Journal of Hazardous Materials, 27 (1991) 61-75
Elsevier Science Publishers B.V., Amsterdam

Closing the gap: Transit control for hazardous material flow

Giampiero E.G. Beroggi and William A. Wallace

Decision Sciences and Engineering Systems, Rensselaer Polytechnic Institute, Troy, NY 12180 (USA)

Abstract

Hazardous material transportation has thus far been addressed only in the context of pre-event and post-event actions, such as regulations, training, vehicle design, route assignment, and risk assessment for the first, and emergency response and recovery for the latter. Little attention has been paid to safety considerations during the period when the cargo is en route, the transit phase. However, the potential for catastrophic loss inherent in hazardous material transports calls for closing the gap between pre-event and post-event actions by controlling the hazardous material flow. Technological advances have demonstrated the feasibility for this new approach and economical considerations its realism. A control and dispatch center with a tracking system, supported by expert system technology including voice generation and flat panel display, is no longer the vivid imagination of audacious decision analysts.

Introduction

The need for better ways to deal with the potential for catastrophic loss inherent in the transportation of hazardous material has been widely recognized and accepted by government, as well as the transportation industry. However, there is justifiable debate on the means for improving safety in hazardous material transport. We would like to propose consideration of a new approach, real-time transit control. Traditional approaches have focused on pre-event measures (e.g., vehicle design, regulations, training, risk assessment, and route assignment) and post-event measures (e.g., emergency response and recovery). Pre-event activities are designed to reduce the risks before the shipment, whereas post-event activities seek quick and efficient ways to minimize impacts in cases of accidents and other disruptions. The public and private organizations responsible for the transportation of hazardous material recognize the limitations of these measures, both in theory and in practice.

The inability to have universal use of "safe" packaging and containment is due to the highly competitive transportation industry which limits, especially for smaller companies, the introduction of technological improvements. Reg-

0304-3894/91/$03.50

ulations can be ineffectual due to the variety of public authorities involved and problems of enforcement. Training is seen as one of the most promising measures, since most of the accidents involving hazardous material are assumed to be caused by human error. However, even properly trained drivers, captains, and pilots are all too often involved in situations which go beyond their cognitive abilities. The major shortcoming of risk assessment is that the available models are based on the presumptive assumptions of having infinite time to perform the analyses and a boundless amount of readily accessible data—both are unrealistic assumptions when dealing with dynamic large-scale systems [1]. Several attempts to assign designated routes to hazardous material shipments resulted in opposition by the transportation industry and problems in reaching a regional consensus among governmental agencies representing the different interests of communities effected.

Emergency Response, as a post-event measure, is probably the most well organized and effective activity in the field of hazardous material transportation. Even so, a recently published report by the U.S. Office of Technology Assessment (OTA) concluded that nearly 75% of the nation's police and firefighters are inadequately trained to respond to accidents involving hazardous material [2].

Concentrating efforts on improving only these traditional approaches will not lead to a satisfactory situation for hazardous material transportation. The most crucial shortcoming of these approaches is that they focus almost solely on the planning phase before a shipment (pre-event measures), and the organizational and technical tasks after an incident (post-event measures). For the time of the shipment itself, the transit phase (i.e., the time of potentially catastrophic loss), no effective safety measures have been suggested thus far, probably because the technology required for implementation was not available.

It is our contention that computer and communications technology needed to provide safer transport of hazardous material is now available. This enables us to close the gap between pre-event and post-event safety measures by introducing Transit Control, the real-time sensing and controlling of material flow in a transportation network.

The idea of transit control in real-time of hazardous material transportations raises four basic questions.

- Why transit control?
- What are the generic tasks and the variables in transit control?
- What are the expected benefits?
- Is it technically and economically feasible?

These questions will be addressed in each of the following four sections. We will conclude with a discussion of the issues that must be addressed in considering implementation.

Why transit control

Statistics reported by the U.S. Department of Transportation (DOT) show that there are more than 180 million shipments transporting 1.5 billion tons of hazardous material each year in the United States, as shown in Fig. 1.

Shipments of hazardous material are made by land, sea, and air modes of transportation (see Fig. 2). More than half of all the hazardous material shipments (1 billion tons) are done by truck. The vehicles used range from tank trucks, bulk cargo carriers, and other specially designed mobile containers to conventional tractor trailers and flat beds that carry packages, cylinders, drums, and other small containers. Eighty million tons a year (5%) are transported by rail, commonly in tank cars.

