Assessing Waterborne Crude Oil Delivery Options

C. MICHAEL WALTON, MARK S. DASKIN, AND PRAMOD ATHALYE

The importance of waterborne delivery of crude oil, whether of foreign import or redistributed domestic, has become increasingly evident. Even with a stabilization of oil imports as mandated by the 1985 import ceiling of 8.5 million bbl/day or a decline in foreign imports, the redistribution of domestic oil from noncontiguous areas and territories, such as the Valdez port of the Alaskan oil fields, will most likely continue to increase. In addition, the ability of Gulf ports to process crude oil in a more cost-efficient manner, due to their extensive infrastructural capacity, will continue to attract foreign and redistributed domestic oil. In response to the increasing value of crude oil, cost-efficiency is necessary in every link of the shipping, distribution, redistribution, and transfer process of delivery. This paper, which focuses on one particular link in the process, has two primary objectives: (a) to review trends in lightering of crude oil from very large crude carriers by small tankers or lightering vessels off the Texas coast and investigate the characteristics of lightering operations based on present and projected conditions, and (b) to study and evaluate costs and environmental issues associated with lightering and two other options—an offshore deepwater port and an industry-proposed method of crude oil transfer. A brief review of waterborne crude oil delivery to the Texas Gulf Coast, a description of lightering operations, and a lightering model analysis with scenario applications are presented in pursuit of the first objective. The cost of transportation and adverse environmental impacts for each option are summarized in connection with the second objective.

With the ever-increasing cost of crude oil, and the related national as well as international ramifications, a variety of opportunities has surfaced. One opportunity concerns the trade-offs associated with the various options of delivering crude oil to the Texas Gulf Coast petrochemical plants. A study was initiated to review and evaluate the waterborne crude oil delivery systems off the Texas coast.

Specifically this paper describes two primary objectives of the study:

1. To review trends in lightering of crude oil from very large crude carriers (VLCCs) and ultra-large crude carriers (ULCCs) by smaller tankers or lightering vessels (LVs) off the Texas coast, and investigate the characteristics of lightering operations based on present and projected conditions; and
2. To evaluate costs and environmental issues associated with lightering and two other options--an offshore deepwater port and an industry-proposed method of crude oil transfer.

CRUDE OIL SUPPLY AND DEMAND

The United States is currently importing between 5 and 8 million bbl/day (MBD) of crude oil, mostly from distant sources such as the Persian Gulf and North and West Africa. The domestic production, which is steadily declining at a current estimated rate of 4 percent annually, translates into a growing concern over imported crude oil. A significant proportion of imported or redistributed domestic crude oil is destined for the ports in the Gulf of Mexico. At present, oil is brought to these ports either by transshipment at deepwater ports in the Caribbean or by lightering off the Gulf Coast. This is a necessity because the United States does not have a deepwater port capable of accommodating VLCCs that have drafts far in excess of the 45 ft associated with most U.S. port and harbor channels.

Another option is the transfer of crude oil at an offshore deepwater port from which the crude oil could be transported to onshore storage facilities through submerged pipelines. One such terminal, the Louisiana Offshore Oil Port (LOOP), is to be operational by mid-1981 off the Louisiana coast. Another similar facility, a Texas Deepwater Port (1), has been proposed for location off Freeport (see Figure 1).

It is likely that the demand for crude oil will be reflected in increased lightering activity. This will necessitate regulation of lightering procedures that are being proposed to ensure safety and environmental standards.

LIGHTERING

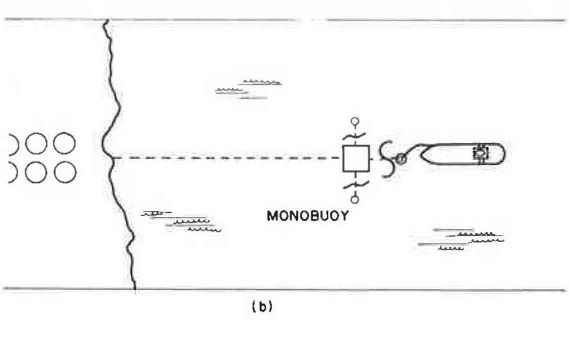
Approximately 2.2 MBD of waterborne crude oil were delivered to the seven major Texas Gulf ports in 1978. Thirty-six percent of this volume (0.8 MBD) was lightered from VLCCs with most of the remaining transshipped from Caribbean ports. Data show an increasing recent trend in lightering activity (1).

Lightering Zones

Location criteria for a lightering zone include cost efficiency and maximum environmental safety. Unfortunately, these two criteria are not always compatible and require a compromise. With respect to environmental safety, two primary factors are distance from shore and remoteness from submerged reef structures that exist in the Gulf off the coast of Texas. Distance from shore is the most important factor to consider as it determines, in large measure, the time required for a spill to reach the shoreline. The longer crude oil "weathers", the less toxic it becomes. Based on estimated average speed of an oil slick and time required for crude oil to lose its toxicity, lightering zones are preferred to be located at least 25-30 miles offshore and desirably 50-60 miles. Excessive distances, however, can hinder the on-site arrival time of additional shore-based spill control equipment.

A primary location cost consideration is minimizing travel time between the zone and port. The

Figure 1. A sketch of an offshore deepwater port.



(a)

(b)

total turnaround time for LVs is a major concern in reducing transportation costs. This suggests that zones should be located as close to the ports as possible. For the Texas Coast, the 100-ft depth lines run 20-30 miles offshore. Therefore, lightering zones should not be closer than 40 miles off the coast of Texas, centrally located to serve several ports, away from major shipping lanes, and remotely located from offshore reef structures.

