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Contents

Foreword

The papers in this Record deal with topics related to marine and intermodal transportation, logistical considerations of freight movement, and environmental issues related to freight transportation.

Chadwin and Talley discuss anticipated trends in vessel design and marine terminal configurations that will facilitate cargo flows. Wei et al. develop a numerical model to estimate delays in barge movements on congested waterways.

Three papers examine environmental aspects of freight movement. Newstrand examines environmental ramifications of shifting freight from water carriage to rail or highway movement. Starry et al. discuss a gravity model to estimate origin-destination pairs and routes for truck shipments of hazardous chemicals. Another perspective on the movement of hazardous materials is presented by Abkowitz et al. They examine trade-offs of safety and operating efficiencies in state-designated hazmat routings. Najafi et al. discuss oil spill response capabilities in South Florida. South Florida's coastline and extensive shallow reef areas present a major challenge to traditional oil spill cleanup procedures.

Rebelo and Thomas evaluate transit corridors from a trade logistics management perspective. Freight corridors, particularly those linking landlocked countries to the sea, are subject to many exogenous factors that are discussed in this paper.

Vessel and Port Technologies at the Turn of the Century

MARK L. CHADWIN AND WAYNE K. TALLEY

Developments in the design and operation of container vessels and ports at the start of the 21st century are discussed. Most changes will be evolutionary, not revolutionary. Techniques and equipment previously used in the most advanced countries or ports will appear in developing countries and smaller ports and terminals. Computerized operating and planning systems now used only in the most advanced terminals will become widespread, and electronically transmitted documentation will become the norm. Among the predictions developed are the following: the trend toward containerization will continue but at a slower rate; surplus capacity will persist; larger, faster gearless cellular vessels will dominate the major trades, but RO-ROs and other types will persist because they are more flexible and ideal for military uses and "ocean ferry" operations; unmanned containerships will not appear, but crews of less than 10 will be commonplace; radical new designs (SWATHs, Trisecs, and "megacontainers") will not be built, but smaller hydrofoils or hovercraft that transport priority containers on short routes will; container terminals will operate 24 hr a day, store containers in stacks rather than on chassis, apply techniques that move multiple containers, and vastly expand use of automated systems and computers; and domestic containerization and the use of "roadrailer" technology will grow rapidly.

Developments in the design and operation of vessels and seaports will influence how international commerce evolves at the start of the 21st century. Those developments are discussed, focusing especially on containerized cargo. Expected changes through the end of this century in the characteristics of the world fleet, ocean carriers' operations, port technology and operation, and intermodal systems are addressed.

Most changes that will occur by 2000 will be evolutionary rather than revolutionary—that is, the application of existing patterns will be widened and technologies already invented will be better exploited. Techniques and equipment previously seen only in the most advanced countries or ports will appear in developing countries and smaller ports and terminals. Large investments that already have been committed will be completed, including bigger and somewhat faster containerships as well as terminal equipment that can move and store containers more quickly. Computerized operating and planning systems now used only in the most advanced terminals will become widespread and standardized, and electronically transmitted documentation will be the norm wherever significant flows of commerce occur.

Rationalization of services and concentration among firms in the industry will continue, and giant multimodal providers of transport services will dominate the major markets. This process, well advanced in the United States, will proceed rapidly in Asia and Europe as well, stimulated by high growth rates in Pacific Rim countries and the likelihood that Europe will be an increasingly unified market from the Atlantic to the Urals. Companies with roots in air transport as well as firms whose origins are in ocean shipping, railroading, trucking, and freight forwarding will play major roles in this process.

THE CHANGING FLEET

Continuation of Containerization

Containerization of cargoes will continue through the 1990s, although probably at a slower rate than in the past. Like other industrial innovations, containerization has experienced S-curve growth, and we are now onto the second curve of the S, the one correlated with industry maturity and more moderate growth rates. Perhaps 60 percent of what had been break-bulk cargo in the 1960s was containerized during the 1970s and 1980s. Even if one expects containerization to reach 85 or 90 percent of the types of general cargoes by the turn of the century, the rate of expansion to new cargoes will necessarily be lower. If world trade overall, including cargoes already containerized, continues to expand as it has during the past two decades (3 to 5 percent a year in tonnage), containerized cargoes will continue grow, although more slowly than in the recent past (*1–7*).

Three factors propel the continued conversion to containers. One is the rapid advance of refrigerated and climate-controlled container technology. Today the containerization of all sorts of perishables—fruit, vegetables, meat, even live seafood—is feasible. Recent advances allow humidity, temperature, damaging gas levels, and other conditions inside a container to be carefully monitored and regulated. Thus, many products transported break-bulk on refrigerator ships will be shifted to containers. As the reefer fleet ages, much of it will be replaced by refrigerated containers carried by containerships and jumbo jets (*8–15*).

Second, the containerization of low value break-bulk and "neobulk" cargoes will grow, partly because carriers' surplus capacity will continue to drive them to find new cargoes to fill vessels and cover costs. This pattern is already obvious in backhauls. Technology will contribute here, too. Specialized

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liners for containers, like the inflatable Seabulk-Powerliner system, make it possible to pour a messy bulk commodity into and out of a standard container. Cleaning and sterilizing techniques such as Sea-Land's Sea-Clean system allow the same container to be prepared in a few minutes for a more conventional cargo (*16,17*). However, traditional methods of shipping bulk and neobulk commodities will usually be less expensive and, thus, will remain dominant.

Third, trade to and from newly industrialized and developing countries will move increasingly in containers. Through the work of the World Bank, many third-world governments have come to understand the linkage between entry into the mainstream global economy and containerization. As a result, container facilities and related infrastructure have become priority items for development programs.

Faster Growth of Capacity

During the 1980s global container-carrying capacity generally ran 20 to 30 percent ahead of demand. According to research by NYK Line, at the end of 1989 the world containership fleet consisted of 1,387 vessels with a total capacity of 1.68 million TEUs. Whereas the fleet grew more slowly toward the end of the 1980s (7 to 11 percent annually from 1987 through 1989), new orders escalated again in 1989 and 1990. Most of these orders are for vessels of more than 2,000 TEUs. Indeed, by the middle of 1991 many carriers had either ordered or put into service "jumbos" in the 3,500- to 5,000-TEU range. Some analyses indicate that carrying capacity in the mainstream East-West trades between Western Europe, North America, and East Asia will grow more than 60 percent before 1995.

Furthermore, expectations that older, smaller containerships would be scrapped as the larger vessels come into service are not being fulfilled. Instead, many of these vessels are being acquired by other operators. They remain in the global fleet, aggravating the surplus problem (*18–21*).

Thus, chronic excess capacity seems inevitable through the first half of the decade. Thereafter, the relationship between supply and demand is less clear. For example, according to a recent forecast by Temple, Barker and Sloane, Inc., if future orders roughly equal capacity eliminated during the 1990s, by 2000 demand will just about catch up with supply. Recent behavior concerning both ordering and scrapping, however, renders such optimism suspect (*22*).

The situation at the turn of the century will almost surely reflect developments in other shipping sectors. If the 1991–1992 recession is long and its effects widespread, energy demand worldwide could stagnate, resulting in lower tanker charter rates. That should be reflected in fewer orders for new tankers and lower prices for new containerships from shipyards desperate to attract customers. Conversely, a strong global economy and a boom in the tanker and bulk trades could raise new containership prices, causing orders for additional container-carrying capacity to be cut back. The Oil Pollution Law of 1990 should have a similar effect, since it will keep some yards busy with refits or with new buildings. Major uncertainties include possible changes in shipyard capacities and scrap prices and alternative technologies to double-hulling (*23–29*).

The containerships themselves will grow larger and somewhat faster. In the early 1980s experts suggested that containership size was approaching geographic, commercial, and technical limits. The geographic bound was the width and depth of the Panama Canal, which limited maximum capacity to about 3,500 TEUs. During the decade trans-Pacific trade grew rapidly, however, and landbridging across the United States increased, facilitated by the introduction of unit trains and double-stack railcars. By 1991 American President Lines had put bigger-than-Panamax vessels into service, and other carriers were operating or building ships with 3,500- to 4,000-TEU capacities.

One commercial concern in the 1980s was that there might not be enough cargo to warrant much bigger ships (a point that is still sometimes troubling). Another was that containers might not be concentrated in sufficient numbers at a small enough number of ports. Cargo concentrations at the largest load-centers—such as Singapore, Hong Kong, Rotterdam, and Los Angeles–Long Beach—have continued to increase, however, allaying the latter anxiety.

There also were technical concerns about the vessels themselves as well as yard equipment and infrastructure in and around the container terminal. There were fears that structural problems with these very large vessels might result in excessive flexing and catastrophic failures. Some adjustments in design and in operation have provided assurance in this regard. Another problem was that the new vessels would be wider than the outreach of existing ship-to-shore cranes. However, by 1991 many terminals had purchased cranes that could work across 16 rows of containers on the ship, accommodating the widest vessels on order. A third fear was that the cranes, yard equipment, and yard operating systems were so slow and inefficient that they would neutralize the advantages of very large vessels. By the early 1990s, however, a few terminals (such as ECT Maasvlatke) were operating with cranes, yard equipment, and computerized management systems efficient enough to strip and reload a 3,000-TEU vessel carrying 40-ft containers in less than 1 day, using three high-speed cranes.

Therefore, many of the concerns that previously constrained containership size have diminished. It appears likely that 2000 will see containerships twice as big as the largest being built just a decade before—jumbos of 5,000 to 6,000 TEUs (*30*). Vessels much larger than that, however, once again raise renewed technical, commercial, and channel depth concerns. Thus, they appear unlikely within the next decade.

The jumbos entering the fleet, at least during the first half of the 1990s, will be somewhat faster than their predecessors, operating at speeds of 22 to 25 knots. Analysis of trade-offs between speed, fuel consumption, and vessel productivity is tricky in a world of volatile fuel prices. However, the consensus is that dramatically higher prices are unlikely during the next several years (*31,32*). Containership operators, therefore, are opting for new vessels that burn more fuel but are 2 to 5 knots faster than their predecessors.

Domination of Cellular Vessels

The trend toward non-self-sustaining or gearless cellular containerships also should continue. All of the jumbos being built or on order at the beginning of the 1990s were of this type, and they appear certain to dominate the major East-West trade routes in the years to come. Vessels of this size and type will compose the bulk of the world containership fleet in tonnage terms.

For a number of reasons, however, containerships with their own gear as well as RO-ROs, LO-ROs, and combination carriers (semicontainerships) will not disappear, even though they use their space less efficiently than gearless cellular vessels. For one thing, they offer the small operator greater flexibility in serving feeder ports and ports in developing countries without wharfside container cranes.

RO-RO vessels and other vessels with independent discharging capabilities will remain attractive for military purposes, as Operations Desert Shield and Desert Storm demonstrated. Therefore, the United States government and others may well subsidize the construction and operation of such vessels (*33,34*). RO-ROs also are useful in the movement of large vehicles and heavy construction equipment and are ideal for shortsea operations, for example along the European and East Asian coasts and among the island nations of the Pacific. Such operations, in fact, are container ferries. Their attraction is the speed with which containers already on chassis can be debarked and depart the terminal on arrival.

Container barging also should grow. Candidates for container barging include shortsea, coastal feeders, and inland waterway operations. Even where ports are equipped with big cranes, the use of seagoing barges and tugs to provide feeder service may be preferable to containerships whose capital and operating costs are much greater. Container barging, already firmly in place along the U.S. East Coast, appears to be an economically attractive alternative for a number of short routes in northern Europe and the Mediterranean as well as Asia and the Pacific (*35–38*).

If the shipping industry were entirely rational, a pattern would emerge by 2000 in which three different kinds of vessels provided three different kinds of service: (*a*) very large, fast, non-self-sustaining containerships that cross oceans and stop at only one or two ports on a range, loading and discharging 1,000 or more containers at each call; (*b*) RO-RO and LO-RO vessels as well as smaller containerships and combination ships (semicontainerships) that serve secondary ports, lower-volume trades, and LDCs; and (*c*) pushbarges, tows, and smaller combination ships that carry 50 to 500 containers at a time and provide coastal, shortsea, and feeder services between load centers and "outports."

Such orderliness is unlikely, however, in the light of the predicted excess capacity. Instead, crossovers of vessel types from one kind of service to another will persist as carriers seek higher load factors and better profits.

Shrinkage, Not Disappearance, of Crews

The technology is at hand to permit the operation of vessels on the high seas without anyone aboard. All necessary information about the vessel's location, the status of its operating systems, and conditions being encountered (weather, sea state, and traffic) could be transmitted automatically to land-based personnel. They could make decisions and transmit instructions back to the vessel that actuated whatever adjustments were needed. Multiple backup systems could ensure against failure. Shore-based emergency teams could be airlifted aboard in a few hours if necessary. Small crews could be put aboard for the portion of a leg in pilot waters, although theoretically even that would be unnecessary.

Unmanned containership operations are unlikely during this decade, however, because of concerns about safety and the environment. Nevertheless, experiments with crews as small as eight were being reported by the end of 1990. Furthermore, there are already some cargo vessels in service (including two Hapag-Lloyd jumbo containerships) that can be "single-handed"; all their systems can be monitored and controlled by one person on the bridge. It appears certain that many containerships of the next generation will have crews less than half the size of their predecessors (*39–45*).

Futuristic Designs

If a vessel could run at 40 knots, it could cross the Pacific in 5 days, cutting current transit times in half. Usually, however, it is more economical to make a ship larger than faster, because of the relatively rigid relationships that exist between hull shapes, material costs, power requirements, and speed (*46*). Thus, the commercial utility of such speeds, when applied to conventional displacement vessels, depends on development of propulsion systems much more powerful but nearly as economical and compact as present ones. Currently, only nuclear power plants appear to offer this combination of characteristics. However, concerns about long-term cost efficiency as well as environmental dangers appear likely to deter widespread application in cargo vessels. An intriguing alternative, superconductivity, also is unlikely to appear in commercial applications before the end of the century (*47*).

Another way to increase speed is to design vessels that move in one medium—only water or only air. Container-carrying submarines appear unlikely because of high construction and fuel costs. Containerships that operate above the water surface, however, such as hydrofoils or hovercraft, appear more feasible. Such vessels currently operate as ferry, sightseeing, or naval craft, so the technology is proven.

Hydrofoils are theoretically capable of 60 to 100 knots, and air cushion craft can attain even higher speeds. Either, if priced appropriately, would broaden the choices available to transportation consumers. Such vessels could move cargo two to four times faster than the fastest displacement ships but could accommodate cargo that was heavier or bulkier than generally appropriate for air freighters. Surface effect vessels would not need to occupy a berth when they reach port. Instead, they could move up a ramp to an inland location where they could be worked with relatively inexpensive yard equipment.

Transoceanic hydrofoils or hovercraft are unlikely before the 21st century due to problems of propulsion, fuel consumption, and durability and stability in heavy weather. However, smaller "air" craft able to transport 50 to 100 high-priority boxes on ferry runs, inland waterways, and short sea routes—for example, in northern Europe, the Mediterranean, and East Asia—appear to be a more reasonable prospect (*48,49*).

Among the innovations in displacement vessels that could occur are new RO-RO ships designed for exceptionally fast loading and discharging. Such vessels could have multiple openings and ramps along their sides, rather than a single one at the quarter or stern.

Megacontainers are another possibility. Since ever-faster port calls are desired, containership design could be rethought in terms of leaving and picking up whole chunks of the vessel—megacontainers—each one of which might hold dozens of containers. Departing megs would be completely prestowed at the terminal before the vessel arrived, and arriving megs could be stripped after the ship departed. The technology for floating or lifting megs off and on the ship already exists in LASH vessels and construction yards.

However, the practicality of megs would depend in part on whether they made discharging and loading a vessel substantially faster and more cost-efficient than simply ganging several high-speed cranes. The terminals' ability to stuff and strip the megs quickly would have to be proven, too; shippers care about speed from door-to-door, not port-to-port. Finally, repositioning of empty megs would pose a costly challenge (*5,50–52*).

A variant on the meg could use existing technology such as LUF-frames or other rolling devices to move blocks of containers on and off a vessel through openings in its side rather than hatches in its deck. Such refits or redesigns could speed the loading and discharging process substantially and reduce reliance on expensive wharfside container cranes.

Even more radical designs have been proposed, including huge container-carrying catamarans (SWATHs or Trisecs) and vessels that would be "made up" like freight trains. Trisecs apply the hydrodynamic advantages of the hydrofoil (low wetted surface, less water resistance) to much larger vessels. They might result in very large-capacity vessels powered by conventional propulsion systems but traveling nearly twice as fast as today's containerships. Although catamarans sidestep some of the constraints of displacement hulls, they pose serious stress and structure challenges of their own (*53*). Like the catamaran, the componentized vessel offers some intriguing advantages but poses engineering headaches. The turn of the century could witness small-scale experiments with both, but neither is likely to be in regular blue water operation.

CARRIERS AND OPERATIONS

If the last years of the century are a period of surplus carrying capacity, carriers will continue to confront the prospect of cutthroat competition, especially in the major East-West markets where overtonnaging appears chronic. Rate wars are one possible reaction. Other responses include increasing concentration and rationalization, capacity-limiting arrangements, government intervention, and product differentiation. These responses are not mutually exclusive. All are being applied already to some degree.

Responses to Competition and Excess Capacity

The 1980s saw a spate of mergers, buyouts, and consolidations. These are likely to continue, resulting in increased concentration. A few ocean carriers (giant transportation firms in many cases) are likely to dominate the biggest trades.

Rationalization among carriers should continue and expand in scope. This means not only traditional methods of collaboration on the water (slot sharing, consortia, and joint services) but landside cooperation as well—the sharing of terminals and inland facilities, box and chassis pooling, and interactive communication and computer systems. Even organizations that have long traditions of self-reliance, Sea-Land and Maersk for example, are finding that they cannot go it alone.

Where traditional liner experiences are unable to curb excess capacity and cutthroat competition, experiments with new mechanisms will occur. The Transpacific Discussion Agreement, which includes independent as well as conference carriers, has succeeded in reducing capacity among its participants, first by 10 and more recently by 13 percent. Such arrangements appear to be spreading elsewhere, for example, the North Atlantic and Europe-Asia trades. Even if they do, they will be under constant pressure—from the signatories themselves, new entrants, and shippers and regulators who question competition-restraining agreements (H. Takakashi, unpublished data, *54–58*).

Governments can facilitate capacity restraint by requiring ship lines they own or subsidize to privatize, operate profitably, or die. Ironically, movement in this direction now appears more rapid in the former centrally planned economies of Eastern Europe than elsewhere, although similar changes are occurring in several developing and newly industrialized countries. However, the arguments in favor of maintaining (or even increasing) carrying and building capacity—national security, employment, and national prestige—remain potent. Thus, governments may well continue to vacillate between policies that stimulate efficiency and encourage expansion (*59*).

Carriers have developed a variety of marketing techniques to cope with intensified competition. Ship lines seek to differentiate themselves by marketing their reliability (fixed day service), their speed (fast transits, dedicated unit trains), the high quality of service (special handling, point-to-point pricing, automated cargo information systems), or their expertise in particular markets or cargoes. Some firms offer comprehensive door-to-door service by internalizing trucking, rail, and other intermediary services. Others sell comprehensive service, too, but use external providers. A third group offers lower cost but lower quality (slower transit times, for example, or port-to-port service only). Some firms lease or own their own terminals; others rely on common-user facilities. Some operate their own feeder networks or unit trains; others depend on common carriers. The pressures on carriers to differentiate themselves—in perception and in reality—will continue unabated.

Choice of Ports, Routes, and Networks

At the heart of product differentiation as well as other strategic issues for the carrier is the choice of ports, routes, and networks. Dramatic options like round-the-world services fire the imagination, but most decisions are much more subtle. In 2000, as now, the choice of network as well as the size and type of ship to use will be heavily influenced by vessel operating costs. Cellular containerships exhibit cost economies of scale when at sea; as the size of ship increases, cost per TEU transported declines. However, while in port these vessels display cost diseconomies; the cost per TEU rises as the ship's size grows. To minimize costs an operator tries to shorten the time in port and maximize the time at sea (*46,60–62*).

Revenue generated and costs incurred are influenced by port consignment size (the amount of cargo awaiting the ship at each call), liner pricing policies, and convexity ratios. Larger port consignment sizes permit fewer calls, allowing a carrier to take advantage of the cost economies of using a larger ship.

Before containerization, ship lines generally used "equalization pricing." The rate for a given type of cargo was the same from any port on one side of an ocean to any port on the other side. Since the shipper was responsible for inland transport to and from the port, total transport cost could be minimized by shipping the cargo out of the nearest port. Thus, ports developed "natural" hinterlands, and an ocean carrier needed to call at each port if it desired to obtain the cargo from each hinterland. This resulted in multiport itineraries (*63–68*).

As vessels have grown in size, however, the economies of containership size while at sea and the diseconomies while in port have driven carriers toward very different network structures. To justify a port call by a jumbo, a relatively large port consignment size is needed. Thus, a liner pricing structure has developed, "absorption pricing," under which shippers are charged a door-to-door rate independent of port choice. Under absorption pricing the choice of port has shifted from the shipper to the ship line, and natural hinterlands have dissipated. The decision to call at a port now hinges on economic trade-offs between diverting a large mainline ship, using a feeder vessel, or using an intermodal transport system (*69*).

PORTS AND TERMINALS

Continuation of Contests

During the 1980s competition between seaports intensified because of multiple factors: government deregulation, landbridging, and the demands of ocean carriers beset with cost, capacity, and profitability problems of their own. None of these factors is likely to disappear during this decade, so intense interport competition generally will persist. In some regions, however, the competition for load-center status will diminish. Long-term terminal contracts and large landside investments will lock carriers into a port for longer periods. Lines will load-center in different ports, with each line achieving a competitive advantage for cargo originating near its chosen port. Some unsuccessful competitors in the load-center game will accept feeder ports status, finding consolation in lower break-even points and in the fact that stuffing and stripping containers generates more jobs and incomes than just handling them. Some ports will attempt to stay in the race by offering very low rates (often subsidized) in the hope of attracting carriers unhappy with the congestion at their region's principal load center.

In the contests that continue, certain traditional competitive advantages will become even more significant—deep channels, speedy access to major shipping lanes, large affluent populations that generate large volumes of imports, and industry bases that generate both exports and imports. A port's competitive situation also is likely to be stronger if it already has well-developed rail, truck, air, and barge services. All of these elements, already important, become more so in an era of 5,000-TEU vessels.

New Foci of Investment

In recent years investments in industrialized countries typically have included deepened channels and berths as well as wharf lengthening to accommodate jumbo containerships. In some ports (Rotterdam and Baltimore, for example) entirely new terminals have been built designed exclusively for container operations. Elsewhere, on-terminal rail facilities, new gates, and access roads have been constructed.

If some of the radical changes in vessel design and container-handling technology become realities, extensive port redevelopment will be required, even in Western industrialized countries. Otherwise, port investment is likely to shift toward rapidly developing countries in Asia and the Pacific as well as Eastern Europe and Latin America. According to some forecasts, 6 of the world's top 10 container ports will be in the newly industrialized countries of East Asia by 2001 (*6,70*).

Protection of the Environment

Seaports, particularly those in large cities, will be confronted by continuing problems of gentrification. More and more ports also will be under public pressure because of concern about road congestion, dredge spoil dumping, dangerous cargoes, air quality, noise, and other environmental considerations.

Environmental concerns and gentrification will force ports to develop terminal sites outside central cities. These forces (together with the ship lines' preference for being nearer the open sea) are likely to lead to the development of terminal sites on newly reclaimed land near the coastline (like Maasvlatke near Rotterdam), on artificial islands within an existing harbor (as in Tokyo and Kobe), or possibly offshore. Where terminal space becomes particularly precious, container marshaling yards and intermodal rail facilities will be shifted to inexpensive inland locations (*71*).

Improvement of Terminal Efficiency

Within the terminals themselves techniques will be applied that vastly improve container-handling efficiency. One change that requires no new technology is operating 24 hr a day, 7 days a week. For the terminal operator, around-the-clock operation is a way to increase effective terminal capacity and smooth peak loads. For the customer it offers greater speed of delivery and convenience. To be cost-effective, however, this innovation usually will require changes in long-standing overtime pay and labor hiring practices.

Terminals will become more stack oriented. A growing proportion of the containers arriving at terminals will arrive by train, barge, and cellular containership—in short, without chassis. Second, busy terminals usually face space constraints. Keeping containers in stacks and chassis in racks saves two to three times the space of chassis-mounted containers (*46*). Third, computer programs for planning and performing complex, interactive yard activities are becoming widely available. They will make reliance on stack operations more acceptable for everyone. Lastly, except in the United States, chassis usually belong to truckers, not ship lines. Containers arriving on truckers' chassis must be dismounted promptly anyway.

Increasing use of stacks is directly tied to the application of advanced container-handling technologies. One group of techniques uses interconnected mechanisms to move individual containers more quickly between storage area and vessel. Another set involves moving more than one container at a time.

A number of mechanically connected ship-to-storage-stack systems for handling containers have been designed, although only one, belonging to Matson Lines, is reportedly in operation. These systems use an oversized transtainer that receives the container directly from the crane, a conveyer monorail system, or a mechanical "merry-go-round" that keeps flows to and from the vessel continuous. Terminals and carriers are likely to remain hesitant to embrace these systems. Their capital costs are very large, and their inflexibility raises questions about their practicality, especially in common user terminals. Furthermore, it is not clear that they would be any faster than several high-speed, dual-trolley cranes supported by appropriate yard equipment and management systems.

Many existing ship-to-shore cranes, transtainers, and straddle carriers can perform "twin-twenty" lifts, in which two containers stacked on top of each other and locked together are moved as a unit. This is rarely done with loaded containers, but there appears to be no mechanical reason why heftier terminal equipment could not lift blocks of four or more containers simultaneously. Other systems for multiple container movement already exist, for example, the LUF system, in which a large tractor tows a platform carrying blocks of four or more containers, and ECT's container "trains," which pull a string of five 40-footers using oversized yard hustlers.

An alternative using automated guidance technologies to move individual containers at high speeds is being tested by ECT. The system uses existing dual-trolley high-speed wharfside cranes, which are served by a fleet of automated guided vehicles (AGVs)—unmanned straddle carriers. At the storage areas the containers carried by the AGVs are removed and stacked by oversized yard gantry cranes that also are unmanned. Under ideal conditions the system reportedly can run at rates up to three times those of conventional terminals. It appears to avoid many of the rigidities that make the mechanically integrated systems unattractive.

The Pervasive Computer

The effects of computerization will become even more widespread. Inexpensive desktop PCs that can perform functions that used to require a mainframe will allow smaller marine terminals to apply sophisticated techniques for tracking and organizing containers. In the yard or at the wharf, workers with hand-held computer terminals will be able to input information immediately, eliminating time lags and errors caused by manual procedures. Artificial intelligence and expert systems will assist in stack layout, stowage planning, and work scheduling. Standardized transponders, bar codes, or other identification devices will facilitate container tracking and storing. Heuristics and optimizing algorithms will replace guesswork in yard management and stowage planning. Menu structures and decision trees will lead even workers who are inexperienced with computers through complicated applications. All sorts of operational and analytic tasks will be done more quickly and accurately than today (*46*).

Labor

These tasks and others will be carried out in an environment of continued pressure to increase productivity caused by tighter intermodal linkages as well as competition between carriers and between ports. One persistent challenge is likely to lie in the area of labor costs and productivity, since labor still often makes up more than half the operating expenditures of a container terminal.

Workers must be more highly educated, and they must undertake more extensive training before they go to work and periodically thereafter. Changes are necessary in the arm's length relationship between terminal managers and unionized workers; restrictive job jurisdictions and work rules; the irregular nature of terminal employment; expensive, often self-defeating job preservation schemes; and the reluctance of both management and labor to consider new methods and technologies. The ports and terminals that make these transitions quickly and smoothly are likely to be the winners in the 1990s and beyond.

