Restricting Hazardous Materials Routes on the Nation's Railroads: Some Considerations for Regulatory Analysis

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Regulating the routing of trains carrying hazardous materials is considered. Possible regulatory approaches, insights from past accident experience, status of related research, estimating population exposure, and determining preferred routes are described. Some major conclusions are as follows: (a) Regulation can be accomplished by route designation or by setting routing standards, but speed reduction and time-of-day restrictions should also be considered. (b) Experience shows that only about one out of three accidents is track-related and that although routing to avoid such accidents would reduce their total number, the proportion of costly equipment-related accidents and high-severity derailments would increase in the absence of speed reduction or time-of-day restrictions. (c) Localized population exposure cannot be estimated with confidence using the leading national network models in their current form because of geographical inaccuracies and the high level of link aggregation. (d) Better data on track conditions and economic impacts are needed, along with better methods for preferred route determination that would consolidate the advances in risk assessment modeling with those in developing efficient routing algorithms.

With the exception of certain radioactive shipments, hazardous materials are generally routed in the same way as other railroad freight. Track quality is sometimes taken into account when routing hazardous materials, but testimony given at the 1987 congressional hearings on DOT oversight of defense-related shipments of toxic chemicals indicates that the railroads do little or no risk analysis. During those hearings, a spokesman for one of the nation's most safety-conscious rail carriers testified that his company does not assess the risks of the various routes that are proposed to shippers. Later on, the executive director of the FRA testified that the government does not require them to, because there are no federal guidelines for the routing of rail shipments of hazardous materials.

Contemplation of regulations for restricting the routes of trains carrying hazardous materials entails the considerations that follow. The discussion is organized into five parts: possible regulatory approaches, insights from accident experience, review of related research, population exposure estimation, and preferred route determination. Although the emphasis is on the last three parts, where specific matters of data, models, and algorithms for evaluating regulatory options are discussed, the earlier parts give rise to two significant conclusions of a more general nature: (a) speed reduction and time-of-day restrictions should be considered in addition to (or in lieu of) regulations that would otherwise be limited to the designation of permissible routes or the prescription of standards for route selection, and (b) the benefits of regulations that would simply divert traffic to better track would be limited by the fact that most accidents are not track-related and that accidents on better track tend to be more severe.

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POSSIBLE REGULATORY APPROACHES

If the federal government were to regulate the routing of rail shipments of hazardous materials, net societal benefit (or disbenefit) and whether that would be the most cost-effective way to achieve further safety, are uncertain. Some reasonable conjectures about possible regulatory approaches can be made, however, on the basis of experience in the highway mode. DOT Docket HM-164 led to the rules that trucks carrying highway route-controlled quantities of radioactive shipments are restricted to the Interstate highway system (or to minimum-risk routes identified by states) because those roads are generally safer than others, and that beltways must be used whenever possible to avoid going through urban areas. Docket HM-203, which is in the stage of proposed rulemaking, considers the possibility of extending restrictions such as these to other hazardous materials.

By analogy, FRA's track class system for regulating train speeds would be convenient for restricting the routes of trains carrying certain hazardous materials shipments (the classes are numbered 1 to 6, ranging from worst to best), although certain nontrivial difficulties must be overcome. Better information is needed to estimate the denominators (i.e., traffic volumes) of accident rates by track class; there is only a limited public record of which track is in which track class; and track class changes over time as track conditions change. Yet, none of these obstacles is insurmountable, and a regulatory approach can be envisioned in which the most hazardous shipments would be restricted to the highest available class of track on the set of plausible routes between every origin and destination. Of course, this approach assumes that higher classes are substantially safer than others when the FRA speed limits are obeyed, which may not be the case (depending on how safety is defined), considering that the original intention of the track class system was to achieve equal safety across all classes. Moreover, such an approach would not by itself discourage routing through urban areas—it might actually encourage it—and compliance would be far more difficult than in the highway mode because of a host of operational complications related to train scheduling, car blocking, and interlining between railroads.

Minimum population exposure would be another possible basis for restricting routes, but even apart from an earlier observation made by Glickman (*1*) that this criterion would in some cases result in an increase in risk because of longer distances associated with more circuitous routes and higher accident rates associated with diversion to lower-quality track, there is a conceptual pitfall that must be avoided: an exposure of 10,000 persons/mi over 10 mi on one route from A to B is not the same as an exposure of 1,000 persons/mi over 100 mi on another route, even though both routes have the same total population exposure of 100,000 persons. The reason is that the number of expected fatalities caused by an accidental release depends on the population density.