Fleet Characteristics

Most VLCCs are owned by the major oil companies or their subsidiaries. For the purpose of this study, these vessels were estimated to have an average deadweight tonnage (DWT) of 250 000. The normal turnaround time between the Persian Gulf area and the Gulf region is approximately 60 days. At present the relative charter costs of VLCCs as compared with LVs is quite low. The LVs are either owned by the oil companies or by small, local shipping lines that operate, lease, or charter these vessels. Their average cargo-handling capacity is about 50 000 DWT, which requires a draft of about 35-45 ft when loaded. Unlike VLCCs, these vessels tend to be relatively old (15-20 years).

Regulations and Safety

The U.S. Coast Guard has proposed safety regulations and standards for lightering operations and associated equipment (1). Objectives, among others, were to minimize the probability of an oil spill that might be caused by the use of substandard equipment or hazardous operating conditions, as well as to develop procedures that would facilitate the control of an oil spill should one occur. The presence of oil spill recovery vessels, related equipment, and personnel is deemed essential for any lightering activity. Except for spills that result from ship collisions or accidents unrelated to operations conducted during the transfer of crude oil, no major oil spills to date have been attributed to lightering operations.

Operational Aspects

Lightering operations are normally conducted with both vessels moving parallel to one another, at low speed, and with an initial minimum separation of 200-300 ft. Gradually the vessels are brought closer to each other until the forward primary fender of the LV makes contact with the hull of the VLCC (see Figure 2).

Although there are no specified offshore lightering zones, most of the lightering occurs in four locations. These zones were enumerated and appropriately plotted on the coastal map (Figure 3) for use in the analysis of lightering operations.

ANALYSIS OF LIGHTERING OPERATIONS

Considering the increasing importance of lightering, an analysis procedure was developed to minimize overall cost ($/bbl) through the reduction of operating delays, number of LVs deployed, and other related factors. Analytical constraints include the amount of crude oil brought into the Texas Gulf region and the location of lightering zones and ports.

A linked queuing model of lightering operations (2) was developed and used for the analysis. The model is depicted in a lightering operations schematic (Figure 4), which shows two VLCCs being served (lightered) in the zone, one VLCC waiting, 13 LVs shuttling between the zone, and a three-berth port. This depicts one particular "state" of the given lightering operation, which is characterized by the number of VLCCs in the system being served and waiting, and the LVs in the system. LVs can be in one of six possible conditions; (a) serving a VLCC, (b) in transit to the port, (c) waiting to unload at the port, (d) unloading at the port, (e) in transit to the zone, and (f) waiting to load at the zone.

The state of the system changes according to the arrival and departure time of VLCCs and the shuttling of LVs between the zone and the port. By determining the long-run average probability of all possible states of the system (the steady-state probabilities), the average operating conditions for a given lightering configuration can be obtained. This includes VLCC and LV delays and the use level of the berths in port.

The linked queuing model consists of two submodels, the LV movement model and the VLCC delay model, linked through a third model of VLCC service time (2). Figure 5 is a macro flowchart of the model system. Inherent in these submodels are assumptions based on the following elementary economic

Figure 2. A sketch of a typical lightering operation.

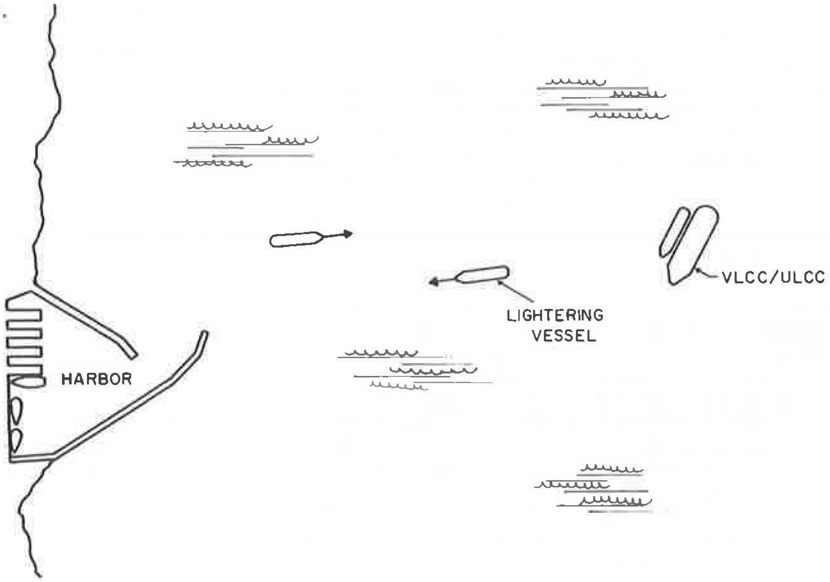


Figure 3. Current lightering areas along the Texas coast and major port groups.

