2005 DEPAEPE-WILLEMS CONTEST SUBMISSION

DETERMINING ECONOMIC EFFICIENCY IN HARBORS
HarborSym, An Application

Shana A. Heisey
U.S. Army Corps of Engineers, Institute for Water Resources
Alexandria, Virginia
shana.a.heisey@usace.army.mil

1.0 ABSTRACT
HarborSym is a simulation model designed to assist in economic analyses of coastal harbors. Developed as a data-driven model, HarborSym has applicability to many different ports. Users customize the tool for a particular study by supplying input parameters, such as information on the harbor network, physical dimensions of channels, transit rules, and vessel calls. Changing data on channel dimensions or the rule structure will show possible changes in vessel delay times resulting from proposed harbor improvements. An application of the model to the Sabine-Neches Waterway showed substantial time savings from several possible channel expansions.

2.0 INTRODUCTION

Coastal ports are vital to the everyday function of America. According to the American Association of Port Authorities, cargo valuing approximately $1.3 billion moves daily through the ports scattered along the U.S. coastline. The inland waterway and coastal ports carry almost 95 percent of the nation's international trade. This amounts to two billion tons of cargo each year, and forecasts predict this amount will double by 2020.[1] Waterway transportation dominates other modes and is in high demand because its unit cost is two to three times lower than that of other modes. Given the limited number of ports and the large quantities moving through them, congestion issues often arise. One potential result of this congestion is traffic delays within individual harbors as operators attempt to manage their movements. Shippers encountering delays face higher total transportation costs, which are eventually passed to consumers in the form of higher retail prices. These costs could potentially be lowered if congestion related inefficiencies within individual harbors are eliminated

The quality and reliability of infrastructure can have dramatic impacts on a nation's international competitive standing. According to research conducted by the World Bank, poor infrastructure can account for forty percent of predicted transportation costs in coastal nations, with a strong relationship between overall trade flows and transportation costs. "Shipping costs … have a major impact on income, both because of the direct costs they impose and because of the gains from trade forgone. [The research] results also point to the potential for reducing these costs through investments in infrastructure."[2] While many of the infrastructure measures identified in the study focus on the landside portion of movements, such as paved road networks, the authors stress the importance of seaside transportation due to its substantially lower unit costs. Maintaining reliable and efficient waterway channels and ports is critical for coastal nations engaged in international trade.

Some nations are blessed with naturally deep water leading into their ports, requiring only minimal investments to maintain navigable channels for ocean-going vessels. Unfortunately, the United States is

[1] www.aapa-ports.org/govrelations
[2] Limao and Venables, "Infrastructure, geographical disadvantage, transport costs and trade", World Bank Economic Review 15, no 3 (2001): p. 451-479.

not such a nation. In 2002 the U.S. Army Corps of Engineers (Corps) engaged in studies examining the benefits of improving different physical aspects of 19 individual coastal ports and an additional six Great Lakes deep draft harbors.[3] Corps studies require examining not only the engineering feasibility of any improvement but also the economic efficiency of all possible alternatives. Navigation projects dealing with channel width related congestion are particularly difficult to analyze because delays occur as a result of the random interactions of vessels within the system. In an attempt to assist with these and future navigation studies, the Corps' Institute for Water Resources developed a simulation model, HarborSym, to track vessel movements within ports and to capture delay times associated with transit restrictions. HarborSym can also be used to evaluate the impacts of existing restrictions within the system, such as navigation rules. This can aid port authorities, governmental bodies, and other stakeholders in understanding congestion problems in their ports and also in identifying the areas of greatest economic impact, thus focusing investigations of harbor improvements.

3.0 BACKGROUND

While each U.S. port is unique in its detailed operations, common elements exist within most major harbors. Ensuring the smooth functioning of thousands of annual vessel movements requires the coordination of many different organizations and often a complex set of rules and operating principles.

3.1 Key Operating Organizations

Because America does not have naturally deep waters leading into most of its major harbors, the Federal government has undertaken the responsibility of providing access for U.S. and foreign vessels. The Corps and Congress identify the optimal channel depth at each port and the Corps periodically dredges the waters to ensure this depth is available for navigation. Other Federal agencies acting as caretakers for the nation's waterway operations are the Maritime Administration and Coast Guard, whose role has been enhanced with growing security concerns. Not only is the Coast Guard concerned with national security at ports, but it also maintains the aids to navigation, which assist the Pilots Association in maintaining safe movements within the port. These private pilot associations operate within all major U.S. ports. They have the responsibility for providing safe passage of vessels from the ocean entrance (the bar), to the destination dock and back out for the ships' departure. To do this, an individual pilot boards the vessel at the bar (or dock for outbound transits) and navigates the ship to its destination (the bar for outbound), communicating with pilots onboard all the other vessels navigating the system. This interaction is successful because the pilots associations in each port devise unique operating rules to govern safe transit within their harbor. While the pilots associations regulate passage in the waterway, the port authorities are often responsible for establishing safe and efficient movements of cargo between the ship and inland origins or destinations. This includes wharfside cargo exchange, removing and loading cargo on the ships, temporary storage of commodities, and access to rail and truck routes. The actual implementation of these activities may range from the port authority being only a facilitator or organizer for private facilities to publicly owned and operated terminals. Owner operated facilities are strictly managed by private entities, servicing only their fleet of ships or limiting access to their choice of carriers, which offers them the greatest autonomy. Port facilities may be tenant operated also, which most typically results when publicly held lands are leased and privately operated. Tenant operated facilities offer greater flexibility to carriers than the more managed arrangement of publicly owned and operated, where the port authority takes a more active role than that of facilitator. In the case of public facilities, the true stakeholders for infrastructure development are the local taxpayers, which creates a different dynamic than that of privately held corporations. Any harbor may have one or a combination of these facilities, depending on the nature of commodities moved through the port and the types of vessel

[3] www.corpsresults.us/navigation/navrecentprojects.htm

operators calling. The vessels are operated by private entities, with each ship carrying cargo from potentially multiple shippers.[4]

3.2 Key Operating Practices

All major ports receive regular calls from a variety of different ship types carrying different commodities. In order to efficiently handle the movements of these vessels, the pilots associations develop complex operating rules to govern harbors. While some of these rules are enforced absolutely, others are implemented with the discretion of individual pilots. Even with some autonomy for individual pilots, vessel operators and port authorities have a reasonable sense that their movements will be treated equitably. There are several different categories of transit rules imposed by the pilots: harbor-wide rules governing specific ship types, and rules that apply only in individual channel segments.

Universal rules include designating general operational or management practices within ports. Often harbors operate under a “first come, first served” structure, such that the first ship available and able to move through the system is permitted to proceed. While equitable, this approach can cause delays if a fast sailing ship is caught behind a slow moving barge. Harbors often have physical structures including sidings, barge shelves, or anchorages to help prevent slow traffic from causing bottlenecks. Another method of managing this problem for high valued commodities or costly ships is to designate certain ship types as “*priority vessels*”. When priority vessels arrive at the harbor they do not face the first come, first served restrictions placed on other vessels; they are able to transit without delay. Because they arrive on a highly predictable schedule, other ships are able to anticipate the priority vessel arrivals and departures, thus avoiding their own delays.