INTERMODALISM

Intermodalism will continue to advance, filling out the spectrum of transportation services in terms of speed and cost. Inevitably, this will mean increased competition between transportation modes, for example, a contest for higher value and perishable cargoes between ships and planes. As containerized cargoes become lighter and more valuable, they become more likely candidates for air freight. Furthermore, shippers are concerned about door-to-door speed. They don't care how fast the ship is, if their cargo is delayed at the port or if inland transportation systems are underdeveloped or unreliable. In parts of East Asia, the Pacific, and the former Soviet Union, inadequate ground infrastructure combined with difficult topography or great distances should make ocean-air intermodalism an attractive alternative. If so, attempts to make air and ocean containers compatible or interchangeable may be resumed.

The continued development of domestic containerization appears to be a necessary corollary of the rapid expansion of intermodalism. (The term "domestic" will be technically inaccurate because many of these containers will cross national borders, for example, within the European Economic Community or between the United States and Mexico. However, they will not have a water leg.)

The operating and capital costs of intermodal systems (double-stack railcars and tunnel, bridge, and roadbed modifications) are so heavy that railroads find them hard to justify on the basis of transoceanic cargoes alone. Thus, domestic moves are becoming an important way for container owners and transporters not only to fill empty backhauls and smooth imbalances in international flows, but also to spread costs and maximize net revenues. Railroads are likely to encourage their customers to switch from piggyback shipment of trailers on flatcars to containers carried by double-stack trains.

As a corollary, the 1990s should see the application to containers of the "roadrailer" technology that is currently used for domestic trailer chassis in the United States. The adaptation would involve building container chassis that have two sets of wheels—one steel, the other rubber. This would allow a container to be converted, in effect, from a railcar to an over-the-road truck body in a matter of minutes.

The issue of container equipment standardization remains a major uncertainty. Many ocean carriers and box lessors continue to offer nonstandard heights, and several major carriers offer lengths in excess of 40 ft. Firms interested in attracting domestic as well as transoceanic cargoes are interested in larger cubes that can compete with 48-ft over-the-road trailers. Efforts are currently under way, especially in Europe, to establish new standard sizes, 49 and 23 ft. Whatever standards the ISO adopts, substantial variations are likely to persist, and the constraints they impose on interchangeability of equipment and flexibility of operation will continue to be a source of inefficiency and expense (*72–75*).

Propelling the continued development of intermodalism are global commercial realities. Just-in-time inventory management techniques and "quick response" retailing were innovations in the 1980s. They will be nearly universal in the 1990s. Growing masses of consumers in an ever-widening number of countries will insist on current fashion, product quality, and producer responsiveness. Product life cycles will continue to shorten, and minimizing inventories of potentially obsolete products will become even more important. Multinationals will use a network of facilities around the world to develop, source, and assemble. The resulting products will be marketed to increasingly affluent populations across the globe.

In such a world, successful international transportation firms must offer not just cargo carriage but a total logistics package that provides frequent and reliable service for goods moving between any origin and destination. Some of the earliest firms to move in this direction have been American, namely CSX-Sealand and APL. They will be joined and perhaps overtaken in the 1990s by European and Asian challengers who can respond effectively to the growing market for door-to-door management of freight movement and for a continuum of transportation products that vary in speed, frequency, dependability, and cost (*76–79*).

CONCLUSION

An attempt has been made to forecast operational realities in ocean container transport at the advent of the 21st century by examining patterns and trends already visible. The predicted changes, therefore, have tended to be evolutionary rather than revolutionary.

Any such forecast is only as robust as the assumptions on which it is based. Optimistically, perhaps, the forecast is premised on moderate, midrange expectations regarding energy consumption and prices, growth trends in the global economy and cargo, the absence of great power conflict, and continued progress toward a globalized economy. Similarly, it was assumed that the discovery and widespread use of wholly new energy sources or materials will not occur in the next decade.

If recent history offers any guidance, it is that some of what appears reasonable and probable may not come to pass.

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Environmental Impacts of a Modal Shift

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The need for a no-build alternative in the environmental analysis of water transportation projects and the environmental compatibility of water transportation are demonstrated. To make the demonstration, cargo from four regularly scheduled vessel movements was theoretically transferred to the highway and rail modes. Included in the cargoes studied were coal, aggregate, petroleum products, and wood paper products. All four movements had highway carriage as a feasible alternative, and two had rail service available. For the four movements, in total, the transfer of cargo from vessels to trucks would result in annual increases of 3,774,328 gal of fuel (an 825 percent increase), 573.9 tons of exhaust emissions (a 709 percent increase), 17.9 probable accidents (a 5,812 percent increase), and the need to dispose of 2,746 used truck tires. In addition, such a modal transfer would result in an additional 1,333 large semitrailer trucks in the travel corridors each day. For the two movements that had possible rail service, the annual impacts of a modal shift from water to rail are an increase in fuel use of 899,741 gal (a rise of 259 percent), an increase in exhaust emission of 265.7 tons (up 408 percent), and an increase in probable accidents of 0.35 (a 150 percent increase). In addition, a modal shift of the cargo from vessels to trains would mean the involvement of an additional 75 trains of 100 cars each at 193 highway crossings and 38 at 177 road crossings.

Concern for the environmental impacts of any activity on or in Minnesota's waterways has generated a great number of studies and will probably continue to cause study. Commercial navigation is often the focus of these analyses. In the majority of the studies, navigation has been viewed as a major contributor to environmental degradation of the waterways as a precondition to the study.

Historically, environmental assessments have confined their transportation-related reviews to the possible impacts from operations of vessels and shoreside support activities. The possible environmental impacts of not developing a waterways project or not maintaining or improving an existing operation are never included in the environmental analysis. Continued concern about the impacts on commercial navigation from such an approach caused the Minnesota Department of Transportation (Mn/DOT) to undertake this study. This analysis examines the type and extent of environmental impacts that could result from a shift from waterborne carriage of certain commodities to other modes of transportation.

Only a few of the many waterborne freight movements from the state's river and Great Lakes terminals are on long-term schedules with consistent travel patterns that allow for impact analysis. Specifically, there are three aggregate, three petroleum product, and four coal movements on the river and one paper-wood movement on Lake Superior that meet the criteria. The river movements average 3,250,000 tons each year. The Lake Superior movement accounts for 375,000 tons each year. In total, these freight volumes account for about 5 percent of the state's total waterborne freight movements, which average approximately 73,000,000 tons annually. The 3.25 million tons of river carriage accounts for approximately 20 percent of the state's annual riverine traffic.

It is suggested that the methodology used in this analysis become an integral part of the evaluation process for environmental studies of future development proposals.

METHODOLOGY

There is a demonstrated need for the movement of the study's commodities. Therefore, total stoppage of the movements was not considered. What is evaluated are impacts associated with the shift of cargo from the water to either rail or highway modes. An analysis of the impacts of a cargo shift from vessel to truck was made for each movement. An analysis of cargo shifts from vessel to truck and from vessel to rail was made for movements where a rail alternative exists or the construction of a rail link is considered feasible. It is not considered likely that the levels of tonnage carried in the study's movement would justify construction of a rail connection.

Table 1 shows the modal factors used in the analysis. Sources of the factors are described in the following text.

Water travel distances were calculated on the basis of navigation charts with support through interviews with navigation industry representatives. Highway distances were taken from Mn/DOT records or, in the case of urban movements, from field measurement. Highway trip lengths were measured on either the shortest, most direct route or the most time-efficient route that did not have prohibitive load restrictions. Rail distances were taken from Mn/DOT records with support from the involved railroads. Rail grade crossing numbers were obtained in the same manner.

Modal fuel efficiencies were taken from a study done by S. E. Eastman (*1*). It is assumed that modal fuel use improvements for each mode have advanced at the same relative pace since that study was made. Fuel efficiencies used here represent industrywide fuel use and commodity carriage. It

TABLE 1 MODAL IMPACT FACTORS

Mode	Fuel Use Ton Miles/ Gallon	Emissions Pounds/ Gallon	Accident Rate/ Incidents
Truck	60	.31	76.6/100,000,000 miles
Rail	204	.69	1/51,310 miles
River	514	.37	1/600,000,000 ton miles
Great Lakes	607	.37	1/2,590,000,000 ton miles

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is recognized that certain dedicated rail movements will generate as much as 800 ton-mi/gal; as a balance, Lower Mississippi water movements will reach 1,200 ton-mi/gal. Great Lakes fuel efficiencies at 607 ton-mi/gal reflect the effectiveness of the nation's deep draft fleet.

Modal emission levels were taken from Environmental Protection Agency (EPA) publications and independent studies made by Mn/DOT's Air Quality Office. That office also reviewed the relationship between emission levels and the different engine sizes for each mode. For study purposes emission levels were taken from EPA documents (*2,3*).

The only emissions considered in this study are exhaust emissions. Since it is impossible to determine the size or duration of the queues of automobiles at rail crossings and signalized intersections caused by additional heavy train and truck movements, the amount of nonexhaust emissions from those automobiles cannot be determined.

Safety data for the modes came from several sources.

Highway accident rates were taken from the Transportation Research Board's study on twin trailer trucks (*4*, Table 4–5). The numbers used represent a weighting of the urban-rural, highway-interstate figures.

In the 5-year period 1986 through 1990, United States Coast Guard records indicate that collisions involving towboats in the St. Paul Marine Safety Detachment's area of control were as follows (*5*):

- 3 collisions between towboats,
- 5 collisions between towboats and pleasure craft, and
- 21 collisions by towboats with fixed objects.

One death and no injuries resulted from the 29 accidents. The death resulted from a pleasure boat running into a barge-tow. The fixed-object collisions involved towboat contacts with bridge piers, sheer fences, gorge ice, the channel bottom, or lock walls. Each of these incidents meets reportability requirements as defined by federal law (46 CFR 4.05-1). None of the towboats used in the scheduled movements in this study were involved in the 29 incidents.

In those 5 years, the towing industry annually averaged 3,478,972,400 ton-mi of carriage in the area. Division of ton miles by accidents indicates approximately one accident per 600,000,000 ton-mi.

The Lake Carriers Association records on U.S. Great Lakes fleet vessels indicate that an accident occurs every 2.6 trillion ton-mi using the same U.S. Coast Guard reporting conditions as river traffic (personal interviews with R. Skelton of the Seaway Port Authority of Duluth, Minnesota, and G. Ryan of the Lake Carriers Association, Cleveland, Ohio, October 1990). The vessel involved in the study's movement between Thunder Bay and Duluth has not had a reportable accident in its 26 years of operation. The probability of its ever being involved in an accident is small; however, an accident probability factor has been incorporated in this study.

The Minnesota Department of Public Safety records for the past decade indicate that there is one highway vehicle-train collision for every 51,310 mi of train travel (*6*, Table 2). That is substantially better than the national average of one accident per 41,000 mi of train travel as reported by the Association of American Railroads. Mn/DOT records indicate that the annual average number of accidents is about 130, with more than 50 percent reporting property damage only. This study uses the Minnesota Department of Public Safety's travel-collision ratio.

Tire use was determined through interviews with industry representatives. There is a significant difference for tire life expectancy between aggregate movements and over-the-road commodity carriage. In aggregate hauling, truck tires last an average of 40,000 mi with only 40 percent of the carcasses recappable and no second recapping (personal interview with P. Gannaway of J. L. Shiely Company, St. Paul, Minnesota, 1990). In over-the-road traffic, tires have a life expectancy of 100,000 mi and an 80 percent recap rate plus a second recapping of 40 percent of the initial recaps (personal interview with R. Rynda, Kampa Tire Company, St. Paul, Minnesota). This results in average tire lives of 56,000 mi for aggregate hauling and 225,000 mi for highway movements.

ANALYSIS OF CARGO MOVEMENTS

Aggregate Movements Pools 2 and 1

The J. L. Shiely Company of St. Paul annually moves in excess of 2 million tons of aggregate from its Grey Cloud Island mines at River Mile (RM) 825.0L and its distribution points at RM 837.2L and RM 843.3R in Pool 2 and RM 853.4R in Minneapolis. There is no existing rail connection between the mines and the distribution yards. Topographic, environmental, regulatory, and economic influences prohibit construction of rail connections. Therefore, only a shift from barge to truck movements was considered for this segment of the study. Major findings of this analysis are that a shift from barge movement to trucks would annually cause

- An increase in fuel use from 72,300 to 690,000 gal,
- An increase in exhaust emission from 13.4 to 106.9 tons,
- An increase in probable accidents from 0.06 to 2.45, and
- The need to dispose of 1,108 used truck tires.

A major impact of the modal shift would be a near doubling of the heavy truck traffic through the city of Newport, Minnesota. Access to the Grey Cloud mines is limited. All truck traffic would enter Trunk Highway 61 at the main signalized intersection of the city's business district. Mn/DOT traffic records indicate that at that intersection the current average daily traffic load consists of 35,500 automobiles and 2,450 commercial vehicles including 1,125 heavy semitrailer trucks. Peak-hour traffic loads include 115 heavy semitrailer trucks. The analysis indicates that the modal shift would add 759 six-axle semitrailer trucks each day to the traffic load and 69 during the peak hours. This section of highway is already close to capacity.

On the basis of an 11-hr workday and a 250-workday year, the mine would load 34.5 trucks per hour. Existing operational loading rates are 1.5 min per truck. Local ordinances prohibit truck movements at certain hours, which limited the working day to a maximum of 11 hr. Even if the work year is expanded to 300 days, the average added hourly truck movement through the area would be 57 heavy vehicles.

Petroleum Product Movements in Pool 2

Movements of refined petroleum products in Pool 2 occur throughout the year. Tank barges are moved between the Pine Bend refinery in lower Pool 2 to several distribution terminals in the upper pool. During the last 5 years these movements have averaged 278 loaded and 278 empty barge trips annually, with an annual average volume of 232,796,400 gal of product or 814,509 tons.

The only feasible modal transfer is from barges to truck. Rail distances between the points are too short and the necessary interchanges too many to make rail an acceptable substitute. Pipelines could not be built on the required routes because of local, state, and national governmental safety and environmental regulations.

Major findings of this analysis are that a shift of this movement from barges to trucks would cause

- An annual increase in fuel consumption from 19,400 to 178,900 gal,
- An exhaust emission increase from 3.6 to 27.7 tons each year,
- An increase in probable accidents from 0.02 to 0.48 a year, and
- The need to dispose of 41 used truck tires each year.

In this shift, increased truck traffic also creates a significant local traffic impact. With a cargo shift from barges to trucks, there would be an increase of 156 loaded and 156 empty tanker trucks moving through the area each working day, for a total additional truck traffic load of 312 five-axle semis. Assuming a standard 10-hr working day for such movements, the shift would mean 31 additional tank trucks each hour. Major portions of the areas that the trucks would traverse are residential.

Coal Movements from St. Paul

Power plants at Alma, Genoa, and Cassville, Wisconsin, and Lansing, Iowa, receive regular barge shipments of coal from Pool 2 in St. Paul. These cargo movements average about 0.75 million tons each year.

In this analysis both rail and highway modal alternatives were considered, although rail connections do not currently exist at these plants. Steep hills and wetland use restrictions would make it difficult, although not impossible, to build rail unloading facilities at the four power plant sites. At Alma, it would be possible to build an extensive overland conveyor system to transfer coal between the two generating plants. Rail movement to these sites is considered in this analysis in spite of these difficulties.

By the same token, movement of these huge quantities of coal by truck would be extremely difficult. An analysis was included to demonstrate the impacts of a shift to trucks.

The most probable transportation change would be to northbound barges from the lower part of the Upper Mississippi River, which would have a significant economic impact on the Twin Cities community.

Major impacts of modal shifts to truck for these coal movements include

- An increase in annual fuel use from 249,900 to 2,136,850 gal,
- An annual increase in exhaust emissions from 46.2 to 331.2 tons,
- An increase of truck traffic in the corridor of 35,407 trucks annually,
- An increase in probable accidents from 0.2 to 10.0 per year, and
- The need to dispose of 1,043 used truck tires each year.

With a modal shift to rail using 100-car trains (each car 100 tons), the major impacts would include

- An increase in annual fuel use from 249,900 to 541,400 gal,
- An annual increase in exhaust emission from 46.2 to 186.9 tons,
- An annual increase of train traffic in the corridor of 75 trains of 100 cars each,
- The involvement of automobile traffic with those 75 trains at 193 grade crossings, and
- An increase in probable accidents from 0.2 to 0.48 each year.

Paper-Wood Product: Lake Superior Movements from Thunder Bay, Ontario, to Duluth-Superior

One consistent Minnesota Great Lakes ship movement is dedicated to the carriage of wood and paper products between the ports of Thunder Bay, Ontario, and Duluth-Superior. Most of the cargo carried in these shipments is not ultimately destined for the Duluth-Superior area but for other points in the Midwest. Since the final destinations of the cargoes are mainly to the south and west of Duluth, movement on corridors other than between Thunder Bay and Duluth-Superior would be unlikely. It is assumed that all products carried on the vessel would remain captive to the corridor.

The average volume of this movement is 375,900 tons of cargo each year. Major impacts of a modal shift to rail for this cargo movement include

- An annual increase in fuel use from 113,674 to 661,765 gal,
- Annual increases in exhaust emission from 21.0 to 129.0 tons,
- An annual increase in rail traffic of 38 trains each of 100 cars,
- Automobile involvement with those trains at 177 grade crossings, and
- An increase in probable accidents from 0.02 to 0.16 per year.

Rail traffic for this movement must follow a circuitous 360-mi route west from Thunder Bay for 200 mi and then southeast for 160 mi to Duluth. Water movement distance for this trip is 184 mi. There are no rail facilities paralleling the Lake Superior shoreline between the two ports. Construction of such a line would be prohibitively expensive both in dollars and in environmental impacts.

The major impacts of a modal shift to trucks for this movement include

- An increase in annual fuel use from 113,674 to 1,212,500 gal,
- An annual increase in exhaust emission from 21.0 to 188.9 tons,
- An increase in probable accidents from 0.02 to 5.4 per year, and
- The need to dispose of 554 used truck tires each year.

The most significant impact of a transfer from vessels to trucks on this movement would be the increased truck traffic on TH 61 along the North Shore. During the summer tourist season this highly traveled road already has a serious conflict between automobile and truck traffic. In the summer, traffic on that stretch of scenic highway grows from an average off-season daily level of 2,800 to 5,500, with a constant heavy-truck traffic level of 402, of which 223 are five-axle semis. Addition of 35,714 truck trips each year, or 120 per day of a 300-workday year, would be a substantial increase. That increase would occur along with the continuing growth in automobile traffic, exacerbating the automobile-truck conflict.

TOTAL IMPACTS OF MODAL SHIFTS

The shift of all cargo in the study's movements from vessels to trucks would result in

- An annual increase in fuel use of 3,763,000 gal,
- An increase in exhaust emission of 570.5 tons each year,
- The need to dispose of 2,746 used truck tires each year, and
- An annual increase in probable accidents of 18.

For those two movements where rail is a feasible alternative, the cumulative impacts would be

- An annual increase in fuel use of 839,600 gal,
- Annual increases in exhaust emissions of 248.9 tons,
- An increase of 75 trains (each of 100 cars) at 193 highway crossings and 38 more at 177 crossings, and
- An annual increase in probable accidents from 0.22 to 0.64.

These environmental impacts would be accompanied by an increase in transportation costs to the shippers as well as increased highway maintenance costs. Increases in costs for highway maintenance would be partially offset by increased fuel taxes.

CONCLUSION

It was the intention of this analysis to demonstrate some of the potential environmental costs of a modal shift from water and the need for the inclusion of a similar type of analysis in environmental studies of water project proposals.

The commodity volumes studied here represent only a fraction of the total waterborne commerce in Minnesota. A similar analysis of all commercial navigation in the state would further demonstrate the environmental compatibility of this transportation mode. It would add even more support for a similar review for all new water transportation projects.

Since a proposal for a water transportation project demonstrates a need for transportation service, an environmental review of the project should not be considered complete without the inclusion of an analysis of the impacts of not building the project. Such an analysis, using the methods in this study or similar techniques, should be part of all future environmental assessments of water transportation projects.

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Oil Spill Response Capabilities in South Florida

FAZIL T. NAJAFI, MURAT BARAN, XIAOYU FU, ANANTH PRASAD, SALIMI T. ESFANDIAR, AND JEAN DUCHER

The oil spill response capabilities of a unique area in the United States, the South Florida region, are examined and assessed. A literature search was conducted and a questionnaire on oil spill cleanup response capability was sent to relevant agencies and contractors. From the data gathered through literature and the questionnaire, a computerized data base was developed with a manual that would enable users to quickly retrieve needed information to plan and assemble manpower and equipment necessary to contain and clean up a major oil spill. A major oil spill would be more disastrous to an unprepared Florida than the *Exxon Valdez* accident was to Alaska. Growing tanker traffic in Florida waters, shortage of cleanup equipment, types of currents, shallow reefs, and vulnerable coastline all contribute to greater potential damage from an oil spill. The few oil cleanup contractors and specialized companies in the state are confined to large cities. It would be almost impossible for these operators to reach a remote oil spill disaster area quickly. Oil spill cleanup contractors are equipped to handle only minor spills and financially they are unable to purchase expensive equipment geared for major spills. The computerized data base should assist the oil spill task force agencies and industry to assemble quickly in response to a major oil spill.

The oil spill cleanup response capabilities in a unique area of the United States, coastal South Florida, are examined and assessed. A literature search was conducted and a questionnaire on oil spill cleanup response capabilities was mailed to relevant agencies and industries. Florida's diverse coastal environment is composed of ecosystems such as mangrove swamps, seagrass beds, coral reefs, sand beaches, and associated wildlife. These ecosystems are important to Florida's environment and are indeed vulnerable to oil spills. For instance, mangroves alone (*a*) are a habitat for fish and other wildlife; (*b*) provide protection against storms and erosion; (*c*) contribute to the environment's biochemistry system; and (*d*) are significant to tourism, wildlife, and personal intangible values (*1*). Mangroves occupy nearly 470,000 acres of southern Florida, and almost 90 percent of the area lies in the four South Florida counties of Lee, Collier, Monroe, and Dade.

An oil spill reaching South Florida beaches would have a great impact on the tourism industry. Furthermore, Florida's coastal lands are used for second homes or vacation homes. The impact of an oil spill on these resources could be severe (*1*). Southern Biscayne Bay and Card Sound are expected to be the most vulnerable to oil spills. Figure 1 presents the sensitive shorelines (e.g., sandy beaches, mangroves, etc.) of South Florida (*2*). Continental Shelf Associates, Inc., estimated that a major oil spill near a coastal recreation area in Florida would reduce tourism by 5 to 15 percent over one season (*2*). A contingency oil spill cleanup program is necessary to deal with a major oil spill in the Florida coastal region. A computerized data base contingency plan has been developed that would enable users to quickly plan and assemble the necessary manpower and equipment in case of a large oil spill and cleanup operation.

EXISTING VESSEL TRAFFIC AND OIL SPILL RISK ANALYSIS

Accidental oil spills from oil transportation and operation activities probably account for the largest source of oil spills

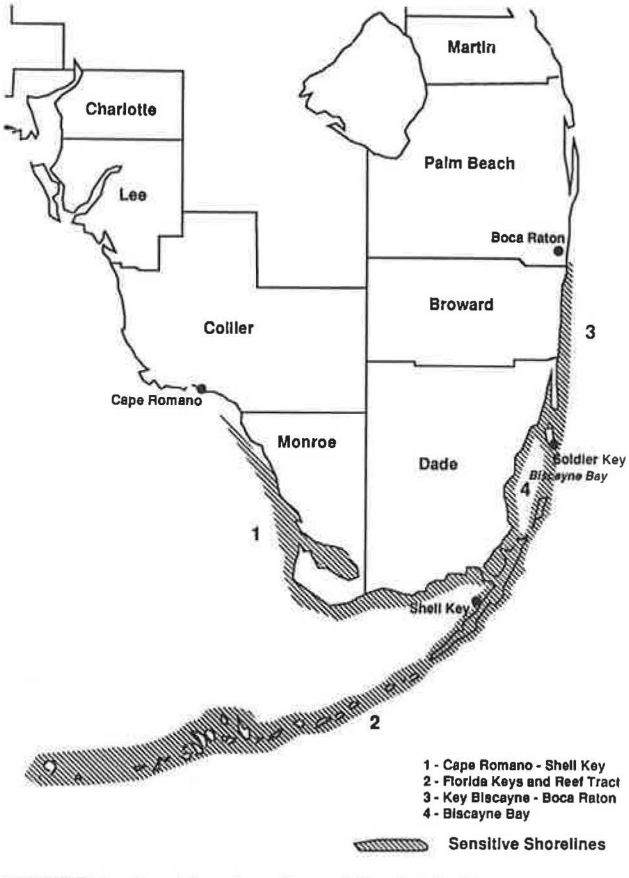

FIGURE 1 Sensitive shorelines of South Florida.

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in the United States (*3*). In order to meet the increasing demand for petroleum and petroleum products, more and more oil-carrying vessels are cruising Florida's coastal waters each year. Florida's geographic location and its natural resources make the state more vulnerable to the consequences of a major oil spill than most other coastal areas in the United States. Oil spills could also affect the state economy by polluting the shoreline or contaminating the fishstock.

On the basis of observations of the United States Coast Guard (USCG), the South Florida Regional Planning Council (SFRPC) estimated that 1.2 billion barrels of oil were transported through the Straits of Florida in 1979 (*1*). In 1989, 93.5 million barrels (13.3 million tons) of petroleum and petroleum products were transported through Port Everglades. This volume is expected to reach 103.2 million barrels by 2000. According to the Department of Natural Resources (DNR), total petroleum transfers of oil products through the ports in the entire state totaled 286.5 million barrels carried in a total of 5,860 transits in 1989 (*4*).

The heavy traffic of large tankers imposes the possibility of a major oil spill in South Florida waters. The four locations identified by SFRPC as hazard areas have a greater potential for an oil spill because of converging or crossing routes of tanker traffic. These areas include 11 nautical miles (nmi) south-southeast of West Palm Beach, which is the crossing point of north-south traffic with westbound traffic; 10 nmi east-southeast of Fort Lauderdale where the north and south routes are intersected by the Port Everglades entrance route; 11 nmi south-southeast of Miami where Miami Harbor trips and through-traffic merge; and the area 12 nmi south of the Dry Tortugas, where the traffic from the Gulf of Mexico converges to enter the Loop Current to travel northeast. Figure 2 shows the oil transportation routes in South Florida.

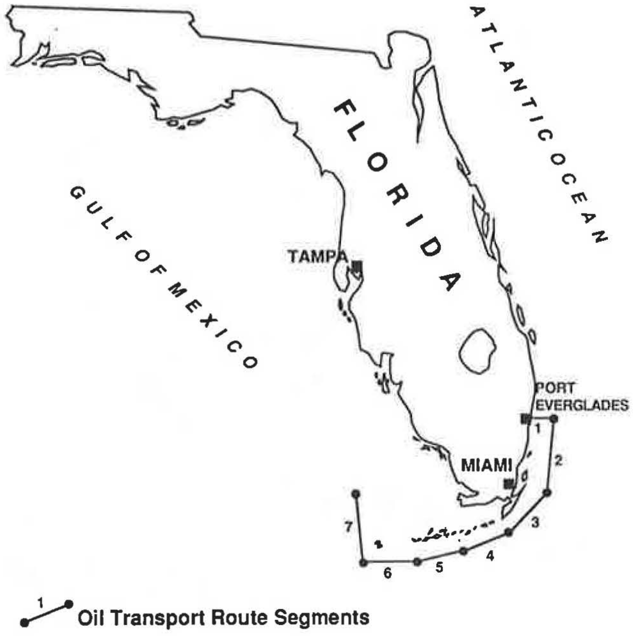

FIGURE 2 Oil transportation routes in South Florida.