Generally speaking, use of any single-risk factor such as track class or population exposure is insufficient, because the combination of multiple factors matters. Whether the regulatory approach is to designate which routes must be used, declare which routes are prohibited, or let the transporters select their own routes as long as they follow certain procedures or meet certain standards in the process of doing so, all pertinent factors must be taken into account.

Another regulatory approach that could be pursued in addition to, or instead of, route restriction is mandatory speed reduction. The degree to which such a measure would reduce the probability that an accident will occur is unknown, although accident reports show that the number of cars damaged or derailed in a mainline derailment—which is an indication of accident severity—tends to increase as the reported speed of the train increases. This number was found to be roughly proportional to the square root of the train speed in the report by Nayak et al. (*2*). To determine from the existing statistical evidence what the overall benefit of a speed reduction policy would be does not appear possible; more extensive engineering analysis is warranted, probably involving the use of simulation models to relate train dynamics to track conditions.

The 1979 near-disaster in Mississauga, Ontario, not only drew a lot of attention, but it also spawned a good deal of research about railroad operations in the Toronto area and elsewhere in Canada, some of which has addressed the speed issue. Speaking on behalf of CP Rail, Kelsall (*3*) cited a study that showed that schedule losses would increase by 174 min for a speed reduction from 35 to 25 mph, creating ripple effects on throughput and marshalling operations elsewhere in the system. Although the report of the Toronto Area Rail Transportation of Dangerous Goods Task Force (*4*) did not advocate such action, the consultant's input to that report provided by Delcan (*5*) recommended that speeds be reduced to the range of 35 to 45 mph.

A federally imposed slow order on certain hazardous materials trains in the United States would be relatively simple to enforce, but whether it would make sense in terms of costs and benefits and whether it would keep risks in urban areas down to an acceptable level have not been determined. Other dimensions of the speed reduction argument that would have to be considered are the operational complications and safety implications of having reduced-speed trains that carry hazardous materials share the same track as normal-speed trains. Unless this situation were avoided by judicious scheduling or by slowing all trains down on the affected routes, the need for additional passing maneuvers might introduce associated risks.

INSIGHTS FROM ACCIDENT EXPERIENCE

Historical accident experience provides some insight into the way that routing restrictions would be expected to affect the frequency and severity of accidents involving hazardous materials. The following observations are based on previously published statistics that are repeated in the accompanying tables.

Track defects are the largest single cause of train accidents, but even if that cause could be totally eliminated by rerouting or other measures, the decline in the number of accidents would be limited to 37.3 percent, and the decline in the level of damages to railroad property to 31.8 percent, according to 1985 FRA reports, as presented in Table 1. The decline in the number of mainline derailments involving releases, amounting to 43.6 percent on the basis of all reports from 1978 to 1986, as presented in Table 2, would exceed the decline in the total number of accidents. Equipment failures, which account for 16.3 percent of all accidents and 33.4 percent of mainline derailments with releases and cause the most damage per accident, would still remain. These statistics indicate that even under the most optimistic scenario, the process of rerouting trains to better track would not be a panacea for concerns about rail safety.

The statistics in Tables 3–5, which present accident experience by track class, provide additional insight into the effects of rerouting. Table 3 indicates that diverting traffic to better track (higher track classes) would create a higher proportion of accidents caused by equipment failures (37.5 percent on Class 4 and 55.1 percent on Classes 5 and 6), which according to Table 1 tend to cause the most damage per accident. Table 4 indicates that the average damage per accident due to all

TABLE 1 TRAIN ACCIDENTS BY CAUSE, 1985 (*6*)

	Track Defects	Equipment Failures	Human Factors	Other Causes	All Causes
Number of Accidents	1,280	559	999	592	3,430
(% by Cause)	(37.3)	(16.3)	(29.1)	(17.3)	(100.0)
Total Damage ($M)	59.7	47.6	46.6	34.1	188.0
(% by Cause)	(31.8)	(25.3)	(24.8)	(18.1)	(100.0)
Damage per accident ($K)	46.6	85.2	46.6	57.6	54.8

TABLE 2 MAINLINE DERAILMENTS BY CAUSE, 1978–1986 (*7*)