Safety based universal rules include enforcing safety zones or requiring tug assistance. Safety zones can limit passing, overtaking, or meeting[5] of all vessels carrying critical or hazardous commodities. Another application of safety zones creates a “bubble” around the critical vessel, forcing all other ships to sail at a specified distance from the ship of interest. For increased safety in some harbors all vessels may be required to sail with tug assistance; in other ports only larger or older vessels face this restriction. While tugs help self-propelled vessels navigate the channel, they can cause operational problems if the tug supply is insufficient to meet the frequency of vessels calling the port.

Reach rules can be categorized as single vessel rules, multiple vessel rules, or tidal rules. Single vessel rules limit the movement of individual ships based on the physical limitations of the channel and the size of the ship. Size parameters restricting movements can include deadweight tonnage, length overall, draft, or beam. Other application of single vessel rules may limit sailing to daylight hours, or restrict movement based on a relationship between the vessel size and the physical dimensions of the channel. Multiple vessel rules restrict interactions of vessels, such as meeting, passing, or overtaking. As with the single vessel rules, these restrict movements based on physical characteristics of vessels or of the channel. These rules may also be set absolutely without any parameters of application, such that no vessels meet, pass or overtake within given reaches. The third category of rules relate to movements with tide. In many ports vessel operators use the additional depth gained by tidal influence to increase the amount of cargo they can carry. Pilots associations develop rules to define the maximum draft, using tide, that vessels can sail in each reach. Tidal rules also govern sailing under current conditions, set in individual channel segments.

---

[4] Ian Mathis, personal communication, 10 August 2004.

[5] Overtaking refers to the action where one vessel moves in front of another ship traveling in the same direction. Passing is defined as two vessels traveling in opposite directions sharing the channel as they move past one another. Meeting is any time two vessels are side-by-side in the channel, regardless of the direction they are traveling, this includes both overtaking and passing.

4.0 HARBORSYM AND THE SIMULATION OF HARBOR ACTIVITIES

The large number of agents, physical constraints, and complex rule structures present in coastal harbors are all complications in evaluating potential improvements. Each agent will maintain a unique opinion and perspective as to what will improve efficiency within the system. While Corps planners must consider these points of view, ultimately decisions on improvements are based on national economic benefits. Different types of projects generate different types of benefits. For projects evaluating channel width constraints, benefits primarily arise from decreased delays, which can be translated into transportation cost savings. Assessing this type of savings can be extremely difficult because it is dependent upon understanding and evaluating the random nature of vessel interactions. Timing of ship arrivals and departures is critical in evaluating harbors because the coincidence of two vessels desiring use of the channel simultaneously has the potential to cause delays with the application of multiple vessel rules. If a rule restricting meeting is in effect in a reach, a single vessel transiting the system will be able to sail unimpeded. If, however, another ship wishes to travel in the same reach simultaneously, one of the vessels will be delayed. The timing of this interaction is influenced by preceding events: the arrival times of both ships, their transit speeds, the amount of time spent at docks, as well as the other rules and vessels within the system. Anticipating the need for two ships to use a channel segment concurrently, the activation of a transit rule, and the duration of resulting delays, are all challenging for analysts to capture in flat spreadsheet models. Numerical simulation models, such as HarborSym, calculate these interactions and can capture delays times resulting from random and predicted movements within the system.

4.1 Introduction to HarborSym

HarborSym is designed as a planning level economic model, not a detailed operational tool. With user provided input data, such as the port layout, vessel calls, and the intricate set of transit rules, the model calculates vessel interactions within the harbor. Vessel call information includes the time vessels arrive at the system, which begins the calculations for an individual vessel call. When a ship arrives at the bar, the model calculates if it can proceed to its destination dock based upon the transit rules and all other vessels within the system. By determining what time the entering vessel will arrive and depart each reach, HarborSym predicts if there will be a rule conflict with any other vessel already moving through the simulation. If so, the entering vessel is forced to delay sailing until the conflict abates. Once a vessel is cleared to proceed to the dock, the model determines the amount of time it will spend at the dock based upon its total cargo and the dock-specific commodity exchange rate. After all necessary commodities are transferred and the ship is ready for departure, it begins the process of testing for rule conflicts again. When it can proceed through all channel segments required to reach the bar without any rule conflicts, the ship may exit the system.

Through this series of calculations, users are provided information on the total time vessels spend in the harbor and the amount of time each is delayed. Time spent in other critical activities is also reported, such as that spent transiting reaches and involved in cargo exchange at the dock. Detailed information on which rules triggered delays for each vessel call is also available. These outputs allow users to understand how the system functions and how that will change under different sets of physical conditions.

4.2 HarborSym Development

Three basic tenants were sought in the development of HarborSym: portability, transparency, and ease of use. IWR desired a model that was applicable to many locations, not specific to a single study, and a tool that allows users and stakeholders to understand the model's internal functioning without knowledge of complex computer languages. To satisfy the needs of flexibility and understandability, the Institute built a custom model without the assistance of any packaged simulation environment. The data, which forms the core of any analysis, is housed in Microsoft Access™ relational databases. Analysts populate these tables through a user interface built in Microsoft Visual Basic™. This interface serves as a translator of the model functionality for the user, preventing them from having to communicate directly with the databases. The interface also communicates with the computational kernel, which processes the analysis once all necessary data has been supplied. Built in C++, the computational engine of the model calculates the vessel times in port based on user supplied arrival times, the system rule structure, and required time ships must remain at the dock.

As the Corps often has many large-scale navigation projects under investigation, IWR did not want to create a model applicable to only one particular study, but rather a generic tool that could be adopted to meet the needs of many other ports. HarborSym was developed using a data driven approach, which gives the tool great flexibility and adaptability for application to various studies. All models rely on data, but the term data driven applies to models that only include the basic behavior of objects in the code, while all parameters of application are left to be defined by the user. In the case of HarborSym, the behavior of vessels within the system is defined and constant among different ports, but users provide the layout of a harbor, the vessel calls, commodity movements and specific application of transit rules. The behavior of a no passing rule, for example, is programmed into the model, meaning how vessels respond to a particular rule, but the specific conditions under which the rule applies are defined in data. If the rule application were determined based on the combined beam width of two passing vessels, the analyst would have to supply the threshold dimensions for the passing restriction. Generally these rules fall into two broad categories: single vessel rules, those restricting the movement of vessels in the waterway irrespective of other ship traffic, and multiple vessel rules, which govern the interactions between vessels. HarborSym can currently accommodate the following transit restrictions:

SINGLE VESSEL RULES

- Restricted movement of a vessel based on its size, which can be defined by maximum deadweight tonnage (DWT), length overall (LOA), or beam.
- No movement based on the vessel's sailing draft, applied with or without tide and current influence.
- No sailing based on a maximum LOA, optionally applied based on the current strength.