Most of the hazardous material transported by barge on in-land waterways

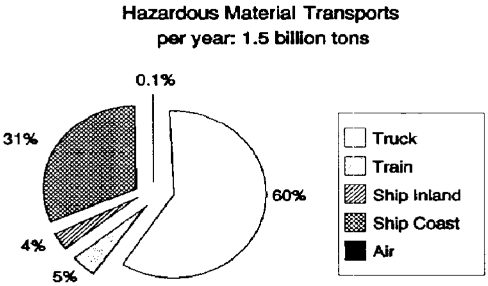

Fig. 1. Estimated amount of hazardous material shipments in the United States by DOT and the Corps of Engineers. Remarkable is that 10% of all the truck shipments involve hazardous material and 5% of the air cargo at the 39 major airports contain (at least small amounts) of hazardous material [3].

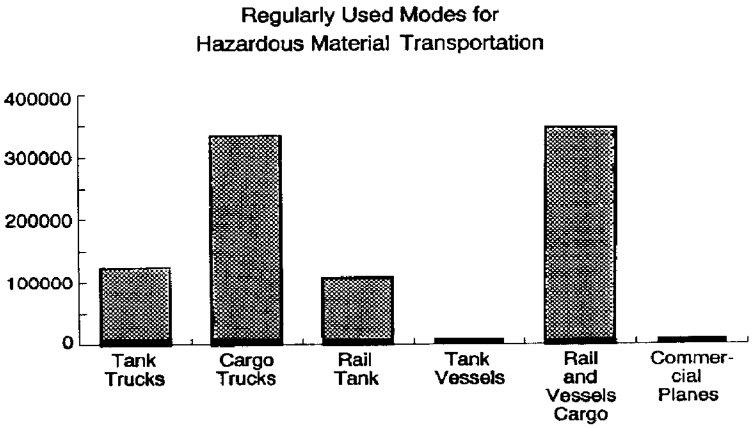

Fig. 2. Number of available units for different transportation modes for the annual 180 million shipments of hazardous material in the United States. Estimations by Federal Government (1982) [3].

is bulk cargo. The U.S. Corps of Engineers estimated that the total in-land waterborne volume is approximately 60 million tons per year. Coastal and inland waterborne volumes, combined, reach 550 million tons annually [3]. Transportation of hazardous material by barge on inland waterways is especially a problem for regions with an extended water network connecting large urban centers. Recent pollution of rivers in Europe by hazardous material witnessed the acute threat of catastrophic events. This situation is particularly acute in the Rhine Valley in Europe as evidenced by recent mishaps that resulted in pollution of the waterways.

The transport of hazardous material by air is performed either in all-cargo aircraft or in belly compartments of passenger aircraft. It is insignificant in total tonnage but constitutes a high number of shipments. A U.S. Federal Aviation Administration Study found that roughly 5% of the aircargo at 39 major airports (overall 300,000 packages) contained hazardous material in rather small parcels of high-value or time-critical material [3].

Data reported to the U.S. Office of Hazardous Material Transports (OHMT) by hazardous material carriers, showed an annual average of 1.25 incidents per 10,000 shipments for the period of 1973–1983. Some experts estimate there may be as many as three to four times as many incidents that are unreported. Statistics by the U.S. Department of Transportation (DOT) showed that in the early 80's there was an annual average of 24 deaths and 663 injuries in hazardous material accidents which correspond to approximately one injured in 880,000 shipments [4] (see Fig. 3).

The U.S. Congressional Research Service's (CRS) study found that human error was judged to be the probable cause of 64% of incidents involving hazardous material, followed by package failure (29%), vehicle accident/derailment (5%), and other (2%).

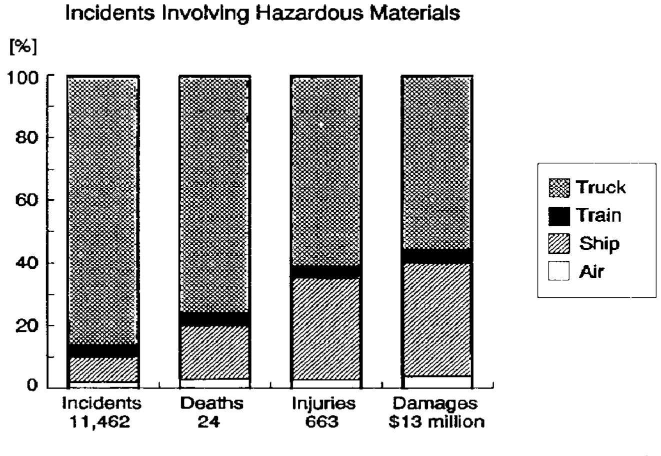

Fig. 3. Incidents involving hazardous material in the U.S.A., 1973–1983. The estimation of damages, $13 million, is considered low. The actual figure might be as much as 10 times higher [3].

