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Real-Time Control of the Transportation of Hazardous Materials

Abstract: Advances in information technology have made possible the real-time control of truck, barge, and ship movement of hazardous materials. This paper will describe a command and control center for the monitoring via satellite of the flow of these materials. A DSS has been developed to support the problem solving and decision making process required in the event of an emergency situation. The ramifications for public and private organizations are also discussed.

INTRODUCTION

Traditional approaches in hazardous material transportation focus on pre-event actions (e.g., vehicle design, regulations, training, risk assessment, and route assignment) and post-event actions (e.g., emergency response and recovery). Pre-event actions aim to reduce the risks before the shipment, whereas post-event actions seek quick and efficient ways to minimize impacts in cases of accidents and other disruptions. Little attention is paid to safety considerations during the period when the cargo is enroute, the transit phase. Public and private organizations responsible for the transportation of hazardous materials recognize the limitations of these traditional actions, both in theory and in practice. We therefore would like to propose consideration of a new approach: ***real-time transit control.***

The recent introduction of advanced location and communications technology made operational management of mobile units feasible. The command and control centers (headquarters) know the exact locations of the vehicles and two-way communications between vehicles and headquarters provide the basis for a new managerial approach in monitoring and dispatching. The major breakthrough in location and communications technology is due to satellite systems which became available only now for commercial purposes. The U.S. Department of Transportation points out in its February 1990 report (11):

"The United States has led the world in developing a satellite-based Global Positioning System (GPS) to check the position of vehicles and cargoes in the air, on the highway and railroads, and in shipping lanes. Yet we have only just begun to tap the potential of electronics to help route vehicles more efficiently and safely. Improved communications through electronic data transmission are producing better information, greater control of vehicles and systems, and increased efficiency. We

will soon see fiber optics transmit electronic data and images across the country at a speed equivalent to 50,000 typed pages per second. New high-performance computing systems will permit calculations necessary for more sensitive weather forecasting and will improve the control and operation of advanced aircraft."

Considering the need for operational support in risk assessment and decision making in hazardous material transportation and the latest advancements in information and navigation technology, we belief that the time is appropriate to address the problem of real-time transit control for hazardous material shipments.

STATE OF THE ART IN REAL-TIME TRANSIT CONTROL

Real-time transit control in air, water, and land shipment has different historical backgrounds. The most advanced real-time control systems stem from air traffic and address mainly issues of *safety*. The maritime industry introduced transit control for *navigation* purposes. Railroad operations require transit control for *scheduling* purposes, and trucking companies start implementing this technology for optimization of fleet management operations, including *routing* (5).

Safety in transit control considers two aspects. The first is to protect the passengers within the mode, also called internal safety, and the second is the protection of the environment surrounding the mode, or external safety. While safety aspects referred traditionally to internal safety, safety concerning hazardous material transportation refers primarily to external safety. The objective is to reduce the risks of individuals who may be unaware of the risky action.

Safety aspects in air traffic are directed towards internal safety. This is so because the risks to the environment are very small compared to the risks the passengers face. In addition to safety, scheduling and routing are for public air transport the most important control measures. Real-time control in rail transport has a strong historical background. Satellite control systems are now being introduced to improve safety and productivity of railroad operations (6). The latest technological developments in the maritime community range from collision avoidance systems to satellite navigation systems. Nevertheless, the maritime culture has precluded any transit control (7), (10). Routing and scheduling are completely oriented towards productivity, all too often neglecting aspects of safety.

The trucking industry is the least developed sector with respect to transit control. Schedules are set by demand and can usually only be changed when the drivers call in from a public phone. Routing decisions are typically made by the drivers with little external assistance. Some private companies have started to implement satellite based tracking systems to reduce deadhead miles and improve productivity (9).