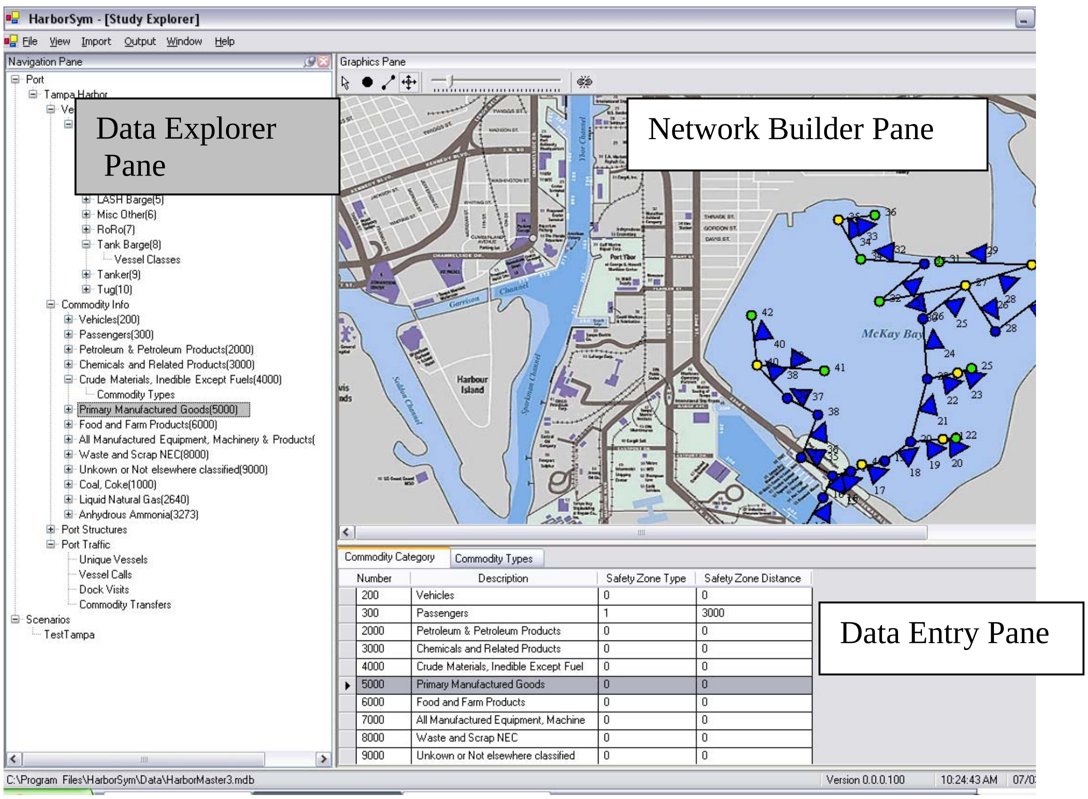
MULTIPLE VESSEL RULES

- No meeting based on the combined beam width of the two ships, with the restriction defined based on a fraction of the channel width.
- No meeting of vessels based on the sailing draft, DWT, beam width, or a combination of any of these parameters.
- No passing priority vessels.
- No meeting vessels carrying "*critical commodities*", which can be any commodity defined by the analyst, typically hazardous cargo, such as liquefied gases.

As long as these generic rules can be applied to cover the transit restrictions within a harbor, the model can be used without any modification to the program code. If a harbor operates under rules not contained in the above set, the behavior can be added to the model. Once added, this new functionality is available for all future studies.

Another benefit of a data driven model is that it leaves less of the model's functionality unknown to users, stakeholders, and reviewers. All different stakeholders in a coastal port represent different interests and priorities for determining the optimal waterway design. While simulation models are vital for assessing the impacts of changes within the system, in order for them to be truly useful stakeholders must have confidence in their results. Data driven models, such as HarborSym, help with this because analysts and observers can see what data underlies the analysis. As these models store more functionality in data, less is left hidden in computer coding. A user interface has been developed for HarborSym, which displays the input data so users can see the relationships between the information as it is entered. This interface also helps stakeholders understand the model since they can see and confirm that the correct information populates the model. Shown in Figure 2, the HarborSym graphical user interface is designed with three different panes, each displays different types of information. The study layout is developed in the network builder pane. The user can add docks or other features in the system by selecting the appropriate icon and assigning it to the correct location. All relevant data can be supplied through the data entry tables, located beneath the network builder pane. The relationship between the data table being populated and the rest of the system is shown in the data explorer pane, on the left hand side of the image. This tree structured, hierarchical system allows the user to identify which data elements have been supplied and which require additional information.

Figure 2. HarborSym Graphical User Interface



HarborSym has additional windows into its functionality to increase user confidence and understanding. A within simulation animation provides detailed information on how the model is applying rules. This visualization is provided as the model computes vessel locations and interactions, and the user can pause the simulation to retrieve additional data on elements within the system.

As it is a planning level tool designed for economic analyses, users of HarborSym are not expect to be familiar with complex programming languages. Analysts communicate with the model directly through the user interface, which requires no understanding of computer programming. This approach allows planners and economists to use the model independently, without relying on someone else to build the model for their study.

Uncertainty in model inputs is accepted and handled through a Monte Carlo simulation, which randomizes certain of the input parameters based upon user provided distributions. In order to capture the impacts of these distributions on the simulation results, multiple iterations must be run for each scenario under investigation. Statistics, including minimum, maximum, and standard deviation, are provided for significant output values, such as the total time vessels spend delayed within the system. Several critical elements are handled with uncertainty in the model, including vessel docking time, commodity transfer rates, and time vessels spent in turning basins. In addition, when a simulation is run on historical data, the vessel arrival times are randomized within a twenty-four hour window around their recorded arrival time. This allows for increased variability in vessel interactions between simulation iterations. Outputs from the simulation are accessible through the user interface and include statistics on total vessel times in the system, at docks, turning basins, and anchorages, as well as delay times. Users are also given statistics on the frequency of rule conflicts[6] in each reach.

Throughout the development process, HarborSym collected functionality in addition to the basic rule behavior to increase its applicability to various ports. Included is the concept of priority vessels, which enables the user to identify ship types that will move unimpeded through the harbor. A tide module was incorporated to calculate the water height and strength of the current for proper application of tide based rules. Vessels are permitted to carry multiple commodities and make intra-harbor movements during a single vessel call. Ships can enter and leave through more than one location and intermediate stops within the system, such as at anchorages, are permitted.