	Track Defects	Equipment Failures	Human Factors	Other Causes	All Causes
Percent with Releases	43.6	33.4	7.3	14.8	100.0

TABLE 3 TRAIN ACCIDENTS BY TRACK CLASS AND CAUSE, 1985 (*6*)

	Track Defects	Equipment Failures	Human Factors	Other Causes	All Causes
Accidents in Track Class 1	678	125	545	226	1,574
(% by Cause)	(43.1)	(7.9)	(34.6)	(14.4)	(100.0)
Accidents in Track Class 2	208	66	154	93	521
(% by Cause)	(39.9)	(12.7)	(29.6)	(17.8)	(100.0)
Accidents in Track Class 3	153	151	93	123	520
(% by Cause)	(29.4)	(29.0)	(17.9)	(23.7)	(100.0)
Accidents in Track Class 4	76	151	77	99	403
(% by Cause)	(18.8)	(37.5)	(19.1)	(24.6)	(100.0)
Accidents in Track Class 5 & 6	6	27	9	7	49
(% by Cause)	(12.2)	(55.1)	(18.4)	(14.3)	(100.0)

TABLE 4 TRAIN ACCIDENTS BY TRACK CLASS, 1985 (*6*)

	Track Class							
	1	2	3	4	5	6	Unknown	Total
All Accidents	1,574	521	520	403	49	10	353	3,430
(% by Track Class)	(45.9)	(15.2)	(15.2)	(11.7)	(1.4)	(0.3)	(10.3)	(100.0)
Damage per Accident ($K)	26.1	51.5	103.9	128.1	138.6	36.6	21.0	54.8

TABLE 5 MAINLINE DERAILMENTS BY TRACK CLASS, 1976 (*2*)

	Track Class				
	1	2	3	4	5 & 6
Number of Derailments	830	1084	1346	672	157
Billion Gross Ton-Miles	15.6	62.8	241	1,140	187
Derailment Rate (per BGTM)	53.2	17.3	5.6	0.6	0.8
Number of Cars Releasing per Hundred Derailments	1.00	2.55	4.13	4.61	6.21

causes tends to increase in higher track classes (amounting to $46.6K in Classes 1 to 3, and $128.2K in Classes 4 to 6). Table 5 indicates that the average number of hazardous materials cars that release per derailment also tends to increase in higher track classes.

The disadvantages of the higher severity of accidents on better track that are demonstrated by these results need to be considered relative to the advantages of lower accident rates. This tradeoff is immediately clear in the case of derailments, where Table 5 indicates that the rate per billion gross ton-miles (BGTM) tends to decrease in higher track classes. If the BGTM estimates by track class in Table 5 are applied to the accident frequencies in Table 3 and the damage statistics in Table 4 (a rough approximation, given that the data are from different time periods), the rate of accidents per BGTM and damage per BGTM also tend to decrease in higher track classes, as presented in Table 6.

In summary, any regulation that encouraged or required hazardous materials traffic to be diverted to better track, where trains are generally permitted to go faster, would tend to reduce the total number of accidents and the associated total damage to track structures and equipment, but would also tend to increase the average number of cars releasing hazardous materials dramatically.

REVIEW OF RELATED RESEARCH

The consequence of a transportation release accident is commonly estimated by sizing up the expected impact area and using a population exposure estimate to determine the expected number of fatalities or injuries in the area. On a given route segment, the risk of an accident can then be determined simply by multiplying the probability that an accident will occur (based on statistical evidence, tempered where appropriate by expert judgment) by the expected consequence if it were to occur. In more elaborate analyses, the risk is expressed instead not as a point estimate but as the estimated frequency distribution of all the different possible magnitudes of the consequence, which is customarily displayed as a risk profile in complementary cumulative form. Either way, the route segments risks can be combined to obtain the risk for the entire route by doing the appropriate calculations.

Risks were expressed both as point estimates (the expected number of fatalities per year) and risk profiles (stressing the annual frequency of high-fatality accidents) in the derailment risk analysis done by the Transportation Systems Center (TSC) in the early 1980s [as described by Glickman and Rosenfield (*8*)], in which catastrophic risks were the principal concern. Consequences were estimated in that analysis by combining the data base of linkwise population densities (constructed in the manner described in the next section) with the expected size of the lethal impact area (assumed to be circular) on any given link in the event of a release of any given type of nonradioactive hazardous material. These estimates were then factored into the risk calculations, which showed that there was a 95 percent chance of no fatalities in a derailment release accident and less than a 1/100,000 chance of 100 or more fatalities. The individual risk of death in a year was found to be about 1 in 32 million, assuming that the entire U.S. population was exposed.