The objective of real-time transit control for hazardous material transportation is to improve external safety without compromising economic aspects. In order to achieve this objective it is important to emphasize time-driven scheduling and dispatcher-controlled routing. The state of the art in air and rail modes comes closest to an effective real-time transit control. Table 1 shows an overview of the state of the art in transit control for the different modes. An "X" denotes that it is used today, and an "(X)" that it is used only partially.

TABLE 1

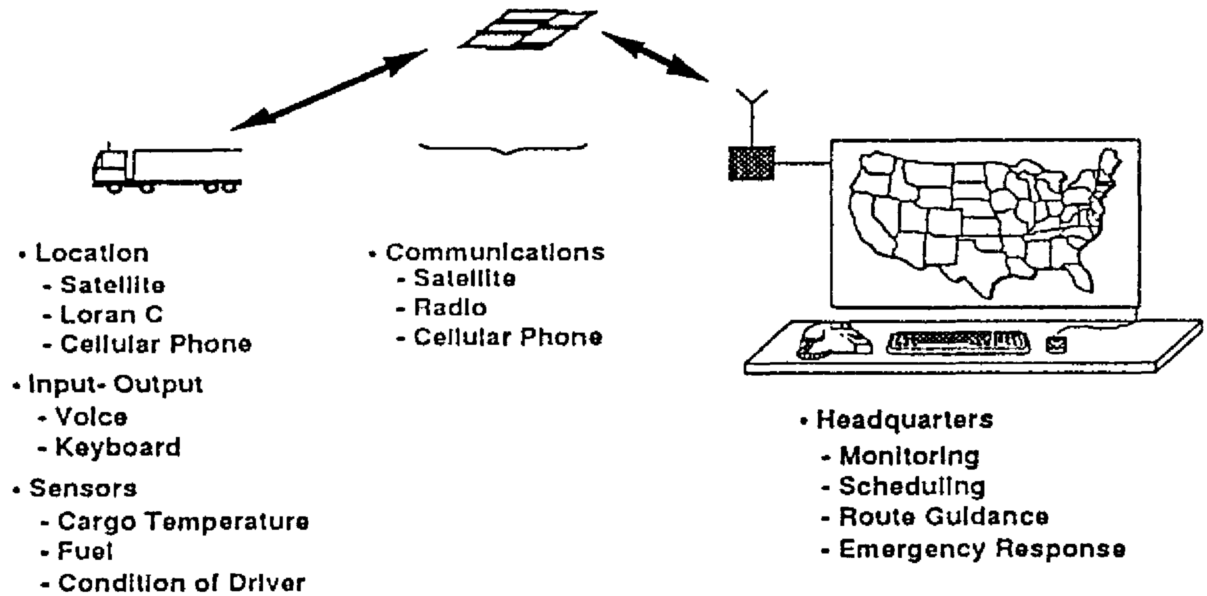
Modes \ Tasks		Safety		Scheduling		Routing	
		Internal	External	Demand	Time	Driver	Dispatcher
Air	Public	X			X		X
	Private	X		X		X	
Water	Inland		(X)	X		X	
	Off-Shore		(X)		X	X	
	Open Water				X	X	
Land	Truck	(X)	(X)	X		X	
	Train	X	(X)		X		X

INFORMATION TECHNOLOGY AND REAL-TIME TRANSIT CONTROL

Several satellite systems are now commercially available which support location and communications between mobile units and the headquarters. The Global Positioning System (GPS) by the U.S. Department of Defense is a constellation of radio navigation satellites that provides extremely high location accuracy 24 hours a day, world-wide. Data about vehicle location, travel speed, fuel, cargo, etc. can be transferred to the headquarters using UHF/VHF satellites. The GEOSTAR system addresses specifically tasks of fleet management. It covers the U.S. and South America with the Radio Determination Satellite System (RDSS). The system features location accuracy 10-100 meters, round the clock operation, real-time location, navigation, communications, and frequent location update. The European counterpart, LOCSTAR, is planned to be operational beginning 1992.