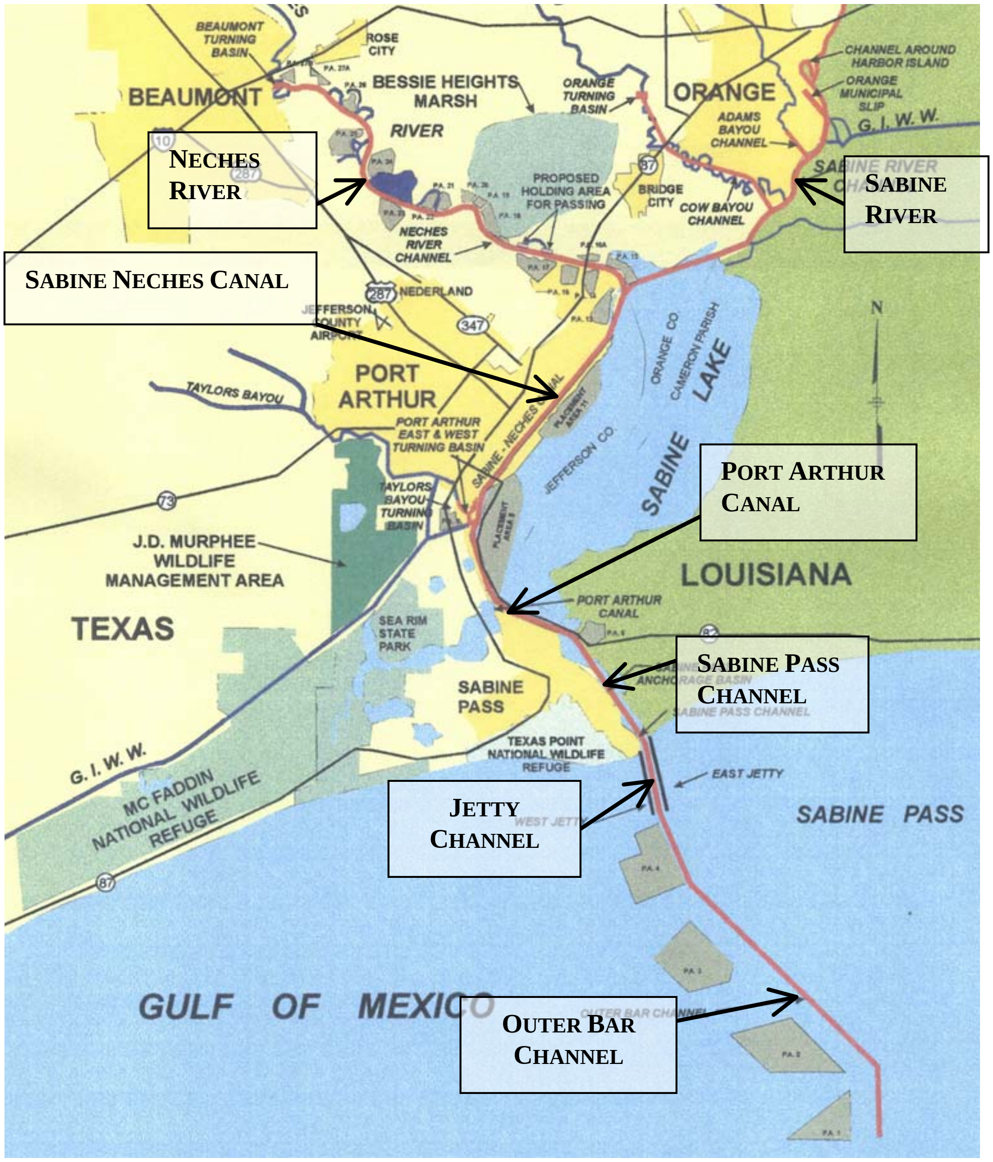
5.0 SABINE-NECHES APPLICATION

HarborSym was first applied to the Sabine Neches Waterway, in southeastern Texas, along the Louisiana border. The deep-water entrance point into this harbor is through the Gulf of Mexico, the waterway then stretches inland approximately 45 miles via the Sabine Neches Canal and the Neches River. Several major petroleum ports utilize this river system, including Port Arthur and Beaumont, Texas. These two ports exchanged over 100 million short tons of cargo in 2001, and ranked as the 28th and 5th largest U.S. ports by volume, respectively[7]. Over 3,800 vessel calls were made in 2001, not including over 15,000 barge movements along the Gulf Intercoastal Waterway, which intersects the main channel. Figure 1 is a map of this waterway.

[6] The term "*rule conflict*" is not meant to imply that traffic rules are broken. This phrase describes the encounter when a vessel is forced to delay sailing due to a transit rule in a particular reach. Rules are never violated during the simulation.

[7] http://www.aapa-ports.org/pdf/01_us_rank_cargo.pdf

Figure 1. Sabine Neches Waterway[8]



This system consists of extremely narrow channel segments complicated with frequent bends that make navigation difficult. Pilot rules in place to accommodate these channel constraints include limiting sailing to daylight hours or preventing meeting of large ships throughout the less navigable segments. These rules often cause delays to vessels and the commodities they carry, decreasing the efficiency of the overall transportation system. To address this problem, the Corps of Engineers, Galveston District, considered widening several channel segments within the system to ease congestion and lessen delays. Field economist found HarborSym helpful in the analysis because evaluating the impacts of these improvements was difficult due to the complicated rule structure and vessel interactions.

---

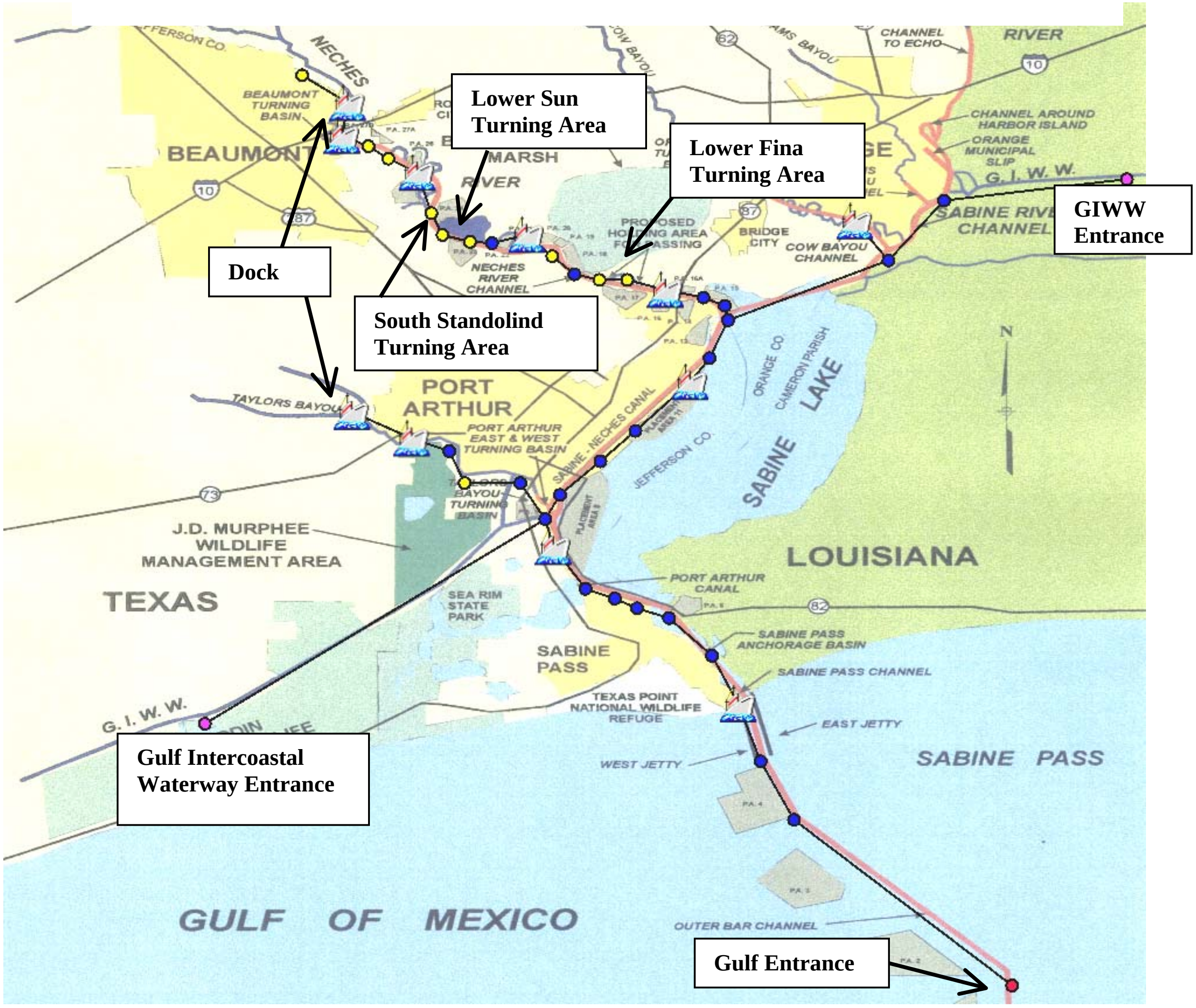
[8] Image provided curtsey of the US Army Corps of Engineers Galveston District.