The routing impact study that accompanied this analysis, referred to in the comments on minimum population exposure in the preceding section, used a simpler approach to estimate the expected annual number of casualties (fatalities plus injuries) associated with any given population avoidance scenario. The conclusion was reached that rerouting to minimize population exposure could reduce the annual expected number of casualties by almost 50 percent nationwide (from 240 to 124) if radical changes in traffic patterns were made, but that some urban areas might suffer at the expense of others, especially if traffic were diverted to poorer track having higher accident rates.

The most detailed analysis of hazardous materials train routing through a localized area was performed by the Toronto Area Rail Transportation of Dangerous Goods Task Force (*4*). The work involved a variety of contractors who spent 2 years looking at many different aspects of the situation. Eleven different candidate routes for through trains were selected and their risks and costs were compared. The conclusion was reached that rerouting was not warranted on the grounds of risk reduction. Nevertheless, on the basis of the observations that were made about the influence of train speed on risk, the Canadian transport minister decided to lower the speed limits on four high-risk track segments. The report also recommended that in the long term, compatible-use buffer zones should be defined and redeveloped adjacent to hazardous materials routes. The shorter-term recommendations include the notions of establishing a nationwide, publicly known track class system that would take nearby population density into

TABLE 6 APPROXIMATE ACCIDENT RATES AND DAMAGE RATES BY TRACK CLASS

Track Class	Accidents	Damage* ($M)	BGTM	Accidents per BGTM	Damage per BGTM
1	1,574	41.1	16	98.4	2.6
2	521	26.9	63	8.3	0.4
3	520	54.0	241	2.2	0.2
4	403	51.6	1,140	0.4	0.05
5 & 6	49	7.2	187	0.3	0.04

*(number of accidents) x (damage per accident)

account, and instituting an accelerated program of track improvements (concrete ties, direct fixation fasteners, and continuous welded rail) in densely populated urban areas.

Other developments in the application of risk analysis to railroad problems outside the United States are also relevant to the assessment of routing options. These include, in reverse chronological order, the British Health and Safety Executive's comprehensive study of chlorine, liquefied petroleum gas (LPG), and ammonia routes using probabilistic risk assessment, which began in 1985 and is still ongoing; the study done for industry by Saccomanno et al. (*9*), which closely examines the statistical basis for accident rates in Canada and includes a case study for LPG; and the extensive study of the risks of chlorine and ammonia transport in the Rijnmond region of the Netherlands, sponsored by the Ministry of Housing, Physical Planning, and Environment (*10*).

Three recent American developments involving the rail transportation of nonradioactive hazardous materials are the route-specific analysis of LPG and chlorine transportation that was performed for the FRA and summarized by Raj and Glickman (*11*), the transportation risk analysis capability developed for the Chemical Manufacturers Association by Pickard, Lowe, and Garrick, Inc. (*12*), and the study of LPG and natural gas liquids by truck and train that was performed by Arthur D. Little, Inc. (*13*), for Santa Barbara County in California. But most of the recent activity related to train routing in this country has dealt with spent nuclear fuel and high-level radioactive waste, typically relying on the INTERLINE model of the U.S. rail network to find the most direct route or the least-exposure route, and the most recent version of the RADTRAN model to calculate the associated point estimate of risk. This approach is illustrated by the study of the national transportation impacts of the commercial radioactive waste management program done by Cashwell et al. (*14*). The two models reside at Oak Ridge National Laboratory (ORNL) and Sandia National Laboratories, respectively.

Some recent advances in computer systems may improve the ability to analyze and weigh the issues involved in routing hazardous materials trains to reduce risk. The digital cartographic data base being incorporated into FEMA's Integrated Emergency Management Information System (IEMIS) contains geographic information taken from large-scale, high-resolution maps, including the 1:100,000 scale TIGER file. The system also has map editing features, meteorological aspects, graphics software, and expert system capabilities, all of which may help to improve the analysis of rail routing scenarios. Some of the same information has already been incorporated elsewhere into new geographic information system software developed specifically for transportation systems analysis at TSC and by a number of commercial vendors.