The three major features of satellite tracking systems are: (i) location sensors at the mobile units, (ii) communications links between the mobile units and the headquarters, and (iii) data processors and user interfaces in the mobile units and at the headquarters. The locations of the vehicles carrying hazardous materials can be determined at any time by satellite technology with high accuracy. Data in- and output is done via a special keyboard or by voice. The importance of natural language-based interfaces for advanced monitoring and communications has been studied for air traffic management, as well as for land and sea based control (8). Sensors installed on the vehicle or ship collect data about the status of the hazardous material and the driver or crew. The real-time data transfer between vehicles and headquarters can now be done via satellite. The locations of the vehicles are displayed on a map-like screen at the headquarters. Due to the amount of real-time information provided by this new technology, a variety of managerial concerns can be addressed which could not be done with traditional dispatching. For example, there can be more efficient scheduling and routing, as well as more responsive emergency management. Figure 1 shows the basic concept of real-time information and decision management.

FIGURE 1



While location and communications are in the process of becoming feasible world-wide and the hardware costs are steadily dropping, information management at the headquarters is still in its infancy. The commercially available software packages that support these satellite tracking systems address typically messaging (sending messages via keyboard), reporting (automatic printing of reports), vehicle positioning/mapping (location of vehicle on a map in different colors for different status and overlay of customized maps), and vehicle tracking (display of travelled route).

Missing features are advanced data analysis capabilities for real-time data as well as for static and dynamic databases about the transportation system. The data analysis tasks can be divided into *geographical data analysis, route selection algorithms, and reasoning models.* Although these three tasks have been incorporated to different extends into Geographical Information Systems (GIS's) and Decision Support Systems (DSS's), the connection between DSS or GIS and satellite systems has not yet been addressed thoroughly (4).

DECISION TASKS AND VARIABLES OF CONTROL

Real-time transit control of hazardous material transportation is defined as the set of activities designed to monitor and guide the hazardous material shipments in a transportation system from origins to destinations. Transit control is performed by a dispatcher at the headquarters. The dispatcher monitors on a large screen the movement of the vehicles and the data about the status of the vehicles and the environment (5).

Changes in environment and vehicle conditions can be anticipated or unexpected. We addressed specifically the unanticipated events for which no actions have been planned in advance. An event that causes a change in the environment or in the vehicles' conditions is a called *real-time event* (RTE). RTE's seldom occur but when they do occur, the dispatcher must have quick and efficient support in risk assessment and route guidance. RTE's can last for a few hours up to a few days. Table 2 show the different classes for real-time events.

TABLE 2

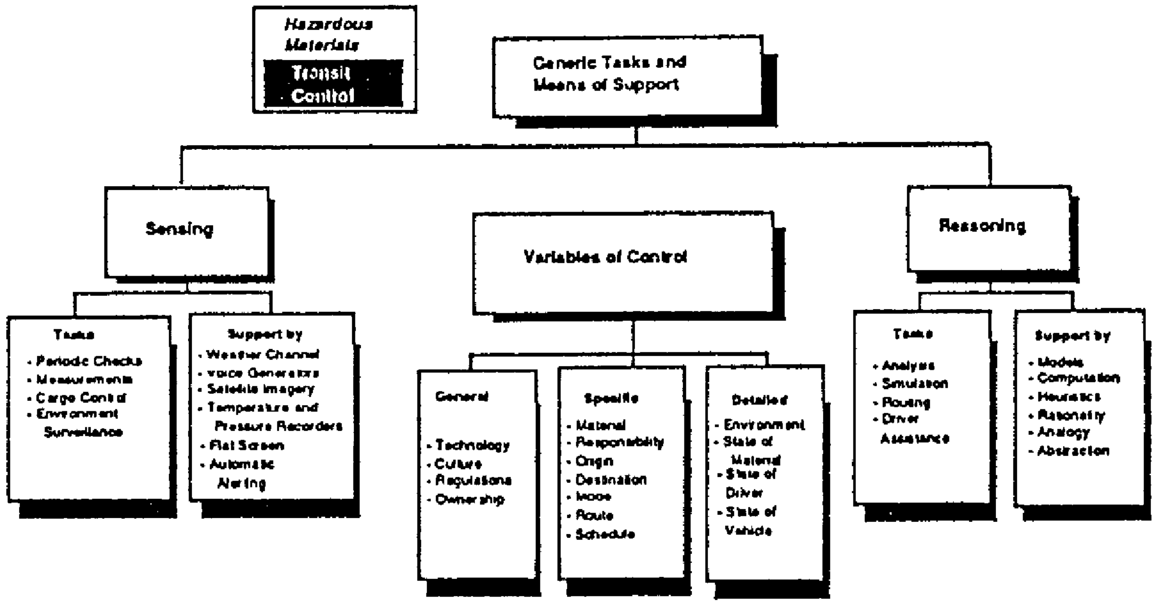
Classes for Real-Time Events		
Natural Phenomena - Weather - Earthquake	**Driver, Handling** - Condition of Driver	**Exposure to Route** - Population - Environment
Condition of Mode - Tires - Brakes - Tank	**Cargo** - Temperature - Pressure	**Condition of Infrastructure** - Road Surface - Traffic