5.1 Building the Sabine-Neches Waterway in HarborSym

The first step in applying HarborSym to the Sabine-Neches study was to identify the network. The study area was decomposed into a series of nodes, with links or reaches connecting all the nodes. The model requires a tree-structured system, meaning only a single path connects any two nodes. In Sabine, 48 nodes were identified, each representing a critical element within the system. These nodes consisted of docks, turning areas, existing changes in channel dimensions, channel junctions, and proposed improvements. Docks were identified using data supplied by the Waterborne Commerce Statistics Center of the Corps[9]. In 2000, over 100 different docks received cargo within the study area. While the model is capable of modeling this number of docks, such a level of precision added unnecessary data collection burdens to the user without enhancing the analytical results. For simplicity, the docks were grouped into aggregate or virtual docks based on geographic proximity. Using this system of aggregation, only 11 different docks were modeled, which were able to accommodate 90-95 of the actual vessel movements and commodity exchanges. Ten turning areas were identified throughout the system; several were designated turning basins designed and maintained by the Corps, while others were unofficial open areas the Pilots utilized out of necessity. Conversations with the Pilots Association helped determine which turning area was used by vessels calling each dock, whether the ships turned before or after docking, and the approximate length of time required to complete the maneuver. According to these conversations, several of these turning areas were used as intermediate holding areas to store vessels when docks reach capacity or when transit rules prevented sailing.

[9] Waterborne Commerce Statistics Center. USACE Navigation Data Center. http://www.iwr.usace.army.mil/ndc/wcsc/wcsc.htm

Figure 3. Sabine-Neches Network From HarborSym



A series of reaches connect the nodes. Dimensions within each reach were assumed constant, and provided by the user, including reach length, width, and depth. Figure 3 above is a representation of the Sabine network, overlaid on a location map. Different icons represent node types; the ship icons indicate the location of the aggregate docks. The analyst determined which rules applied in the different reaches and supplied the model with the specific parameters of application for the different reaches. In Sabine, the rules were generally assigned as:

OUTER BAR CHANNEL

- No meeting day or night when the combined beam width of the two vessels exceeds one-half the channel width.

JETTY CHANNEL, SABINE PASS CHANNEL, & PORT ARTHUR CANAL

- No meeting day or night when the combined beam width of the two vessels exceeds one-half the channel width.
- No meeting day or night of a vessel equaling or exceeding 85,000 deadweight tons with a vessel equaling or exceeding 30,000 deadweight tons drafting 25 feet or more.

- No meeting day or night if either vessel is equal to or greater than 48,000 deadweight tons and drafts 30 feet or more.

SABINE NECHES CANAL
- No meeting day or night when the combined beam width of the two vessels exceeds one-half the channel width.
- No meeting day or night of a vessel equaling or exceeding 85,000 deadweight tons with a vessel equaling or exceeding 30,000 deadweight tons drafting 25 feet or more.
- No meeting day or night if either vessel is equal to or greater than 48,000 deadweight tons and drafts 30 feet or more.
- Daylight only sailing for vessels exceeding 85,000 deadweight tons, 875 foot length overall, or 125 foot beam.

NECHES RIVER
- No meeting day or night when the combined beam width of the two vessels exceeds one-half the channel width.
- No meeting day or night of a vessel equaling or exceeding 85,000 deadweight tons with a vessel equaling or exceeding 30,000 deadweight tons drafting 25 feet or more.
- No meeting day or night if either vessel is equal to or greater than 48,000 deadweight tons and drafts 30 feet or more.
- Daylight only sailing for vessels exceeding 85,000 deadweight tons, 875 foot length overall, or 125 foot beam.
- No meeting at night of vessels with combined drafts equaling or exceeding 70 feet.

Two different sources populated the vessel call information. The Waterborne Commerce Statistics Center provided detailed information on vessel movements and commodity flows through the harbor. This included information on entrance point into the system, destination dock, physical characteristics of the vessels, and cargo types and quantities. Simplifications were made to the detailed data provided by WCSC; vessels were assumed to carry only one commodity type and visit only one dock. The nature of commodity movements through this system is such that these simplifications did not impact a significant amount of vessel calls.[10]

To further populate the model, Pilot transit logs were consulted. These records traced the vessels as they moved through the harbor, giving information on vessel arrivals, transit times, time spent at the docks, and delay time at the gulf entrance point. This information was used to populate the cargo exchange rates and vessel speeds within the reaches. For each trip, the Pilots recorded sailing times throughout the harbor. Analysts used this information with the distance between the recording locations to determine vessel speeds. The approach was problematic because within transit delays caused by slow moving traffic was already built into the transit speeds. As barges were the primary source of within transit delays, vessel calls from this population were not included in the simulation. This avoided compounding the problems they inflict and since this ship type was not impacted by the transit restrictions, thus not benefiting from the proposed improvements, it was not critical to the analytical results.

5.2 HarborSym Calibration for the Sabine Neches Waterway

The historical data compiled from WCSC and the Pilots Association, along with the existing channel dimensions and rule structures, enabled analysts to test and calibrate the model. Processing this data in HarborSym and comparing the results to recorded statistics made it possible to evaluate the effectiveness

[10] It should be noted that the analysis presented here for the Sabine-Neches Waterway was completed using an earlier version of the model. Subsequent versions have eliminated these simplifications.

of the model in simulating this particular system. Compared in Table 1, the results show discrepancies between times recorded by the Pilots and the simulation outputs.