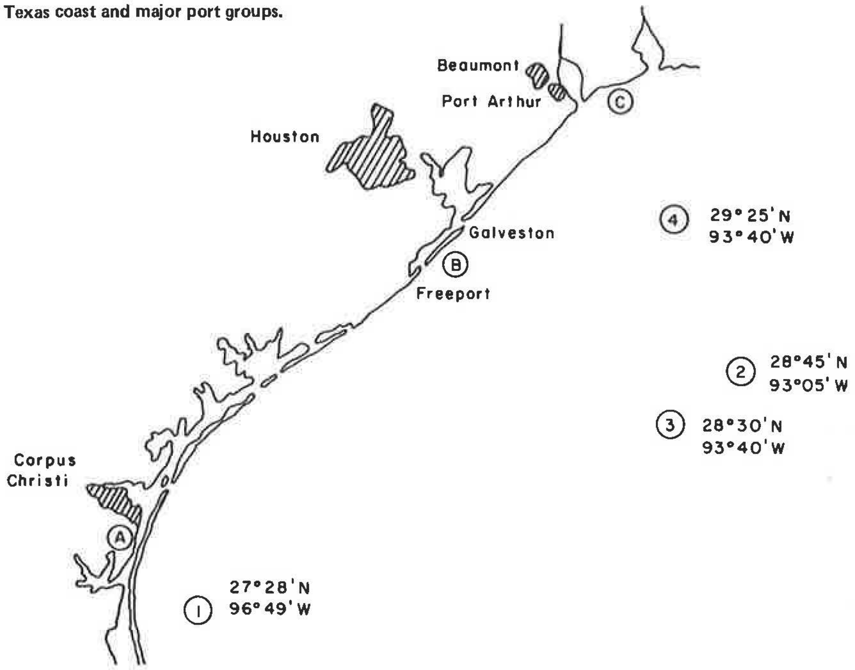
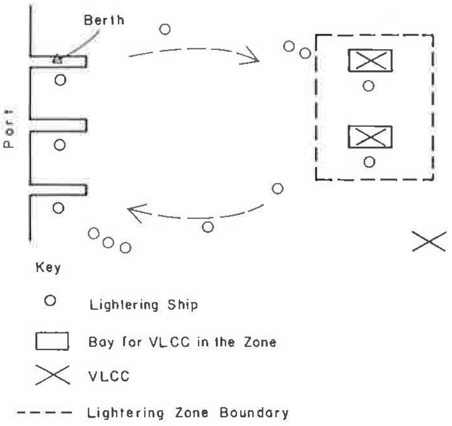


Figure 4. Schematic of lightering operations.



considerations: (a) The number of berths in the port should not exceed the number of LVs and (b) the number of VLCCs that can be simultaneously served should not exceed the number of LVs deployed. The three submodels are briefly described below.

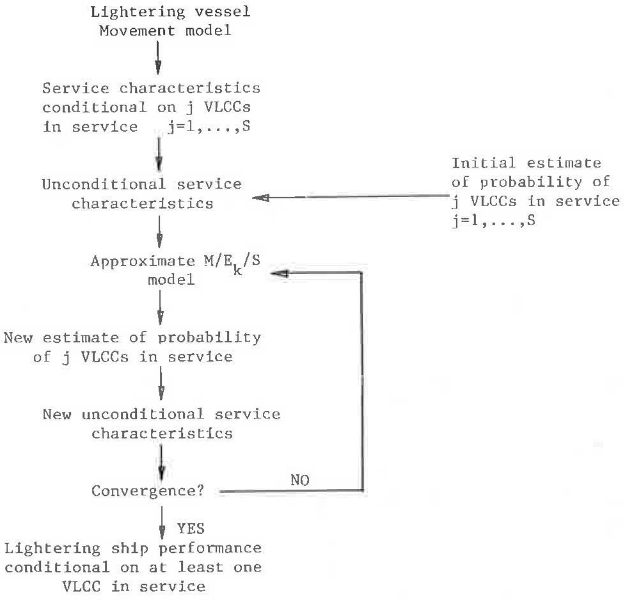
Lightering Vessel Movement Model

A cyclic queuing model developed by Gordon and Newell (3) has been used to describe LV movements, conditional on at least one VLCC in service. The model has also been used by Koenigsburg and Lamin in a study of transoceanic ship movements (4).

LV movements are divided into four components: loading at the zone, travel to the port, unloading at the port, and travel to the zone. Possible delays are assumed during the loading and unloading components. The loading, unloading, and shuttle times between the zone and the port are assumed to be exponentially distributed, independent, random variables.

For a given number of LVs and a given number of LVCCs in service, the model determines the probability of finding j LVs in each component, for all possible values of j. The number of LVs in each component summed over all components must equal the number of LVs deployed for each state of the system. The model obtains, in particular, the probabilities of j LVs loading or waiting to load. These probabilities are used in the VLCC service time model. The LV model is solved for all possible numbers of VLCCs--from one to the maximum that can be served simultaneously.

Figure 5. Macro flow chart of model system.



VLCC Delay Model

An approximate model of an $M/E_k/S$ finite queuing system was developed to estimate VLCC delays. The model assumes that VLCC arrivals follow a Poisson distribution, service times follow an Erlang-k distribution, and a maximum of 30 VLCCs can queue for service.

The model estimates queue lengths and delays for a given service time distribution. The probability of j VLCCs in service, for j = 1...S, is also given. These results are conditional on a given service time distribution.

It is assumed that, if service times are described by an Erlang-k distribution, each VLCC brings with it k units of work, and each of these units requires an independent, exponentially distributed period of time for completion (5). Instead of accounting explicitly for the remaining work units at the end of service at each of the servers, as an exact model would entail, the approximation is based on the total number of work units in the system. According to some preliminary tests, the model slightly underestimates the total times in the system. Daskin and Walton (2) are pursuing refined approximations. The model is exact if the service times are exponential or if there is only one VLCC bay in the lightering zones.

VLCC Service Time Model

The VLCC service time model consists of two parts. The first determines the mean and variance of the service times, conditional on a given number of VLCCs in operation. The probability of finding j lightering ships at the zone, conditional on a given number of VLCCs in service, is employed. These probabilities are determined by the LV movement model.