The dispatcher monitors vehicles and environment for any RTE's that are perceived to affect either safety or transportation costs. The activities of the headquarters, which will be referred to as generic tasks, can be subdivided into *sensing* and *reasoning* (5). *Sensing* refers to monitoring the transportation system for RTE's, including periodic checks, measurements, cargo control, and environment surveillance. *Reasoning* refers to analysis, risk assessment, simulation, routing, and pilot assistance.

The variables of the control model can be divided into classes of flexibility. General variables are the available technology to support the control unit and the drivers, regulations, culture, and ownership. They are usually constant for the transit phase but very important for management strategies. The introduction of real-time transit control in hazardous material transportation will have an important impact on regulation and responsibility concerning issues of safety. Regulations promoting safety are general in scope. This often results in contradicting interpretations by different communities which causes serious managerial problems for shipping companies. Real-time transit control provides the means for operational management, so that safety issues can now be addressed on the operational level. This will shift the focus from prescriptive dispatching to predictive control, since the dispatcher knows the actual locations of all the shipments and he can change the routes in real-time.

More specific variables of control are the material itself, origin and destination, the transportation modes, routing, ard scheduling. The detailed variables of control, which are highly variable in time, are the environment, the state of material, the condition of driver (or captain and pilot), and the state of the vehicle. The detailed variables of control are also referred to as real-time events. The generic tasks and the variables of control are shown in Figure 2.