TABLE 1. Comparison on Historical Records and Simulation Outputs

	Historical Average	Simulation Average
Total Time in System	78.07 [1]	71.3
Time at Dock	53.26	50.9
Time Delayed at the Bar	6.2	4.1

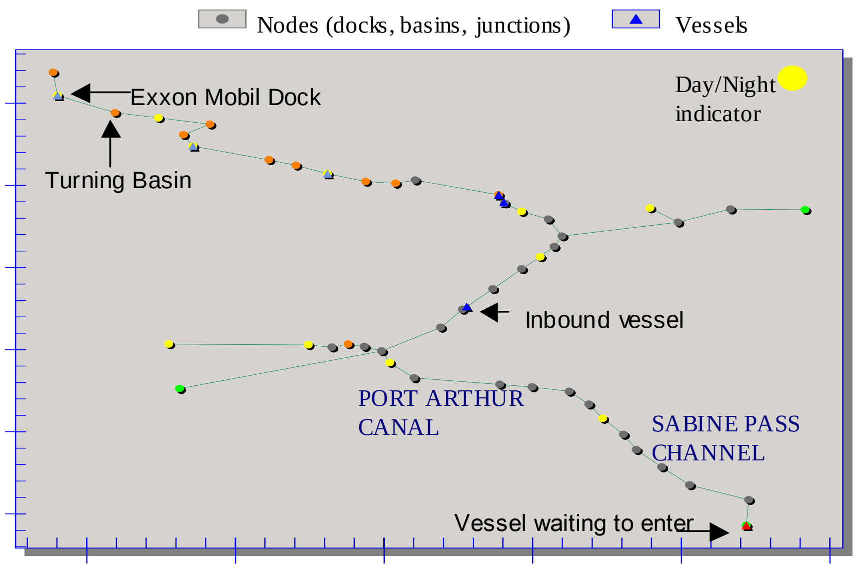
[1] Time in hours per vessel

The Pilots Association provided several possible explanations for the differences between their records and the simulation results. Many activities undertaken within the harbor are not recorded and not included in the model. Vessels will spend time with bunker and ballast activities, but HarborSym does not accommodate these actions. In addition, small or incomplete datasets provided the basis for several important data elements, including the commodity transfer rates and vessel speeds. Initially, cargo exchange rates provided by the dock operators populated the model. Simulation results using this data showed average vessel times at dock less than that displayed in Table 1. One rational for that result was that vessel lay time at the dock was not included; the model estimated productive time at dock based solely on the amount of cargo and the user provided commodity exchange rate, thus any time vessels spent at the dock, such as voluntary delays, were missed. As an alternative, analysts developed exchange rates based upon the Pilots records, but this too was imperfect given the use of aggregate docks.

The application of rules may be a key component to the discrepancies in results. As an analytical model, HarborSym has perfect foresight in the application of rules. It knows exactly when vessels will occupy reaches simultaneously and can predict precisely when it is acceptable to proceed from a dock or the bar. Even with constant communication and years of practice, the Pilots rely on judgment and experience to gauge when vessels can move. As a result, the Pilots may hold vessels at the dock or bar longer than the model because their ability to predict the exact timing of interactions is less precise. The model is also forces the system to impose the rules absolutely, but in reality each individual Pilot is granted the flexibility to use professional judgment in determining safe conditions. While this might lead the senior pilots to apply the rules liberally, the less experienced pilots may be more cautious in their movements.

In addition to using the model outputs, HarborSym's within simulation animation contributed to the calibration process. This provided analysts with a visual representation of the model's computations, which allowed them to understand how the rule structure was being implemented. Displayed in Figure 4, the animation represents vessels as triangles moving through the network. As the model calculates the status of a vessel changing from in-progress to delay, its representative triangle will become red. When this occurs, analysts can select the icon to retrieve additional information on the ship and determine the cause of any delay. This visual feedback, along with the corroboration of discrepancies between historical statistics and simulation output, provided sufficient verification that the model was accurately representing the harbor's transit rule structure. As differences between the model results and historical records were largely understood, and their causes, such as data imperfections and analytical simplifications, would be present in both the with and without project scenarios, the study team and the Pilots Association felt comfortable proceeding with the HarborSym analysis.

Figure 4. HarborSym Within Simulation Animation



5.3 Analyzing Proposed Channel Improvements

The following table outlines the proposed channel improvements evaluated with HarborSym. These include widening two major channel segments, the Sabine Pass Channel and Port Arthur Canal, as well as expanding three turning basins along the Neches River. Analysts evaluated these improvements by examining how the Pilots would alter their rule structure with the wider channels in place. Ships traversing both the Sabine Pass Channel and Port Arthur Canal faced rules restricting passing of vessels with beam widths exceeding one-half the channel width. During interviews, the Pilots indicated that this rule would remain in place after the widening, however, because the improvement would leave the channel 200 feet wider, the restriction would relax from restricting the passing of vessels with combined widths exceeding 250 feet to combined widths of 350 feet. Pilots also indicated that the other transit rules in these channels, which restrict vessel meetings based on deadweight tonnage or draft values, would be completely relaxed.

TABLE 2. Existing and Proposed Dimensions

Location	Improvement Type	Existing Dimension (Feet)	Proposed Dimension (Feet)
Sabine Pass Channel	Channel Widening	500	700
Port Arthur Canal	Channel Widening	500	700
Lower Fina Turning Basin	Basin Expansion (depth)	19	34
Lower Sun TB	Basin Expansion (depth)	19	34
South Standolind TB	Basin Expansion (depth)	19	34

In addition to the channel widening improvements, which were the primary focus of modeling efforts, the study team also examined the benefits from deepening the existing channel. Economic impacts from changes in channel depths typically result from altering vessel loading patterns or inducing alternate vessel types and sizes to call the port. Because HarborSym is designed as a tool to evaluate vessel interactions and the changes resulting from widening projects, analysts conducted the main deepening analysis external to the simulation. Several of the rules in critical reaches were based on depth, so it was predicted that deepening the channels would yield impacts resulting from rule-based vessel interactions.

Thus, the analysis included an incremental examination of deepening improvements within the model in order to capture any decrease in delays resulting from deeper channels. Table 3 outlines the proposed channel deepenings that were examined using HarborSym.

TABLE 3. Existing and Proposed Channel Depths

Reach	Existing Depth (Feet)	Proposed Depth (Feet)	Change in Depth (Feet)
Outer Bar Channel	42	50	8
Jetty Channel	40	50	10
Sabine Pass Channel	40	50	10
Port Arthur Canal	40	50	10
Taylor's Bayou	40	50	10
Sabine Neches Canal	40	50	10
Neches River	40	50	10

5.4 Analysis Results

The analysis considered the deepening and widening scenarios incrementally, based on simulations of 100 iterations each. Table 4 shows several different statistics comparing both the existing condition to an alternative including deepening, widening both channel segments, and expanding all the turning basins. These statistics present the variability among iterations due to the uncertain model inputs.

TABLE 4. Results Distributions From Two Simulations

	Without Project				SPC & PAC with TB[1]			
	Av.	Std. Dev.	Min.	Max.	Av.	Std. Dev	Min.	Max.
Time in System	71.3[2]	36.6	10	290.9	68.8	35.5	10	276.9
Time Waiting	10.4	13.1	0	158.6	7.9	10.4	0	118.3
Wait Entry	4.1	6.2	0	70.5	2.5	4.3	0	19
Wait at Dock	4.9	9.3	0	158.6	2.7	5.5	0	112.1
Wait at FN[3]	1.4	5.2	0	140	2.7	6.6	0	113

[1] SPC is Sabine Pass Channel; PAC is Port Arthur Canal; TB is Turning Basin

[2] Time in hours per vessel

[3] FN is "facility node", either turning area or anchorage

Table 5 shows successive decreases in delay times with each additional alternative. Based on HarborSym analyses, the average vessel is expected to spend 71.3 hours in the system under the existing conditions, with approximately 10.4 of those hours attributed to delays. By implementing all the channel deepenings and widening only the Port Arthur Canal reaches, on average the total time each vessel spends inefficiently delayed falls by 1.2 hours. If all the improvements are implemented, average delays for each vessel call could fall by approximately 2.5 hours. Given that there are over 3,000 vessel calls annually, these savings could be substantial.