The second part of the model computes the unconditional mean and variance of VLCC service times. The probability distribution of the number of VLCCs in service, derived from the VLCC delay model, is employed to obtain the unconditional mean. Since this delay model depends on the service time distribution, which, in turn, depends on the output of the delay model, the two models must be solved iteratively until they converge to a common service time distribution. This process is initiated by assuming that the distribution of the number of VLCCs in service corresponds with a finite queue M/M/S system with state-dependent service time durations.

The model converges when k, the shape parameter of the service time distribution, is not altered from one iteration to the next and when the percentage of change in the mean service time is less than a user-specified value, h. For a low h value of 0.01, the model has never required more than 11 iterations.

Once the model has converged, the probability distributions of LV movements, conditional on a given number of VLCCs in operation, are combined with the VLCC delay model approximation of the probability distribution of the number of VLCCs in service. This gives an estimate of the number of LVs in each of the four components mentioned earlier, conditional on at least one VLCC in service. The model inputs appear in the table below:

Input Type	Description
Primary	Number of lightering vessels
	Number of berths in port
	Number of VLCC/ULCCs that can be served simultaneously
Secondary	Arrival rate of VLCC/ULCCs
	Size of lightering vessels
	Distribution of VLCC/ULCC sizes
	Mean loading and unloading times for lightering ships
	Mean travel times for lightering ships to and from port
Model control	Iteration limit
	Convergence criterion

The model outputs are given in the following table:

Output Type	Description
VLCC/ULCC	Mean and variance of number in system and in queue
	Mean service, queuing, and system times
	Estimated state probabilities
Lightering vessel	Mean and variance of number of lightering vessels in each of four components
	Mean and variance of number of lightering vessels delayed loading and unloading, given at least one VLCC/ULCC in service
	Distribution of all possible numbers of lightering vessels in each component, given j VLCCs in service, j = 1,...,S

Model Uses and Analysis

The linked queuing model was used for an analysis of lightering operations for the following scenarios: current lightering operation, lightering with the minimum shuttle time between a current lightering zone and port (minimum time), future lightering operation with a ceiling of 8.5 MBD on imported oil (through the year 2010), and future lightering operation without restrictions on volume of imported oil.

The model results were used to estimate costs associated with a lightering operation. These durations are sensitive to mean arrival rate of VLCCs, service time durations of LVs, and number of LVs.

Since VLCC arrivals in the Gulf region are nonscheduled (assumed to follow a Poisson distribution in the model), no control, other than diverting a VLCC to another lightering zone, can be exercised over arrival rates to alter lightering operations.

Given the four general offshore lightering locations, a relatively constant shuttle time between these zones and the ports has been established. There is also little variability in the loading and off-loading time of crude oil, which is a function of the equipment used. Therefore, the variable that can be employed to control an operation is the number of LVs used.

The ports segmented into three groups to reduce the number of computer runs of the model. The port groups appear below:

Port	Port Group
Corpus Christi	A
Freeport, Houston, Galveston	B
Beaumont, Port Arthur-Lake Charles	C

The model inputs for each operational case were derived according to the procedures described below.

Current Lightering Operations

A direct comparison can be made regarding the operational characteristics between port groups and zones if the number of VLCC bays in a lightering zone is held constant. One VLCC bay was considered.

The number of berths available in port was assumed to be sufficient for the operations (i.e., equal to the number of lightering vessels). This assures no waiting time in the port.

Table 1 lists the destination and volume of crude oil lightered in each zone. The arrival rates of VLCCs for each zone and port group were computed by using the volume of crude oil lightered during the period January-June 1978. The results are listed in Table 2.

Table 1. Total tonnage per lightering zone.

		Lightering Zones			
Port Group	Port	27°28′ N, 96°49′ W (1)	28°45′ N, 93°05′ W (2)	28°30′ N, 93°40′ W (3)	29°25′ N, 93°40′ W (4)
A	Corpus Christi	2 007 800	-	430 000	-
B	Freeport, Galveston, and Houston	61 400	1 245 609	6 660 809	-
C	Lake Charles and Port Arthur-Beaumont	-	35 220	7 547 851	145 330
Total (January-June 1978)		2 069 200	1 280 829	14 638 660	145 330

Table 2. Current VLCC arrival rates (ships/h).

	Lightering Zone				
Port Group	1	2	3	4	LV DWT at Each Port Group
A	0.002 10	-	0.004 5	-	55 000
B	0.000 06	0.001 3	0.006 97	-	50 000
C	-	0.000 04	0.007 9	0.0015	47 000

Table 3. Estimated shuttle time for lightering vessels between various lightering areas and port groups.

	Shuttle Time^a (h)			
Port Group	Zone 1	Zone 2	Zone 3	Zone 4
A	8.6	49.3	42.9	46.1
B	32.1	21.4	17.9	13.2
C	43.9	14.3	15.0	6.8

Note: Possible error of ±20 miles between port groups and lightering zones.

[a] Based on an overall speed of 5 knots/h.

Figure 6. An example of VLCC waiting and service time durations (assuming port group A, Zone 1, with 1 VLCC bay).

