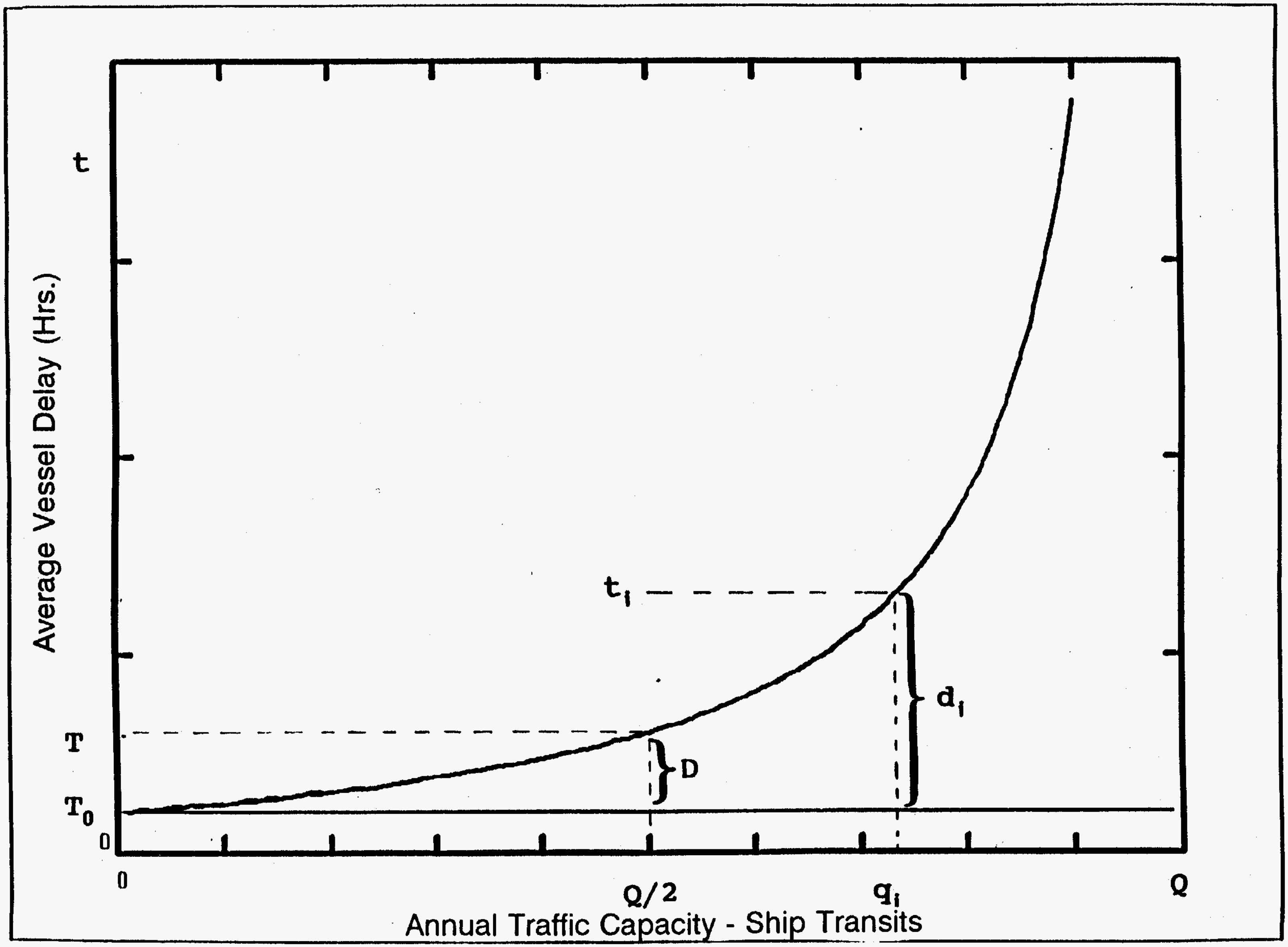


SCHEMATICS OF ALTERNATIVE
SEA LEVEL PLANS - ROUTE 10

Figure 3



ORGANIZATION OF WAM Figure 4



DELAY/CAPACITY CURVE

Figure 5

TABLE 1
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