TABLE 5. Average Vessel Times Under Proposed Improvements

	Existing Condition	With All Channel Deepenings Only	All Deepenings & Widen Sabine Pass Channel	All Deepenings & Widen Port Arthur Canal	All Deepenings & Widen Both SPC & PAC[1]	All Deepenings & Widen SPC, PAC & Turning Basins
Avg. Vsl Time in System	71.3 [2]	71.2	70.2	70.1	69.3	68.8
Avg. Vsl Time Waiting	10.4	10.2	9.2	9.2	8.3	7.9
Avg. Vsl Time Wait Entry	4.1	3.9	2.8	3.3	2.5	2.5
Avg. Vsl Time Wait Dock	4.9	4.9	5	4.6	4.6	2.7
Avg. Vsl Tim Wait FN [3]	1.4	1.4	1.5	1.2	1.3	2.7

1 SPC is "Sabine Pass Channel" & PAC is "Port Arthur Canal".

2 Time in hours, average reported based on 100 iteration simulation.

3 FN is "facility node", either turning area or anchorage.

These decreases in times spent within the system, particularly the times spent waiting, are translated into potential savings in transportation costs. The model assigns standard vessel operating costs, published by IWR[11], in order to determine the total annual transportation costs for all vessels moving within the given simulation period. Presented in Table 6, these results show the incremental change in transportation costs for a one-year simulation. The incremental benefits reflect the change in costs resulting from including each additional project alternative. Deepening all the proposed channels will decrease depth based rule delays and will yield an estimated decrease in transportation costs of $285,000. If the Sabine Pass Channel is widened in addition to the proposed deepenings, the incremental benefit is estimated at $1.4 million, and if the Port Arthur Canal is further added, the additional benefit would be approximately $1.5 million.

TABLE 6. Annual Transportation Costs and Incremental Benefits

	Annual Transportation Cost ($1000)
Existing Condition	$110,921
With All Channel Deepenings Only	$110,636
All Deepenings & Widen Sabine Pass Channel	$109,200
All Deepenings & Widen Port Arthur Canal[1]	$109,040
All Deepenings & Widen Both SPC & PAC[2]	$107,731
All Deepenings & Widen SPC, PAC & Turning Basins	$107,442

1 Incremental change is measured between all channel deepenings and adding the increment of widening Port Arthur Canal. Likewise for the remaining alternatives.

2 SPC is "Sabine Pass Channel" & PAC is "Port Arthur Canal".

11 Economic Guidance Memo #02-06, FY2002 Deep Draft Vessel Operating Costs. General Planning Guidance. USACE Directorate of Civil Works, Planning and Policy. http://www.usace.army.mil/inet/functions/cw/cecwp/General_guidance/guidance.htm.

6.0 ADDITIONAL ANALYSIS

For this particular project, the Corps focused detailed investigations on structural improvements. As outlined in Tables 2 and 3, the alternatives evaluated included dredging deeper and wider channels in various critical locations. Traffic management alternatives were not expressly evaluated. One approach to traffic management, or non-structural harbor improvements, is changing the Pilot imposed restrictions. Such an approach can be modeled in HarborSym.

A key rule faced in many reaches restricts the meeting of vessel if their combined beam width exceeds one-half the width of the channel. In most reaches, this prevents vessels from meeting if their beam width exceeds 250 feet. This rule is imposed and enforced by the Pilots Association based upon their perception of the clearance required to pass vessels safely. If, however, they relaxed this rule slightly, additional vessels would be able to avoid delays because the random occurrence of their interactions would pass with greater frequency. In HarborSym, changing the meeting restriction from beam widths of 0.5 to 0.6 times the channel width can simulate this hypothetical relaxation. As expected, the average vessel time in the system, delay time, and total transportation costs all fell with the new rule structure. Shown in Table 7, the average time vessels spent delayed fell by 0.7 hours, from 10.4 hours under the existing rule structure and channel dimensions, to 9.7 hours with the same channel dimensions but an alternative rule structure. The annual transportation costs fell by over $1.1 million. If this new rule is implemented in conjunction with all of the Corps proposed structural improvements, additional savings are possible. Total transportation costs would be approximately $106 million, a decrease of 4.1 percent from the current condition with existing rules and channel dimensions. These savings show the potential timesavings resulting from relaxing this restriction but do not account for any increased risks associated with the new rule.

TABLE 7. Comparison of Results Under Alternative Rule Structures

	Existing Conditions			With All Proposed Improvements		
Rule Structure	Total Transportation Cost	Average Vessel Time in System	Average Delay Time	Total Transportation Cost	Average Vessel Time in System	Average Delay Time
0.4 channel	$111,975.0	72.1	11.1	$108,177.3	69.3	8.3
Existing	$110,921.3	71.3	10.4	$107,442.1	68.8	7.9
0.6 channel	$109,822.0	70.7	9.7	$106,338.6	68.2	7.2
Nighttime sailing	$100,443.2	64.9	3.9	$97,197.3	62.7	1.7

Conversely, the costs associated with the Pilots adjusting their rules to regulate the channels more conservatively can also be examined. For example, if the Pilots feel the one-half channel width rule does not allow them sufficient clearance to pass vessels comfortably, the restriction might be tightened to prevent passing of vessels with a combined beam width exceeding 0.4 times the channel width. As this prevents vessels from meeting with combined beam widths exceeding 200 feet compared to the existing restriction of 250 feet, more ships will face delays. According to HarborSym, average delays would rise by 0.7 hours with the existing channel dimensions, which corresponds to an average annual increase in the total transportation costs of approximately $1.05 million.

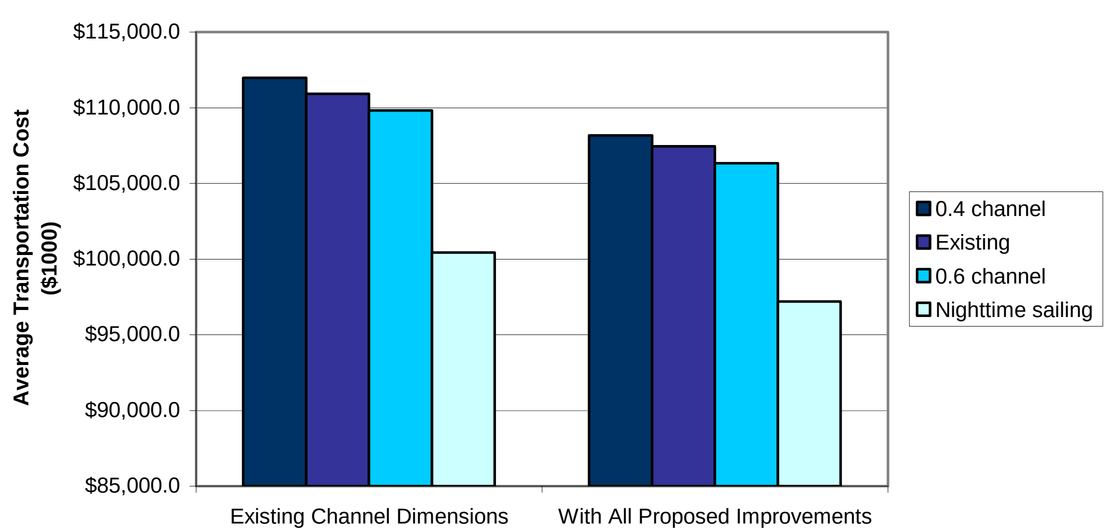
A more startling impact results from examining the restrictions on nighttime sailing within the harbor. Currently, Pilot restrictions prevent the movement of many large vessels during non-daylight hours. Specifically, these rules are structured as:

- Daylight only sailing for vessels exceeding 85,000 deadweight tons, 875 foot length overall, or 125 foot beam in the Sabine Neches Canal and Neches River.
- Vessels with combined drafts equaling or exceeding 70 feet cannot meet at night in the Neches River.