A powerful workstation capability has also been developed by the International Institute for Applied Systems Analysis (IIASA) in Vienna for processing and displaying high-resolution geographic information. With support from the Dutch government, this system has been enhanced with a hazardous materials data base, a transportation network generator, and a risk assessment module based on the SAFETI software package, which takes in meteorological information, land use data, and other risk factors, and produces sophisticated graphics displays that superimpose risk contours onto detailed location maps. A recent report from IIASA (*15*) documents how the system is being used to analyze the risks of chlorine transportation on railroads in the Netherlands.

POPULATION EXPOSURE ESTIMATION

Population exposure is obviously a major consideration in analyzing the risks of hazardous material train routes. Even low levels of radioactive exposure cause great public concern because of health effects such as latent cancers and genetic defects, and in the case of many nonradioactive hazardous materials, a release that results in a fire, explosion, or toxic vapor cloud can expose a large segment of the general public to immediate harm. High concentrations of residential and working populations are the primary focus in most accident scenarios, but motorists, students, shoppers, and others can also be exposed to risk, depending on the time, location, and severity of the accident.

The TSC derailment and routing studies pioneered the notion of systematically combining census data with the attributes of a transportation network model for the purposes of hazardous materials risk assessment. Residential population counts from the 1970 U.S. Census were updated to produce 1976 estimates for every enumeration district in the 48 contiguous states. Then the population within a mile-wide band centered on each of 17,000 links of the railroad network model was estimated following the method of Haaland and Heath (*16*), in which the centroid of every enumeration district was assigned to the appropriate cell of a national latitude-longitude grid. The network model was superimposed on this grid and, for each link, the populations in the cells within or incident to the surrounding band were accumulated. The result was then divided by the corresponding area to yield an estimate of the population density. The same general approach for estimating population exposure, in which rail network models similar to the TSC one are used, has been used by ORNL and ALK Associates of Princeton, and by researchers at Vanderbilt University who are concerned primarily with highway applications. ORNL and ALK were recently engaged by the U.S. Department of Energy to analyze the routing of rail shipments of radioactive debris from Three-Mile Island to the Idaho National Engineering Laboratory. For a discussion of this experience, see the review conducted at TSC by DOT's Research and Special Programs Administration (RSPA) (*17*).

In their more localized study of the risks on two highway routes and one rail route that are used to transport LPG through Toronto, Saccomanno et al. (*9*) estimated population exposure in much finer detail. Using land use maps based on aerial photographs of the area, they estimated the population in each of the buildings adjacent to roads and railroad lines, distinguishing among single-family dwellings, apartment buildings, townhouses, industrial and office buildings, commercial buildings, and schools, thereby producing estimates of the exposed residential population (which they assumed to be constant throughout the day and night) and the exposed employment population (which they assumed to be daytime only).

In the highway mode, the nonradioactive routing guidelines of FHWA, as described by Barber and Hildebrand (*18*), suggest that census tract maps be used to determine population exposure and that employment exposure also be taken into account. Similar suggestions were made in the guidelines for routing radioactive materials on highways that are published by DOT's Research and Special Programs Administration (*19*). An illustration of an application of the FHWA approach to the Dallas-Fort Worth area was provided by Kessler (*20*).

Of course, the estimate of risk on a route segment is only as good as the information that goes into its calculation, and the method for estimating population exposure using the TSC/ORNL/ALK models has some critical deficiencies originating in the fact that the original FRA network model was not intended for hazardous material routing and risk analysis. One problem is that the network links and nodes do not always line up well with the actual locations of tracks and junctions; in fact ORNL has indicated that the level of precision is only about 10 km [see Committee on Government Operations (*21*, p. 201]. Another problem is that the practice of using a single number to represent the estimated population exposure on each link masks significant variations in the exposure level over the course of the tens or hundreds of miles of a link's length. Unless the links are disaggregated to follow the shapes of the actual routes more closely (to intercept the correct census districts and to avoid the masking effect), serious distortions in the measurement of population exposure can arise. For example, if link A is long and passes through mostly rural areas except for one large urban area, whereas link B is short and passes through a number of small urban areas, then the calculated population density may be lower on link A because so much of its length has a low population. Clearly, each of these links should be split into urban and nonurban segments.

A similar problem is created by the nonuniformity of accident rates on links. Accidents depend on the nature of the track structures and grade and curvature features, along with other factors that contribute to operating hazards. If these characteristics vary substantially from one part of a link to another, then they cannot be adequately represented by a single average value for the accident rate. Therefore, if either track class or speed limit is used as a surrogate for operating conditions, its value needs to be ascertained along each segment of the links on the routes of interest.