FIGURE 2



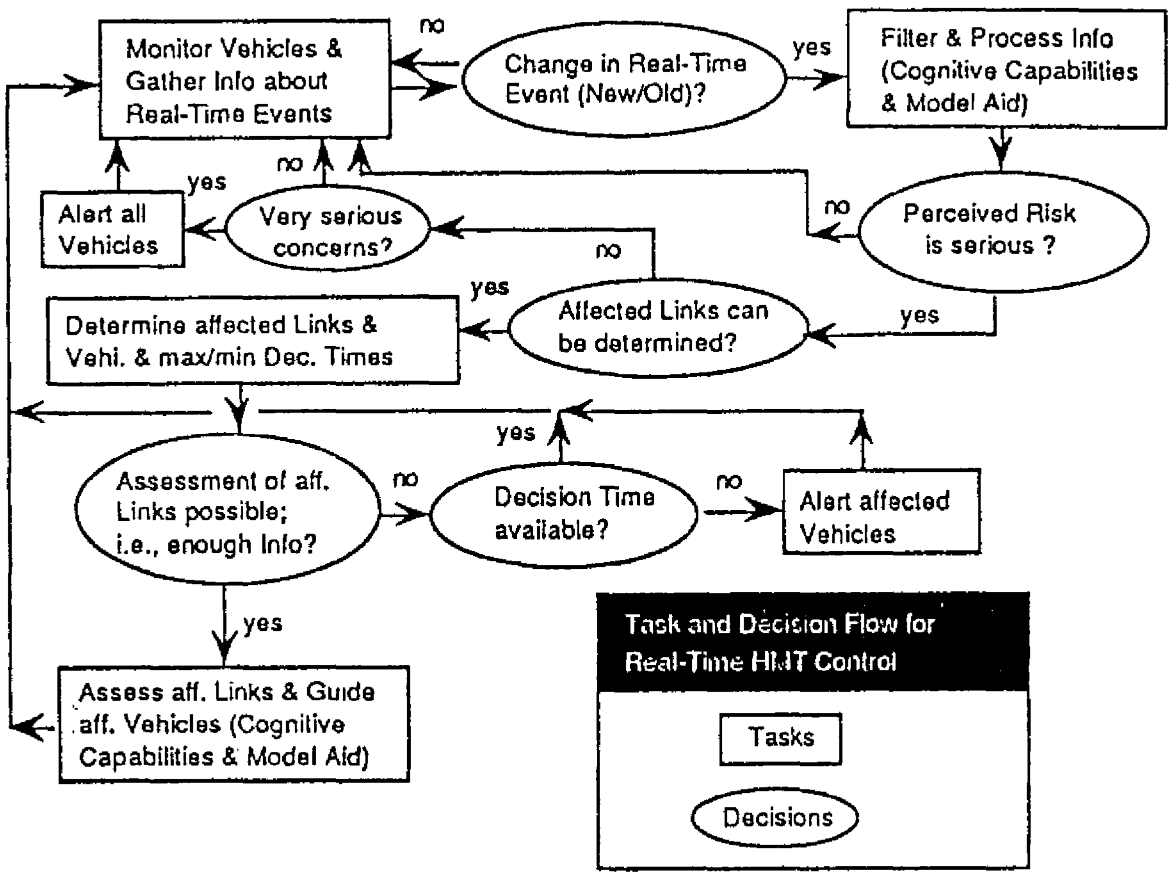
The two tasks that have been addressed within this research are *risk/cost assessment* and *route guidance* for hazardous material transportation. The purpose of the control center is to support drivers in cases of RTE's which are perceived as serious changes in safety or operating costs. Most of the time, however, the dispatcher is merely monitoring the movement of the hazardous material units on a large screen, without active intervention.

Given the continuous update of real-time data and information, the tasks and the decision processes referring to monitoring, risk/cost assessment, and route selection must be analyzed from a dynamic point of view. The dispatcher changes from the monitoring task to the risk/cost assessment task only if a RTE seems to affect safety or transportation costs. The occurrence of RTE's, such as bad weather or traffic accidents, is unpredictable. Data and information about the event can be very limited both in quantity and quality. The first task is therefore to filter and process any incoming information. Depending on the results, the dispatcher might decide to alert immediately all vehicles or only those that are possibly affected by the RTE. A vehicle is affected by a RTE if its planned route goes through the region affected by the RTE.

An important parameter is the time it takes the vehicles to reach the region affected by the RTE. If the vehicles are far away from the region affected by a storm, the dispatcher can postpone his decisions, while he must act fast if the vehicles are close or already within the region.

After risks and costs of the affected links have been assessed, the system computes new optimal routes for the affected vehicles. It thereby can produce three types of results. First, it can suggest stopping certain vehicles and waiting until the RTE is over, second, it can suggest rerouting certain vehicles to avoid hazardous driving conditions, and third, it can suggest for some vehicles continuing the shipment on the planned route if the RTE is not to dangerous. The updated routes are then transferred to the drivers. Figure 3 shows the task and decision flow.