OIL SPILL RESPONSE CAPABILITIES

Figure 3 shows the South Florida oil spill response information system. On the basis of the system represented in this figure, a computerized data base was developed. It is explained in detail at the end of this section. Figure 3 shows that the response teams include federal, state, county, and city contacts. To ensure a quick response to oil spills, the federal response organization established a National Response Center (NRC), the National Response Team (NRT), the Regional Response Center, Regional Response Teams (RRTs), and an On-Scene Coordinator (OSC) (*5*). In the event of a major oil spill beyond the control of the RRT, the NRT can be actuated. The NRT may (*a*) monitor the spill, evaluating the reports of the OSC; (*b*) request oil spill response resources from federal, state, local, or private organizations; and (*c*) coordinate other activities as may be required to ensure that the effective oil spill response plan is in operation (*5*). OSCs are predesignated federal officials from USCG or the Environmental Protection Agency (EPA). The OSC collects facts about the spill, identifies the spill's potential impact, and estimates cleanup costs. The spiller is responsible for the spill. The OSC will hire commercial contractors and monitor the cleanup activity. If commercial resources are not available, the OSC will deploy federal resources. Federal personnel and equipment can be obtained from the National Strike Force and the U.S. Navy (*5*). The OSC will also implement the following actions: (*a*) immediately notify the RRT and NRC, (*b*) classify the size of the discharge and determine the proper course of action, and (*c*) determine the state or local government cleanup capabilities to carry out response actions (*5*).

The South Florida region's oil spill response capability analysis is based on a methodology to gather information from oil cleanup contractors, cooperatives, equipment manufacturers, the Marine Spill Response Corporation (MSRC), Florida port authorities, DNR, EPA, and USCG.

The two main factors in analyzing the existing oil spill response capabilities in the South Florida region are the quantities and types of oil cleanup equipment available in the area and the contractors' locations and their expected response times to an oil spill.

To assess the existing capabilities and update the equipment inventories, cleanup contractors and cooperatives were asked to send their equipment lists. Despite the reluctance of some contractors, most responded (see Table 1).

During the course of this study, DNR, USCG, MSRC, EPA, and others were contacted to identify Florida state oil spill cleanup contractors. After identifying these contractors, a simple questionnaire was prepared and sent out asking contractors about their existing equipment inventories, types of equipment, average oil spill response time (e.g., mobilization, travel, and installment), and mode of transportation. These details are explained in the following sections.

CONTINGENCY PLAN

"The Florida Coastal Pollutant Spill Contingency Plan has been developed in compliance with Section 376.07(2)(e), Florida Statutes. It is in support of the Region IV Contingency Plan as it relates to spills occurring in coastal waters" (*6*).

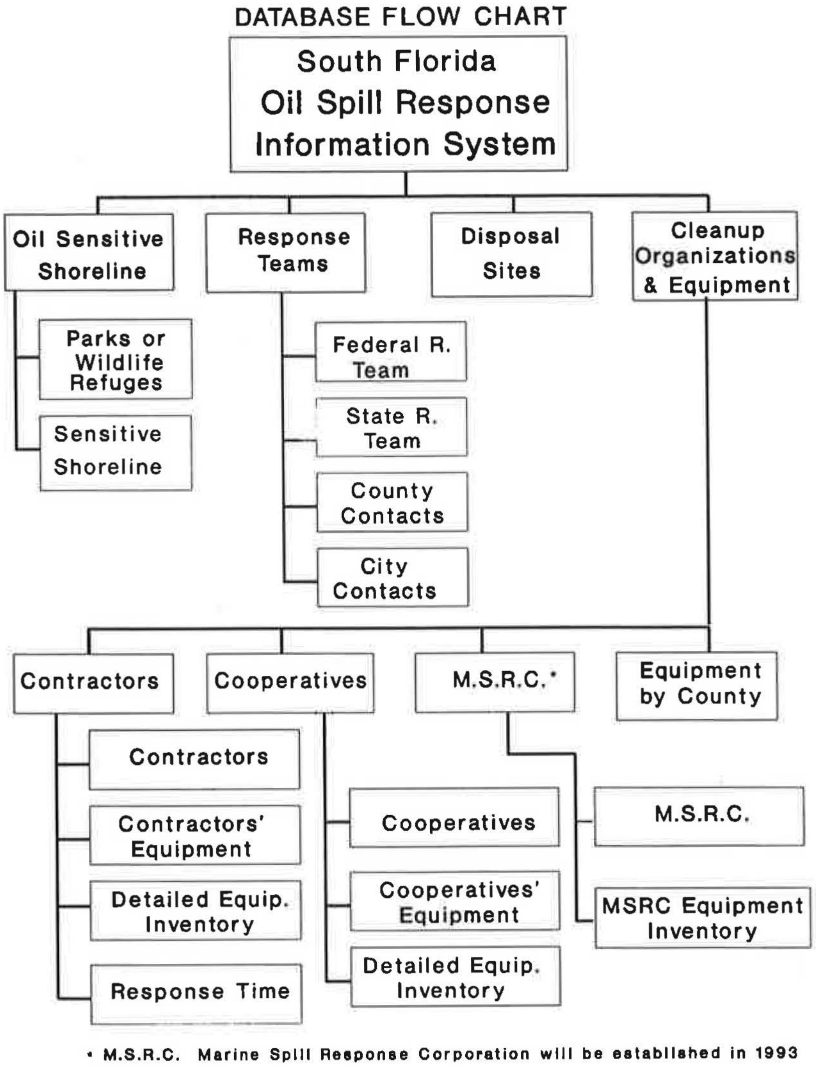

FIGURE 3 South Florida Oil Spill Response Information System.

The objective of the contingency plan is to coordinate federal, state, and local government activities in responding to an oil spill. Under this plan, the state has an oil spill task force composed of trained individuals. The state OSC is responsible for state cleanup and monitoring.

The State Response Team (SRT) is composed of DNR, the Department of Environmental Regulation (DER), the Department of Community Affairs, the Department of Commerce, the Department of Highway Safety and Motor Vehicles, the Department of Law Enforcement, the Department of Legal Affairs, the Department of Military Affairs, the Department of Transportation, the Game and Fresh Water Fish Commission, Governor's Office, and the Department of Health and Rehabilitation Services. The chairperson of SRT is the executive director of DNR or the secretary of DER. During a pollution incident, the chairperson is responsible for the overall management of SRT (*6*).

To identify Florida state oil spill cleanup response capabilities, a questionnaire was prepared and mailed to various agencies and contractors responsible for oil spill cleanup. Additional relevant information was obtained through telephone and personal contacts.

CLEANUP EQUIPMENT ANALYSIS AND EXISTING CAPABILITIES

The existing capabilities depend on the resources that can be supplied by the cleanup contractors and cooperatives. The most important resources are equipment and personnel. Most of the cleanup equipment is owned by contractors and cooperatives, whereas the personnel supply mainly depends on contractors. Major types of equipment that are used in a cleanup operation consist of containment and recovery devices. Booms, skimmers, suction hoses, boats, and storage tankers are the most needed equipment supplied by the contractors or cooperatives in an oil spill response (see Table 2).

Performances of these equipment items, particularly booms and skimmers, are as important as their quantity and capacities in determining the effectiveness of a response operation.

Booms are used to

- Contain a spill,
- Thicken the oil layer to ease oil recovery,
- Deflect the spill from sensitive areas, and
- Remove the spilled oil.

TABLE 1 TYPE OF INFORMATION RECEIVED FROM CLEANUP CONTRACTORS

Company Name	Location	Equipment List	Response Time
O.H.M. Corp.	Clermont	yes	yes
Cliff Berry	Ft. Lauderdale	yes	no
Danmark	Miami	yes	no
Need a Diver	Tampa	Does not respond to spills anymore	
Haztech	Tampa	yes	no
Clean Harbors	Apopka	no	no
Diversified Environmental Services	Tampa	yes	yes
Florida Spill Corp.	Cocoa	yes	yes
Cape Canaveral	Cape Canaveral	yes	no
Riedel-Peterson	Mobile	yes	yes
Environmental Recovery Group	Atlantic Beach	yes	no

To meet these requirements, a broad variety of equipment has been designed along with different methods of deployment. Among different types of booms, harbor, river, and offshore booms are the main categories. Compared with river and harbor booms, offshore booms are larger and heavier, which enables them to be used in open sea conditions. However, the effectiveness of these boom systems depends on environmental conditions (see Table 3). In South Florida, adverse weather conditions, such as high winds and waves that would restrict the use of offshore booms and other cleanup equipment, are the main concern of response personnel.

Skimmers are used to recover the oil contained by the booms. Their performance is affected by oil viscosity and often by the physical properties of oil. Different skimmer systems have varying oil recovery capacities, but usually the capacity of a certain skimmer decreases once the oil becomes emulsified. In South Florida, the winter months are the most critical time, since water temperatures become relatively cold, which speeds emulsification. According to oil spill cleanup contractors, during winter months a quick containment and recovery response (6 to 8 hr after the spill), before emulsification of the oil can take place, is essential.

The existing oil spill cleanup equipment owned by contractors and cooperatives is limited in the handling of a major oil spill. The type of equipment owned is another problem, since only a small part of it could be used for major offshore

TABLE 2 MAJOR OIL CLEANUP EQUIPMENT QUANTITIES IN FLORIDA

Contractor/Cooperative	Skimmers	Booms (ft)	Hoses (ft)*	Boats	Tankers (gal)
Cape Canaveral Marine Services	1	5000	900	7	N/A
Cliff Berry	N/A	4000	yes	3	14300
Danmark	4	2400	yes	24	N/A
Diversified Environmental Services	1	2350	N/A	4	10000
Environmental Recovery Group	3	2000	9700	2	40000
Florida Spill Response Corp.	4	3500	yes	8	28800
Haztech	3	6700	N/A	3	6700
O.H. Materials	1	2000	4100	3	3000
Riedel-Peterson Environmental Services	3	3000	250	2	N/A
Tampa Port Committee Spillage Control	N/A	2800	yes	1	2500
Port Everglades Spillage Committee	N/A	1500	yes	1	N/A
Port of Palm Beach	1	4000	N/A	N/A	N/A
Port of Miami	1	8380	yes	N/A	N/A
Jacksonville Pollution Control	8	6750	yes	3	5500

* a yes response indicates that an exact amount or quantity was not specified

TABLE 3 CONDITIONS THAT AFFECT THE DEPLOYMENT OF BOOMS

Ideal	> Increasing Difficulty >	Adverse
Water Conditions		
Calm		Waves
Still		Currents
Shallow		Deep
Fresh		Salt
Location		
Ponds		Oceans
Inland		Offshore
Weather Conditions		
Calm		Windy
Warm		Cold
Dry		Rain
Clear		Foggy
Light Conditions		
Daylight		Darkness

Source: Oil Spill Barriers and Their Use, Environment Canada, 1981

oil spills. Most of the equipment owned is suitable for responding to minor and inland spills, which occur more frequently. Past experience shows that with existing capabilities, minor or moderate spills could be cleaned successfully. However, according to DNR statistics, the largest oil spill that occurred in Florida between 1975 and 1990 was 108,000 gal. The frequency of minor spills and the low possibility of a major oil spill put other limitations on the existing capabilities. The private sector, namely third-party contractors, usually has the equipment needed for events occurring more frequently. This enables response to as many spills as possible within a certain time frame and continued competitiveness in the sector.

SIGNIFICANCE OF RESPONSE TIME

One of the major factors affecting the success of a cleanup operation is the time lapse between the occurrence of the spill and the start of the cleanup. An effective response should include the presence of all of the available equipment and personnel at the spill site in the shortest time possible. Since most of these resources are supplied by the cleanup contractors and cooperatives, it is important to assess their capability of reaching the spill location within a certain time frame. Figure 4 shows assumed oil spill locations, cleanup contractors, and major cities in the South Florida region.

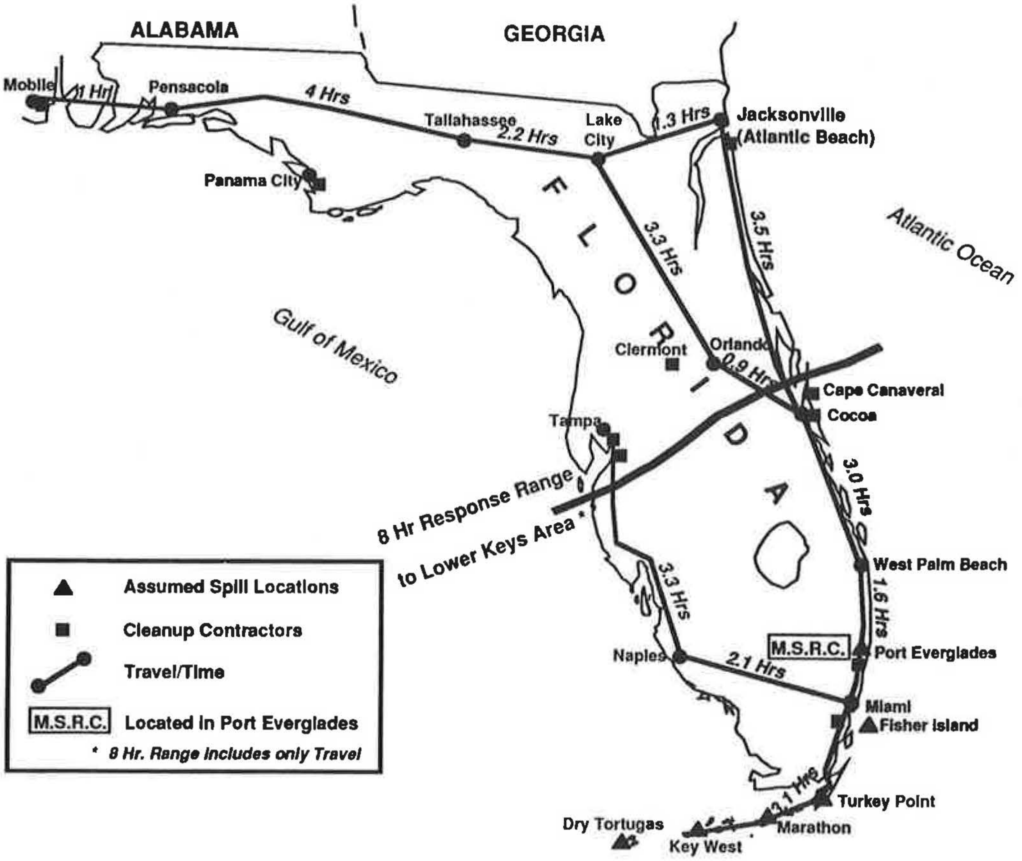

FIGURE 4 Assumed oil spill locations, cleanup contractors, expected travel time for cleanup contractors, and cities in the South Florida region.

TABLE 4 ESTIMATED RESPONSE TIME, FLORIDA SPILL RESPONSE CORPORATION, COCOA, FLORIDA

Oil Spill Location	Components of Response Time (hours)		
	Mobilization	Travel	Installment
Port Everglades	3/4	3	3/4
Miami Beach	3/4	4	3/4
Turkey Point	3/4	4	3/4
Marathon	3/4	5	3/4
Key West	3/4	6	3/4
Dry Tortugas	3/4	7	3/4

To assess the response time to an oil spill, contractors were requested to provide their expected response times to spills occurring at different locations in South Florida. Table 4 gives the replies of the contractors who responded.

Response times for all of the contractors were projected (see Tables 5 through 8). The following assumptions were made in calculating the figures for the response timetable:

1. Mobilization time of the contractor, 1 hr;
2. Installment time of equipment, 1 hr; and
3. Travel time, distance/50 mph average speed.

Figures were rounded to the next hour.

On the basis of the response time of the contractors to a distant spill location, the two time brackets of 6 to 8 hr and 14 to 16 hr were chosen to assess the available equipment within these time periods after the spill. According to contractors, 6 to 8 hr is the limit when oil starts to emulsify during cold weather and cool water temperatures. This is significant to Florida especially during winter months when the oil would emulsify faster and make recovery difficult after 8 hr. Another consideration in this time period is the spreading of oil under adverse weather conditions and currents. The second response time period, 14 to 16 hr after the spill, was set as an arbitrary limit for milder weather conditions and warmer water temperatures.

TABLE 5 ESTIMATED RESPONSE TIME, DIVERSIFIED ENVIRONMENTAL SERVICES, TAMPA, FLORIDA

Oil Spill Location	Components of Response Time (hours)		
	Mobilization	Travel	Installment
Port Everglades	1	5	2
Miami Beach	1	6	2
Turkey Point	1	*	2
Marathon	1	9	2
Key West	1	11	2
Dry Tortugas	1	*	2

* Data not provided

TABLE 6 ESTIMATED RESPONSE TIME, RIEDEL-PETERSON ENVIRONMENTAL SERVICES, MOBILE, ALABAMA

Oil Spill Location	Components of Response Time (hours)		
	Mobilization	Travel	Installment
Port Everglades	1/2	13	1/2
Miami Beach	1/2	13	1/2
Turkey Point	1/2	*	1/2
Marathon	1/2	15	1/2
Key West	1/2	16	1/2
Dry Tortugas	1/2	19	1/2

* Data not provided

In evaluating the response capabilities within these time periods, the number of feet of boom that could be transported to the site was chosen as the basic criterion. It was assumed that once the oil is contained by the booms, it would be possible to remove it with the available recovery devices or with the additional equipment that could be pooled from other farther locations. For the spill location, the Lower Florida Keys area, where logistics would play a major role in implementing the cleanup action, was chosen. The small amount of equipment stockpiled and the long distances between the existing contractors and the region were also significant.

FUTURE OIL SPILL RESPONSE CAPABILITIES

After the 1989 *Exxon Valdez* oil spill, the Petroleum Industry Response Organization, in early September 1990, announced the formation of MSRC. MSRC will be the world's largest and perhaps most effective oil spill response network when it becomes operational in 1993 (*7*). MSRC is an independent,

TABLE 7 ESTIMATED RESPONSE TIME, OHM CORPORATION, CLERMONT, FLORIDA (KEEPS EQUIPMENT IN BOCA RATON)

Oil Spill Location	Components of Response Time (hours)			Total Time (hours)
	Mobilization	Travel	Installment	
Port Everglades	1/2	1/2	1	2
Miami Beach	1/2	1/2	1	2
Turkey Point	1/2	2 1/2	1	4
Marathon	1/5	3	1	4.2
Key West	1/5	4 1/2	1	5.7
Dry Tortugas	*	*	*	*

* Data not provided

TABLE 8 EXPECTED RESPONSE TIMES FOR CONTRACTORS

Company Name	Location	Response Times for Locations* (hr)				
		a	b	c	d	e
O.H. Materials	Clermont	3	4	5	6	8
Cliff Berry	Ft. Lauderdale	2	3	4	5	7
Denmark	Miami	3	2	3	4	6
Environmental Recovery Group	Atlantic Beach	10	11	12	13	15
Diversified Environmental Services	Tampa	7	8	9	10	12
Haztech	Tampa	7	8	9	10	12
Florida Spill Response Corp.	Cocoa	6	7	8	9	11
Riedel-Peterson	Mobile	15	16	17	18	20

* Spill Locations:

a. Port Everglades
b. Miami Beach
c. Turkey Point
d. Marathon
e. Key West

nonprofit corporation with headquarters in Washington, D.C. and five regional response centers, including Port Everglades in Southeast Florida. The centers will be capable of responding to a spill of 30,000 tons (216,000 barrels). The Port Everglades site, which is the headquarters of the Southeast region, will be manned around the clock by 64 people. Jacksonville and Tampa sites will be two of the five equipment prestaging facilities for the Southeast (*8*). In full operation, MSRC will have 400 staff and more than $300 million worth of oil spill cleanup equipment distributed among the regional centers. MSRC plans to establish a 5-year, $35 million relevant research program (*8*).

SOUTH FLORIDA OIL SPILL RESPONSE INFORMATION SYSTEM: COMPUTERIZED DATA BASE

Purpose

The purpose of the South Florida Oil Spill Response Information System is to enhance existing response capabilities and to assist officials in handling oil spills by providing the necessary data. The data base contains information on oil-sensitive areas, addresses and phone numbers of contact personnel, and a list of oil spill cleanup contractors and equipment.

Features

DBASE3 PLUS is a popular data base management language that can run on an IBM PC/AT or compatible in a DOS environment. This system was selected to write the oil spill response information system. The system is run by loading the data base diskette into a drive, retrieving the main menu screen, and selecting the desired option. For each record the system includes on-screen options such as add, delete, edit, search, view, list print, and so forth. The system has the following features:

1. The ability to access data from a file and from several files at any time,
2. Data updating and editing capability on the screen,
3. Automatic calculation of the total number of pieces of cleanup equipment by updating the detailed equipment inventory of the contractors and cooperatives,
4. Printing options for data file records, and
5. A menu-driven program with on-screen information providing easy access to higher and lower levels of the system.

Description

The information system consists of four subsystems: oil-sensitive areas in South Florida, oil spill response teams, available disposal sites, and cleanup organizations and equipment.

Oil-Sensitive Areas in South Florida

This subsystem includes two parts: (*a*) sensitive shorelines and (*b*) parks and refuges.

Sensitive shorelines consists of information on the sensitive shorelines in South Florida. The area is divided into four regions on the basis of each area's characteristics and related oil spill impacts as follows: Cape Romano to Shell Key, Florida Keys and Reef Tract, Key Biscayne to Boca Raton, and Biscayne Bay.

Parks and refuges includes the list of parks and refuges in South Florida and the associated oil spill impacts.

Oil Spill Response Teams

The subsystem contains the addresses and phone numbers of the following oil spill response agencies: RRT, SRT, city, and county.

Available Disposal Sites

This part includes information about available county oil disposal sites in South Florida.

Cleanup Organizations and Equipment

This subsystem provides information on oil spill response organizations and available equipment in South Florida. The cleanup organizations are divided into three parts: cleanup contractors, cleanup cooperatives, and MSRC (in 1993). Also included are their equipment inventories and expected response times for potential oil spills in different locations of South Florida. Information on cleanup equipment in this section is limited to basic types of equipment. Another subsection provides more detailed information about the types, models, and capacities of available equipment.

The developed computerized data base can be used by different industries and government agencies. The relevant industry could use this program to update its equipment inventory and response time. Government agencies could use the program to update relevant oil spill cleanup activities.

The Florida oil spill SRT can be responsible for keeping the file up-to-date. The updated information can be disseminated by the SRT to relevant agencies, cities, counties, and industries.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the literature search, responses to the oil spill questionnaires, and personal visits and interviews, it is concluded that South Florida is one of the regions most vulnerable to the consequences of oil spills. The increasing oil tanker traffic, fragile coastline, associated wildlife, geographical complexity of the region, and the Loop Current factor all add to the risks associated with an oil spill. On the basis of this study, the conclusions and recommendations are as follows:

1. There is a requirement for more offshore containment and recovery equipment in Florida. Cleanup contractors, cooperatives, and other county agencies should be encouraged to increase their equipment inventories to be able to respond to major offshore spills. Efforts should be made and plans prepared to stockpile some of this equipment and the necessary trained manpower at strategic points and vulnerable areas of the South Florida region such as the Lower Keys.

2. South Florida has not yet faced a catastrophic oil spill. Such an event would require an effective and combined response from all the responsible units in the region. Coordination of these units is a key issue for the success of the operation and is addressed in the federal and state contingency plans. Answers to questionnaires indicate that contingency plans should be dynamic plans that would also be adequate for major oil spills. State plans should be updated regularly because of turnover in the organizational section and should include the use of expert consultants. USCG officials suggest that all existing oil spill contingency plans should be revised. Their experience indicates that no clear lines of authority or good coordination among contingency plans, either public or private, exist. To determine the applicability of contingency plans and enhance oil spill response capabilities, systematic drills should be conducted involving all units in the region. Emphasis should be given to unannounced drills.

Florida must examine the plans of other states. For instance, the recent legislative changes in California (Chapter 1248), the Oil Spill Prevention and Response Act (*9*), has application in South Florida. "The bill would create the Oil Spill Response Trust Fund. The bill would require every operator of a refinery to pay an oil spill response fee of 25 cents per barrel of crude oil received" (*9*). The establishment of such a fund in Florida might create future funding for purchasing suitable cleanup equipment.

3. Equipment inventories supplied by contractors and cooperatives should be updated regularly, and drills must be conducted to verify the availability of existing equipment to locations in South Florida.

4. Better data on transportation patterns, weight limits, and other details on spilled oil in South Florida are needed. According to these data, certain areas could be identified where spilled oil would be carried away by currents without contacting the shoreline. In the event of an accident, damaged tankers could be towed away to one of these preidentified areas, where it would be safer to proceed with the lightering and cleanup operations.

5. Most of the responses to the questionnaire indicate that the buffer zone around the Florida Keys would help to a great degree to protect the reefs from oil spills due to groundings and give response officials time to plan and assemble forces. However, some officials state that this would increase the possibility of collisions due to narrowed shipping lanes. In this regard, tanker traffic through the Straits of Florida should be monitored more closely and additional measures should be taken if necessary.

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Truck Transportation of Hazardous Chemicals

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Because data on truck movements of specific hazardous chemicals are not available, methods for estimating them are needed. One possible method of collecting data is through surveying or reporting movements by truckers or shippers. A less costly alternative is to use secondary data on production and consumption of chemicals to identify the chemicals that are moving, the probable origin-destination pairs of these movements, and the probable routes taken. An approach that relies chiefly on secondary data is developed. The basic data on production and consumption came from available data bases on chemicals and chemical producers in the United States. These data were used to determine the chemicals that account for at least 80 percent by volume of hazardous chemicals moving by truck in the United States and to identify major producers and consumers of each chemical. Through interviews with these producers and consumers, rules were developed for estimating the modal split among truck, rail, and water transport on a chemical-by-chemical basis. A gravity model was applied to estimate the origin-destination pairs and routes for truck shipments. A description of the approach and the results of its application to three large-volume hazardous chemicals are presented.

The transportation of hazardous materials is a matter of increasing concern to regulatory authorities. Actual data on the volume of hazardous materials transported throughout the United States are not available, but estimates place the total in excess of 1.5 billion tons per year (*1*). Truck, water, and rail account for nearly all hazardous materials shipments; air shipments are negligible in volume. Fuels such as gasoline and diesel account for about half of the hazardous materials transported; chemicals account for most of the remainder.

Data collected through the Interstate Commerce Commission's (ICC's) 1 percent Waybill sample have been analyzed to provide in-depth information on rail movements of hazardous chemicals. Some data on coastal and inland waterway movements are available through the Army Corps of Engineers. No data are available on truck transportation of chemicals.

Because of the increasing intermixing of freight and passenger vehicles on the nation's roads and highways, incidents involving truck movements of hazardous materials frequently involve exposure to the general population. The U.S. Department of Transportation (DOT) has extensive data on highway incidents involving hazardous materials and chemicals, but does not have comparable volume data with which to establish failure rates (i.e., the percentage of shipments involved in incidents). Consequently, regulatory authorities and planners lack the critical information they need to make decisions regarding training, regulatory policies and programs, and enforcement strategies. Inadequate or inappropriate emergency response training can delay cleanup and increase the hazards associated with spills and other incidents.

The importance of obtaining better information on truck transportation of hazardous materials is great. An approach that estimates the volume of specific chemicals moving by highway in the United States, the origins and destinations of these shipments, and the ton-miles moving through each state is described. The scope of the research includes

- Identification of the chemicals accounting for at least 80 percent of truck shipments of nonfuel hazardous chemicals in the United States (excluding those moving in international commerce);
- A methodology to estimate truck shipments of specific chemicals, including origins and destinations of major producers and consumers and ton-miles transported through each state by truck; and
- Application of the methodology to three chemicals to evaluate its ability to provide the information desired.