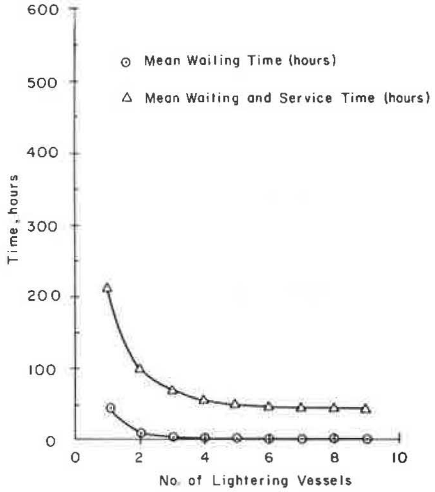
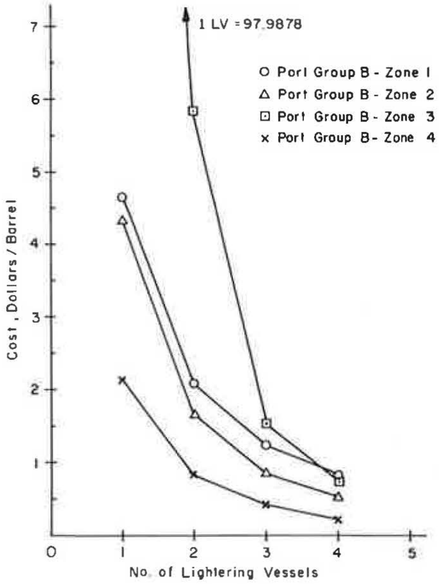


Figure 7. Lightering cost, port group B.



Lightering Under Minimum Shuttle Time

Minimum time refers to the shuttle time between a port group and the nearest lightering zone. The matrix (Table 3) shows that zones 1, 4, and 4 are the nearest to port groups A, B, and C, respectively. The model runs were computed with the assumption that all the crude oil lightered in different zones and destined for a port group was lightered in the nearest zone.

Future Lightering Operations

The year 2010 was chosen as the analysis horizon. Two scenarios were considered under this case: (a) restriction of crude oil import by a ceiling of 8.5 MBD and (b) no import restrictions.

The key simplifying assumption in this case was that the share of crude oil transshipped in 1978 would remain constant through 2010. The average VLCC/ULCC DWT was increased to 350 000 to reflect the growing size of these vessels. Most of the remaining assumptions such as LV DWT were assumed to remain constant (50 000 DWT).

Figure 6 represents an example of waiting and service time durations of VLCCs and LVs, given a varying number of LVs servicing one VLCC. Beyond a certain number of LVs, the waiting and service time durations for a given arrival rate of VLCCs are not reduced appreciably. There is a trade-off between these durations (costs of operating and delay) and the number of LVs deployed.

Figure 7 is an example of estimated total lightering cost versus the number of LVs deployed by lightering zone. These suggest that beyond the use of three LVs, there is no significant reduction in costs. The number of LVs that yields minimum cost is a function of a given VLCC arrival rate, the mean number of LVs at the zone (waiting to lighter), and the probability of LV delay. The LV delay increases with an increase in the number of LVs. The duration of this delay cannot be estimated from this model as

Figure 8. Total lightering cost, restricted import case.

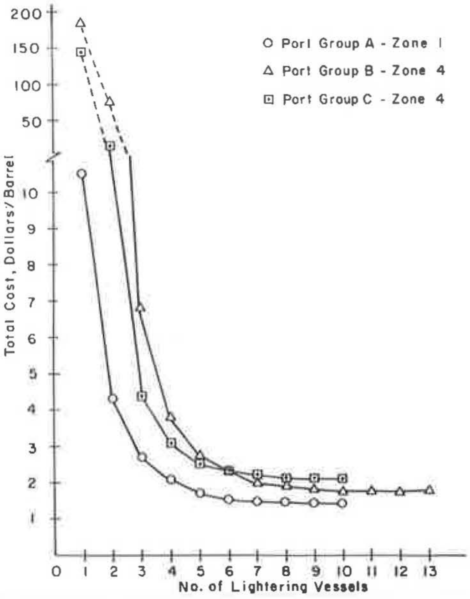
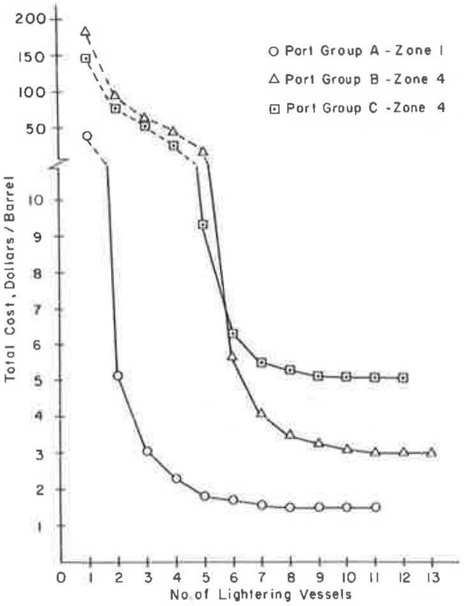


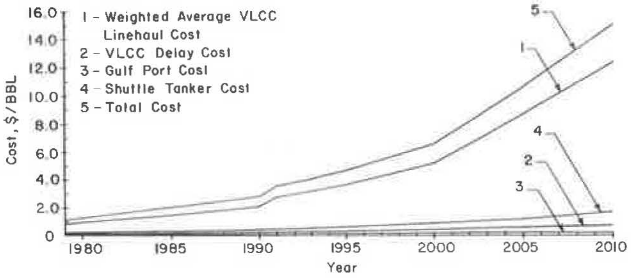
Figure 9. Total lightering cost, unrestricted imports.



it is currently designed. Recent extensions to this model and the development of alternate lightering models allow estimation of this delay. Second, there is also the possibility of port delay because of a nonavailability of berths, although a sufficient number of berths for a lightering operation have been assumed in the model runs. A more realistic inference is that three LVs would be appropriate. Figure 8 shows the total lightering cost estimated for the import restricted case by port group and closest lightering zone.

Next, the model computed the results for lightering operations under the no-restriction case. Runs with one VLCC bay in a lightering zone revealed relatively high values of waiting and service times for the arrival rates corresponding to zone 4. Figure 9 shows the total lightering costs.