FIGURE 3



OPERATIONAL RISK ASSESSMENT AND DECISION SUPPORT

Potentially catastrophic situations such as real-time events occur relatively infrequently, but when they occur, the dispatcher must act under great stress. He must assess the effects of these events on transportation costs and safety and analyze routing alternatives for the vehicles. The information available to the dispatcher to assess risks and costs will usually be incomplete and inaccurate. This implies that a decision model for real-time decision making must consider humans' limitations in assessment and choice under uncertainty and time constraints. Past research shows that under stress and time pressure, decision makers tend to make biased assessments and choices are made according to outstanding characteristics or even randomly. It is therefore important that the assessment and decision models be based on cognitive aspects concerning the human dispatcher.

A real-time decision model for hazardous material transportation has been developed (2), (3). The major difference to traditional strategic modelling approaches in operational management is the human element. Therefore, the decision support model is based on a set of *cognitive assumptions* about the human dispatcher performing the analyses. It is thereby assumed that the dispatcher assesses the effects of RTE's on safety and transportation costs by changing the risk and cost values of specific objects of interest (entities) along the road links. Examples of entities are bridges, intersections, and road segments in urban areas. It is further assumed that the dispatcher sees the route selection problem as a network problem with the links as the decision variables. Due to the high uncertainty in risk assessment, it is assumed that the dispatcher feels more comfortable assigning risk-entities to well defined ordinal preference classes rather then assessing them numerically. Costs are expressed in dollars, except if they are "too high" or if they can be neglected. In addition, it is assumed that the dispatcher has limitations in assessing preferences for compound entities.

The problem specific interpretations of these cognitive assumptions define the assessment spectrum for risk and cost preferences, and the principles of preference assessment. The dispatcher must assign each entity to one element of the assessment spectrum. The preference of a route is the "sum" of the link-preferences, where "sum" is defined according to a reasoning logic constituted by a preference algebra and two sets of axioms. The algorithm chooses the optimal route (considering the two criteria of risk and cost) from the origin of the vehicle to its planned destination by combining links according to the following priorities:

(1) it never takes a 'closed' link;
(2) among the 'open' links, it avoids as much as possible the high-risk links;
(3) if there are no high-risk links (or for ties), it takes the most economical route; and
(4) if there are still ties, it avoids as much as possible the low-risk links.

Based on the preference algebra, a mathematical description can be given. Each link on the transportation network is characterized by an overall link preference which depends on the cargo and the time the shipment is expected to be on the link. Let n be the number of nodes on the network, $\pi_{ij,k}^{(Y)}(c,t)$ the preference for the link l_{ij} due to the attribute 'Y' ('R' for risk, 'C' for cost) of the k-th entity, given the cargo (c) and the time (t). The x_{ij}'s are the decision variables, which are 1 if the link l_{ij} is chosen for the final route and 0 otherwise. Then, the objective function for the operational routing problem is the following:

$$\text{maximize} \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k\in l_{ij}} x_{ij}\otimes\pi_{ij,k}^{(Y)}(c,t); \quad Y\in\{R,C\}$$

The objective function states that the optimal route is the one with highest preference. It can be proven that the optimal route is the one with lowest preference class being maximal; in cases of ties (several routes have identical lowest preference class), the route with the least number of elements out of this preference class is the most preferred one. The first summation over 'k' is the overall preference for each link l_{ij}; the other two summations over 'n' are for the total network preference, where 'n' is the number of nodes.

The characteristic of this novel route selection model is that it computes optimal routes according to outstanding and not weighted characteristics. Traditional strategic models compute optimal routes by considering simultaneously cost and risk aspects. For this operational model, however, risk and cost assessment is based on ordinal and cardinal values and the preference algebra uses consequently a mixed calculus. In addition, the axioms of the preference algebra, which are derived from the cognitive assumptions, result in a calculus that does not involve trading off risks and costs but only considers whether risks dominate costs or vice versa. It can further be shown that this approach is in full compliance with the traditional principles of decision making under uncertainty (2), (3).