These statistics reflect annual averages and do not show the potential for catastrophic loss. It is the nature of some hazardous material shipments that a single accident causing catastrophic loss could change the statistics dramatically. For example, worst case estimates showed that a major radioactive release in New York City could result in 3,000 deaths and decontamination costs of more than $2 billion, or that 18,000 city residents could be killed by an accident involving just one tanker of chlorine [4]. Several incidents in recent years proved that the potential for catastrophic events cannot be ignored. Their impact would have been consequential if some of the accidents happened at different times, places or under different conditions.

The following accidents demonstrate the role that transit control could play in preventing potentially catastrophic hazardous material releases.

- *In 1978, a train derailed in Waverly, Tennessee, causing a propane car to explode, 16 persons were killed and 50 injured* [5].

Train derailments are usually the cause of badly designed/maintained tracks. The condition of the tracks and the environment would be continuously monitored by the control center. Information on abnormal track conditions could be forwarded to the engineer.

- *In Kenner, Louisiana (November 1980), six persons were killed by a gasoline fireball created when a train collided with a gasoline tank truck at a grade crossing* [5].

Transit control could have warned the truck driver of an approaching train.

- *On December 3, 1985, a tank truck carrying 11,000 gallons (41,000 l) of gasoline burst into flames as a result of a blown tire, interstate 95 remained closed for several days, since one section had melted and needed to be replaced* [6].

Critical points on a vehicle, such as brakes and tires, can be monitored as part of transit control. The driver could have been warned about the tire condition.

- *In Littletown, New Hampshire, a tank trailer loaded with 9,200 gallons (33,000 l) of propane jack-knifed on a icy hill and tipped on his side about 75 yards from a large storage tank of liquid propane and less than 100 yards from several large fuel oil storage tanks. Fortunately, no propane leaked from the truck, but a diesel fuel tank was ruptured. Until the propane was safely transferred, 1500 people within half a mile were evacuated (February 11, 1982)* [6].

The control unit continuously screens the road conditions and the environment in general. Here again, the driver could have been warned by the control unit.

- *On July 11, 1978, a tank truck carrying liquid propylene ignited, causing a large fireball in the vicinity of a crowded campsite in Spain. The catastrophic incident caused approximately 170 deaths and numerous injuries* [6].

A control unit could have seen the truck approaching the campsite. An alternate route would have been computed and forwarded to the driver in order to avoid the densely populated area.

- *At 11 p.m. on March 23, 1989, the captain of the Exxon Valdez radioed to the*

Coast Guard that he was turning left from the outbound to the inbound lane to avoid ice. Soon, the Coast Guard lost the ship on the radar. The captain turned over control to the unqualified third mate. The ship ran aground after failing to turn on time. Companies that boasted they had the equipment and manpower in place for a quick cleanup turned out to have hardly anything available and lost irreplaceable days getting into action. The result was a 10.5 million gallons oil spill, killing at least 34,000 birds and 984 sea otters – the largest wildlife catastrophy in U.S. history [*7,8*].

A satellite based transit control system would have been able to track the ship and the unqualified mate would have been identified by the control unit [9].

These are some of the more spectacular accidents involving hazardous material. Less dramatic disruptions occur almost daily. For example in 1980, the Hazardous Materials Response Team of the Houston's Fire Department responded to 297 calls involving hazardous material what corresponds to an average of nearly one call a day. The U.S. Coast Guard reported 6,700 oil spills during 1988, ten of which involved at least 100,000 gallons.

It is evident that transit control of hazardous material flow has indisputable benefits. However, transit control is not an alternative but part of a safety system. By connecting the on-going efforts in improving pre-event and post-event actions with the control of hazardous material flow in real-time, the existing gap in safety will be closed efficiently and effectually.