METHOD OF APPROACH AND PROJECT RESULTS

Identification of Hazardous Chemicals Accounting for at Least 80 percent of Truck Shipments

Review of Chemicals

To begin the process of identifying the chemicals that make up at least 80 percent of U.S. truck shipments of (nonfuel) hazardous chemicals in 1987, a list of chemicals meeting the following three criteria was prepared: (*a*) the level of 1987 U.S. production or consumption of the material was in excess of 25,000 short tons (or approximately 830 to 850 truckloads per year); (*b*) the chemicals were considered hazardous as defined by DOT's *Emergency Response Guidebook* (*2*); and (*c*) the chemicals were shipped by truck.

A total of 306 candidate chemicals or groups of chemicals with U.S. production or consumption of at least 25,000 short tons were identified. Of these chemicals, 108 large-volume chemicals were not included in the *Guidebook*; since they were not considered hazardous, they were dropped from study. In addition, 26 plastics and resin groups that are not listed

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separately in the *Guidebook* were excluded, as were two of the candidate groups that were gross mixtures, n-paraffins (C10-C16) and mixed linear alcohols (C6-C11), and 15 minerals and metals.

Each of the remaining 159 individual chemical candidates identified as large-volume and hazardous chemicals was studied to determine if it is shipped by truck. Five chemicals were excluded because they were not shipped by truck. Twenty chemicals were identified as "Note Presently Authorized" or "Forbidden" by the National Tank Truck Carriers, Inc., (NTTC) in the *Hazardous Commodity Handbook* (*3*). A representative of NTTC indicated that these chemicals cannot be shipped by tank truck, but they can be packaged in drums or similar containers and shipped by truck. Evidence was obtained indicating that only three (ethane, ethylene, and tetraethyl lead) of these "Not Presently Authorized" or "Forbidden" chemicals were not shipped in drums, bags, cylinders, cartons, and so forth. Therefore, it was concluded that the rest of these chemicals should be retained in the study. The 147 chemicals, given in Table 1, were identified as the large-volume hazardous chemicals that are moved by truck in the United States.

TABLE 1 LARGE-VOLUME, HAZARDOUS CHEMICALS SHIPPED BY TRUCK

Chemical	Production Volume, 1987 (Thousands of Short Tons)
Sulfuric Acid	39235
Propane	26896
Nitrogen	24515
Oxygen	16669
Ammonia	16100
Calcium Oxide	15733
Sodium Hydroxide	11486
Chlorine Gas	11019
Phosphoric Acid	10685
Sulfur	10321
Carbon Dioxide	8307
Ethylene Dichloride	7878
Ammonium Nitrate	7612
Nitric Acid (100% Hno3 Basis)	7225
Benzene	5904
Ethylbenzene	4630
Vinyl Chloride	4201
Styrene	4007
Methanol	3769
Toluene	3223
Ethylene Oxide	2921
~~Hydrochloric Acid (100%)~~	~~2869~~
P-xylene	2578
Methyl-t-butyl Ether	1757
Phenol	1676
Acetic Acid, Synthetic	1623
1,3-Butadiene	1465
Ethanol (Synthetic)	1434
Aluminum Sulfate	1426
Carbon Black (Furnace Black)	1362
Vinyl Acetate	1253
Acrylonitrile	1250
Formaldehyde	1232
Cyclohexane	1137
Propylene Oxide	1105
Acetone	1048
Butyraldehyde	879
Acetic Anhydride	858
Adipic Acid	795
Isopropanol	685
Nitrobenzene	625
1-Butanol	575
Argon	560
Acrylic Acid	550
Hexamethylenediamine	543
Isobutylene	518
Hydrogen Cyanide	516
Methyl Methacrylate	514
Phthalic Anhydride	508
O-xylene	470
Methylene-diphenylene Diisocyanate	467
Cyclohexanone	465
Barite	448
Aniline	430
Hexane	426
Phosgene	421
Linear Alkylate Sulfonate	399
Hydrogen	389
Carbon Tetrachloride	374
Acetaldehyde	363
Toluene Diisocyanate	357
Methylchloroform	347
Phosphorus	344
Methyl Ethyl Ketone	336
Sodium Chlorate	289
Tripropylene (Nonene)	275
Hydrofluoric Acid	274
Methyl Chloride	261
Methylene Dichloride	259
N-butyl Acrylate	258
Potassium Hydroxide	246
Perchloroethylene	237
1-Butene	231
Calcium Carbide	230
Sulfur Dioxide	229
Epichlorohydrin	225
Chloroform	224
Propylene Tetramer (Dodecene)	200
Maleic Anhydride	193
Dichlorodifluoromethane (F12)	184
Acetylene	182
Carbon Disulfide	180
Ethylene Glycol Monobutyl Ether	175
Bromine	168
Ethyl Acrylate	162
Hydrogen Peroxide	153
Chlorodifluoromethane (F22)	142
N-pentane	142
Propionaldehyde	140
Ferric Chloride	137
Nonylphenol	137
Sodium Chromate/dichromate	128
Chlorobenzene	123
Naphthalene	121
Monoethanolamine	116
Activated Carbon	109
Ethyl Acetate	107
~~Phosphorus Trichloride~~	102
N-butyl Acetate	101
Isobutyraldehyde	99
Trichloroethylene	98
N-propanol	93
Barium Sulfide	92
N-heptane	89
Calcium Hypochlorite	88
Sodium Cyanide	85
Isobutanol	83
Pinene	78
Sodium Hydrosulfite	78
Ethyl Chloride	77
Tetrahydrofuran	77
Methyl Isobutyl Ketone	76
Chloronitrobenzene	73
Sodium (Metal)	72
Phosphorus Pentasulfide	70
Hexene-1	61
Propionic Acid	59
Acrylamide	56
Chlorinated Isocyanurates	55
Isoprene	54
Zinc Sulfate	54
Ethylene Glycol Monoethyl Ether	53
P-dichlorobenzene	52
Dicyclopentadiene	50
Hydrofluosilicic Acid	50
Benzoic Acid	48
Isobutyl Acetate	44
Atrazine	43
Ethylene Glycol Monoethyl Ether Acet	42
Ethylenediamine Tetraacetic Acid	41
Furfural	40
Sodium Hydrosulfide	40
Ethylenediamine	39
Dimethylamine	37
Cu Sulfate	36
Ethylene Glycol Monomethyl Ether	36
N-propyl Acetate	35
Aluminum Chloride	33
Benzyl Chloride	33
Phosphorus Oxychloride	31
Ethylene Dibromide	30
Zinc Chloride	28
Isopropyl Acetate	27
Isopropylamine, Mono	27
Methylamine	26
Sodium Phosphate, Tribasic	26
Amyl Alcohol	25
Total For 147 Chemicals	288792

Source: SRI International

Verification That Chemicals Compose 80 percent of Truck Shipments

Alternative methods for determining whether the large-volume chemicals identified constitute at least 80 percent of the truck movements of hazardous chemicals were investigated.

In the absence of 1987 data on the quantity of the 147 chemicals and other hazardous chemicals shipped by truck in the *Guidebook*, available production data (or consumption data for the few cases where production data were unavailable) were used as a surrogate for shipment quantities to estimate the percentage of the total quantity of hazardous chemical truck shipments represented by the 147 chemicals. That is, it was assumed that the total quantities shipped by truck were proportional to the total quantities produced. Summation of the production data for the 147 chemicals gave a total production figure of approximately 289 million short tons. However, no production data were readily available for the other individual chemicals listed in the *Guidebook*, so a method to estimate these data was sought. Since known mixtures (e.g., mercaptan mixture, aliphatic) and unspecified compounds (e.g., organic compound of arsenic, liquid, not otherwise specified) listed in the *Guidebook* are specifically excluded from the study, these mixtures and compounds were deleted, and the remaining items in the *Guidebook* were then processed to eliminate duplicate names.

This produced a list of 1,338 individual hazardous chemicals (not including the 147 chemicals). Seven of these, with a total production of 69 million short tons, were previously identified as large-volume chemicals that are not shipped in significant quantities by truck. Of the remaining 1,331 smaller-volume chemicals, production figures were readily available for only 10. (These 10 chemicals had a total 1987 production of 0.1 million short tons, or an average production of about 10 thousand short tons.) An estimate was needed for the average production quantity of the remaining 1,321 individual hazardous chemicals in the *Guidebook*. Many of these chemicals were known to have very small production levels, although separate figures were not available. Nevertheless, an average production quantity for each of these chemicals of 12.5 thousand short tons (one half of the 25 thousand short tons used as the cutoff for identifying the 147 large-volume hazardous chemicals) was used to estimate their total production. The results of this analysis are summarized in Table 2.

As Table 2 indicates, the 147 chemicals represent at least 95 percent of the total production and, in spite of the uncertainties in the various assumptions, these 147 chemicals are believed to represent well over 80 percent of the individual hazardous chemicals shipped by truck. (Subsequent analysis indicated that it is likely that the larger the production volume, the lower the percentage of chemical transported by truck.)

TABLE 2 BREAKDOWN OF HAZARDOUS CHEMICALS

	Millions Tons Produced	Percent
147 large-volume chemicals	288.8	95
10 smaller-volume chemicals	0.1	nil
1321 other chemicals	16.5	5
Total	305.4	100

Source: SRI International

The preceding estimates are similar to ones developed by the Office of Technology Assessment, which estimated nearly 50 million tons of hazardous chemicals in the top five five-digit Standard Industrial Classification codes moved by truck in the United States in 1977 (*4*). We made the following calculation to demonstrate comparability: net product availability (i.e., production available for off-site deliveries) for the three chemicals analyzed account for 80 to 90 percent of total production. Approximately 20 to 25 percent of net production moves by truck. Multiplying 305 million tons by 80 to 90 percent and then by 25 percent gives 65 to 70 million tons shipped by truck in 1987, or a level consistent with 3 percent per year growth between 1977 and 1987.

Volume Transported by Truck

A methodology was developed for estimating the volume of a specific hazardous chemical transported by truck. Three chemicals were selected to test the methodology—1 butanol, dodecene-1, and phosphorus pentasulfide. For each chemical, the producers, plant locations, and capacities were identified from existing data bases. Since some chemicals are used in the manufacture of other chemicals at the same plant, the quantities used in this so-called captive production are not available for shipments elsewhere. To calculate captive production, other chemicals produced in the same plant as the chemical under investigation were identified and the amount of the chemical under investigation that is needed in the production of these other chemicals was determined. When this quantity was subtracted from the estimated production capacity, the net product availability for shipment off-site was determined.

The plants consuming the chemicals were next identified as well as their locations and the total quantity of the chemical needed to meet each plant's requirements. By subtracting the quantity of the chemical produced at the plant from the total plan requirement, the so-called net product requirement was calculated. For example, if Plant A produces 100 short tons of Chemical X and requires 50 tons of Chemical Y in the manufacture of Chemical X, then Plant A must either produce 50 tons (or more) of Chemical Y or obtain it from another plant or company. If a fraction of the 50 tons (e.g., 25 tons) is produced at Plant A, the net product requirement for Chemical Y is 25 tons.

Once these data were assembled, specific information from secondary sources and discussions with industry representatives was obtained on a chemical-by-chemical basis to estimate modal splits. The steps used to calculate modal share were as follows:

- The modes used to ship each chemical were determined through data from the ICC 1 percent Waybill sample, review of waterborne commerce and other data, and interviews with producers and consumers of the chemical.
- Using the information gained from the preceding sources, the modes that generally would be used for shipment sizes and location of shipping and receiving plants for each chemical were determined. For example, large consumers (e.g., those

requiring over 2,000 short tons per year) generally are served by rail or barge rather than truck; origin-destination pairs along inland or coastal waterways tend to use barge or ocean vessels for large shipments.

- Locations of terminals for each chemical, if any, were identified.
- Chemicals with multimodal shipments were identified; for example, rail to a terminal and truck from the terminal to the consumer.
- Rules (described in the next section) were established for each chemical to identify the mode or modes used to deliver shipments to each consumer. Using these rules, the amount of each chemical moving by truck to each consuming plant was estimated.

Gravity Model

A gravity model was developed to assign product flows between producers and consumers. A standard gravity equation was initially used to develop the model, although adjustments were made to make the model appropriate to the specifics of the analysis. Because there were no data available for model calibration, standard coefficients were applied, as described later.

Basic Model

The underlying theory of a gravity model in transportation is similar to Newton's law of universal gravitation, which states that the attractive force between two bodies is proportional to the product of their masses divided by the square of the distance separating them. This model subjectively conforms to the general notion of how one might consider cargo flows to be apportioned between producers and consumers. The shorter the distance between an origin-destination pair, the greater the likely cargo flow between them. Also, the larger the industrial activity in the origin-destination pair, the greater the likely cargo flow between them. This is a widely applied and accepted model and has been shown to be a fairly good predictor of movements (*4*).

To demonstrate how gravity models work, consider chemical production sites, $p(i)$, and a series of consumption plants (sites), $a(j)$. Furthermore, assumed that distance, cost, or some other measure of impedance between Locations i and j is available and termed $r(i, j)$. The basic premise of the gravity model is that the flow from Origin i to Destination j will be proportional to

$$\frac{p(i) * a(j)}{r(i, j)^2} \tag{1}$$

More specifically, the flow, $f(i, j)$, from Origin i to Destination j is given by

$$f(i, j) = K * \frac{p(i) * a(j)}{r(i, j)^2} \tag{2}$$

where K is the proportionality constant. Often K is computed as an appropriate normalizing factor to make the double sum of the $f(i, j)$ equal to some already known total flow.

When historical data are available, the gravity model is often generalized to the form

$$f(i, j) = K * \frac{p(i)^L * a(j)^M}{r(i, j)^N} \tag{3}$$

where the exponents L, M, and N together with the factor K are calibrated from historical data using a least-squares approach. Unknown future flows can be estimated using the right-hand side of Equation 3. In addition, a normalization is usually required, effectively replacing K in Equation 3 by the quantity $K' * K$, where K is derived from the least-squares calibration and K' from normalizing the double sum of the $f(i, j)$.

Most practical implementations of the gravity model differ somewhat from Equation 3, and the implementation used in this study is no exception. In particular,

- Each $p(i)$ is equal to net production available for truck shipments at Plant i;
- Each $a(j)$ is set equal to the estimated demand for the chemical delivered by truck at Plant j;
- Because historical data on hazardous chemical shipments are not available, the standard practice was used of assuming that L and M equal 1 and N equals 2 (*5*);
- The impedance relation, $r(i, j)$, was initially taken as the distance between the plants, but was subject to further modifications, as explained later in this section; and
- The normalization was done individually for each consuming plant, changing the value of K in Equation 3 into $K(j)$.

Captive Consumers

Adjustments were made to the model to reflect captive consumers, that is, consuming plants owned by the same parent company as producing plants. The modification affects the impedance function, $r(i, j)$. For plants owned by the same company, the impedance between the two points was multiplied by an affinity factor, C, where $0 < C < 1$. Because $r(i, j)$ is squared, the affinity factor effectively increased the attractiveness between two plants owned by the same company by a factor of $1/C^2$. Using $C(i, j)$ as the affinity factor to adjust the impedance function, replacing K with $K(j)$, Equation 3 becomes

$$f(i, j) = K(j) * \frac{p(i) * a(j)}{[C(i, j) * r(i, j)]^2} \tag{4}$$

For this study, the affinity factor, $C(i, j)$, was set equal to ⅓ when origin Plant i and destination Plant j were owned by the same company, and equal to 1 when they were not.

Terminals

Distribution of one of the chemicals analyzed involved terminal facilities. A producer may serve a consumer with direct shipments from the production facility or by shipments from a terminal. To account for terminals, the model was adjusted as follows: each consumer was allowed to be served by each producer, but the method of service from the producer was based on the "least-cost" impedance. To compute the least-cost impedance, the total rail miles from the producing plant to each terminal was obtained. The rail miles were converted into truck-equivalent miles by using a conversion factor of 40 percent. That is, each rail mile costs about 40 percent of a truck mile. This estimate was based on the results of telephone discussions with railroads and trucking companies involved in transporting chemicals. If a producer had, for example, two terminals, the effective impedance to a consumer was calculated for direct truck shipments from the plant and for transshipments through each of the two possible terminals. For shipments directly from the producing plant, the impedance was simply the road mile distance; for the terminals the impedance was the truck-equivalent miles from the producing plant to the terminal plus the actual road miles from the terminal to the consuming plant. The smallest of these impedances was selected for use by the gravity model to calculate the flow matrix. All flow from Producer i to Consumer j was assumed to move only through this minimum impedance route; flows from the producer's other terminals to this consumer were set to zero. The formula for determining the $r(i, j)$ component of impedance then became

$$r(i, j) = \min[d(i, j); e(i, 1) + d(1, j); e(i, 2) + d(2, j) \ldots] \tag{5}$$

where $d(i, j)$ denotes the highway mileage between the production plant or Terminal i and consumption Plant j, and $e(i, k)$ denotes the truck-equivalent miles (calculated as 40 percent of railway miles) between the production plant and Terminal k.

Normalization To Satisfy Constraints

The origin-destination flow matrix was doubly constrained:

- The sum of each column must equal the amount consumed by destination Plant j, or $\Sigma_i f(i, j) = a(j)$.
- The sum of each row must be less than or equal to the amount available at origin Plant i, or $\Sigma_j f(i, j) \le p(i)$.

The initial flow matrix $f(i, j)$, denoted $f^I(i, j)$, was originally completed using Equation 4 with all $K(j)$ set equal to 1 (i.e., no normalization, and impedance as defined by Equation 5). Next, a normalization algorithm was applied that attempted to ensure that the matrix's double sum equaled total consumption, that is,

$$\sum_i \sum_j f^P(i, j) = \sum_j a(j) \tag{6}$$

where $f^P(i, j)$ denotes the postnormalization flow matrix. This calculation is done by normalizing individually each column to $a(j)$ to reduce or limit to a single column the distortions any extremely short distance would otherwise produce within the entire matrix. Thus, the normalization constraint in Equation 6 can be restated as

$$\sum_i f^P(i, j) = a(j) \tag{7}$$

and the normalizing factor, $K(j)$, for Column j in Equation 4 is

$$K(j) = \frac{a(j)}{\sum_i f^I(i, j)} \tag{8}$$

As indicated, $\Sigma_j f^I(i, j)$ does not need to equal $p(i)$ because the row sums are only constrained to be less than or equal to available production. In general, the sum of the $p(i)$ usually exceeds the sum of the $a(j)$. However, after the normalization conforming to Equation 8 has been performed, the following additional constraint is checked:

$$\sum_j f^P(i, j) \le p(i) \tag{9}$$

Because the sum of the $p(i)$ was usually larger than the sum of the $a(j)$, the constraint in Equation 9 was often satisfied for all i without the need for any further adjustments. However, if for any i, Equation 9 was not satisfied, an additional normalization was conducted for that row. This row normalization was analogous to the column normalization. The procedure was followed by a series of iterations normalizing in turn by column and by nonconforming row until a convergence observing constraints imposed by both Equations 7 and 9 was achieved or until an iteration limit was reached.

Truncation

The unaltered gravity model has a tendency to assign at least a small increment of flow to all $f(i, j)$. In reality, such small commodity flows do not occur. The model, therefore, has a provision to truncate all $f(i, j)$ below a minimum threshold value and set the cell value to zero. For the applications contained in this paper, the minimum value was set equal to 20 tons per year (or one average-sized bulk truckload per year). The truncation was applied after the completion of all normalizations. To return the remaining flows to balance and conformance with constraints, the normalization algorithm was executed again. Note that, if an $f(i, j)$ was zero, all normalization operations left it unchanged.

Special Cases

During discussions with chemical producers, it was discovered that some consuming plants, as a matter of policy, do not purchase from specified companies regardless of price. For these cases, the appropriate $f(i, j)$s were set equal to zero.

Model Results

The gravity model was applied to the three sample chemicals.

Dodecene-1 (Propylene Tetramer)

Dodecene-1, with an estimated 1987 U.S. production of 200,000 short tons, is in the middle third of the list of 147 chemicals. It is a high-boiling liquid classified as propylene tetramer in Guide 27 (fire explosion and health hazard) in the *Guidebook*. The supply of this chemical is principally from four sources in Texas. (Exports account for about half of U.S. production of dodecene-1), and these shipments move directly from producing plant to oceanborne carrier.) Consumption of dodecene-1 is primarily for the production of branched dodecylbenzene, tridecyl alcohol, and dodecylphenol.

No entries for dodecene-1 under any of its names were available from the 1 percent Waybill sample. However, it was learned that there are rail shipments; because of the small size of these shipments, they may have been missed in the sample or included in an "all other" category.

Discussions with industry representatives indicated that shipments of dodecene-1 move by rail, ship, pipeline, and barge. Eight of the 13 consumers of dodecene-1 were identified as locations receiving truck shipments, but truck shipments account for only about 25 percent of domestic shipments.

Table 3 gives the input data on producing and consuming plants used for the gravity model, and Table 4 gives the resulting flow matrix for dodecene-1.

Of the estimated 11,616 ton-mi of dodecene-1 moved by truck in 1987, nearly 20 percent occurred in Texas, a major consuming and producing state (see Table 5). About 10 percent of ton-miles occurred in Ohio, which has a production facility and a consuming plant that receives 15 percent of the estimated truck shipments of the chemical. About 14 percent of ton-miles occurred in Pennsylvania, a state that has neither production nor major consumption facilities of dodecene-1. Other states with neither production nor consumption facilities that have relatively large percentages of ton-miles include Alabama, Louisiana, Mississippi, Oklahoma, Tennessee, and Virginia. Because the volume of production and consumption of dodecene-1 is relatively small, terminal facilities have not been established to offset the cost of some truck movements.

TABLE 3 GRAVITY MODEL INPUT FOR DODECENE-1

Hazardous Chemical Distribution Gravity Estimation Model—Run Title: DODECENE-1

Parameters for use in this run...
NDIGTRT = 2 (Iteration control and no. digits right of decimal points in flow printouts)
DISTMIN = 1.000 (Distances below this value set to this in gravity equation)
FLOWMIN = 0.020 (Predicted flows below this value truncated to zero)
SAMECOF = 3 if Producer and Consumer same company
PRODEXP = 1.000 (Exponent on production in gravity equation)
CNSMEXP = 1.000 (Exponent on consumption in gravity equation)
DISTEXP = 2.000 (Exponent on distance in gravity equation)

Identifier	Company	Plant Location	ZIP Code	Baseline Impedance	Net Product Availability (Thousands of Tons)
CHV1	Chevron	Houston, TX[a]	77015	0.0	150.00
COA1	Coastal	Corpus Christi, TX	78403	0.0	10.00
SUN1	Sun	Toledo, OH	43693	0.0	23.00
UNO1	Unocal	Beaumont, TX	77704	0.0	10.00
Total Available for Off-Site Consumption					193.00

Identifier	Company	Plant Location	ZIP Code	Consumption (Thousands of Tons)
BUF1	Buffalo	Buffalo, NY	14240	0.60
DIX1	Dixie	Bayport, TX	77062	0.60
GAF1	GAF	Calvert City, KY	42029	1.00
HUM1	Humphrey	North Haven, CT	06473	0.60
LUB1	Lubrizol	Painesville, OH	44077	2.20
MIL1	Milliken	Inman, NC	29349	0.60
MON1	Monsanto	Kearny, NJ	07032	6.00
PHI1	Phillips	Borger, TX	79007	3.50
Total Consumption				15.10

[a] This is a terminal, not a plant. The plant is in Richmond, CA, and the product is shipped by water to the Houston terminal, and from there to customers.

Source: SRI International

TABLE 4 ORIGIN-DESTINATION MATRIX FOR TRUCK MOVEMENTS OF DODECENE-1

IDs		BUF1	DIX1	GAF1	HUM	LUB1	MIL1	MON	PHI1
	Sums	0.60	0.60	1.00	0.60	2.20	0.60	6.00	3.50
CHV1	7.63	0.12	0.60	0.69	0.27	0.13	0.41	2.41	2.99
COA1	0.35	0	0	0.02	0	0	0	0.13	0.19
SUN1	6.66	0.48	0	0.23	0.31	2.07	0.15	3.27	0.15
UNO1	0.45	0	0	0.05	0.02	0	0.04	0.19	0.16

Source: SRI International

1-Butanol (n-Butyl Alcohol)

1-Butanol, which appears in the top one-third of Table 1, is a low-boiling liquid classified in Guide 26 (fire or explosion and health hazard) in the *Guidebook*. The chemical is principally used directly as a solvent and for the production of methacrylate esters, glycol ethers, and butyl acetate.

U.S. production of 1-butanol in 1987 was estimated to have been 575,000 short tons, of which 450,500 short tons was available for shipment to off-site consumers. All production was in the Texas-Louisiana region, whereas consumption of the chemical was concentrated in the Chicago, New Jersey, and Los Angeles areas. Six producers (five of which have terminals) and 67 consuming plants were identified.

Once production and consumption data were collected, shipments by modes other than truck were eliminated. These other means of shipment were determined to be rail and barge through examination of the rail 1 percent Waybill sample, waterborne commerce data, and discussions with producers and consumers of 1-butanol.

On the basis of conversations with major producers and consumers, it was determined that most of the large-volume shipments of 1-butanol are made primarily by barge using inland and coastal waterways. These interviews verified our belief that waterborne shipments are very important in the delivery of 1-butanol to the largest consumers, whose plants are located near navigable waterways. It was also learned that the companies using 1-butanol as a solvent had it delivered by truck in mixed shipments via compartmented tankwagons (cargo tank trucks). However, many of the tankwagon shipments originated from terminals located near major consuming centers, including the Newark, New Jersey, Chicago, Illinois, and San Francisco–Oakland, California, metropolitan areas, and in South Charleston, West Virginia, and Kingsport, Tennessee. 1-Butanol is generally shipped by rail to these terminals and distributed by truck from the terminals to final customers.

Although this study excluded overland movements of international shipments, the levels of exports and imports of

TABLE 5 TRUCK SHIPMENTS OF DODECENE-1 BY STATE, 1987

State Identifier	State Name	Ton-Miles (Thousands)
AL	Alabama	871.9
AR	Arkansas	338.0
CT	Connecticut	34.2
GA	Georgia	139.5
IL	Illinois	23.8
IN	Indiana	33.4
KY	Kentucky	199.4
LA	Louisiana	991.8
MD	Maryland	33.2
MO	Missouri	64.5
MS	Mississippi	509.6
NC	North Carolina	13.2
NJ	New Jersey	428.1
NY	New York	58.2
OH	Ohio	1,145.0
OK	Oklahoma	919.8
PA	Pennsylvania	1,664.0
SC	South Carolina	36.6
TN	Tennessee	791.4
TX	Texas	2,264.4
VA	Virginia	987.1
WV	West Virginia	78.8
Total		11,615.9

Source: SRI International

1-butanol during 1987 were estimated. Imports were negligible (5 short tons). Although 93 thousand short tons of 1-butanol were exported, 93 percent of these shipments departed directly from ports in the Houston-Galveston area. Thus, it is unlikely that a significant amount of 1-butanol is shipped by truck to the ports.