A PROTOTYPE DECISION SUPPORT SYSTEM FOR REAL-TIME CONTROL

We developed a prototype DSS for real-time control of hazardous material transportation that supports a dispatcher of a truck fleet in assessing hazardous driving conditions and selecting safe and cost effective routes (4). The system incorporates graphical display and analysis, decision and reasoning models, and voice output. Our focus was on the design of the DSS and the incorporation of decision algorithms. Real-time data input is therefore simulated but the DSS could easily be connected to a satellite tracking system.

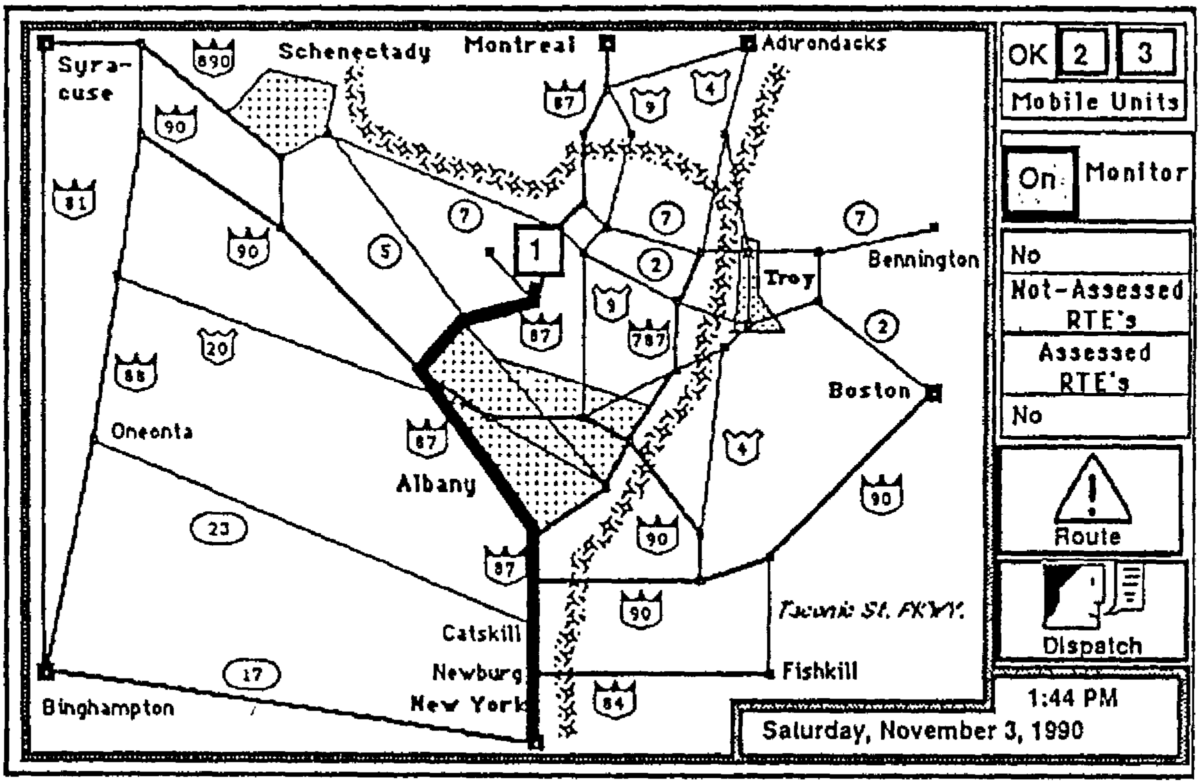
The prototype DSS is written in an hypermedia environment which allows the combination of text, graphics, audio, and video. The object oriented programming structure of hypermedia has advantages over sequential processing. It offers more flexibility and power in the development as well as in the execution phase. The hypermedia environment used for this DSS is Apple's HyperCard. The DSS is written on a Macintosh SE/30. Besides having all the advantages of hypermedia, HyperCard supports text processing and drawing. In addition, it offers its own fully developed programming language, called Hypertalk which can also read and write data to other files and control other programs.