Figure 10. Lightering costs (distant sources), 1979-2010.



It may be inferred that having more bays reduces the waiting time durations of VLCCs but increases the service time durations in some instances. An optimization of total lightering costs associated with these durations would indicate the optimum lightering conditions. The results obtained from this approach suggest that the use of such a model can provide insight into the operational aspects of lightering activities. It should be emphasized that the results discussed above are tentative and suggestive in that the models used are all conceptual and preliminary. The inferences derived from the model output were used in the cost analysis.

CRUDE OIL TRANSPORTATION COST ANALYSIS

The cost analysis focused on the per-barrel transportation cost of oil delivered to the Texas Gulf Coast processing centers from 1980 to 2010. For this cost analysis, only crude oil transfers from the Arabian Gulf and North and West Africa were used. Mexico was treated separately. The three options evaluated are defined as lightering, an offshore deep-water port, and an industry proposed lightering system.

Lightering

In the analysis of lightering the following cost categories were included: shuttle tanker transportation cost, Gulf port charges, VLCC/ULCC delay cost, and VLCC/ULCC line-haul cost.

A summary of lightering costs from 1980 to 2010 is shown in Figure 10 (1). Line-haul costs were separately computed for the Persian Gulf, North Africa, and West Africa and then a weighted average of line-haul cost, based on the expected volume of oil from each of these sources (Persian Gulf, 70 percent; North Africa, 2 percent; and West Africa, 28 percent), was calculated.

Offshore Deepwater Port

The state of Texas and others have explored the feasibility of constructing a deepwater port off the Texas coast. This port requires construction of an offshore platform, monobuoys, terminal-to-shore pipelines, and onshore storage facilities. In addition, construction of new pipelines, connecting the onshore storage with various refineries along the coast, would be necessary. The two primary cost items of this option are a deepwater port tariff and a pipeline tariff.

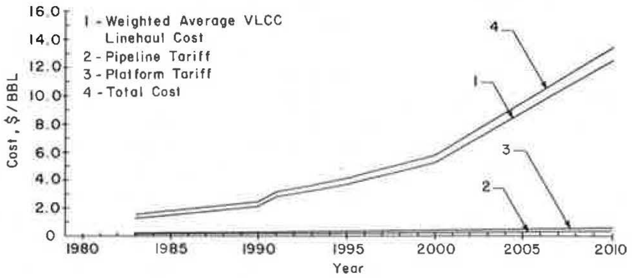
A summary of costs for the deepwater port (1983-2010) is shown in Figure 11 (1). Line-haul costs were slightly higher for the deepwater port than for a lightering system.

Industry-Proposed Lightering System

The industry-proposed lightering system is a combination of various transshipping, lightering, and offshore monobuoy system characteristics. It would involve a smaller initial cost than an offshore port but a higher operating cost. The cost items for this option (assuming that VLCC delay costs are effectively reduced to zero) are (a) tariff (includes the cost incurred due to mooring ULCC at the platform or monobuoy), (b) shuttle tanker transportation cost, (c) Gulf port charges, and (d) VLCC/ULCC line-haul cost. The cost categories for these options are summarized in Table 4.

This operation, shown in Figure 12, uses an ULCC permanently moored offshore served by VLCCs arriving from distant sources in transferring the crude oil. LVs in turn transfer this crude oil from the ULCC to port. This scheme aims to reduce the delay and, hence, the cost of VLCCs. The transportation costs for the industry proposal are shown in Figure 13. Because the industry proposal analysis used Corpus Christi costs, both line-haul and port-shuttle tanker costs are different from the lightering costs.

Figure 11. Offshore deepwater port costs (distant sources), 1983-2010.



Comparison of Various Import Methods

Figure 14 shows the total costs of the three import methods for 1980-2010. The offshore deepwater port is shown to have a slight cost advantage over the other two options.

ENVIRONMENTAL CONSIDERATIONS OF TRANSSHIPMENT

Crude oil is a complex mixture of hydrocarbons and organic compounds, including sulfur, nitrogen, and oxygen. The hydrocarbons are mostly toxic. Because oil possesses a lower specific gravity than water, it tends to remain on the surface and spread when spilled. Wind and water currents are primarily responsible for directing the drift of an oil slick and its determining rate of spread on the surface.

Once the highly volatile, toxic fractions are exposed to the air and water, they dissipate rapidly due to evaporation, solution, emulsification, and precipitation. This process is known as "weathering." The weathering rate is highly dependent on the type of oil, climate conditions, and sea conditions. Evaporation is most crucial in the early stages of a spill because it involves the most highly toxic and volatile components. The majority of the toxic components dissipate in the first 24-36 h.

The location of an oil spill relative to biologically sensitive environment is perhaps the most crucial determinant of the ecological impact of an oil spill. In Texas, an offshore spill is generally less environmentally damaging than one that occurs with the bays. Most biologically sensitive plant and animal life is sheltered from the open sea by the barrier island and, in the event of an oil spill, their protection would be relatively easy.

Oil pollution damages occur immediately and have

Table 4. Cost items associated with various means of crude oil transshipment.

Item	VLCC/ULCC Line-Haul Costs	VLCC/ULCC Delay Costs	Pipeline Tariffs	Gulf Port Charges	Shuttle-Tanker Costs	Platform (Facility) Tariffs
Lightering	√	√		√	√	
Texas deepwater port	√		√			√
Industry-proposed lightering system	√			√	√	√

Figure 12. A sketch of industry-proposed lightering.