Transit control: definition, tasks, and state of the art

Transit control for hazardous material flow can be defined as the set of activities, designed to control the transit of discrete hazardous material units on a predefined network from all the origins to all the destinations.

The network consists of nodes and links. Nodes are generally defined as geographical locations with at least two alternatives for moving cargo, such as airports, intersections, harbors, etc. Links are direct connections between two nodes. According to this definition, the hazardous cargo will change mode at one of the nodes. There are two sets of special nodes: origins and destinations of hazardous material which must, from a point of view of safety, be considered in a special way.

The control center we envision for accomplishing the tasks of transit control will be able to manage simultaneously several hundred discrete hazardous material units, moving on different modes. It will be equipped with several computer terminals for human control, a flat display for projection of the transportation network and visual monitoring of the hazardous material flow, and voice alerting. Incoming data from periodical sensing of the sources of risk must be filtered and processed. Reasoning and data management are supported by expert system based technology, requiring human intervention only in cases of increased alert. Any significant change in the risk sources will appear on the large display, for minor events in yellow, and for major events in red. Besides the control tasks, other secondary activities can be performed in the control center, such as simulation of unfavorable constellations, display of potential dispersion clouds, or even simulation and testing of emergency response plans. The control center will be staffed on a 24 hour basis with a small group of dispatchers/controllers.

The process of control can be generalized as one of (1) sensing the present and perceiving an anticipated environment, (2) comparing both to a desired state, and (3) if there is a gap, taking action to bring the present or future state in concordance with the desired state. In order to effect this process, one must gather and store data. This data must then be processed in a form that is meaningful and of value in making the decisions needed throughout the control process [10]. The activities of the control center, which will be referred to as generic tasks, can be subdivided into sensing and reasoning. Sensing refers to periodic checks, measurements, cargo control, and environment surveillance. These tasks will be supported by weather channel, voice generators, satellite imagery, temperature and pressure recorders, flat screen, and automatic alerting. Reasoning refers to analysis, risk assessment, simulation, routing, and pilot assistance. These tasks are supported by models, computation, heuristics, analogy, rationality, and abstraction.

The variables of the control model can be divided into classes of flexibility. General parameters (usually constant for the transit phase) are the available technology to support the control unit and the drivers (or captains and pilots), regulations, culture, and ownership. More specific parameters are the material itself, origin and destination, the transportation modes, routing, and scheduling. More detailed parameters of control, and thus 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.

Another component of the control model is the set of risk sources. Six major risk classes can be delineated: (1) natural phenomena (weather, earthquake, etc.), (2) characteristics of those responsible for driving the vehicle, vessel or airplane in transit, (3) exposure level of the route (population density, environmental conditions, etc.), (4) vehicle/ship condition (tires, brakes, steering, etc.), (5) cargo (temperature, pressure, etc.), and (6) condition of infrastructure (road surface, traffic density, etc.).

The modes used to perform the transit from origin to destination can be divided into three classes: (1) land (truck, cars, train, etc.), (2) water (inland, off-shore, open water), and (3) air.

We envision a control center performing these tasks in a dynamic setting supported in sensing and reasoning by appropriate technologies. These technologies include satellite imagery, decision support systems with advanced graphical interface, voice generator, and sensors. The decision making tasks will be addressed through a human–machine system, where the technology will support the human making the decisions (see Fig. 4).

Transit control, in general, is not a completely new idea. Safety in transit control considers basically two aspects. The first consideration is usually to protect the passengers within the mode, also called internal safety. The other aspect is protection of the environment surrounding the mode, or external safety. Safety concerning the shipment of hazardous material refers in general to external safety. Therefore we are considering the risk of individuals who may be unaware or uninvolved in the risky action, the transportation of hazardous material. Air traffic of hazardous material would be the exception — one would be concerned with both. We are not unconcerned about the driver (or captain or pilot) or crew but external safety seems to be the primary consideration in the transportation of hazardous.material.

The most advanced organization in transit control is air traffic control. Safety aspects are directed towards internal safety due to the passengers and cargo and not the external environment, primarily because it is difficult to define. Scheduling and routing are for public air transport the most important control measures. A similar situation is encountered in the rail transport where control has a significant historical basis. The latest efforts to improve safety and productivity of railroad operations indicate the use of satellite imagery for control systems located in Rail Operations Control Centers (ROCS) [11]. Safety is improved by: (1) movement authority including monitoring, direction, and automatic enforcement, (2) monitoring and alerting of specificed hazards, (3) continuous train position information, and (4) dispatcher-initiated emergency stops. Routing and scheduling for rail transportation are also major control measures.