These rules are prevalent in critical channels and impact many of the vessel calls. HarborSym was used to analyze their impact and determine the level of benefit if these restrictions were eliminated due to the availability of Vessel Tracking Systems (VTS), Global Positioning Systems, or other technology increasing the safety of nighttime sailing. Under the existing channel dimensions, the results shows a fall in average delay time of 6.6 hours, which corresponds to $10.7 million savings in average annual transportation costs. If these rule changes were implemented along with the structural improvements, on average the total delay time would only be 1.7 hours, saving $10.2 million over implementing the structural improvements alone. The incremental transportation cost savings from only implementing rule changes to implementing both the new rule structure and also the structural, dredging improvements was $3.2 million.

These results are shown graphically in Figure 5 below. The change in average transportation cost under different rule scenarios is shown for both the existing channel dimensions and also for the proposed structural changes.

Figure 5. Transportation Cost Under Alternative Rule Structures



These results may suggest an alternative approach to formulation than that historically implemented by the Corps. Typically, engineers and planners, in conjunction with local stakeholders, develop alternative improvements. Discussions with the Pilots Associations reveal how their operating practices may change as a result of these different improvements. With knowledge of the specific economic impact of different rules, planners could instead meet with the Pilots to determine what improvements would be required for them to change their rule structure. This could help target project formulation such that proposed alternatives would address the areas with the greatest impact on delay times and transportation costs.

HarborSym can be a useful tool in determining which of the many rules within a port have the greatest impact on vessel movements.

For example in the Sabine-Neches Waterway, simulations of the existing conditions revealed the rules and reaches that caused the greatest impact on transiting vessels. HarborSym collects information on which rule causes each vessel to be delayed. At a specific time during the simulation, a vessel may be delayed due to multiple rules within different reaches, so assigning the total delay time attributable to each rule is difficult. However, the model does provide general information on which rules impact the vessels. In Sabine, rules restricting nighttime sailing based on vessel size in the Neches River triggered vessel delays more than rules in any other reaches. These same rules, applied in the Sabine Neches Canal, occurred with slightly less frequency. Likewise, when considering all the different rule types, transit restrictions in the Neches River and Sabine Neches Canal triggered the most vessel delays. Rules in the Port Arthur Canal and then the Sabine Pass Channel, the channels with Corps proposed structural improvements, followed in the total number of vessels impacted. Improvements implemented to relax restrictions in reaches within the rivers of greatest impact, the Neches River and Sabine Neches Canal, would influence the majority of deep draft vessels calling the harbor. While the study team did examine this possibility, neither of these channel segments was considered feasible for the specific structural improvements proposed due to the presence of landmasses on either side of the rivers.

7.0 CONCLUSION

Harbors function as the interactions of many different agents coming together to move goods into and out of a nation. Maintaining these activities seamlessly is vital to the functioning of a nation's economy. For many ports along the U.S. coastline, shallow or narrow channels leading from the deep ocean water to the docks may threaten these activities. Determining the need for expanding these channels requires a complex economic analysis that depends on the random interactions of multiple vessels moving simultaneously in a single channel segment. Through application, HarborSym has proven to be a useful tool in assisting with these types of analyses. HarborSym is designed as a planning-level tool to aid in plan formulation and to help determine economic impacts of different improvements. Unique to HarborSym is its inherent portability built into the data driven structure of the model. This framework allows users to adapt the model to their own port without requiring changes in the underlying computer code. Although creating a generic model is the ultimate design goal of the development team, it is acknowledged that each port represents a unique set of problems. As HarborSym, in its current state, cannot presume to meet the needs of every problem in each port, further development is planned in increase the model's applicability. Future extensions include the ability to simulate safety zones, allowing for a buffer around ships carrying critical or sensitive commodities. Relaxing the requirements of a tree-structured network will make HarborSym useful in harbors with multiple routes between docks, while increasing the elements handled with uncertainty, such as providing variability in transit speeds, will provide more robust outputs from multiple iterations of the Monte Carol simulation. Currently underway are efforts to finalize a vessel generator, which will create synthetic shipment lists based on user provided statistics, thus lessening the overall data burden. As these and other improvements are implemented, HarborSym will become a tool more ports and harbors can use during planning investigations.

8.0 ACKNOWLEDGEMENTS

The development of HarborSym has been a collaborative effort between the Institute for Water Resources, Corps field offices, and private corporations. Dr. David Moser and Keith Hofseth at IWR have been fundamentally involved with HarborSym since its inception. Dr. Richard Males of RMM Technical Services wrote the computer code and Cory Rogers of CDM designed and implemented the user interface. The tidal prediction engine was developed by Phil Thornton of Warkworth, NZ, and is used with his permission. Gloria Appell, Corps Galveston District, provided extensive assistance on the Sabine-Neches application of the model, and Rebecca Moyer, Corps Jacksonville District, offered support during the Tampa Harbor application. Ian Mathis, of IWR, has provided valuable insight into the general functioning and operations of coastal ports.

REFERENCES

American Association of Port Authorities, Government Relations. 2003. American Association of Port Authorities. http://www.aapa-ports.org/govrelations/

Economic Guidance Memo #02-06, FY2002 Deep Draft Vessel Operating Costs. General Planning Guidance. USACE Directorate of Civil Works, Planning and Policy. http://www.usace.army.mil/inet/functions/cw/cecwp/General_guidance/guidance.htm

Limao and Venables, “Infrastructure, geographical disadvantage, transport costs and trade”, World Bank Economic Review 15, no 3 (2001): p. 451-479.

Mathis, Ian. Personal Communication. 10 August 2004.

Moser, David, Keith Hofseth, Shana Heisey, Richard Males, and Cory Rogers. “HarborSym: A Data-Driven Monte Carlo Simulation Model of Vessel Movement in Harbors”. Proceedings of HMS2004.

Pachakis, D., and A.S. Kiremidjian. 2003. “Ship Traffic Modeling Methodology for Ports”. Journal of Waterway, Port, Coastal, and Ocean Engineering, American Society of Civil Engineers, Vol. 129, No.5: 193-202.

Value to the Nation. 2004. U.S. Army Corps of Engineers. http://www.corpsresults.us/navigation/navrecentprojects.htm

Waterborne Commerce Statistics Center. USACE Navigation Data Center. http://www.iwr.usace.army.mil/ndc/wcsc/wcsc.htm