Another refinement would be to make the size of the surrounding bandwidth that influences link-by-link population exposure estimation depend on the hazardous material and on the volume of the containment vessel, because the size of the impact area is a function of these factors. The importance of this consideration was demonstrated by Chin and Cheng (*22*) who showed that the ORNL national highway network model produces significantly different minimum-population routes between Hoboken and San Diego, depending on whether the band around each link is 1, 3, or 5 mi in width.

The need to address time-of-day variations in population exposure was demonstrated by a study of weekly traffic patterns in Washington, D.C., which found that the population in business districts increased by a factor of as much as eight from night to day, while the population in residential districts increased by a factor of as much as two-and-a-half from day to night (*23*). Thus, the advisability of operating on a particular route can depend on the time of day at which the shipment is made. If time-of-day variations are ignored because residential census data alone are used, then it is conceivable that the following kind of error could be committed: the safest route appears to be one that goes through a busy commercial area in which few people live, and therefore a hazardous materials train is routed through that area during the busiest hour of the workday, even though the exposed population is actually high.

Time-of-day population variations also need to be taken into account because temperatures tend to be cooler and atmospheric conditions tend to be more stable at night, so that the behavior of a gas cloud emanating from a release will depend to a large degree on when the release takes place. In many cases, it will be better if the cloud is blown away by the wind, as long as this process does not result in a highly toxic vapor being sent into a highly populated area that would otherwise be spared. Yet another reason to be concerned about time-of-day variations is that the consideration of curfews as an alternative to, or in addition to, routing restrictions requires that population exposure be estimated as a function of the proposed curfew periods.

Unfortunately, the only apparent source of comprehensive employee population statistics at the federal level is the manufacturing census, and only about one of every five American workers is employed in the manufacturing sector. Thus, only broad-brush attempts to account for the effects of time-of-day population variations on risk may be possible when large regions of the country are being investigated, and more specific treatments of these effects may have to be limited to localized routing studies in which land use data and other local information are available.

A final observation on population exposure estimation has to do with the importance of basing routing decisions on the combined influence of risk factors rather than on their individual magnitudes alone, a point that was raised earlier but which is worth reiterating in the context of this discussion. Measures of individual factors such as minimum total population exposure that contribute to risk should not be used as a sole criterion for routing because it is important to know whether locations of high population exposure coincide with locations where accident rates are high, and it is impossible to tell whether this is the case on the basis of an average value that creates the potential for distortion by smearing the variations in population exposure along a route.

PREFERRED ROUTE DETERMINATION

There are basically two ways to determine the most favorable routes for hazardous materials shipments: (a) identify the candidate routes and compare them according to some criterion, and (b) identify the criterion of interest and generate the optimal route that best satisfies it. If safety is the only concern and only one aspect of risk is of interest (e.g., fatal accidents), then a single criterion will suffice. But if there are other concerns such as cost, some of which may be in conflict with the primary concern or with each other, or if other aspects of risk are also of interest (e.g., nonfatal accidents), then there may be no single best route and the process of comparing or generating routes will have to be repeated for each different point of view.

Unless there are many candidate routes—a condition that is not likely to hold over shorter distances or in regions where the rail system tends to have a tree structure, with only one path between any pair of nodes—and unless other complications such as scheduling requirements are introduced, the first way will generally be satisfactory; that is, simply enumerate the routes, calculate the risk for each one, and compare the results. The second way requires estimating the risk on every link of a network model and then using a pathfinding (shortest-path) algorithm to find the combination of links that, when they are strung together, constitutes the least risky way to get through the network.

Pathfinding algorithms are easy to program on a computer and run fast even on large networks. Because they are insensitive to what the numbers on the links indicate, the algorithms can be used to find an optimal path on the basis of any criterion for which the link numbers are additive. (Point estimates of risk are usually additive, as are cost estimates.) Such algorithms provide the most efficient means of finding the best route for a long trip through a complex network. Pathfinding algorithms have been used extensively with the TSC/ORNL/ALK models to estimate actual routings of cross-country and regional movements of chemicals, petroleum products, high-level nuclear waste, and other freight. The numbers on the links in these applications are their actual lengths adjusted by a factor that makes mainline links more attractive (shorter) than branchline links, A-mainline links more attractive than B-mainline links, and A-branchline links more attractive than B-branchline ones. These models may not truly simulate actual routing decisions, which are in reality based on a complex combination of considerations such as operating efficiency, scheduling requirements, freight rates, and train make-up. Although their accuracy has never been scientifically validated, they are useful nonetheless.