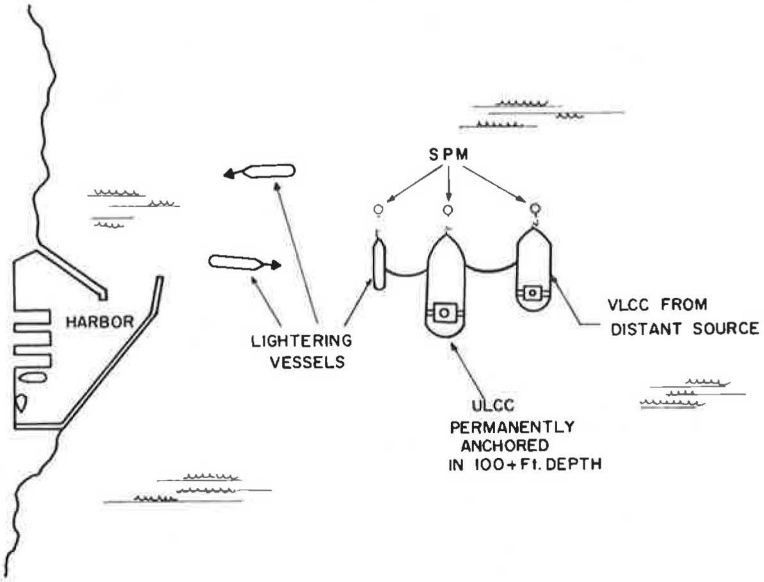


Figure 13. Industry-proposed lightering system costs (distant sources, 1981-2010.

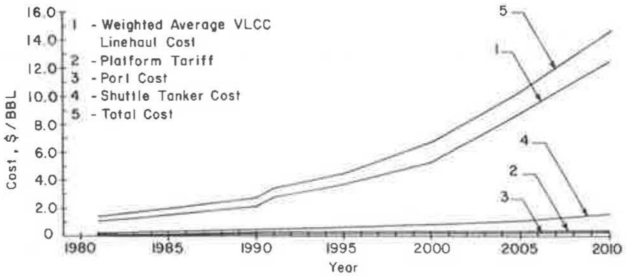
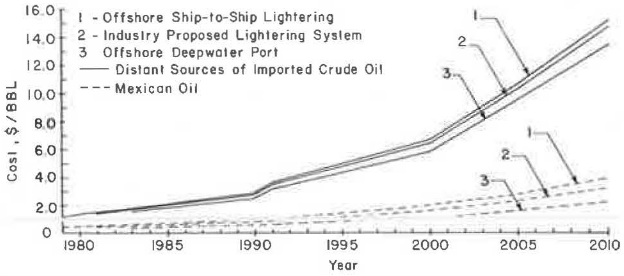


Figure 14. Cost comparison of various import methods, 1980-2010.



long-lasting effects, although the recovery of most living systems is usually rapid and complete. Short-term damages are easier to assess than long-term, in which no evidence is seen for several months or even years following an accident.

It should be noted that apart from crude oil, many chemicals, dispersants, solvents, and cleaners used in spill clean-up operations can cause more damage than naturally degrading oil.

The potential impact associated with each method of transshipment was estimated on the basis of the environmental and economic effects of oil spills. The impact potential is a combination of spill probabilities and possible exposure to critical habitats. Spill probabilities are based on the complexity of operations, both human and mechanical. These complexities include spills that occur from cargo exchange, ship collision, or pipeline failure. Exposures to critical habitats were determined by noting the location of potential spills, according to each type of operation, and comparing them with the location of critical habitats. Spill control response to these locations was considered.

CONCLUSIONS AND COMPARISONS

Lightering

Present delivery methods include unrestricted lightering (ship-to-ship transfer) in Texas offshore waters and Caribbean transshipment. Both methods at present require the entrance of oil-carrying vessels into Texas bay systems to reach the port and refinery facilities.

Approximately five lightering operations may be necessary to unload each VLCC that yields as many as 10 cargo transfers. Statistics indicate that human error and mechanical failure are the primary causes of oil spills (1). For example, the spill frequency for lightering is about 12.1×10^{-3} spills/transfer operation, while the magnitude of potential spills averages about 2.32×10^{-6} units spilled/units transferred (6). The average operational spill, associated with mechanical failure or human error during cargo transfer, either at sea or in port, is approximately 238 bbl. The estimated average size spill, resulting from a minor VLCC collision, is approximately 2400 bbl, while a major VLCC accident spills approximately 112 000 bbl. A spill that results from the grounding or collision of a lightering vessel (possibly within the bays) can approach 95 000 bbl (1).

The most important environmental safety consideration is the entrance of lightering ships into bay systems along the major deep-draft inshore channels. These channels and associated passes are heavily traveled by other types of shipping. Forecasts of other types of shipping and oil importation indicate that the number of lightering ships will also increase, which suggests increased congestion of the ports, waterways, and fairway anchorages. Many lightering ships lack modern navigational equipment, further increasing the possibility of an accident.

The above considerations are significant, not only in terms of the increased risk of collisions or grounding, but also because the resulting spills are close to critical habitats. Nearly all inshore shipping channels involved in the transportation of petroleum products pass near or directly through critical habitat areas. If a spill occurs in these areas, little or no time will be available for weathering, containment, or exclusion procedures; this will result in possible severe environmental damage and economic ramifications.

A lightering-related spill that occurs in offshore waters would have a minimal environmental impact because there would be sufficient time for weathering and enactment of exclusion procedures. Possible exceptions to these safeguards occur in the instances of extremely large spills, tanker collisions just outside major passes, or tropical storms, generating large waves that carry oil past the exclusion booms into the bay areas.