The modular structure of the programming environment and the available high-level commands cut down significantly the development time and reduce the chances of error. If order to improve execution speed, procedures with extensive number crunching are compiled in lover level languages and integrated in HyperCard as external commands (XCMD). With the recent release of HyperCard 2.0, execution speed has been improved significantly since it compiles the scripts in memory. HyperCard is especially suited for control tasks. In conjunction with Macintosh's serial port, it is capable of transmitting and receiving control codes and data. These capabilities provide the basis for connecting this DSS easily to a satellite tracking system. Another advantage of developing the DSS on the PC level is that hardware costs are low and the DSS has a high portability. This makes testing and implementation of the DSS into companies' headquarters easier to achieve (1).

A transportation network from the Capital District region of New York State, has been chosen. The road network consists of 69 links. In order to allow for various transportation environments, selected highways, rural, and inner-city roads have been considered. Three vehicles have been chosen for this prototype. The monitoring screen shows the road network on which the three vehicles move. Information about the road links and vehicles can be obtained by clicking on them. Figure 5 shows the Monitoring Screen.

By clicking on the buttons on the right of the map, different menus are activated, such as initializing vehicles, monitoring, defining and deleting RTE's, risk and cost assessment, routing, and information transfer to the vehicles. The monitoring or the movement of the vehicles can be activated or deactivated by clicking on the button "Monitor." Before any other tasks can be done, the monitoring process must be interrupted. The button underneath the monitoring button allows the user to define or delete real-time events or to obtain information about them. If the field above the button "Non Assessed RTE's" is "Yes" and blinking, then a RTE has been located (region and name are defined and affected vehicles determined) or deleted, but the affected links have not been assessed yet. The field underneath the button "Assessed RTE's" shows "Yes" if there are any assessed RTE's and "No" otherwise. The next button underneath is clicked when a vehicle has to be routed or rerouted. The "Dispatch" button is clicked when a new route must be transferred to a vehicle.

FIGURE 4



Each vehicle has a *card* reserved on which information about the vehicle is held. This includes start time, origin, destination, cargo, planned route, and the real-time events affecting the vehicle's route, if there are any. After the vehicle is initialized, the optimal route can be determined. Routing and rerouting can be done using the whole network or only a sub-network which has to be defined by the dispatcher. Choosing a sub-network allows a dispatcher to exclude certain links from the optimal route.

This DSS has been presented to experienced dispatchers for a practical assessment. The response was in general quite positive and some useful suggestions will help improving the next step of our research - a large scale pilot study. We intend to equip a truck fleet with this technology and to monitor and guide the shipments from a central control unit. The objective is to gain more insight into managerial aspects and to show that this new approach does in fact contribute to the safe shipment of hazardous materials.

CONCLUSIONS

Efforts to improve safety in hazardous material transportation have focused on the pre-event and post-event activities. Considering real-time transit control as an implementable safety measure was until recently premature. Technological advancements, however, have proved its feasibility and first applications of satellite based tracking systems in the trucking industry showed its realism. We therefore developed a decision support system that helps a dispatcher of a truck fleet assessing hazardous driving conditions and selecting safe and cost effective routes. The risk and cost assessment models consider the dispatcher's limitations in assessment and choice under stress and time constraints.

The increasing amount and complexity of hazardous materials in conjunction with economic changes, such as the opening of borders in the new Europe, will create new problems that cannot be addressed anymore in a purely strategic sense. There is also an ever increasing concern about the potentially catastrophic impact of accidents involving these materials. This concern is being reflected in economic loss to the carriers and owners of these materials. This cost plus the public concern for the damages that may not be easily reduced to economic terms will result in a call for more control of the transportation of these materials.

The 80's were dedicated to the development of pre-event and post-event activities as part of a national strategy. We propose that the technology is now available to focus the safety efforts of the 90's on a new concept, the development of real-time control of hazardous material flow - a transit control system to promote the safe and economic shipment of hazardous materials on air, land, and sea.

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