Latest technological developments in the maritime community range from collision avoidance systems to satellite navigation systems. Nevertheless, despite these technological advances and the potential for effective regulation, the maritime culture has precluded any transit control. Therefore, there has not been any decline in the accident rate of about one ship loss per day, carrying the potential for an ecological disaster [9,12]. Routing and scheduling are completely oriented towards productivity, all too often neglecting aspects of safety.

The trucking industry is thus far the least developed transportation mode with respect to transit control. Some private companies have started to implement satellite based tracking systems permitting a dispatcher to control and route vehicles on an on-line basis [13]. This technology permits the dispatcher to sense the vehicle location, the cargo condition (temperature), and the amount of gasoline. All these tasks are performed in real-time. Nevertheless, except for a few special cases in the nuclear industry, such transit control is not used in trucking of hazardous material. Results of a study concerned with the implementation of this technology for emergency response showed promising re-

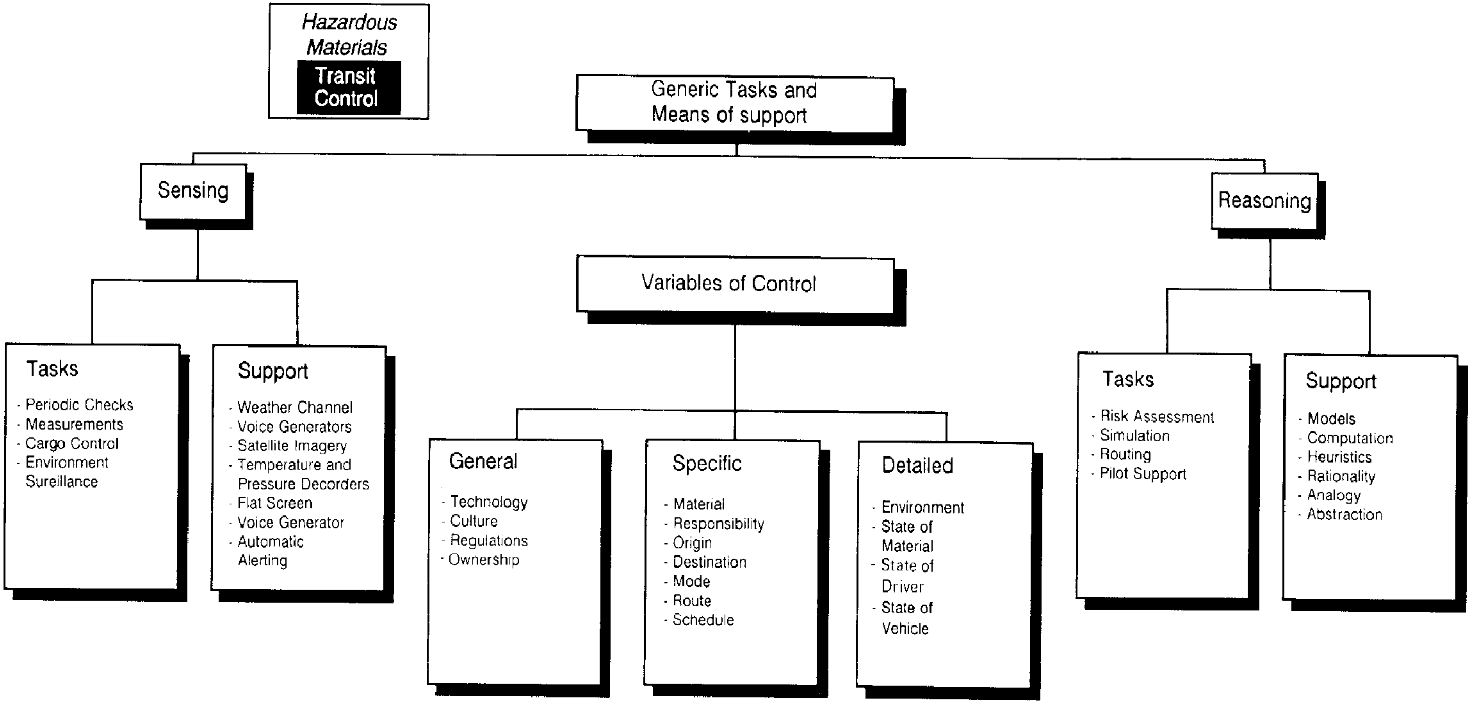

Fig. 4. The variables of control influence the generic tasks sensing and reasoning.

sults, both from a technical and a economic viewpoint [13]. In the trucking industry, schedules are set by demand and routing decisions are typically made by the driver without external assistance.