The preceding information and analysis of the rail shipment data led to the conclusion that consumers near navigable waterways received barge shipments. Rail shipments were used for large-volume movements not located along waterways and for movements from production to terminal facilities. Truck movements are generally limited to short-haul (e.g., from a terminal to the end user) or small-volume shipments in drums. Consequently, most 1-butanol moved by rail or barge—only about 20 percent of 1-butanol, measured by tonnage, moved any distance by truck. Furthermore, most truck shipments originated at terminals rather than at the producing plant; only about 12 percent of total truck movements were estimated to originate at the producing plant. Consequently, total ton-miles of 1-butanol truck shipments, estimated at 30,243 in 1987, tended to be minimized through market forces seeking least-cost solutions. As a consequence of the use of terminals, most of the highway miles of truck transport of 1-butanol occurred in either producing or consuming states. There were a few exceptions: for example, Arizona, New Mexico, and Indiana, where truck movements occurred because of transshipment from a producing state or terminal to a consumer. Table 6 gives the estimates of highway miles and ton-miles of 1-butanol moved by truck in each state.

Phosphorus Pentasulfide

Phosphorus pentasulfide, with an estimated U.S. production of 70,000 short tons in 1987, is representative of a chemical in the lower third by size of production of the chemicals given in Table 1. It is a high-melting solid classified in Guide 41 (may ignite in presence of moisture and produce poisonous gas) in the *Guidebook*. Phosphorus pentasulfide is used primarily for production of pesticides and lubricating oil additives. Production occurs in four plants, and there are 13 major consuming plants, widely distributed from the Northeast to the Southeast.

Few shipments were recorded on the 1 percent Waybill sample, and all of these shipments were from the producers to Bayway, New Jersey, or Houston, Texas. No sufficiently detailed data on waterborne commerce of this chemical were available.

Phosphorus pentasulfide was shipped directly from producing plants to consumers by rail and truck. Some specific information was obtained that was used to adjust the input to the gravity model: one of the four producers did not sell phosphorus pentasulfide on the merchant market, one consuming plant receives shipments only by rail, and one plant does not obtain any phosphorus pentasulfide from the closest producing plant.

The model results indicated that about 88 percent of the shipments of phosphorus pentasulfide moved by truck. Because of the dispersed nature of production and consumption and the heavy reliance on trucks, an estimated 27,472 ton-mi of phosphorus pentasulfide moved by truck in 1987 (see Table 7). Nearly a quarter of the ton-miles are in Pennsylvania, a state with a production plant. Other states with about 10 to 15 percent of ton-miles are Ohio, Illinois, Indiana, and Missouri. Most of these states have either a production or consumption facility (see Table 7).

CONCLUSIONS

The primary objective of the research was to determine whether secondary data sources can provide estimates of truck move-

TABLE 6 TRUCK SHIPMENTS OF 1-BUTANOL BY STATE, 1987

State Identifier	State Name	Ton-Miles (Thousands)
AL	Alabama	1,019.1
AR	Arkansas	81.6
AZ	Arizona	1,061.7
CA	California	7,292.4
CT	Connecticut	187.3
DC	District of Columbia	23.3
DE	Delaware	182.2
FL	Florida	39.8
GA	Georgia	440.3
IA	Iowa	30.5
IL	Illinois	1,280.8
IN	Indiana	1,678.3
KS	Kansas	57.4
KY	Kentucky	240.6
LA	Louisiana	1,611.5
MA	Massachusetts	10.2
MD	Maryland	355.3
MI	Michigan	2,319.4
MO	Missouri	139.0
MS	Mississippi	553.9
NC	North Carolina	1,753.8
NJ	New Jersey	671.6
NM	New Mexico	442.6
NY	New York	56.0
OH	Ohio	867.8
OK	Oklahoma	92.0
PA	Pennsylvania	121.7
SC	South Carolina	241.4
TN	Tennessee	363.1
TX	Texas	3,202.0
VA	Virginia	2,077.4
WI	Wisconsin	114.8
WV	West Virginia	1,634.1
Total		30,2242.7

Source: SRI International

ments of hazardous materials within the United States, and, if so, the relative degree of accuracy of these estimates. On the basis of the study results for the three chemicals evaluated, we determined that secondary sources can provide reasonable estimates of truck moves.

- The 147 large-volume chemicals that constitute at least 80 percent of truck movements of hazardous chemicals in the United States were identified.
- The total volume of shipments for each of the 147 chemicals by all modes of transportation within the United States can be estimated from secondary sources.
- The number of producers for the three chemicals evaluated ranged from 4 to 6, and the number of consuming plants ranged from 13 to 67. Therefore, it was possible to contact many of the major producers and consumers with a minimum of difficulty.
- On the basis of experience with the three chemicals evaluated, we believe that the origins (producers) and destinations (consumers) of the 147 chemicals can be determined for all but minor consumers. That is, for the three chemicals evaluated, we were able to identify a very high percentage (about 80 to 90 percent) of the consumption of the chemicals by specific plant location. For one chemical, dodecene-1, there was considerable international trade that was not evaluated in this research.
- The modal split for each chemical was estimated using an approach that reflects the specifics of the chemical, locations of production and consumption facilities, and size of shipments. Data to estimate modal split were obtained from the ICC 1 percent Waybill sample, other secondary sources, and interviews with producing and consuming companies.
- When producers or consumers are concentrated in one or a few areas, the volume of ton-miles moving through various states is not significantly affected by the allocation of flows by the gravity model. For 1-butanol and dodecene-1, most of the supply is from Texas, and plants are situated close to each other. Consequently, the same highway routes would be used to move chemicals to consuming plants in the Northeast or Midwest, irrespective of producer.
- The use of terminals can significantly reduce the ton-miles of chemicals transported by truck, especially in states that are neither producers nor consumers of the chemicals.
- As indicated in Table 8, the percentage of production moved by truck is negatively correlated with volume of production for the three chemicals studied. Whether this is true for all 147 chemicals is unknown, although it seems likely.
- Table 8 also indicates the average net consumption of plants using truck transport compared with other modes. Truck deliveries are significantly lower for the two chemicals evaluated with the largest volume of production (1-butanol and dodecene-1).

TABLE 7 TRUCK SHIPMENTS OF PHOSPHORUS PENTASULFIDE BY STATE, 1987

State Identifier	State Name	Ton-Miles (Thousands)
AL	Alabama	449.8
AR	Arkansas	333.4
DE	Delaware	37.5
GA	Georgia	20.8
IL	Illinois	3,156.4
IN	Indiana	2,800.4
KS	Kansas	871.0
KY	Kentucky	38.0
LA	Louisiana	914.1
MD	Maryland	153.0
MO	Missouri	3,254.3
MS	Mississippi	1,514.5
NJ	New Jersey	996.0
OH	Ohio	4,484.7
OK	Oklahoma	344.1
PA	Pennsylvania	6,356.4
TN	Tennessee	412.6
TX	Texas	647.8
VA	Virginia	461.9
WV	West Virginia	225.8
Total		27,472.4

Source: SRI International

- The volume of production and consumption may not be accurate guides for estimating ton-miles of the chemical transported by truck because the mid- to larger-volume chemicals tend to be handled by modes other than truck, whereas the smallest-volume chemicals of the 147 evaluated may rely almost exclusively on truck transportation. For example, consumption of 1-butanol was nearly 7 times the volume of phosphorus pentasulfide in 1987, but truck ton-miles of phosphorus pentasulfide nearly equaled truck ton-miles of 1-butanol. (Because of its very hazardous nature, special handling is necessary.)
- The approach presented in this paper provides valuable information on truck movements of hazardous chemicals in the United States. If all 147 chemicals are evaluated, the data base will be able to provide (*a*) estimates of total ton-miles of large-volume hazardous chemicals moving in the United States by mode; (*b*) estimates of large-volume chemical truck ton-miles moving through each state; (*c*) information on whether terminal facilities reduce truck ton-miles of specific chemicals through intermediate (nonproducing or consuming) states; and (*d*) a listing of producers, consumers, and types of transportation used to serve markets.

TABLE 8 TRUCK AND NONTRUCK PRODUCTION AND TRANSPORTATION BY CHEMICAL

	1-Butanol	Dodecene-1	Pentasulfide
Off-site consumption (000's tons)	401.7	59.5	59.4
Truck transportation (000's tons)	83.2	15.1	52.5
Percent truck (percent)	21	25	88
Plants receiving chemical by barge or rail transportation			
Number	13	5	1
Average annual consumption (000's of short tons)	50.38	20.08	less than 10
Plants receiving chemical by truck transportation			
Number	54	8	12
Average annual consumption (000's of short tons)	1.54	1.89	4.37

Source: SRI International

FUTURE WORK

The results indicated that the procedure developed is worth further study. Over the next year, the authors plan to conduct the following research:

- Develop a graphics package to display model results visually,
- Test the results against known incident and spill data as a means of verifying reasonableness of the estimates, and
- Apply the methodology to additional chemicals to further refine the general results.

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Selecting Criteria for Designating Hazardous Materials Highway Routes

Mark Abkowitz, Mark Lepofsky, and Paul Cheng

Passage of the 1990 Hazardous Materials Transportation and Uniform Safety Act in the United States will result in state designation of hazardous materials through routes. Several alternative criteria have been recommended for consideration in implementing this policy, many of which represent explicit trade-offs in terms of safety and operating efficiency. The impact of using alternative criteria and criteria weighting for route selection is explored. This is examined through the use of a network analysis tool designed explicitly for hazardous materials distribution risk management. A study region consisting of the truck highway network in Southern California is used to illustrate several considerations that will need to be addressed during the implementation process. A number of findings are reported concerning route selection, risk equity, public perception, and emergency preparedness. Collectively, they identify the types of problems that may be encountered in the establishment of routing guidelines by the states, implementation of state route selection procedures, and issues related to federal preemption. Areas in need of additional study are also described, with an eye toward establishing some standardization in approach and perhaps analysis tools that would satisfy both state and industry concerns.

The safe movement of hazardous materials (including wastes) is receiving increased attention because of growing environmental awareness of the potential health effects of a release-causing incident. Pressure has been placed on the regulatory process to designate routes for dangerous goods transport that emphasize safety considerations. Notwithstanding the importance of operational safety, the efficiency with which these movements occur remains an important objective.

The significance of this problem is apparent. It is estimated that 1.5 billion tons of hazardous materials are shipped annually across the nation's transportation systems (excluding pipelines); moreover, these volumes are growing (*1*). As these shipments occur between large numbers of shipping and receiving points in the continental United States, routing policy will have a profound effect on the pattern and volume of hazardous materials flow.

The impact of using alternative criteria and criteria weights for the selection of designated hazardous materials transport routes is explored. This analysis has been motivated by the provisions of the 1990 Hazardous Materials Transport and Uniform Safety Act, in which multiple criteria have been suggested for consideration in determining highway route selection. Several important findings are reported that have the potential for significantly influencing policy and program implementation in this area.

The analysis was performed using HazTrans, a risk management, routing, and emergency planning software tool, designed explicitly for application to the transport of hazardous materials. (HazTrans is a registered trademark of Abkowitz and Associates, Inc.) Although HazTrans is capable of representing any point-to-point movement by highway, rail, barge, or intermodal transport in the continental United States, this analysis was purposely focused on highway shipments of hazardous materials in Southern California. Restricting the geographical area of interest to a relatively small study region was sought to demonstrate that even for a limited application, major findings emerge with significant policy implications. Not only do these findings appear to be transferable to other geographical regions of the country, but the issues have the potential for becoming more contentious with increasing shipment length and number of states involved.

SYSTEM DESCRIPTION

Conceptually, HazTrans consists of two major components, a mapping system and an analysis methodology, which are fully integrated. The mapping system uses geographic information systems referencing that enables the user to display color maps of the continental U.S. highway network or subsystems (e.g., Interstate highway system only), and provides the capability for the user to "zoom" into or out from a geographical area at whatever level of precision is desired (*2*). The mapping system also permits labeling of the highway network from a choice of several descriptors, such as route number, city name, segment number, and segment length (*3*).

Once a routing analysis has been conducted, additional features are included in the mapping system to permit the user to observe the analysis results on the screen. These include color-coded drawings of the most effective route based on the routing criteria selected by the user, relevant evaluation measures for the selected route, and an ordered listing of route segments traversed from the point of origin to the shipment destination.

The routing analysis component consists of the following features: (*a*) system selection, (*b*) criterion selection, (*c*) origin and destination specification, (*d*) node/link inclusion or exclusion, and (*e*) highlight identification.

Criterion selection allows the user to identify which routing criteria to apply to the analysis. Presently, five criteria and several variations are available for selection: (*a*) minimize shipment distance, (*b*) minimize travel time, (*c*) minimize release-causing accident likelihood, (*d*) minimize population exposure, and (*e*) minimize "risk" as defined by federal rout-

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ing criteria guidelines (*4*). Travel time on the road network is derived using formulas developed by the American Association of State Highway and Transportation Officials and the Federal Highway Administration (*5*).

If population exposure is selected as a routing criterion, the user is asked to specify the bandwidth of exposure from the transport segment from a choice of 0.25, 0.50, 1, 3, 5, and 10 mi. These distances correspond to evacuation distances for various hazardous materials according to the DOT *Emergency Response Guidebook* (*6*). Population is computed directly from U.S. Bureau of the Census digitized residential population files, overlaid on the respective transportation network (*7*).

If release-causing accident likelihood is selected, accident rates are derived on the basis of truck accident rates involving hazardous materials movements for the different functional classifications that appear in the U.S. highway network (*8*). Release probabilities are based on various container configurations and highway location (*9*).

Beyond representing the classic definition of risk (release-causing accident likelihood multiplied by exposed population), the analyst may also distinguish between technical and perceived risk, so that differences between public perception and technical judgment can be identified and addressed by the risk communication process.

The user is not restricted to a single criterion selection for each analysis. Rather, multiple criteria may be selected, and the user can adjust the weights on each criterion to reflect the importance of each in defining an effective route. This feature is extremely useful for assessing the implications of selecting preferred routes on the basis of alternative criteria and ranking of their importance (*10*).

Origin and destination selection permit the user to specify the movement under consideration. These shipping and receiving locations can be identified by either designating an appropriate point in the transport network or selecting an appropriate zip code.

Node/link inclusion or exclusion are powerful techniques for requiring a shipment to pass through or avoid specific locations during the conduct of an analysis. This permits the user to identify the most effective route if the shipment must pass through a location, either to drop off or pick up a partial load, or because routing regulations require the use of a certain transport segment. It also provides for avoidance of locations where routing restrictions apply or it is determined that the location is unsafe due to excessive accident likelihood, population exposure, or some other reason. In cases where the user wishes to perform a risk assessment on a specific route, the route restriction function can be used to designate this route for exclusive consideration.

Highlight selection allows the user to specify conditions of road segments, which, if not met, can result in either identification of these sites on the map or the exclusion of these segments from analysis consideration. For example, what might appear to be the preferred route for a shipment in terms of the entire movement from origin to destination could pass through individual network segments where accident likelihood or population exposure exceeds a level that the user may consider to be unacceptable. The user can subsequently determine whether to impose special conditions on these high-hazard locations, such as the use of escorts, or could remove the segment from subsequent routing consideration.

HazTrans also comes with a powerful editing capability that allows the user to query the characteristics stored within any physical segment of the road system. When this information is displayed, the user may opt to change certain characteristics to reflect updated status (e.g., new accident rates) or to handle "what if" scenarios (e.g., lane expansion). Both temporary and permanent changes to the system can be accommodated through the edit feature.

ANALYSIS METHODOLOGY

The five criteria available for consideration represent a wide range of safety and efficiency issues associated with hazardous materials shipments. Minimization of distance or travel time reflect the way in which hazardous goods would be moved in the absence of any constraints imposed by safety regulation. Most carriers would operate under minimum travel time conditions, favoring Interstate and other major highways in lieu of minor roads that may save a few miles but take much longer to traverse.

Minimization of release-causing accident likelihood and population exposure represent separate safety components. Taken collectively, however, they represent the traditional definition of risk, consistent with the definition of risk used in federal routing criteria guidelines (*4*):

$$\text{Risk} = \sum_{i=1}^{n} (\text{RATE}_i)(\text{POP}_i) \qquad (1)$$

where

n = total number of segments composing the route,
RATE_i = release-causing accident rate on Segment i, and
POP_i = exposed population within a specified distance band on Segment i.

This measure is unitless in dimension, although it is extremely useful for comparison purposes among various routing alternatives.

To structure the analysis methodology, therefore, travel time and risk were selected as criteria of primary interest. Population exposure embedded in the risk measure was defined as the population residing within a 5-mi band of the transport segment. This corresponds to a typical evacuation range for poisonous-by-inhalation chemicals such as chlorine.

The transport network selected for the analysis was the highway network in Southern California. All Interstate, state, and U.S. highways in Southern California were represented, and a variety of shipment origins and destinations were specified for analysis consideration. As mentioned previously, the limiting of the application to such a small region does not appear to have compromised in any way the transferability of the results to intrastate movements in other states or to interstate transport.

ANALYSIS RESULTS

The following discussion documents the results of a number of routing analyses performed in the study area on the basis of the prescribed methodology. Several cases are reported, each illustrating important findings from this exercise.

Case 1: I-10 at Arizona Border to Vandenberg, California

A number of analyses were performed on this shipment using alternative criteria and criteria weights. These ranged from a route designation based on minimizing travel time to one based on minimizing risk. Several additional applications were performed in which both criteria were considered simultaneously, applying corresponding weights to each criterion reflecting various levels of relative importance (e.g., 75 percent travel time minimization, 25 percent risk minimization; 50 percent travel time minimization, 50 percent risk minimization; etc.). In this fashion, the full spectrum of safety and economic trade-offs could be investigated.

Figure 1 shows a map of four distinct routes that emerged from this process. Route 1 represents the route that minimizes travel time. Route 2 was selected on the basis of applying routing criteria with a 75 percent weight on travel time minimization and a 25 percent weight on risk minimization (the same route was obtained when risk and travel time were weighted equally). Similarly, Route 3 represents an application of criteria with a 25 percent weight on travel time minimization and a 75 percent weight on risk minimization, and Route 4 is based exclusively on risk minimization.

Several observations are apparent when reviewing these results. First, the application of different criteria and criteria weights results in the selection of different preferred routes. Although this result may be intuitive, this finding confirms that when risk criteria are applied, routes other than what would currently be used by industry are selected. It also suggests that this may become a contentious issue since carriers would be required to take a more circuitous route if risk minimization is mandated or recommended as a route designation guideline.

Another important and related finding is that if designated routes are based solely on risk minimization, they result in selection of routes that are so circuitous that they appear to be economically infeasible. As noted in Table 1, Route 4 more than doubles the travel time compared with the minimum travel time route (Route 1). Furthermore, although this route minimizes risk because of the low population exposure, the likelihood of an accident actually increases because of the longer time exposure and use of lower-quality roads. This suggests that any reasonable system of designated routes must seek a compromise solution that introduces improved safety without making the trip extremely cumbersome. The important implication of this finding is that routing regulation should not be based exclusively on finding the least-risk route. This implies that regulators should focus on practical improvements to safety rather than risk reduction as an absolute goal.

Fortunately, this case also illustrates that this problem may be reconcilable by finding advantageous trade-offs between travel time and risk achieved by adjusting criteria weights. As can be seen in Table 1, Route 2 (75 percent travel time minimization, 25 percent risk minimization) identifies a route that, compared with Route 1, introduces only a 3 percent increase in travel time while reducing risk by 70 percent. This trade-off would improve public safety considerably with a negligible effect on carrier efficiency. Similarly, Route 3 introduces an 8 percent increase in travel time while reducing risk by 82 percent.

Emergency Response

The trade-off introduced by evaluating economic and safety criteria becomes even more complex when emergency preparedness is included in the decision process. A data base of California Highway Patrol response locations was used to evaluate response coverage to segments of the routes shown

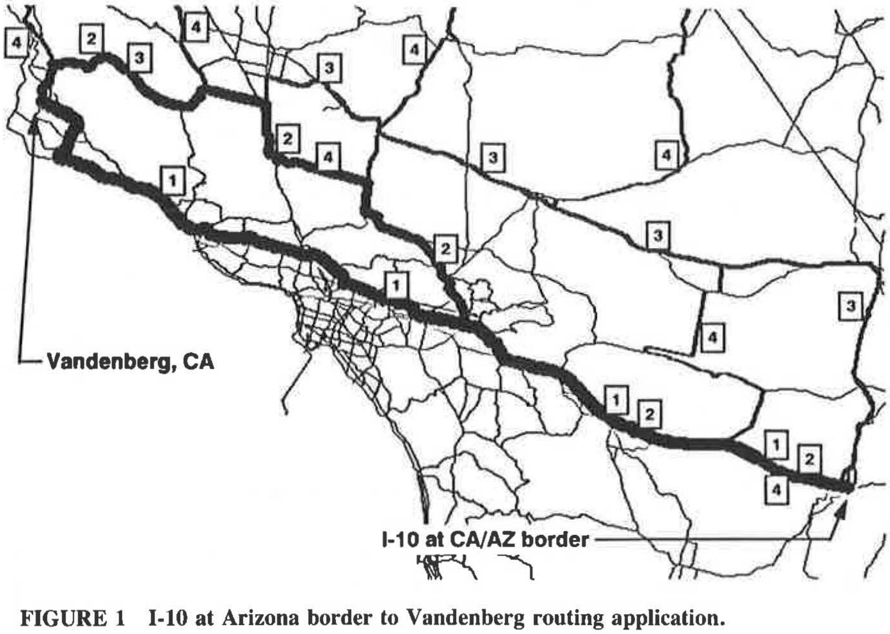

FIGURE 1 I-10 at Arizona border to Vandenberg routing application.

TABLE 1 CASE 1 ROUTE ANALYSIS IMPACTS

Route	Distance	Travel Time	Population	Accident Likelihood	Risk
1	388.88	7h 55m	3,059,409	0.000306	17.84
2	435.29 +12%	8h 11m +3%	819,688 -73%	0.000376 +23%	5.44 -70%
3	493.14 +27%	8h 32m +8%	214,961 -93%	0.000433 +42%	3.17 -82%
4	973.83 +150%	19h 27m +146%	311,859 -89%	0.000613 +100%	0.92 -95%

in Figure 1. For the purposes of this illustration, adequate response coverage was considered to be on-site arrival of a response unit within 45 min of incident report. The results appear as follows:

Route	*Percentage of Route with Adequate Coverage*
1	100
2	97
3	83
4	55

The implication of these results is that routes that travel through heavily populated areas are also likely to have better response coverage. The impact of routing along lower-risk alternatives, therefore, might lead to situations in which incidents that do occur will be subject to lower-quality response. From purely a risk standpoint, this may be considered acceptable. However, from the standpoint of the individuals that reside along these routes, the potential for more severe health consequences can be expected. This suggests that if routes are going to be designated where adequate response does not currently exist, a reallocation of resources to improve response capability in deficient areas is necessary.

Case 2: I-40 at Arizona Border to Vandenberg, California

The only adjustment made for this case is the movement of the shipment origin slightly north to the I-40 border entry from Arizona into California. Route maps are shown in Figure 2, and the route analysis impact is given in Table 2.

As in Case 1, alternative routes are selected depending on whether the criterion is exclusively travel time or risk minimization. However, in this instance, Route 1 prevails across a spectrum ranging from exclusively travel time minimization through a weighting of 25 percent travel time minimization and 75 percent risk minimization. Route 2 appears only when risk minimization is the sole criterion. The trade-off at that point is a doubling in travel time for a much lower percentage reduction in risk.

This case illustrates three additional findings. First, the "inflection" point, the place at which different trade-offs emerge when considering multiple criteria, occurs at different criteria weightings than in Case 1 (see Figure 3). This suggests that a routing policy that sets specific criteria weights to be used in designating routes is not advisable.

Second, this case, when combined with Case 1, illustrates that even minor changes in the location of shipping points modify the transport network and correspondingly the routing alternatives. This result, considered in the context of the hundreds of thousands of daily hazardous materials shipments with different origins and destinations, suggests that a sophisticated network analysis tool will probably be needed to address these considerations.

Finally, this case demonstrates that some shipments will present more reasonable political solutions than others in terms of the trade-off between carrier efficiency and public safety.

Case 3: Capistrano, California, to Thousand Oaks, California

For Case 3, a new origin-destination pair was selected, representing a trip through metropolitan Los Angeles. Two routing

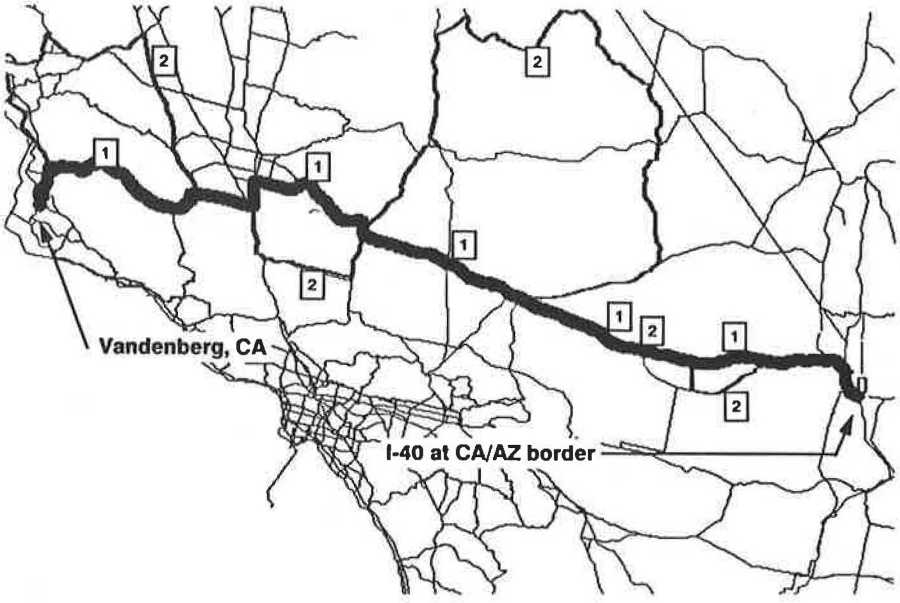

FIGURE 2 Routing from I-40 at Arizona border to Vandenberg.

TABLE 2 CASE 2 ROUTE ANALYSIS IMPACTS

Route	Distance	Travel Time	Population	Accident Likelihood	Risk
1	409.99	7h 5m	195,473	0.000350	2.37
2	864.65 +111%	17h 9m +142%	284,919 -46%	0.000540 +54%	0.76 -68%

analyses were performed, each focusing on the identification of the preferred route based on a criteria weighting of 25 percent travel time minimization and 75 percent risk minimization. The difference between the analyses is that in the first a risk-neutral risk preference is assumed, whereas in the second a risk-averse risk preference is represented. The population bandwidth used for this application was 1 mi.

Risk neutrality, or "technical risk," assumes that one incident causing 100 fatalities is equivalent to 100 incidents causing one fatality each, since in both cases one can expect a consequence of 100 fatalities. Risk aversion, on the other hand, associates a much greater risk with a single incident causing 100 fatalities than with 100 incidents each causing a single fatality. Risk-averse behavior is often thought to be more representative of public perception, particularly as the public views transportation safety. This is supported by public reaction to the very few airline accidents each year that result in multiple fatalities in contrast to highway accidents, which cause few fatalities per accident but result in nearly 50,000 fatalities annually on the nation's roadways.

Mathematically, risk preference is represented in the risk definition as follows:

$$\text{Risk} = \sum_{i=1}^{n} (\text{RATE}_i)(\text{POP}_i)^k \qquad (2)$$

where

n = total number of segments composing the route,
RATE_i = release-causing accident rate on Route Segment i,
POP_i = exposed population on Route Segment i, and
k = risk preference.