Spill control response is generally slow or nonexistent in current lightering operations except in some spill-equipped port areas. In one case, a major shipping company supplies its own tender vessel to each lightering operation. Today, private shipping companies have the complete responsibility to report spills, establish safety methods, and maintain the proper equipment.

Proposed Offshore Deepwater Port

From consideration of the economic and environmental aspects of these options, the offshore deepwater port was found to be most desirable. Only one cargo transfer operation is necessary per VLCC at an offshore monobuoy. The oil would then be pumped to onshore storage or refinery facilities at Freeport through submerged pipelines. The potential occurrence of operational spills is therefore restricted to the offshore location where environmental impact potential is the lowest. In addition, the oil comes ashore at only one location along the coast and that location can be chosen as to eliminate any direct contact with a critical habitat area.

Spill probabilities are also reduced due to the increased simplicity and control of operations. The average size of a spill resulting from a VLCC accident is the same as a spill from a lightering accident. The average spill size from a pipeline rupture would be 19 bbl with a credible maximum of 10 000 bbl based on the engineering design features of a 52-in pipeline with pressure sensing, loss-metering system, and the ability to induce some suction on rupture lines (1). The average operational spill that occurs at the off-shore site would be 15 bbl, while spills from offshore and onshore terminal facilities would average 19 bbl.

Summary

Unrestricted lightering, as it occurs today, has the highest risk potential, mainly due to the operational complexity and the high exposure to critical habitats at numerous locations along the coast. The calculation of spill probabilities for lightering have yielded results that are 60 percent higher than methods employed in operations of an offshore port. With the opening of LOOP, the United States will have its first offshore port and a laboratory for further observation and study. The ultimate assessment of the utility of offshore deepwater ports awaits the operational experience of this facility.

ACKNOWLEDGMENT

This study was performed at the Center for Transportation Research at the University of Texas at Austin. We wish to thank the sponsor, the Bureau of Engineering Research of the College of Engineering at the University of Texas at Austin. The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the sponsors. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. C.M. Walton and M.S. Daskin. The Utility of Offshore Lightering Under Alternative Proposals. Center for Transportation Research, Univ. of Texas at Austin, Transportation Research Rept. 65, Aug. 1980.
2. M.S. Daskin and C.M. Walton. A Performance Model of Supertanker Lightering Operations. Proc., 1980 Summer Computer Simulation Conference, Seattle, Aug. 25-27, 1980.
3. W.J. Gordon and G.F. Newell. Closed Queueing Systems with Exponential Servers. Operations Research, Vol. 15, No. 2, April 1967, pp. 254-265.
4. E. Koenigsberg and R.C. Lam. Cyclic Queue Models of Fleet Operations. Operations Research, Vol. 24, No. 3, May-June 1976, pp. 516-529.
5. D. Gross and C.M. Harris. Fundamentals of Queueing Theory. Wiley, New York, 1974.
6. Establishment of Designated Lightering Zones: A Positive Measure in Minimizing Environmental Risks. Engineering Computer Optechnomics, Inc., 1979.

Application of Freight Network Model to Coal Transportation Studies

ARTHUR F. HAWNN, FRANCIS M. SHARP, MARK VEITH, MARK SILVERMAN, AND MARK COHN

This paper examines the transportation freight model (TFM) developed by the U.S. Army Corps of Engineers. The focus is on coal movement on inland waterways. TFM is a simulation model to assess the interregional modal share of commodity movement, waterway link capacity, and performance characteristics. TFM consists of a transportation network of links and modes (water, rail, highway), performance functions, cost-capacity functions, transport technology, transportation market equilibrium, network adjustment, and commodity flow input. Commodity input was categorized in two groups—coal and all other commodities for 1972 and 1976. Simulation and validation results were compared with actual values in terms of such parameters as total tons, ton miles, mills per ton, average length of haul, and water-rail modal splits. These comparisons indicate that TFM can be used for macroanalysis of waterway commodity flow analysis.

Coal has been designated as the keystone of the U.S. fuel supply for the future because it is a domestic fuel source in abundant supply. The economic impact and competitiveness of increased coal use in industry and electric power generation are determined in large part by the delivered price of coal. A significant component of the delivered price of coal is the transportation margin. For example, the cost of delivery of coal via rail frequently is 30 percent or more of the delivered price of coal. Consequently, coal consumption forecasts should be based on transportation cost data consistent with the market.

Conversely, transportation costs are a function, in part, of the quantity of coal shipped. Specific plans for capital plant, e.g., rail lines and navigational facilities, are cost-justifiable only with traffic volumes above certain minimums. Representation of the partial equilibria (coal demand on transportation cost and transportation costs/constraints on demand for coal) and the equilibrium adjustment mechanism (the transportation market) are elements of a transportation market analysis.

Development of forecasting models with intensive data requirements is a difficult task. However, significant research and development have occurred in this analytic arena. Prudent linking of existing modules may provide significant capability for prediction of coal transportation margins and coal shipments for given macroscenarios.

Under the U.S. Army Corps of Engineers Inland Navigation Systems Analysis (INSA) program, the Office of the Chief of Engineers (OCE) developed the transportation freight model (TFM), a multimodal, bulk-commodity simulation. To meet the national requirement for detailed coal transportation analysis, the OCE and CEXEC, Inc., of McLean, Virginia, initiated a project to evaluate the TFM in light of OCE needs for detailed local traffic analyses and national needs to enhance coal-market policy analysis tools.

STUDY OVERVIEW

The objective of the study documented in this paper is to assess the applicability of the TFM to coal transportation studies. These objectives are

1. To ensure the input data and the model logic to be internally consistent and output results to