The objective of transit control is to improve external safety with the transport of hazardous material without compromising the safety of the driver, crew, and cargo (internal safety). In order to achieve this objective we will need to emphasize time driven scheduling and dispatcher controlled routing. The state of the art in air and rail modes comes closest to what we see as an effective transit control.

Realism of transit control

The most significant technological innovation for supporting transit control in the transport of hazardous material is satellite-based vehicle identification and location coupled with on-line communication between vehicle/vessel and a control center. Vehicle location by satellite can be performed with sufficient accuracy for many needs [14]. This technology enables a dispatch and control unit to control the actual location of any vehicle in real-time–at any time over a large geographical area. The ability to locate vehicles by satellite is relatively recent but has drawn considerable attention due to its favorable cost/performance ratio [14]. Transportation carriers are starting to use this technology because it can offer an economic advantage in timeliness and energy costs. However, little attention has been paid to public safety attributes of these tracking systems [15]. Many different vehicle location and navigation systems using satellites are in operation, being implemented or proposed. Their performance varies due to their characteristics and user requirements. The range of vehicle navigation systems goes from radio based navigation systems to voice recognition and generation which will be available in the near future. For the case of radio navigation, private or public radio stations transmit updated traffic situations and provide the driver with useful information about actual traffic conditions.

Several European countries, i.e., West Germany, Austria, Switzerland, and Luxembourg, started during the early 1970's to implement a radio information system for motorists [16]. Traffic police cars transmit messages to the police operation center which are then passed on to the traffic studios of the various regional FM-broadcast stations. From there the traffic information is transmitted together on a special identification frequency. Car radios are equipped with a special decoder so that the radio frequency will automatically turn on the radio or switch to the traffic radio messages disregarding the radio's actual operational mode, e.g, tape, zero speaker volume, radio off, etc. These messages not only describe the traffic situation but also provide motorists with navigation recommendations such as detours [16]. Driver support in general, and especially for the shipment of hazardous material should not be underestimated, especially in Europe where a motorist has to drive only a few hundred miles before entering a new country, with a foreign language and different traffic regulations, e.g., no night driving (or weekend traffic for loaded trucks).

A major research program in vehicle tracking is known as PROMETHEUS, a joint effort involving the European car industry, the electronics industry, and universities. It includes research on custom hardware for intelligent processing in vehicles, methods and standards for communication, and traffic scenario for assessment and new systems. Industry research is oriented toward driver assistance by electronic systems, vehicle-to-vehicle communications, and vehicle to environment communications [16].

The most common and currently used radio-based location system in the U.S. is based on the commercially available LORAN-C transmission system used by the U.S. Coast Guard which provides continuous positioning of several tenths of a mile accuracy on a global basis [14]. The most promising satellite system for vehicle tracking is the Global Positioning System (GPS) which uses medium altitude satellites. Twenty-four hour GPS service has become fully operational in 1990 with an accuracy of some few meters and world-wide coverage [11].

Despite these advancements, navigation, as part of transit control, requires that appropriate interfaces and decision models interact with these satellite tracking systems. This requirement has been recognized in the emergency management community where efforts are underway to couple expert system technology with mathematical models and integrate the result with an advanced Geographical Information System (GIS). The GIS's are ideally suited for capturing, analyzing, and displaying large volumes of land-based data on changing demographic and environmental conditions.

One of the most powerful commercially available GIS is ARC/INFO, a product of ESRI Systems, Inc. Some of the features of ARC/INFO are relational database management, map overlay, query, and interactive graphics display. Probably the most important feature of ARC/INFO for hazardous material transportation is the capability of geographic network analysis. The system has the ability to analyze and model networks such as city streets, waterways, or highways. In addition, it can serve as a tool for vehicle route selection, and time/distance flow analysis [17].