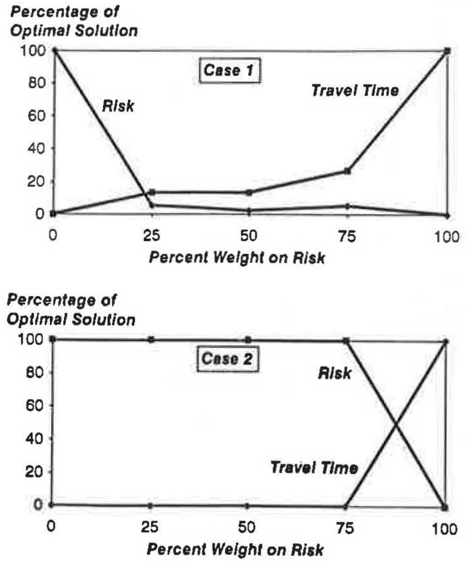

FIGURE 3 Comparative analysis of routing trade-off functions.

In this formulation, a value of $k = 1$ would represent a risk-neutral position, whereas a value of $k > 1$ would represent risk-averse behavior, with greater levels of risk aversion associated with higher values of k.

The mapping and evaluation results of this analysis appear in Figure 4 and Table 3, respectively. As can be seen, the identified routes deviate from one another north of Los Angeles, with the risk-averse path traversing segments with greater accident likelihood but lower population exposure compared with the risk-neutral path. Although it might appear to be less desirable because of its higher accident likelihood, Route 2 emerges as the preferred choice under risk aversion because of the magnified effects of a small reduction in population exposure.

Although statistically the difference between these routes may not appear to be that great, it is important to recognize that the public would perceive a different preferred route in this instance than would be identified using a technical risk measure alone. This, in general, leads to a perplexing question as to which risk measure is more appropriate, since routing is inherently a public policy consideration. At a minimum, it suggests that if regulators use technical risk in their route designation studies, attention must be devoted to the identification of preferred perceived routes, with attempts made to educate the public to recognize the bias in their perception.

CONCLUSION

Several important findings have emerged in the course of this analysis:

- The application of different routing criteria and criteria weights results in the designation of different preferred routes. When risk criteria are included, routes other than those currently used by industry will be selected.
- Route designation based solely on risk minimization will result in the selection of routes that are so circuitous that they appear to be economically infeasible. Furthermore, they will typically lead to higher release-causing accident likelihood, although the consequences should an accident occur are likely to be less catastrophic. Any reasonable system of designated routes must seek a compromise solution that introduces improved safety without making the trip extraordinarily cumbersome.
- Routes that appear to offer reduced risk may often be accompanied by inadequate response coverage. If routes are going to be designated where adequate response coverage does not currently exist, resources should be committed to provide adequate safety standards.
- Advantageous trade-offs can be found among safety and economic criteria by adjusting criteria weights. However, the criteria weighting at which these benefits emerge and the magnitude of these benefits are shipment-specific. Consequently, rules that set specific criteria weights to be used for route designation are not advisable.
- Each origin-destination shipping pair defines a different network of routing alternatives, implying that preferred routes

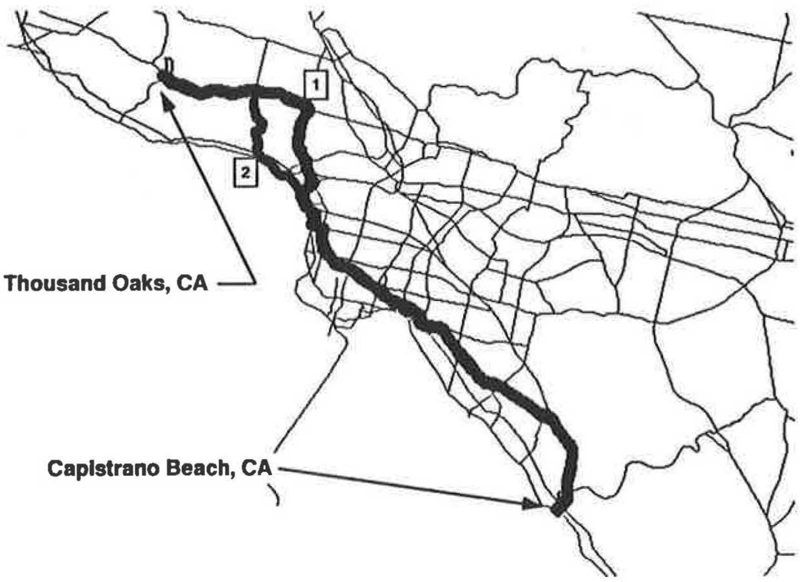

FIGURE 4 Capistrano Beach, California, to Thousand Oaks, California, routing applications.

TABLE 3 CASE 3 ROUTE ANALYSIS IMPACTS

Route	Risk Preference	Distance	Travel Time	Population	Accident Likelihood
1	Neutral	101.48	2h 47m	3,363,710	0.000064
2	Averse	101.33 -0.1%	2h 48m +0.6%	2,906,111 -14%	0.000090 +41%

could be shipment-specific. This raises the question of whether regulators should (*a*) designate a route network or (*b*) designate a methodology that shippers and carriers must use to select routes for the shipment under consideration, particularly for ultrahazardous materials. In either case, the use of sophisticated network analysis tools may be warranted.

- Public perception of preferred routes will differ from those identified on the basis of technical risk. These differences must be reconciled either through incorporation of risk perception into risk assessment methodology or through the risk communication process.

Collectively, these findings identify the types of problems that will be encountered in the establishment of routing guidelines by the states, implementation of state route selection procedures, and issues related to federal preemption. Additional study is clearly warranted, with an eye toward establishing some standardization in approach and perhaps analysis tools that would satisfy both regulatory and industry concerns.

ACKNOWLEDGMENT

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Transit Corridor Evaluation: A Guide from a Trade Logistics Management Perspective

J. REBELO AND S. THOMAS

A methodology to evaluate transit corridors from a trade logistics management perspective is proposed. The approach is based on the authors' extensive experience with transit corridors throughout the world and, more recently, on a major effort recently completed by the World Bank to study transit corridors linking landlocked countries (LLCs) to the sea in West Africa. The need to quantify the overall benefits and costs to each of the countries involved is suggested taking into account factors that, at first sight, may not seem directly related to the actual flow of goods but that are perceived by both shippers and freight forwarders to be major determinants in the choice of one corridor over another. Such exogenous factors include but are not limited to the trucking allocation agreements (e.g, the one-third/two-thirds rule) between LLCs and transit countries, the maritime shipping codes (e.g., the UNCTAD 40/40/20 Code of Conduct), customs procedures, freight forwarding fees, and storage policies. Proper quantification of net benefits or costs for each of the countries involved in the transit movement is probably the first step for serious negotiations of transit policies, customs, and trade facilitation procedures between the governments involved. The periodic estimation of those benefits and costs may also serve as a deterrent to unilateral decisions by customs and transport ministries to alter facilitation procedures without proper assessment of the economic and financial impact of those changes on their countries and their importers or exporters.

A major effort to study transit corridors linking landlocked countries (LLCs) to the sea in West Africa was recently completed by the World Bank (*1–3*). The study reiterates the need for an approach that quantifies the overall benefits and costs to each of the countries involved, taking into account factors that, at first sight, may not seem directly related to the actual flow of goods but that are perceived by both shippers and freight forwarders to be major determinants in the choice of one corridor over another. Such exogenous factors include but are not limited to the trucking allocation agreements (e.g., the one-third/two-thirds rule) between LLCs and transit countries (TCs), the maritime shipping codes (e.g., the UNCTAD 40/40/20 Code of Conduct), customs procedures, freight forwarding fees, and storage policies. Proper quantification of net benefits or costs for each of the countries involved in the transit movement is probably the first step for serious negotiations of transit policies, customs, and trade facilitation procedures between the governments involved. The periodic estimation of those benefits and costs may also serve as a deterrent to unilateral decisions by customs and transport ministries to alter facilitation procedures without proper assessment of the economic and financial impact of those changes on their countries and their importers or exporters.

To illustrate the order of magnitude of the costs incurred with transit traffic flows in the Sahelian region, the World Bank study estimates that in 1987, the total direct generalized costs (including ocean shipping costs) for the 337,000 tonnes of transit traffic to and from Mali were approximately U.S. $100 million. The total economic cost for Mali for this transit traffic was roughly 5 percent of the estimated gross domestic product (GDP) for 1987. Payments to other countries for the transit traffic totaled U.S. $48 million, approximately 50 percent of total direct costs. To obtain a significant reduction of the direct cost of transit traffic and of payments to other countries, Mali should attempt to reduce shipping rates for its imports and exports. A reduction of 25 percent of the present conference rates by using a combination of nonconference and tramp shipping would reduce the transport bill by 10 percent and the payments to foreign countries by 18 percent. These results highlight the importance of reducing shipping rates and suggest that Mali should attempt to take as much advantage as possible of the nonconference shipping market. Moreover, an analysis of the composition of total generalized costs of imports to Bamako that originated in Atlantic Europe suggests that shipping rates represent 33 to 37 percent of the cost per tonne, whereas land transit costs and port charges account for 30 to 33 percent and 6 to 9 percent, respectively. Delays in ports and terminals due to low productivity and slow customs clearance and red tape add 29 to 45 percent of total time from origin to destination and are longer than the sea leg of the movement, which represents 29 to 36 percent of the total time, depending on the seaport chosen. Analysis of the composition of total transit time is necessary to identify major bottlenecks and estimate the inventory costs incurred with the movement. The latter reflects the inventory financing costs to the consignee, since the capital invested in the imported goods en route could be earning interest elsewhere. In the case of Mali the inventory costs estimated at a 10 percent interest rate ranged from 7 to 8 percent of total costs.

Similarly, the study estimates that the total costs for Burkina Faso's international traffic in 1988 were U.S. $133 million, or 23 percent of the total value of its imports and exports and 7 percent of its GDP. The land transport portion of that bill was roughly U.S. $73 million (4 percent of GDP), and the ocean shipping costs were estimated at U.S. $33 million (2 percent of GDP). Furthermore, it was estimated that Burkina's general cargo generates annual gross revenues of U.S. $30 million (about U.S. $100/ton) for Côte d'Ivoire and U.S. $3.3 million for Togo (about U.S. $50/ton). In Niger, the total

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World Bank, 1818 H St., N.W., Washington, D.C. 20433.

generalized cost in 1988 for international traffic was estimated at U.S. $150 million or 37 percent of total imports. The land transport cost for that traffic was estimated at U.S. $67 million (3 percent of GDP), and the ocean shipping costs amounted to U.S. $36 million, or 1.5 percent of GDP. The international traffic of Niger generated annual gross revenues of U.S. $25 million (U.S. $100/ton) for Benin, U.S. $7.6 million (U.S. $86/ton) for Togo, and U.S. $3.3 million (U.S. $90/ton) for Nigeria. In short, the costs and benefits involved in transit movements are important, and their proper evaluation is crucial if decision makers are interested in assessing the impact of major changes in transport policy and facilitation procedures.

The technical and economic evaluation of transit corridors that link LLCs to the sea is somewhat complicated, because one must take into account the infrastructure, operations, and institutional aspects in at least two countries and often in more than three countries. Furthermore, the analysis must examine in detail the custom procedures, intercountry agreements, and trade facilitation procedures in all the countries involved. The economic evaluation of improvements in a transit corridor would usually be incomplete if only the effects on transit traffic were considered. Normally transit infrastructure is an integral part of the domestic transport network of the TC. It is the nature of most transport investments that the improvement of the infrastructure for one specific flow will also improve conditions for all other traffic using the same infrastructure. Consequently, three distinct flows may have to be considered: (*a*) transit traffic (between the LLC, the seaport, and overseas), (*b*) domestic traffic (internal transport of goods within the TC or LLC), and (*c*) mutual trade or regional traffic (goods flowing between the LLC and the TC).

To appraise any infrastructural improvement to the transit system, the costs and benefits stemming from each of these individual flows must be estimated. Moreover, as discussed previously, the distribution of net benefits between the LLC and the TC must also be considered. It is necessary to evaluate the financial effects for both countries, and then the real resource effects, because market prices often do not reflect social costs. The appraisal is further complicated when transit goods are carried in vehicles owned by nationals of both the TC and the LLC. The relatively simple appraisal technique used in most transport investments (multiplying total flow by the unit reduction in social costs) is inadequate. A much more complex analysis of flows and costs, together with consideration of competition within the transport sector, is required. The following guidelines were developed from corridor studies carried out by the Technical Department of the Africa Region of the World Bank during the last 2 years and the prior experience of the authors with transit transport throughout the world. It is hoped that the guidelines will help to provide a basic methodology for the analysis of transit corridors linking LLCs to the sea.

DATA COLLECTION AND ANALYSIS

The proposed approach for the evaluation of transit corridors is based on analytical audits of infrastructure, operations and traffic, trade facilitation, trade logistics, and institutions. The audits form the basis of an in-depth economic evaluation of the costs and performance in each corridor. The objectives of the individual audits and possible approaches to their conduct are described in the following sections.

Infrastructure

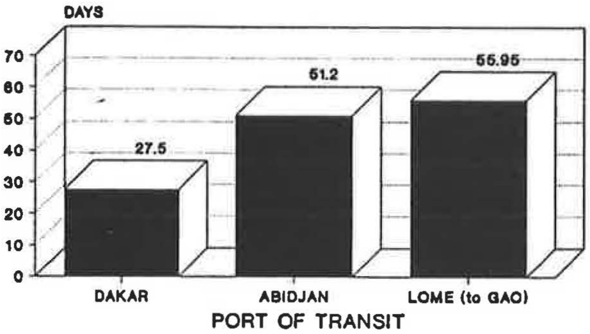
The objective of this audit is to detail the physical characteristics of the infrastructure in each of the identified corridors. The survey would necessarily collect information on both movement links and interchange nodes within the transport corridors. The information required would include

- Transport movement links—distances between major origins and destinations by mode and country (e.g., distance by road from Bamako to border with Côte d'Ivoire and from border to port of Abidjan); specification of infrastructure (e.g., paved, gravel, or earth road or gauge of railway); condition of the infrastructure by main link; speed, axle loads, and other physical restrictions; and number, type, and location of controls and checkpoints;
- Transport interchange and cargo storage points—port infrastructure, port equipment, storage capacity and condition, customs facilities, and specific transit facilities; location, size, and capacity of inland transfer terminals and handling equipment available (e.g., rail/road transfer terminals, railway yards, container terminals, and bonded warehouses); and
- Infrastructure costs—expenditure actually allocated to the maintenance of the existing corridor infrastructure and an estimate of the expenditure that should be allocated for adequate maintenance of the infrastructure.

Operations and Traffic

It is essential to understand how each mode in the corridor operates, what type of equipment is used, performance levels, operating costs, and constraints. The following list gives a guide to the approach needed:

1. Identify detailed time schedules for each mode. This should include loading, unloading, and waiting times; movement times; and delays at customs, checkpoints, and border crossings (see Figure 1). Several transport operators and freight forwarders should be contacted and the schedule prepared by main commodity and consignment type (general cargo, containerized, dry and liquid bulk, etc.). Identify the potential for reducing total transit time and the constraints to such reduction.
2. Identify the characteristics of the vehicle fleets used (e.g., size and axle configuration of trucks and wagons, type of containers, ship type and size).
3. Determine the tariffs charged by each mode or, when applicable, the door-to-door tariff. Because discounts may be common, a range of customers must be contacted. Conference rates are a reference point for ocean shipping tariffs, but, given the extent of discounts used by the conference and "outsider" shipping, best estimates of average tariffs will have to be based on interviews with shippers and freight forwarders.



COMPOSITION OF TRAVEL TIME TO MALI FOR IMPORTS ORIGINATED IN ATLANTIC EUROPE (DAYS)

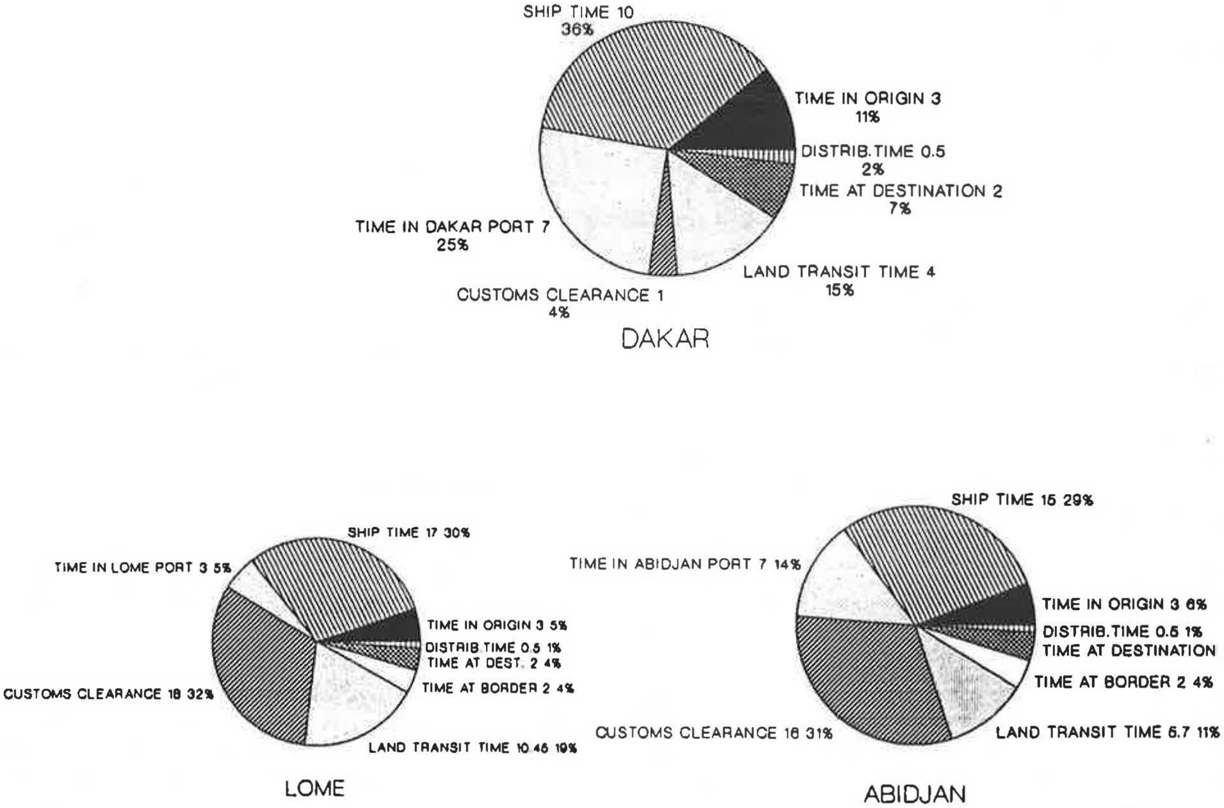


FIGURE 1 Transit times to Bamako from an origin in Atlantic Europe (1987).

4. On the basis of vehicle and infrastructure characteristics, estimate, wherever possible, long-run variable transport operating costs for each mode and corridor. The analysis should determine where inputs, such as fuel and spares, are purchased and the incidence of indirect taxation.
5. Obtain commodity flows via each corridor for the previous 5 years. Regional and transit traffic should be distinguished. Regional traffic refers to trade exchanges between neighboring countries and often involves different procedures and formalities.
6. Understand the organizations operating the corridors—ownership and control, employees, profitability, subsidies, own account versus for hire, and so forth.
7. Obtain information on the operating strategies used by each mode (groupage services, wagonload, block movements, unit trains, etc.).
8. Determine the nationality of the transport operators and whether there are formal or informal traffic-sharing arrangements, national fleet protection, and so forth.

Trade Facilitation

It is essential to understand fully the procedures and documentation necessary for the conduct of foreign trade. This would include the procedures required to obtain import-export licenses as well as the procedures and documentation required for customs clearance. The following approach is suggested for this aspect of the study:

1. Documentation: Identify all documents required for the import or export of each product (import license, certificate of origin, clearance papers, letter of credit, chamber of commerce authorization, shipping documents, etc.), the time required for each document, and the difficulties faced.
2. Freight forwarding: Identify which firms are branches of international freight forwarders and which are local freight forwarders.
3. Freight bureaus: Check whether there is a requirement to use an entity in control of arranging overseas freight movement.
4. Customs procedures for imports-exports in both LLC and TC: Identify the constraints posed by the procedures and the need for and cost of informal payments to customs to expedite clearance. Do informal payments allow underdeclaration of cost, insurance, and freight (C.I.F.) values?
5. Identify nominal and effective use of international customs procedures, such as the Transport International Ferroviaire or the Transport Routier Inter-Etats in the region. Identify use of other procedures, including police- or customs-controlled convoys.
6. Ascertain the availability and quality of telecommunications, telephone/fax/telex. Identify problems with the transmission of documents required for customs clearance.

Trade Logistics

The objective of this audit is to document the overall door-to-door movement by each available route and mode: the delays and constraints, the combined customs procedures, total number of halts or inspection stops, and all the elements that differentiate one route from another.

1. Use the information obtained in the operations audit to determine direct costs for a shipper using that route. Direct costs are only the costs incurred in cash and do not include time-related costs such as delays and reliability or the costs of insurance, loss, or damage.
2. Use the information collected in the operations audit to estimate overall transit times by route and the equivalent inventory costs as a function of the C.I.F. value and financing costs. Estimate also the variability of transit times and the probability of late arrivals (reliability). This information should then be valued as a function of the C.I.F. value.
3. Calculate the cost of insurance for traded goods, the actual loss and damage to goods imported or exported, and the extent to which insurance compensates for such losses. Calculate the total cost of loss and damage provision, including the cost of delay in settling insurance claims.
4. The addition of the direct (Item 1) and indirect (Items 2 and 3) costs will provide an estimate of the overall generalized financial costs to the user. Comparison of the route-generalized costs and the distribution of transport flows may indicate anomalies. Such anomalies should be investigated to determine whether certain costs have been missed or whether shippers place higher valuations on time or reliability (see Figure 2).

Trade-Transit-Transport Institutions

This audit identifies the institutional environment in which the shippers, transport operators, and government organizations perform. The institutional environment often has a direct and significant effect on the costs, capacity, and efficiency of routes. It plays, therefore, a significant role in route and transport mode choices:

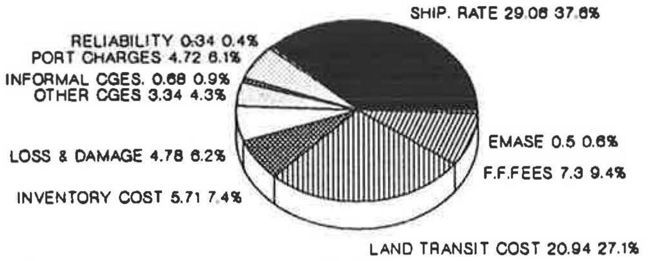
1. The scope and effectiveness of trucking regulation in both LLC and TC on market entry, operations, vehicle loads, tariffs, and so forth;
2. The main institutions involved in transit movements (e.g., shipper's council, chamber of commerce, national shipping company, and trucking association), their roles in the transit process, their relative strength, and the constraints they create;
3. The scale and distribution of private-sector involvement in the freight forwarding and transport industries: size and ownership of companies, local and overseas participation, and extent of competition;
4. Availability of credit and foreign exchange to individual entrepreneurs;
5. The role played by the central bank and commercial banks in trade-transit operations;
6. The effect of parallel markets for foreign exchange on the choice of route/modes/transporters by shippers;
7. Institutional arrangements for trade insurance—role of local insurance companies;
8. The nominal and effective implementation of the UNCTAD Maritime Code (40/40/20 rule); and
9. Traffic sharing between LLC and TC nationals—agreements, institutions, and enforcement.

Any other institutional aspects should be noted in this audit and the constraints they create on their advantages should be clearly documented. The audit should include an analysis of the main institutional constraints within the system and discuss possible reforms of the system. Any proposed reform, such as privatization or total deregulation, should be accompanied by a sketch analysis of whether it is economically feasible and realistic in the social-political-economic environment of the corridor.

ECONOMIC EVALUATION OF INTERNATIONAL TRANSIT COSTS

National Identification of Transit Costs and Benefits

In the analysis of transit corridors, it is essential to understand that, unlike transport within a country, transit necessarily involves at least two countries. In most cases, there is one LLC (e.g., Mali) and one TC (Côte d'Ivoire or Senegal), but there are instances where an LLC (e.g., Burundi) has to cross several TCs (Rwanda, Uganda, and Kenya). Economic costs or benefits can occur for both the LLCs and TCs, and they must be separately identified: an economic cost to one country



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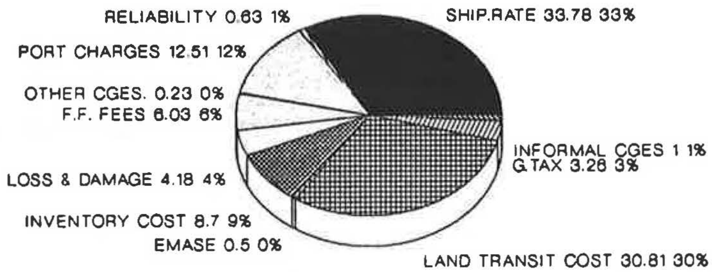

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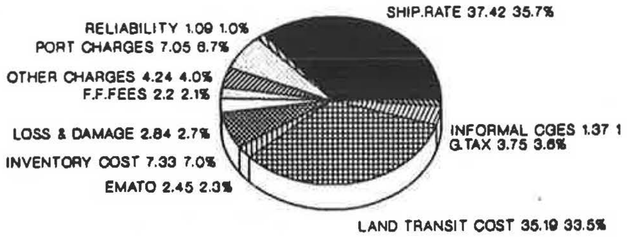

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FIGURE 2 Composition of direct generalized costs, imports to Mali, 1987 (thousands of FCFA/tonne).

may be, at least partly, a benefit to the other. Therefore, the economic costs of these international transit flows cannot be evaluated using the same methodology applied to national transport movement within countries. Each cost must be evaluated from the perspectives of both the LLCs and TCs.

In principle, all charges paid in the transit country (port and storage charges, customs charges, etc.) are economic costs to the LLC. These economic costs should be multiplied by the relevant shadow foreign exchange rate to reflect the true resource loss for the economy of the LLC. The transfer of resources from the LLC may or may not give a real resource gain to the TC. If the transit revenues, multiplied by the shadow price of foreign exchange in the TC, are higher than economic costs incurred in providing these transit services, then there is a social profit or gain for the TC. If, however, the services are priced below their real economic costs, there will be a net economic loss to the TC, and the transit country should adjust its prices to reflect economic cost.

An improvement of the transit system that lowers the transport costs for the LLC may or may not be of benefit to the TC, depending on what that improvement entails in terms of economic benefits or costs to the TC. The private sector (freight forwarders, port administration, container companies, etc.) could receive higher financial gains, but if prices are distorted, the overall economic impact on the country could be negative. The economic evaluation of costs is further complicated by the nationality of the transporter carrying the transit goods. Transit goods are often carried by trucking companies from both the LLC and TC, and there are often agreements regulating national shares in the international trucking market (the trucking agreement between Mali and Côte d'Ivoire stipulates a ratio of 2:1 in favor of Malian trucks).

If the transporter is from the LLC, the costs of truck transport are the economic costs of vehicle operations. Estimation of these costs can be complex:

1. Inputs purchased in the TC valued at financial price adjusted by the shadow price of foreign exchange;
2. Inputs purchased in the LLC valued net of indirect taxes and the foreign content adjusted by the shadow price of foreign exchange;
3. Basic labor costs adjusted by the shadow price of labor, foreign exchange payments for trip expenses adjusted by the shadow price of foreign exchange; and
4. Vehicle annual capital charges estimated on the basis of the real capital cost adjusted by the shadow price of foreign exchange and the social discount rate of the LLC.

If the transporter is from the transit country, the transport charge can be considered as an economic cost and should be multiplied by the shadow price of foreign exchange. Minor adjustments would need to be made for any border taxes or tolls levied by the LLC on foreign trucks or indirect taxes if a significant volume of inputs is purchased within the LLC. If the transporter is controlled by the LLC until the border and by the TC from the border to the port [e.g., Mali Railways (RCFM) to the Senegal border and then Senegal Railways (RCFS) to Dakar], a combined approach is necessary. In the case of the Mali-Senegal rail movement, the total transit resource cost would be the sum of the economic long-run variable railway cost of RCFM to the border and the tariff charged by RCFS from the border to Dakar, multiplied by a shadow price of foreign exchange in Mali.

All other costs involved in the movement of goods (shipping rate, storage charges, port charges, and distribution charges) should be examined in a similar fashion (i.e., determining economic costs on the basis of who incurs the costs and where). The same costing approach should be applied to the other components of generalized transport costs (inventory costs, loss and damage, etc.), which are discussed in detail elsewhere (*1*).

Route and Mode Choice

User's Perspective

A Malian importer deciding whether its imports from France should go via the Port of Dakar (Senegal) and then by rail to Bamako or by the Port of Abidjan and then by truck to Bamako would not only consider the freight costs (freight bill to the port) involved but also other factors that in the industrialized countries are generally taken for granted. For example, the Malian importer or its agent will in most cases investigate the average time the shipment takes at each port, the delays at the border, the degree of loss and damage due to pilferage or poor handling, the availability of truckers and railcars at the ports, and the respective waiting time and the cost of informal charges required to move the freight to Bamako. Furthermore, the agent will check whether there are special taxes on each of the ports and the reliability of the trip times normally suggested by the truckers or indicated in the rail schedules. He knows that his goods, for which he already paid an F.O.B. price to either Dakar or Abidjan, cost an additional amount of money for each extra day they stay en route. This cost is, at least, equal to the interest he forgoes if he had the amount equivalent to the cost of the money in a bank account. How can he capture all these costs to know what is the actual "freight bill"? He needs to look at the generalized cost [i.e., the freight bill (tariff) plus all the other time-related costs representing inventory costs plus reliability plus the informal charges he must pay to get the goods to his door].

There is nothing new in the concept of generalized cost. Most logit models used to estimate modal split in urban transport compare the preference of the user for two or more modes that are weighed against each other by comparing their generalized cost, which includes the tariff plus the waiting time due to different frequencies, the reliability of the system, and some value of comfort. The user who wants to minimize costs will choose the route with lower generalized costs. The modal split usually reflects this, not just the tariff.

Government's Perspective

Whereas the private shipper or importer tries to minimize its costs (although most often it does not pass on its savings to consumers because in most developing countries there is hardly any competition), government has another perspective. Indeed, government not only wants to minimize the overall economic costs of imports but also wants to increase the net revenues generated by these shipments by internalizing most of the expenses and revenues generated by the transit movement. For example, in the Dakar-Bamako rail route both Senegal (TC) and Mali (LLC) would split the rail revenues according to the tariffs they practice. Each country would receive a share of the rail revenues proportional to the distance traveled. In the Abidjan-Bamako truck route the revenues generated by the movement will in general go to the country to which the trucking firm belongs, and since the assignment of the truckers is made according to the one-third/two-thirds rule, in which truckers will be 33 percent from the TC and 67 percent from the LLC, the revenues will in general be split that way. However, since most of the truckers have to wait several days in Abidjan for their turn to pick up cargo, they generate expenses, which represent net revenues for Côte d'Ivoire. In addition, they also tend to fill their trucks as much as they can in Côte d'Ivoire, because fuel is cheaper than in Mali. In the process, they may not be paying their fair share of road user charges in Mali while they are paying it in Côte d'Ivoire.

So, although LLC governments want to keep a certain route diversification to avoid being captive to only one TC, they also want to know how much the revenues are that they generate to the TCs through transit movements so that they can strike reasonable agreements in the sharing of infrastructure investments in the railways, roads, and ports; in the customs area; and in the trucking and shipping arrangements. That is why a method should be used to first estimate the direct generalized cost from the point of the user or on a commodity basis, and then averages should be used in a more complex spreadsheet to determine the economic benefits and costs for the LLC and TC.

Generalized Transport Costs: Concept

Since a primary measure of effectiveness to compare costs and benefits for the LLCs and TC is generalized transport cost by route and mode, it is important to discuss the concept of generalized transport cost in some detail. Direct transport and transit charges are only elements of much larger total transit-transport costs faced by the LLC. The concept of generalized cost is based on the fact that direct costs are only one element of the total transport cost. The prices charged for handling and moving freight are important, but the same is true for the costs attached to average transit time, the reliability of delivery times, and the loss and damage to goods [reliability and loss and damage are defined elsewhere (*1,4*)]. For example, the longer the transit times, the higher are the inventory financing costs for the owner (consignee), because the capital invested in the goods could be earning interest elsewhere. These other, more indirect transit costs may, when taken together, be far higher than the direct transport prices charged, although they are not reflected in terms of immediate out-of-pocket costs. Any improvement that reduces the direct costs of transport may also affect these other elements of generalized cost and thus the total benefits of the improvement.

The concept of generalized cost is not unique to the transport of transit goods and applies to all freight movement. Generalized costs explain why goods do not always travel by what is apparently the cheapest route. It is, however, of particular importance in the transit situation, where most of the benefits from a reduction of "other costs" in the TC are usually internalized within the LLC. Three other costs are thus of little economic significance to decision makers in the TC unless they can be appropriated by changes in pricing policies.

OVERALL EVALUATION OF TRANSIT IMPROVEMENTS

From the analysis of the effects of an improvement to the transit system, a stream of net benefits for each country will emerge (see Table 1 for an example). The distribution and even total level of benefits may not, however, be unique, but vary with the particular pricing decisions made. If all the benefits are passed to the LLC, there will be an increase in traffic. On the other hand, if the benefits are appropriated by the TC, there will be no change in traffic flows. Most likely pricing decisions have to be estimated and the sensitivity of overall benefits to changes in pricing have to be tested.

To appraise any infrastructural improvement to the transit system, the costs and benefits stemming from each of the three individual flows (transit, mutual, and domestic) must be estimated. Moreover, as discussed previously, the distribution of net benefits between the LLC and the TC must also be considered. It is necessary to evaluate the financial effects for both countries, and then the real resource effects, because market prices often do not reflect social costs.

The net present value (NPV) of the discounted flow of net benefits and the capital costs of the improvement should be calculated. In national transport analysis a single NPV is calculated, but in the transit situation a number of calculations are relevant: (*a*) NPV(a) to LLC, indicating whether it is economically viable for the LLC to invest; (*b*) NPV(b) to the TC within whose territory the improvement is located; (*c*) NPV(c) to both the LLC and the TC within whose territory the improvement is located; and (*d*) NPV(d) to the region including the LLC and all TCs. The need for NPV(a) is clear. NPV(b) will indicate the likely willingness of the TC to either invest or accept the investment. It is possible that while the NPV(a) and NPV(b) are negative, the combined NPV(c) will be positive, suggesting that some type of joint funding would be desirable.

Often NPV(d) will be the same as NPV(c), but where there are several transit corridors and traffic is responsive to changes in the cost and quality, transport gains to the LLC and one TC may be offset by losses to other TCs. The regional NPV(d) indicates whether the improvement would be feasible if the entire regional transport system was under unitary control. If NPV(d) is negative, there should, theoretically, be other arrangements that could improve the welfare of all countries in the region.

Overall, when improvements to the transit system are considered, a number of possibilities exist with respect to the level of total benefits and their distribution between the two countries:

1. Investments that can be undertaken by the TC for its own benefit, either because it reduces the social cost of internal transport or because it increases the social surplus from transit goods;
2. Investments that could be financed entirely by the LLC and that would yield sufficient internal benefits to the LLC through reductions in the generalized cost of transit;
3. Investments that yield benefits to both countries but not to a sufficient scale for either country to invest. The investment would be economic, however, if both countries were prepared to invest in the improvement to that point where the yield was equal to their respective social rates of return. The total capital that they might be prepared to commit would be greater than the actual cost of the improvement;
4. Investments that yield benefits to one country but disbenefit the other or where there are mutually exclusive alternatives and the share of the benefit between the two countries is dependent on the alternative chosen; and
5. Investments that are profitable for one country within its own territory as long as some complementary improvement is made within the territory of the other country. Both investments must therefore be considered as a package to see whether either the complementary investment is profitable in its own right or whether the benefits from the package are sufficient to make both investments profitable.

Geographical realities suggest that the impetus for change should come from the LLC. Unless the LLC takes the initi-

TABLE 1 EVALUATION OF MAIN MALIAN TRANSIT ROUTES

Cost Components, per Ton, 1987 (Costs in FCFA/tonne)[1]	Dakar Route	Abidjan Route	Lome Route
A. Direct Costs			
a Shipping Rate	28 812	32 122	37 417
b Freight-forwarders	6 832	3 937	2 197
c Port Charges	4 538	9 937	7 049
d Informal Charges	706	1 001	1 370
e Other Transit Fees	587	139	4 237
f Loss and Damage	2 361	3 858	2 841
g Inventory Costs	5 520	7 055	7 327
h EMAs Costs	500	500	2 450
i Reliability	333	496	1 092
j Guarantee Tax	0	1 950	3 754
k Land Transit Charges	23 821	28 664	33 874
Total Direct Costs of Transit (A)	74 009	89 658	103 608
B. Breakdown of Direct Costs			
B1-Direct Costs in Transited Country (B)	34 154	28 479	30 774
% of Transit Costs (A)	46 196	31 896	29 796
B2-Direct Costs in Mali (C)	21 215	36 898	39 900
% of Transit Costs (A)	28 796	41 296	38 596
B3-Direct Costs in Other Countries (D)	10 426	12 873	21 674
% of Transit Costs (A)	14 196	14 496	20 996
C-Indirect Benefits for Transited Country			
Total Indirect Costs in Transited	7 515	7 020	4 446
Country (E)	34 154	28 479	30 774
Total Direct Costs in Transited Country	28 233	24 791	27 319
Value Added by Direct Costs	20 718	17 771	22 872
(V)	28%	20%	22%
Balance (Net Economic Benefit)			
=V-E			
% of Transit Costs (A)			
D-Indirect Costs for Landlocked Country (Mali)			
Net Indirect Costs in Mali	7 916	635	1 578
(F)	74 009	89 658	103 608
Total Direct Costs within and outside	81 925	90 293	105 186
Mali (A)	111%	101%	102%
Balance (Net Economic Cost for Mali)			
A+F			
% of Transit Costs (A)			

1/ 1 US$= 300 CFA during the study. CFA is the common currency of Senegal, Côte d'Ivoire, Togo and Mali.

ative in suggesting improvements and agreeing to either total or partial financing, it is quite possible that transit systems will remain underdeveloped or will be developed suboptimally: investments may be made by the TC that conflict with the needs of the LLC. In these circumstances the LLC must be prepared to compensate the TC for introducing desirable changes and forgoing changes that are inimical to the LLC's interests.

CONCLUSIONS

In the consideration of transit situations, it cannot be stressed sufficiently that there are always at least two countries, two sets of social and financial costs and benefits, and two social opportunity costs of capital. Simple addition of benefits by either country or by international aid donors ignores the reality of the situation. Bargaining over the share of profits or social surplus may be inevitable, and the result is economically indeterminate. A minimum level of benefits, either originating in the country or being transferred, will be required to ensure that the internalized benefits yield a sufficient social rate of return to each country. For many improvements, the LLC may have to decide what is the maximum it is prepared to pay for an improvement and the TC the minimum it is prepared to require for accepting the improvement. If the minimum required by the TC is greater than the maximum the LLC is prepared to pay, the improvement is unlikely to take place. If, on the other hand, the minimum required by the TC is less then the maximum the LLC is willing to pay, improvements can be achieved.

Investment in the TC may be the only way in which the LLC is able to remedy the shortcomings in the transit system. Ideally, it should be prepared to invest until benefits from the marginal investment are just equal to the social opportunity cost of capital. In reality, some premium above the social cost of capital may be required to compensate for the various unquantifiable costs resulting from uncertainty attached to such investment. This would be particularly true if a socially acceptable rate of return was only made possible by the transfer of some of the profits made in the transit country.

Many infrastructure projects are conventionally evaluated over a 20-year economic life, and may have a much longer physical life. It is possible that political relations between the LLC and TC or within the region may change during the period and alter country needs and priorities. The need for a political relationship must therefore introduce an element of uncertainty into the analysis of joint projects. The LLC may have to guarantee a minimum flow of transit traffic to make the project worthwhile for the TC.

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Computational Characteristics of a Numerical Model for Series of Waterway Queues

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A numerical method has been developed for estimating delays on congested waterways represented by series of G/G/1 queues (i.e., with generally distributed arrival and service times and one chamber per lock). It is based on a metamodeling approach that develops simple formulas to approximate the results of simulation models. The functional form of the metamodels is derived from queueing theory, whereas their coefficients are statistically estimated from simulation results. The algorithm scans along a waterway and sequentially estimates at each lock the arrival distributions, departure distributions, and delays. It can be applied to systems with two-way traffic through common bidirectional servers as well as to one-way traffic systems. Computational results are presented to illustrate the speed and convergence properties of the algorithm and to investigate some of its variants. The algorithm works satisfactorily and flexibly with different convergence criteria and scanning processes. For an illustrative 20-lock system, parameter estimates converge with five iterations and less than 3 sec of CPU time to differences lower than 0.1 percent between successive iterations. The computation time increases only linearly with the number of locks in the system, thus allowing the analysis of very large systems of interdependent queues.

Inland waterway transportation is important in the United States and elsewhere, especially for heavy or bulky commodities, since it is inexpensive, energy efficient, and safe. Most U.S. waterways consist of stepped navigable pools formed by dams across natural rivers. The lock structures used to raise or lower vessels between adjacent pools constitute the major bottlenecks in the waterway network (*1*) and generate extensive queues. Some locks have only one chamber, whereas others may have two parallel chambers whose characteristics may differ. The service time distributions at locks depend heavily on chamber size and tow size distributions. The lock service time distributions would be affected by the chamber assignment discipline at locks with two dissimilar chambers.

The waterway locks constitute a series of queueing stations. In queueing terms, locks are the servers and tows are customers waiting to be served by locks. Tows from both directions, upstream and downstream, share the same lock servers, whereas in most other queueing systems servers are exclusively one-directional. Hence, the term "two-way traffic operations" characterizes the lock system analyzed later.

Arrival and service time distributions at locks are fairly complex. Carroll et al. (*2*) and Desai (*3*) found that service times are not exponentially distributed, and arrivals are not Poisson distributed. Other standard distributions have been tested for the present study without consistent success. Thus, empirical distributions (specified for 50 intervals) are used here for simulation, whereas general tabular distributions, described usually only by their means and variances, are used for queueing models. Although locks with a single chamber may be modeled as G/G/1 queueing systems (i.e., general arrival/general service times/1 server per station), locks with two parallel chambers may not be treated simply as G/G/2 queueing systems unless these chambers are identical.

Considerable interdependence may exist among locks in a series. The departure distributions differ from the arrival distributions since the service time distributions change the tow headways. Departures from one lock usually affect arrivals at the next lock. Interdependence among locks increases the difficulty in estimating systemwide delays since the interarrival time distributions from adjacent locks must be identified at each lock. Two-way traffic operation through common servers complicates the interdependence of lock delays and precludes the use of some otherwise interesting queueing models.

Random failures (called stalls) contribute significantly to the difficulties in estimating delays. Stalls, which interrupt lock operations and thereby increase delays, are relatively rare compared with other events and difficult to predict. Thus, Kelejian's efforts to model stall frequencies and durations have not yet yielded strong results despite the rigorous statistical methods employed (*4*).

The following special problems are encountered in estimating delays of waterway queues:

1. Arrival and service time distributions are too complex for analytic solutions and do not match known statistical distributions.
2. Parallel chambers are not identical.
3. Service time distributions are affected by the chamber assignment discipline.
4. Considerable interdependence exists among a series of locks.
5. Two-way traffic operates through bidirectional chambers.
6. Arrival distributions depend on distances and speed distributions between locks, as well as departures from adjacent locks.
7. Stalls increase the means and variances of delays.

Delay estimation for a realistic lock queueing system has been undertaken by Dai and Schonfeld (*5*,*6*,*7*) using several

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approaches, including queueing theory, simulation, and numerical methods. Their simulation model deals with all seven problems listed and is efficient for analyzing particular system configurations. However, when large numbers of system alternatives must be evaluated for investment scheduling, a much faster numerical method, which approximates the results of simulations, becomes preferable. The primary purpose of this paper is to assess the computational characteristics of the numerical method developed for this role. In particular, the number of iterations and the computation time required to reach convergence using various criteria and scanning procedures are investigated. The effects of system size (i.e., number of locks) on computational requirements are also examined.

LITERATURE REVIEW

The available analytic solutions for estimating delays in G/G/1 queues are inadequate. Kleinrock (*8*) suggested an approximation solution for a G/G/1 queue with heavy traffic, which is a useful upper bound for average waiting times in G/G/1 queues. Bertsimas (*9*) derived an exact solution for mixed generalized Erlang distributed arrivals and service times. However, without a departure function this result is difficult to extend to a series of locks.

Exact solutions for networks of queues are still limited to Markovian networks. For more general networks of queues, approximation methods are employed by Whitt (*10*) and Albin (*11*) for system performance analysis. The underlying concept is to decompose the network into individual queues that are analyzed independently and then recombine the results. Their efforts are valuable but employ unreasonable coefficients of variation (standard deviation divided by mean) and are not applicable to bidirectional servers.

System simulation models to analyze lock delays and tow travel times were developed by Howe (*12*) and Carroll and Bronzini (*13*). These two models, which did not account for stalls, required considerable data and computer time. However, simulation models can, in principle, represent the complexities of traffic on waterway networks much better than analytic queueing models.

A new waterway simulation model was developed by Dai and Schonfeld (*5*). This model accommodates generally (i.e., arbitrarily) distributed trips and service times. It can also evaluate stall effects. This simulation model requires only a few seconds to a few minutes on a PS/2 computer for each run, depending on traffic volumes, simulation period durations, network size, and so forth. Still, it is hardly affordable for direct application in large combinatorial network investment problems.

To avoid the computational expense of simulation, a metamodeling approach (*14*) was developed. This approach consists of (*a*) developing and validating a simulation model to represent waterway networks with queues at locks, (*b*) formulating functions developed from queueing theory for delays through series of locks, (*c*) statistically estimating the parameters of these functions using simulation results, and (*d*) employing an iterative sequential scanning procedure to estimate interarrival and interdeparture time distributions lock by lock until results converge at each lock. Thus, relatively simple equations may serve as a proxy for the simulation model.

SIMULATION MODEL

The simulation model developed for this work is documented in Dai and Schonfeld (*5*). Only a brief description is provided below.

The simulation model was developed using the lock performance monitoring system (PMS) data base, which includes detailed information on traffic through the locks as well as physical aspects of lockages (*15*). The simulation model is programmed in Fortran-77, which provides great flexibility in modeling. Basically, it is a stochastic, microscopic and event-scanning simulation model that can handle any distributions for trip generation, travel speeds, lock service times, and tow sizes. Currently, tabular distributions based on empirical observations are used for most input variables. A FIFO (first-in-first-out) service discipline is currently used. This model simulates two-way traffic through common servers and accounts for stalls.

The validation results (*5,6,7*) show that the overall mechanism of the simulation model is correct, and that the simulated average waiting times for each lock and for the entire series of locks are closely similar to those observed. Dai (*6*) documents the statistical methods used in developing, validating, and applying the simulation model.

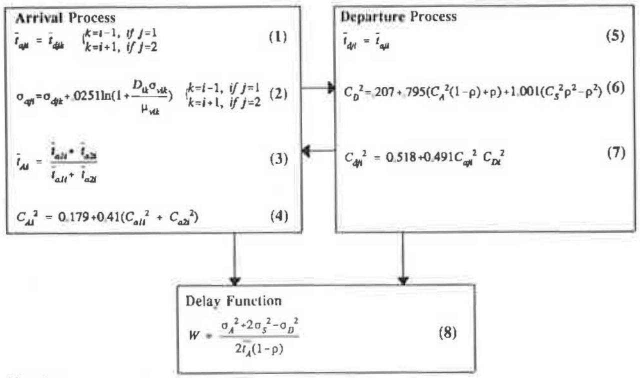
NUMERICAL METHOD

Overview

A numerical method has been developed for estimating delays through a series of queues with bidirectional servers. A brief description of the method follows. Details of its development and validation are provided elsewhere (*6,7*).

The method consists of three major modules, namely arrival processes, departure processes, and delay functions (as summarized in Figure 1), which are applied in that sequence at each lock. The basic concept is to decompose the waterway system into locks (which remain interdependent since they are affected by inflows from adjacent locks), identify the parameters of the interarrival and interdeparture time distributions for each lock, and then estimate the implied waiting times. The structure of the equations used in each module is based as much as possible on queueing theory, and the parameters in those equations are statistically estimated on the basis of simulation results. Currently, the following assumptions are used in the numerical method:

1. Interarrival times and service times are generally distributed.
2. Each lock has one chamber.
3. Inflows and outflows occur only at the two end nodes of a series of locks.
4. The average upstream volumes are equal to the downstream volumes in the long run.
5. The long-run volume to capacity (V/C) ratio is less than 1.0 at every lock.



Notation:

C_{Ai}	: coefficient of variation of interarrival times at Lock i
C_{aji}	: coefficient of variation of directional interarrival times for Direction j and Lock i
C_{Di}	: coefficient of variation of interdeparture times for Direction j and Lock i
C_{dji}	: coefficient of variation of directional interdeparture times for Direction j and Lock i
C_S	: coefficient of variation of service times
D_{ik}	: distance between Locks i and k
i	: index of currently scanned lock
j	: direction index (1 = downstream, 2 = upstream)
k	: index of adjacent locks
$\bar{t}_{Ai}$	: mean interarrival time at Lock i
$\bar{t}_{aji}$	: mean interarrival time for Direction j and Lock i
$\bar{t}_{djk}$	: mean interdeparture time for Direction j and Lock k
μ_{vik}	: mean tow speed between Locks i and k
σ_{aji}	: standard deviation of interarrival times for Direction j and Lock i
σ_{djk}	: standard deviation of interdeparture times for Direction j and Lock k
σ_{vik}	: standard deviation of tow speeds between Locks i and k

FIGURE 1 Structure of numerical method.

Assumptions 2, 3, and 4 are only applicable to the numerical method. The simulation model is not limited by those assumptions. The numerical method can provide a quick and inexpensive analysis of lock delays. However, Assumptions 2, 3, and 4 limit fairly significantly the applicability of the currently developed numerical method and necessitate the substitution of the simulation model when significant deviations from those assumptions must be considered. With some extensions to the numerical method, Assumptions 2 and 3 may be eliminated. Assumption 4 could be relaxed fairly easily even though it is usually realistic for waterways. Assumptions 1 and 5 should be kept since they reflect realities rather than analytic limitations.

Structure of Numerical Method

To estimate delays in a queueing system, we need to know the means and variances of the interarrival, interdeparture, and service time distributions. For series of G/G/1 queues and bidirectional servers, a difficulty arises in identifying the variances of interarrival and interdeparture times. Because the interarrival times at each lock depend on departures from both upstream and downstream locks, the variances of interarrival times cannot be determined from one-directional scans along a series of queues. To overcome such complex interdependence, an iterative scanning procedure is proposed. The core concept is to decompose the system into individual locks and then sequentially analyze each of those locks. At each lock, the tow arrivals from both directions are first combined into an overall arrival distribution and then split into two directional departure distributions.

The algorithm is initiated by scanning along waterways from either direction, sequentially estimating the interarrival and interdeparture time distributions for each lock. Initially assumed values for the variances of interdeparture times from the opposite direction must be provided for the first scan. Then, the scanning direction is reversed and the process is repeated, using the interdeparture time distributions for the opposite direction estimated in the previous scan. Alternating directions, the scanning process continues until the relative difference in the preselected convergence criteria stays within preset thresholds through successive iterations. Waiting times at locks can be computed in every iteration (and then used as convergence criteria) or just once after all iterations are completed.

Arrival Processes

The mean and standard deviations of interarrival times are estimated in two steps. First, the means and standard deviations of directional interarrival times at a particular lock are estimated from the interdeparture time distributions of the adjacent locks. If flows are conserved between locks and if the V/C ratio is less than 1, such relations are represented in Equation 1 (variables are defined in Figure 1):

$$\bar{t}_{aji} = \bar{t}_{djk} \qquad \begin{cases} k = i - 1 \text{ if } j = 1 \\ k = i + 1 \text{ if } j = 2 \end{cases} \tag{1}$$

Because speed variations change headway distributions between locks, Equation 2 was developed to estimate the standard deviation of directional interarrival times at one lock.

$$\sigma_{aji} = \sigma_{djk} + \underset{(.002)}{.0251} \ln\left(1 + \frac{D_{ik}\sigma_{vik}}{\mu_{vik}}\right) \quad \begin{cases} k = i - 1 \text{ if } j = 1 \\ k = i + 1 \text{ if } j = 2 \end{cases} \tag{2}$$

$R^2 = 0.999954$ $\quad n = 107$ $\quad S_e = 0.0586$ $\quad \mu = 5.1685$

This suggests that, theoretically, the standard deviation of directional interarrival times should be equal to the standard deviation of directional interdeparture times plus an adjustment factor depending on the speed distribution and distance.

Second, the overall mean and coefficient of variation of interarrival times for this lock are estimated on the basis of the coefficients of variation of directional interarrival times.

$$\bar{t}_{Ai} = \frac{\bar{t}_{a1i} * \bar{t}_{a2i}}{\bar{t}_{a1i} + \bar{t}_{a2i}} \tag{3}$$

$$C^2_{Ai} = \underset{(0.027)}{0.179} + \underset{(0.014)}{0.41}(C^2_{a1i} + C^2_{a2i}) \tag{4}$$

$R^2 = 0.9188$ $\quad n = 79$ $\quad S_e = 0.0059$ $\quad \mu = 0.988$

In Equation 4, the coefficients of variation of upstream and downstream interarrival times carry the same weight in estimating the overall variance of interarrival times, since the mean directional trip rates are equal (Assumption 4).

Departure Processes

The departures module estimates the mean and coefficient of variation of interdeparture times. On the basis of the flow conservation law, if capacity is not exceeded, the average directional interdeparture equals the corresponding interarrival time:

$$\bar{t}_{dji} = \bar{t}_{aji} \tag{5}$$

The coefficient of variation of interdeparture times is estimated in two steps. First, the coefficient is estimated for combined two-directional departures. Departure processes with generally distributed arrivals and service times are analyzed using Laplace transforms (*8*). Some analytic relations obtained are shown in Dai (*6*). The following metamodel was eventually developed to bypass the difficulties of determining the variance of the lock idle times:

$$\begin{aligned} C_D^2 = {} & \underset{(0.065)}{0.207} + \underset{(0.066)}{0.795}[C_A^2(1-\rho)+\rho] + \underset{(0.0046)}{1.001}(C_S^2\rho^2-\rho^2) \end{aligned} \tag{6}$$

$R^2 = 0.9984 \quad n = 79 \quad S_e = 0.0058 \quad \mu = 0.8311$

Next, the coefficient of variation of directional interdeparture times is estimated. The following metamodel was developed for this purpose:

$$C_{dji}^2 = \underset{(0.0056)}{0.518} + \underset{(0.0068)}{0.491}\, C_{aji}^2\, C_{Di}^2 \tag{7}$$

$R^2 = 0.9710 \quad n = 158 \quad S_e = 0.013 \quad \mu = 0.9164$

Delay Function

The delay function is intended to estimate the average waiting time at a lock. By applying Marshall's formula for the variance of interdeparture times (*16*), an exact solution for the average waiting time W was obtained as follows:

$$W = \frac{\sigma_A^2 + 2\sigma_S^2 - \sigma_D^2}{2\bar{t}_A(1-\rho)} \tag{8}$$

In this delay function, the average waiting time increases as the variance of interarrival and service times increases and decreases as the variance of interdeparture times increases. The average waiting time approaches infinity as the V/C ratio approaches 1.0.