The Joint Research Center, Commission of the European Community, Ispra, Italy developed a prototype risk management system called IRIMS (Ispra Risk Management Support System). It contains several simulation models which can be used for environmental assessment, risk analysis and system optimization, in the European setting. The system is implemented on a SUN-3/160 work station running under the UNIX operating system. Its architecture consists of several modules, including a hazardous material database, industrial accident report, transportation risk/cost analysis (including optimal routing), and environmental impact assessment. One goal of this project is to improve the system by incorporating the mapping capabilities of an advanced GIS [18].

As previously noted, the Association of American Railroads and the Railway Association of Canada are jointly developing a real-time, satellite based Advanced Train Control System (ATCS) for safer and more productive rail operations. The ATCS consists of (1) a color graphic display monitoring the locomotive, (2) a multisensory position information system, including transponder or satellite, (3) a two-way digital communications network for the rail system, (4) wayside switch and detector interfaces, and (5) a central computer. Operations are made more productive by (1) sophisticated traffic planning and supervision, (2) new train information for the dispatcher and train crew, including a dynamic track map and locomotive status, and (3) instructions channeled from the railroad order desk directly to the locomotive cab [11].

The University of Calgary is developing a land-based system to assist automobile drivers in finding the optimal route, given the current position and a destination. The system is intended to enable a user to (1) position a vehicle using signals from satellites and information from on-board differential positioning devices, (2) plot the position on a flat panel display, (3) call up a digitized-electronic map of the area and see the vehicle's position relative to a desired location, and (4) obtain instructions (visual or audio) using an expert system on how to proceed in an optimal manner from the present to the desired location [19].

A potential application of GIS with a reasoning capability is in emergency management. Several fire departments and police centers have stored data for emergency response into a GIS environment. Such a "graphic database" has a wide variety of applications. One important convenience of these mapping systems is their graphical display capability. The user can zoom into detail, move the map in all directions, magnify selected regions, add or remove specific data sets, etc. This capability of graphical scanning is a critical step in any risk assessment for transit control.

The third technology needed to develop a transit control system is communications technology. Recent advances in telecommunications have led to a variety of networks all over the world [20]. The importance of network systems has been recognized by the U.S. Government by promoting the development of the National Research and Education Network which is designed to be the information superhighway of tomorrow [21]. This high-capacity state-of-the-art computer network will be able to link supercomputers, libraries, national databases, and academic and industrial researchers into a unified infrastructure.

One of the most important parameters for safe hazardous material transport is the weather. Weather predictions are most easily available through the 24 hour Weather Channel on television and radio.

The AURA project in Spain (Automatic Regulated Urban Access) is an example of the implementation of expert system technology with weather data for real-time traffic control. Sensors were installed along two highways to gather real-time data on road surfaces (dry, wet, frozen), meterological conditions (visibility, temperature, humidity), and traffic pattern (intensity, occupancy, speed, structure). These data are transmitted through a network to a processing center were recommendations are sent back to signal screens along the highway. These recommendations were aimed at informing the driver about opening and closing of new lanes, recommended speed, and head light signals for access to the freeway. It is intended that the system will be able to "reason" about anticipated traffic problems, such as traffic density and accidents, and provide appropriate guidance to the driver [22].

A powerful and effective method of acquiring data in real-time is aerial reconnaissance and photo interpretation which were born during World War II, and are used in various fields. By 1966, satellite imagery expanded the capabilities of aerial data acquisition even further. There is no doubt that this technology would be very useful for hazardous material flow control [23].

Other sources for data acquisition (in real-time) are the vehicle/vessel itself which can transmit observations to the central control unit through on-line connection, local police, and fire personnel. The control center will have data on such characteristics of the environment surrounding various transportation routes, as well as the emergency response resources — both human and material.

Conclusions

Efforts to improve safety in the transportation of hazardous material have focused on the pre-event and post-event activities. This orientation has resulted in a major deficiency not considering sufficiently the transit phase of the shipments. By closing the gap between pre-event and post-event activities through a real-time control and support of cargo, environment, and vehicle, many incidents can be avoided and potentially catastrophic loss minimized. Considering 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. Moreover, trends toward transit control by the different transportation modes will facilitate the acceptance of real-time control of hazardous material flow.

A central dispatch and control unit, equipped with technology for sensing, reasoning, and communication will be able to monitor and control several hundred cargos simultaneously. The system monitors the environment, especially the major sources of risk, in order to assure a safe movement of the hazardous material flow along a predefined network. In cases of disruption, decision support systems will provide needed assistance to the decision makers in the control center, enabling them to manage any situation that could result in catastrophic loss.