Comparison of Simulated and Numerical Results

To validate the numerical method, its results were compared with the results of the previously validated simulation model. Various system configurations were compared, including the relatively large 20-lock system given in Table 1.

The parameter values for this test system (e.g., means and standard deviations of input distributions and distances between locks) were obtained from random number generators, except for traffic volumes, which were assumed to be 10 tows/day in each direction throughout the system. Table 1 gives the input parameters and a comparison of waiting times, which are the output variable of greatest practical interest. It can be seen that the numerical model estimates aggregate waiting times within 7.85 percent of the simulated ones. At individual locks the percentage error can be considerably greater, especially when absolute errors are very small (e.g., in comparisons with zero waiting times). The comparisons of intermediate outputs (e.g., the parameters of directional interarrival and interdeparture time distributions) show that differences below 10 percent are achieved. The detailed validation results are presented in Dai (*6*).

COMPUTATIONAL TESTS

A number of computational tests have been conducted to investigate the speed, accuracy, and convergence properties of the numerical method. Some of the results obtained are presented here. All were obtained with the two-directional iterative algorithm (coded in Fortran-77) compiled and executed on an IBM PS/2 model 70 personal computer with an 80386 processor and an 80387 math coprocessor.

Any variable that is computed in every iteration of the algorithm may be used to check for convergence and stop the algorithm when further changes between iterations become arbitrarily small. The most interesting candidate variables for convergence criteria are the variances in the interdeparture times from each lock (which affect error propagation) and the waiting times in queues (which are the output variables of greatest practical economic interest).

The convergence threshold may be specified as a relative change in the value of a variable from one iteration to the next (i.e., a ratio or percentage change) or an absolute difference. The ratios may be large if and when some variable values approach zero even though absolute differences may be insignificant.

Convergence may be sought on the basis of aggregate or systemwide outputs (e.g., total delay per tow through a series of locks) or may be based on localized outputs (e.g., delay at each lock). In principle, it should be easier to reduce changes between iterations to x percent for a systemwide variable than for every single location in that system.

The original algorithm used the squared coefficients of variation of directional interdeparture times (VARDEP) as the convergence criteria. In this work, the individual lock waiting times (LOCWAIT) and system weighted waiting times (SYSWAIT) are also tested as convergence criteria. Waiting times must then be computed in every iteration rather than just at the end.

The required inputs for the algorithm include the inflow rates, V/C ratio and service time variance at each lock, distances between locks, means and standard deviations of tow speed distributions, and the choice of convergence criterion. We generally used 0.001 as the convergence threshold (i.e.,

TABLE 1 VALIDATION OF NUMERICAL METHOD FOR 20-LOCK TEST CASE

Lock	σ_{A}[a]	C_{A}[b]	σ_D	C_D	σ_S	C_S	V/C	Dist[c]
1	1.21	1.01	0.92	0.77	0.52	0.56	0.78	7.04
2	1.18	0.98	1.17	0.98	0.10	0.70	0.12	49.04
3	1.20	1.00	0.91	0.76	0.74	0.69	0.90	46.05
4	1.19	0.99	1.05	0.88	0.69	0.76	0.75	47.74
5	1.20	1.00	1.02	0.85	0.81	0.78	0.86	105.56
6	1.19	0.99	0.90	0.75	0.61	0.60	0.84	71.76
7	1.19	0.99	1.05	0.88	0.91	0.84	0.90	39.91
8	1.21	1.01	1.20	1.00	0.13	0.57	0.19	91.12
9	1.19	0.99	0.94	0.79	0.65	0.65	0.83	60.55
10	1.17	0.97	0.99	0.83	0.75	0.74	0.85	22.44
11	1.21	1.01	1.08	0.90	0.56	0.71	0.66	53.38
12	1.22	1.02	1.20	1.00	0.23	0.67	0.28	89.78
13	1.22	1.02	1.19	0.99	0.28	0.69	0.34	103.77
14	1.23	1.02	0.89	0.74	0.57	0.57	0.83	125.02
15	1.21	1.01	1.16	0.97	0.35	0.71	0.41	105.41
16	1.22	1.02	1.18	0.99	0.37	0.80	0.39	80.29
17	1.21	1.01	1.02	0.85	0.45	0.57	0.66	99.98
18	1.20	1.00	0.95	0.79	0.62	0.64	0.81	65.54
19	1.18	0.99	1.13	0.94	0.45	0.74	0.51	42.38
20	1.22	1.02	0.96	0.80	0.71	0.70	0.85	96.75

	Estimated Waiting Time, hrs/tow			
Lock	Numerical	Simulation	Difference	%
1	2.15	2.04	0.11	5.31
2	0.00	0.01	-0.01	--[d]
3	6.91	6.37	0.54	8.48
4	1.91	1.78	0.12	6.88
5	4.71	4.20	0.50	11.96
6	3.39	2.67	0.73	27.19
7	7.76	7.23	0.53	7.38
8	0.00	0.04	-0.03	--
9	3.30	2.83	0.47	16.48
10	4.21	3.73	0.49	13.02
11	1.10	1.08	0.01	1.04
12	0.08	0.10	-0.03	-27.02
13	0.13	0.17	-0.04	-22.84
14	3.33	3.20	0.13	4.19
15	0.22	0.26	-0.04	-16.41
16	0.21	0.26	-0.05	-19.91
17	0.95	0.99	-0.04	-4.26
18	2.80	2.74	0.06	2.29
19	0.42	0.45	-0.03	-7.54
20	4.34	4.27	0.08	1.81
System	47.92	44.44	3.49	7.85

[a] σ_i: Standard deviation of interarrival time, interdeparture time, and service time distributions, respectively.

[b] C_i: Coefficients of variation of interarrival time, interdeparture time, and service time distributions, respectively.

[c] Dist: Distance to the next lock, in miles.

[d] Not applicable.

results were considered sufficiently accurate and additional iterations were deemed unnecessary when the variables chosen as convergence criteria changed by less than 0.1 percent from the previous iteration).

Three-Lock Systems

The first test concerns the eight three-lock systems analyzed in Dai (*6*). These eight systems (described in Table 2) were originally used to show the performance of various algorithms. The distances and speed distributions between locks were kept equal within each of these eight systems. Using VARDEP, LOCWAIT, and SYSWAIT as convergence criteria, the estimated individual lock delays and system delays and number of iterations required are listed in Table 3. Also included are the simulated waiting times. Generally, the three criteria perform equally well for each of the eight systems in terms of number of iterations required for convergence. The SYSWAIT criterion produces slightly faster convergence than the others.

While assessing the differences in the number of iterations required with various criteria in System 1, we found that delays at low V/C ratios are so small that relative differences may be large and unstable even for very small changes in the absolute magnitudes of delays. Consequently, more iterations are required to satisfy a relative threshold. If, instead, we set an absolute threshold for delay (e.g., less than 0.001 hr/tow difference between successive iterations), System 1 converges at the fourth iteration for both LOCWAIT and SYSWAIT.

We also sought to check whether the convergence was monotonic (i.e., whether the changes always decrease through successive iterations). We found that relative changes decrease monotonically for all systems when SYSWAIT, but not VARDEP or LOCWAIT, is the convergence criterion. However, the magnitudes of various criterion variables change monotonically through successive iterations for all systems, as shown in Table 4. It seems that monotonic convergence is

TABLE 2 PHYSICAL CHARACTERISTICS OF THREE-LOCK SYSTEMS

System	Lock	Two-way Flow Rate tows/day	V/C	Distance miles	Tow Speed miles/day μ_v[a]	σ_v[b]	Variance of Service Time hr^2/tow^2
1	1	6.0	0.01	5	270	85	0.0007
	2	6.0	0.07	5	270	85	0.0360
	3	6.0	0.17	5	270	85	0.1897
2	1	12.0	0.15	5	325	102	0.0309
	2	12.0	0.34	5	325	102	0.1620
	3	12.0	0.25	5	325	102	0.0915
3	1	18.0	0.22	5	108	34	0.0309
	2	18.0	0.03	5	108	34	0.0006
	3	18.0	0.50	5	108	34	0.1618
4	1	24.0	0.50	5	162	51	0.1883
	2	24.0	0.29	5	162	51	0.0646
	3	24.0	0.67	5	162	51	0.3330
5	1	27.0	0.75	10	108	34	0.2271
	2	27.0	0.57	10	108	34	0.1279
	3	27.0	0.89	10	108	34	0.3167
6	1	27.0	0.75	20	216	68	0.1616
	2	27.0	0.57	20	216	68	0.0909
	3	27.0	0.89	20	216	68	0.2259
7	1	28.5	0.60	5	325	102	0.1557
	2	28.5	0.05	5	325	102	0.0011
	3	28.5	0.80	5	325	102	0.2738
8	1	28.5	0.35	60	162	51	0.0645
	2	28.5	0.60	60	162	51	0.1882
	3	28.5	0.80	60	162	51	0.3332

[a] μ_v: Average tow speed.
[b] σ_v: Standard deviation of tow speeds.

more difficult to achieve for local variables when the algorithm scans along the series of locks in alternating directions. When an iteration is defined as a two-way scan (e.g., first upstream, then downstream, and only afterwards compare results to the previous iteration), monotonic convergence is achieved for the local variables LOCWAIT and VARDEP. It is achieved without two-way iterations for the aggregate variable SYSWAIT which, incidentally, requires 3 to 12 percent less CPU time than the local criteria.

The algorithm was also allowed to run for 100 iterations to check the convergence and CPU times for various criteria. The results were quite satisfactory since no system ever diverged in this experiment. This is illustrated in Figure 2 using System 6 as the example.

Twenty-Lock Systems

To further check the behavior of the algorithm, we randomly generated parameter values for a 20-lock system in which the values of the V/C ratio were uniformly distributed between 0 and 1, and the coefficients of variation of service time were uniformly distributed between 0.2 and 1.0. This test system was assumed to have equal mean inflow rates in the two directions, as well as identical tow speed distributions and distances between any pair of locks. Table 5 describes this 20-lock system.

The aggregate results for the 20-lock system are summarized in Table 6. We found that the number of iterations required for convergence within 0.001 is almost identical to the numbers in Table 3, even though this 20-lock system is more than six times larger. This suggests that the algorithm may be applicable for very large systems. Comparisons of CPU times required for convergence again confirm that the aggregate criterion SYSWAIT saves iterations compared with the local criteria LOCWAIT and VARDEP and reaches convergence with approximately 25 percent less CPU time. As in 3-lock systems, the 20-lock system never diverges, and the monotonic properties with various criteria are similar. With the LOCWAIT criterion a single violation of monotonic convergence was found at Lock 2 in the fourth iteration. Consequently, one more scan is desired to bring the entire system into convergence. Such violations were never found when the aggregate convergence criterion SYSWAIT was used or when iterations were defined to consist of two scans in alternate directions.

The relation between system size and computational requirements was also examined using the 20-lock system and arbitrarily chosen subsets of that system. The CPU times and number of iterations required for convergence in various system sizes are shown in Figure 3. It again seems promising that the number of iterations does not change much for different criteria and system sizes. The CPU times seem roughly proportional to system sizes in all cases. Figure 3 demonstrates the apparently linear relations. We sought to statistically estimate the relations between CPU time and the number of locks in the system, using the following structural form:

TABLE 3 COMPUTATIONAL COMPARISON FOR VARIOUS CRITERIA IN THREE-LOCK SYSTEMS

		Estimated Waiting Time, hrs/tow						
			VARDEP		LOCWAIT		SYSWAIT	
System	Lock	Wsim[a]	Wv[b]	Dv[c]	W_L	D_L	Ws	Ds
1	1	0.0003	0.0001	-0.0002	0.0001	-0.0002	0.0001	-0.0002
	2	0.0153	0.0175	0.0022	0.0176	0.0023	0.0176	0.0023
	3	0.0989	0.0990	0.0001	0.0990	0.0001	0.0990	0.0001
	Total	0.1145	0.1166	0.0021	0.1167	0.0022	0.1167	0.0022
Required Iterations			5		7		6	
2	1	0.0334	0.0290	-0.0044	0.0290	-0.0044	0.0290	-0.0044
	2	0.2316	0.2289	-0.0027	0.2289	-0.0027	0.2289	-0.0027
	3	0.1139	0.1099	-0.0040	0.1099	-0.0040	0.1099	-0.0040
	Total	0.3789	0.3678	-0.0111	0.3678	-0.0111	0.3678	-0.0111
Required Iterations			5		5		5	
3	1	0.0542	0.0528	-0.0014	0.0528	-0.0014	0.0528	-0.0014
	2	0.0008	0.0001	-0.0007	0.0001	-0.0007	0.0001	-0.0007
	3	0.4621	0.4660	0.0039	0.4660	0.0039	0.4659	0.0038
	Total	0.5171	0.5189	0.0018	0.5189	0.0018	0.5188	0.0017
Required Iterations			5		5		4	
4	1	0.4355	0.4404	0.0049	0.4404	0.0049	0.4404	0.0049
	2	0.0962	0.0999	0.0037	0.0999	0.0037	0.0999	0.0037
	3	1.2028	1.1844	-0.0184	1.1844	-0.0184	1.1844	-0.0184
	Total	1.7345	1.7247	-0.0098	1.7247	-0.0098	1.7247	-0.0098
Required Iterations			4		4		4	
5	1	1.3926	1.4693	0.0767	1.4693	0.0767	1.4693	0.0767
	2	0.3901	0.4127	0.0226	0.4127	0.0226	0.4127	0.0226
	3	4.9837	4.7980	-0.1857	4.7980	-0.1857	4.7980	-0.1857
	Total	6.7664	6.6800	-0.0864	6.6800	-0.0864	6.6800	-0.0864
Required Iterations			4		4		4	
6	1	1.2203	1.3038	0.0835	1.3038	0.0835	1.3038	0.0835
	2	0.3286	0.3416	0.0130	0.3416	0.0130	0.3416	0.0130
	3	4.4608	4.2983	-0.1625	4.2983	-0.1625	4.2983	-0.1625
	Total	6.0097	5.9437	-0.0660	5.9437	-0.0660	5.9437	-0.0660
Required Iterations			4		4		4	
7	1	0.5430	0.5900	0.0470	0.5899	0.0469	0.5899	0.0469
	2	0.0012	0.0001	-0.0011	0.0001	-0.0011	0.0001	-0.0011
	3	2.0874	2.0906	0.0032	2.0906	0.0032	2.0906	0.0032
	Total	2.6316	2.6807	0.0491	2.6806	0.0490	2.6806	0.0490
Required Iterations			4		3		3	
8	1	0.1372	0.1405	0.0033	0.1405	0.0033	0.1405	0.0033
	2	0.6381	0.6592	0.0211	0.6592	0.0211	0.6592	0.0211
	3	2.3165	2.3146	-0.0019	2.3146	-0.0019	2.3146	-0.0019
	Total	3.0918	3.1143	0.0225	3.1143	0.0225	3.1143	0.0225
Required Iterations			4		4		4	

[a] Wsim: Waiting time estimated from simulation.
[b] Wi: Waiting time estimated when criterion i used.
[c] Di: Difference between numerically estimated waiting time at a given iteration and simulated waiting time = Wi - Wsim.

$$\mathrm{CPU}_i = K_i N^{P_i} \qquad (9)$$

In Equation 9 CPU_i is the central processing time using Convergence Criterion i, K_i and P_i are statistically estimated parameters associated with Criterion i, and N is the number of locks in the system. The P_i parameter was expected to be very close to 1.0, on the basis of the nearly linear relations shown in Figure 3, and indeed turned out to be nearly 1.0, confirming the essentially linear relation. The value of P_i was, therefore, fixed at 1.0, and the remaining parameter K_i was estimated as indicated in Table 7.

The small standard errors and high R^2 again confirm that CPU time is essentially linear with respect to the number of locks in the system. Among the three criteria, the aggregate criterion SYSWAIT has the smallest standard error and highest R^2, suggesting it yields not only the fastest but also the most predictable computer times. The structural form of Equation 9 forces the computer time function through the origin, since Equation 9 has no intercept. When an intercept A_i is provided in Equation 10 (presumably to reflect the fixed times required for setup or input and output functions), even better fits were obtained, as indicated in Table 7.

$$\mathrm{CPU}_i = A_i + K_i N \qquad (10)$$

The best fit is again obtained for the SYSWAIT criterion. Thus, based on our very small sample, the best estimate of CPU time (in seconds to reach convergence within 0.001) for N-lock systems is obtained with the SYSWAIT criterion as

$$\mathrm{CPU} = 0.107 + 0.0853N \qquad (11)$$

Table 6 shows that convergence to within 0.1 percent difference between successive iterations is reached in 1.75 sec of CPU time for the 20-lock system and SYSWAIT criterion. The corresponding time for the simulation model to analyze the same 20-lock system on the same computer is 53 min per replication (i.e., 1,590 min or 95,400 sec for 30 replications).

TABLE 4 CONVERGENCE PROPERTIES FOR VARIOUS CRITERIA IN SYSTEM 2

Criterion: VARDEP

	Magnitude, Dir 1			Relative Difference, Dir 1		
Iter	Lock 1	Lock 2	Lock 3	Lock 1	Lock 2	Lock 3
1	0.9930	0.9629	0.9715	--[a]	--	--
2	1.0027	0.9724	0.9715	0.0098	0.0098	0.0000
3	1.0027	0.9778	0.9802	0.0000	0.0056	0.0090
4	1.0030	0.9780	0.9802	0.0003	0.0002	0.0000
5	1.0030	0.9782	0.9804	0.0000	0.0002	0.0002

	Magnitude, Dir 2			Relative Difference, Dir 2		
Iter	Lock 1	Lock 2	Lock 3	Lock 1	Lock 2	Lock 3
1	0.9456	0.9214	0.9889	--	--	--
2	0.9884	0.9705	0.9889	0.0453	0.0533	0.0000
3	0.9884	0.9715	0.9907	0.0000	0.0011	0.0018
4	0.9897	0.9725	0.9907	0.0013	0.0010	0.0000
5	0.9897	0.9726	0.9907	0.0000	0.0000	0.0000

Criterion: LOCWAIT

	Magnitude			Relative Difference		
Iter	Lock 1	Lock 2	Lock 3	Lock 1	Lock 2	Lock 3
1	0.0177	0.1994	0.1065	--	--	--
2	0.0287	0.2254	0.1065	0.6167	0.1304	0.0000
3	0.0287	0.2283	0.1098	0.0000	0.0126	0.0312
4	0.0290	0.2288	0.1098	0.0110	0.0023	0.0000
5	0.0290	0.2289	0.1099	0.0000	0.0004	0.0007

Criterion: SYSWAIT

	Magnitude	Relative Difference
Iter	System	System
1	0.3236	--
2	0.3606	0.1142
3	0.3667	0.0171
4	0.3676	0.0023
5	0.3677	0.0004

[a]Not applicable.

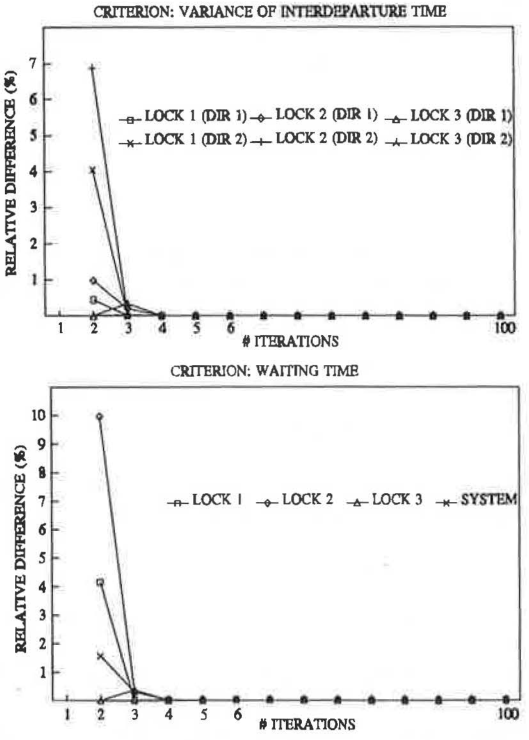


FIGURE 2 Convergence for three-lock system with various criteria.

Thus, in this case simulation requires 54,514 times more CPU time than the numerical method. However, it should be noted that our simulation runs were designed to extract very precise estimates for estimating new metamodels. We usually simulated 22,000 tows, discarded the first 10,000 of those, and replicated the simulation 30 to 80 times for each "data point." For practical application, the simulation would require 10^4 to 10^5 times more CPU time than the numerical method.

Double Scanning Versus Single Scanning

In the baseline algorithm an iteration consists of scanning the waterway from one end to the other (i.e., in one direction). The next iteration would then scan in the opposite direction. The results obtained so far suggest that a smoother convergence may be obtained by double scanning (i.e., checking for convergence only after two full scans in opposite directions are completed). With such double scanning, the changes in variables are always found to decrease (or at least not increase) with each successive convergence check, which is performed every second iteration by comparing Iteration i with Iteration $i - 2$ (instead of $i - 1$).

However, double scanning imposes a computer time penalty by increasing the number of iterations required for convergence to a specified threshold. That is indicated in Table 8, where the convergence threshold is still 0.001. There are

TABLE 5 RELEVANT DATA FOR THE 20-LOCK SYSTEM

Lock	V/C	C_s^a	Cap^b	μ_s^c	σ_s^{2d}
1	0.5625	0.2482	48	0.5000	0.0154
2	0.2473	0.2591	109	0.2198	0.0032
3	0.4505	0.3725	60	0.4004	0.0223
4	0.4098	0.2942	66	0.3643	0.0115
5	0.9865	0.8953	27	0.8769	0.6163
6	0.2148	0.2328	126	0.1909	0.0020
7	0.8315	0.5422	32	0.7391	0.1606
8	0.7088	0.3447	38	0.6300	0.0472
9	0.8563	0.9832	32	0.7612	0.5601
10	0.5989	0.8641	45	0.5324	0.2116
11	0.2065	0.6823	131	0.1836	0.0157
12	0.0510	0.5392	529	0.0453	0.0006
13	0.9894	0.8309	27	0.8795	0.5340
14	0.5051	0.4834	53	0.4490	0.0471
15	0.6715	0.6363	40	0.5969	0.1442
16	0.6728	0.7805	40	0.5980	0.2179
17	0.9475	0.6943	28	0.8422	0.3419
18	0.8662	0.4078	31	0.7700	0.0986
19	0.9074	0.4017	30	0.8066	0.1050
20	0.8711	0.9968	31	0.7743	0.5957

Inflow Rate of Direction 1 (tows/day)	13.5
Inflow Rate of Direction 2 (tows/day)	13.5
Convergence Threshold	0.001
Tow Speed (miles/day)	213.48
Standard Deviation of Speed (miles/day)	67.68
Distance between Locks (miles)	20.0

[a] C_s: Coefficient of variation of service time distribution.

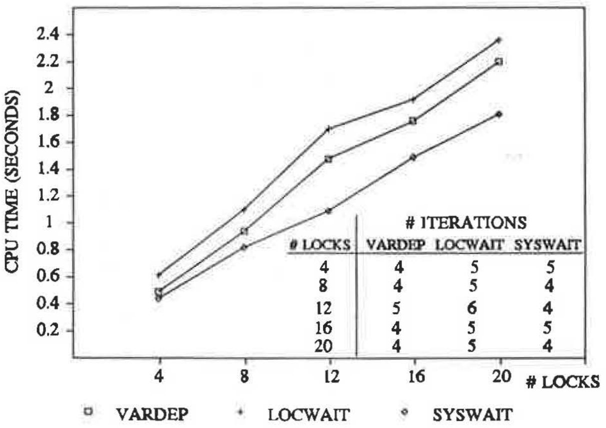
[b] Cap: Lock capacity, tows/day.

[c] μ_s: Mean of service time distribution, hrs/tow.

[d] σ_s^2: Variance of service time distribution, hrs^2/tow^2.

TABLE 6 COMPUTATION RESULTS FOR THE 20-LOCK SYSTEM

	VARDEP	LOCWAIT	SYSWAIT
Required Iterations for Convergence Within 0.001	4	5	4
CPU Time (seconds)	2.15	2.36	1.75
Total Waiting Time (hrs/tow)	151.2056	151.2044	151.2056
100 Iterations			
Divergence	None	None	None
CPU Time (seconds)	31.25	34.38	27.14
Total waiting time (hrs/tow)	151.2043	151.2043	151.2043



	# ITERATIONS		
# LOCKS	VARDEP	LOCWAIT	SYSWAIT
4	4	5	5
8	4	5	4
12	5	6	4
16	4	5	5
20	4	5	4

FIGURE 3 Relations between system size and computational speed.

two reasons for the penalty. First, an even number of iterations is required in double scanning, even when convergence is reachable with one less iteration. Second, a larger change may be expected after two iterations than after one, making the same threshold (e.g., 0.001) harder to satisfy.

Thus, it seems that double scanning provides added reassurance that the algorithm converges in a smooth and well-behaved way. However, since convergence seems so assured regardless of scanning procedure, it seems preferable to opt for the computation savings of single scanning.

CONCLUSIONS

A numerical method has been developed to estimate waterway travel times through a series of lock queues. This nu-

TABLE 7 PARAMETERS FOR CPU TIME VERSUS SYSTEM SIZE

Criterion	K_1	Standard Error of K_1	Standard Error of CPU Estimate	R^2	A_1
Eq. 9					
VARDEP	0.1129	0.0026	0.0774	0.9867	
LOCWAIT	0.1245	0.005	0.1482	0.9537	
SYSWAIT	0.0925	0.0019	0.0578	0.9885	
Eq. 10					
VARDEP	0.106	0.0055	0.0696	0.9919	0.102
LOCWAIT	0.108	0.0084	0.1074	0.9817	0.242
SYSWAIT	0.0853	0.0024	0.0315	0.9974	0.107

TABLE 8 ITERATIONS REQUIRED FOR VARIOUS SCANNING PROCESSES

3-Lock System 1	VARDEP	LOCWAIT	SYSWAIT
Single Scan	5	7	6
Double Scan	6	8	8
20-Lock System			
Single Scan	4	5	4
Double Scan	6	6	6

merical method was estimated from simulation results. It can approximately duplicate simulation results for complex systems of interdependent queues, while requiring 10^4 to 10^5 times less computer time than simulation. The basic approach used in this numerical method and several of its components (or "metamodels") should lead to numerical analysis methods for other types of queueing networks with greater complexity.

This paper focused on the main computational characteristics of the baseline numerical method and some its variations. The main computational findings are as follows:

1. Variables other than the original interdeparture time variance VARDEP are suitable as convergence criteria. In particular, the aggregate waiting time SYSWAIT yields convergence faster than the other variables considered. Not surprisingly, more iterations may be needed if a specified convergence threshold (e.g., 0.1 percent) is to be satisfied at every location and in every direction rather than for an aggregate criterion.
2. Convergence to within 0.1 percent of values in the previous iteration is achieved relatively quickly (typically in four to six iterations), even when that 0.1 percent threshold must be satisfied everywhere in a 20-lock system.
3. Convergence is achieved smoothly and, with rare exceptions, differences in the variable values decrease with each successive iteration. The exceptions are all traceable to scans in alternating directions and can be avoided by double scanning before convergence checks or by always scanning in the same directions. However, since convergence seems always assured, the single scanning in alternating directions seems preferable to save computer time.
4. The computer time required by the algorithm seems to be linear with respect to the number of locks in the system. It also seems to be predictable. Thus, the numerical method should analyze efficiently relatively large systems of interdependent queues.

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