There is general agreement that we will continue to use our transportation systems to move a wide variety of hazardous materials. We are also seeing an ever increasing concern about the potentially catastrophic impact of accidents involving hazardous material. This concern is being reflected in economic loss to the carriers and owners of this material. 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 hazardous material.

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.

Acknowledgements

The research was supported by the U.S. National Science Foundation under a rapid assessment grant from the Natural and Manmade Hazard Mitigation Program, the Swiss National Science Foundation and the Swiss Academy of Engineering Sciences.

References

1 J. Suokas and R. Kakko, On the problem and future of safety and risk analysis, J. Hazardous Mater., 21 (1989) 105-124.

2 G.D. Haddow, The safe transportation of hazardous materials, Transportation Quarterly, 41 (1987) 318-322.

3 Transportation of Hazardous Materials: State and Local Activities, Office of Technology Assessment, Washington, DC, 1986.

4 Programs for Ensuring the Safe Transportation of Hazardous Materials, U.S. General Accounting Office, Washington, DC, 1980.

5 T.S. Glickman, Hazardous materials routing-risk management or mismanagement? Resources, 3 (1988) 11-13.

6 A.B. Boghani and K.S. Mudan, Comparative risk assessment of transportation of hazardous materials in urban areas, Arthur D. Little, Cambridge, MA, 1987.

7 R. Behar, Joe's bad trip, Time Magazine (1988, July 24) 42-47.

8 P.A. Wittman, The stain will remain on Alaska, Time Magazine (1989, September 25),pp. 58-59.

9 J. Harrald, H. Marcus and W.A. Wallace, The management of a maritime crisis: The integration of planning, prevention and response, Interfaces, 25 (5) (1990) 14-30.

10 W.A. Wallace, Command and control: A team problem solving and decision making process, RADC/COE, Griffis AFB, New York, NY.

11 R.D. Burns and D.B. Turner, Safety and productivity improvement of railroad operations by advanced train control systems, Joint IEEE/ASME Railroad Conf., Philadelphia, PA, April 25-27, 1989, Inst. Electr. Electron. Eng., New York, NY, 1989, pp. 33-38.

12 C. Perrow, Normal Accidents. Living With High Risk Technologies, Basic Books, New York, NY, 1989.

13 J.M. Morentz, A case study for the future, Hazardous materials tracking with computers and communications, Symposium on Information Technology and Emergency Management, Gatlinburg, TN, Res. Alt., Inc., Rockville, MD 1988, pp. 42-45.

14 R.D. Briskman, Vehicle location by satellite, International Congress on Transportation Electronics, Dearborn, MI, October 17-18, 1988, IEEE cat. no. 88CH2533-8 247-249.

15 J.M. Morentz, An Automated Crisis Response System for Hazardous Materials Transportation Emergency in New Jersey, Division of Environmental Quality, Department of Environmental Protection, Trenton, NJ, 1989.

16 P. Bumann, Vehicle communication in Europe, International Congress on Transportation Electronics, 1988, 229-235.

17 J.T. Dangermond, Software for geographic information management, Symposium on Information Technology and Emergency Management, Gatlinburg, TN, Res. Alt., Inc., Rockville, MD 1988, pp. 71-72.

18 R.J. Peckham, P. Haastrup and H. Otway, A computer-based system for risk management support, Decision Support Systems, 4 (1988) 481-489.

19 C.B. Harris, R. Goss, J. Krakiwsky and H.A. Karimi, Optimal route information system–automatic vehicle location (AVL) route determination, Department of Surveying Engineering, University of Calgary, Calgary, Alta., 1987.

20 W. Wallace, On managing disasters: The use of decision aid technologies, In: A. Kirby (Ed.), Nothing to Fear: An Examination of Risks and Hazards in American Society, University of Arizona Press, Tempe, AZ, forthcoming.

21 The National Research and Education Network (NREN), Produced by the Coalition for National Research and Education Network, 112 16th Street, NW, Suite 600, Washington, DC 20036, 1989.

22 J. Cuena, Building expert systems based on simulation models: An essay in methodology, Facultad de Informatica, Universidad Politechnica, Madrid, Spain, 1988.

23 D.A. Brugioni, Aerial reconnaissance and photo interpretation in emergency management, Symposium on Information Technology and Emergency Management, Gatlinburg, TN, Res. Alt., Inc., Rockville, MD 1988, pp. 122-126.