The research related to the determination of preferred routes that has been published in the technical literature can be divided more or less into two groups: (a) risk assessment procedures that could have been used in conjunction with route enumeration or generation, but were not, and (b) theoretical route generation methods that could have been used in conjunction with risk assessment, but were not. The first group is represented by the Battelle Pacific Northwest Laboratory studies performed for the U.S. Department of Energy (DOE) on propane and chlorine transportation by rail, as documented by Geffen et al. (*24*) and Andrews et al. (*25*), respectively. The second group is represented by Batta and Chiu (*26*), who describe a relatively abstract approach for dealing with variations in population exposure when finding least "obnoxious" routes by means of a shortest-path algorithm, and by Turnquist (*27*), who proposes a hybrid simulation and shortest-path scheme that accounts not only for multiple criteria and for uncertainties in their measurement, but also for scheduling considerations.

Multiple-criterion pathfinding algorithms have the advantage of reducing the computational effort that is required when a number of different measures of effectiveness are of interest. Algorithms such as the one described by Henig (*28*) are capable of efficiently identifying the set of Pareto-optimal solutions to the routing problem, that is, those solutions with the property that if one of the measures could be improved by changing routes, then another one has to be worsened. Knowledge of this set of routes provides a clear understanding of the tradeoffs that exist among alternative routes. The entire set of Pareto-optimal solutions could be identified instead by successive applications of a single-criterion algorithm, but not necessarily by using a weighted sum of the individual objectives (as in the case of the TRANSNET at Sandia National Laboratories), an approach that also suffers from the fact that it is difficult at best for decision makers to articulate in advance the values of the weights that reflect the relative importance (to them or to society) of the various criteria.

Available techniques for preferred-route determination are preferable. However, risk assessment models should be integrated into the process of applying these algorithms. Ideally, such models would be computationally straightforward yet sensitive to variations in the major factors that affect risk. When supplied with adequate data and accompanied by an appropriate network model, these analytical tools would produce credible benefit-cost estimates for evaluating the options for potential regulatory action.

CONCLUSION

A complex combination of factors contributes to the risk of hazardous materials transportation, including (but not limited to)—on the probability side—track defects, equipment failures, and human factors, and—on the consequence side—meteorological factors, population exposure, and deficiencies in emergency preparedness. Some factors such as train speed could affect both the probability and consequence of an accident. Research on the advisability of regulating railroad routes to achieve risk reduction—whether by designating a system of preferred routes or by promulgating a set of guidelines for route selection—has to give due consideration to all these factors and their interactions, as well as to the direct cost implications and indirect economic effects of any proposed regulations. The importance of this observation is demonstrated by the possibility that routing based solely on population avoidance could result in higher risks in some locations, and that diverting traffic to better track without reducing train speeds would likely result in fewer but more severe derailments.

If the regulatory objective is to designate a system of preferred train routes for certain hazardous materials, then on the basis of the discussions in the preceding sections, the following research requirements should be met: (a) a national network model should be developed that is sufficiently accurate and detailed enough to reflect important locational variations in population exposure and operating conditions; (b) a corresponding data base reflecting track class or other link-by-link measures of track condition should be established; (c) improvements in the methods for determining the corresponding population exposure estimates, including a practical way to account for time-of-day variations, should be made; (d) existing models for estimating probabilities and consequences of average-severity and high-severity accidents should be reviewed and, if necessary, modified or replaced; (e) the functional relationship between reduced operating speeds and accident causation needs to be better understood; and (f) a methodology for estimating the economic effects of potential routing regulations should be established.

Alternatively, if the regulatory objective is to establish standards and associated guidelines for selecting preferred routes (as has recently been proposed for the highway model in proposed bill H.R. 3520 in conjunction with reauthorizing the

Hazardous Materials Transportation Act), then a less ambitious research effort needs to be undertaken to identify the soundest set of principles for routing. By means of a series of case studies of carefully selected situations that are representative of the range of possibilities that might be encountered, a number of analyses could be performed to determine the relative effectiveness of different types of guidelines. Items (d)–(f) would still be required in their entirety, but items (a)–(c) could be scaled back and produced only for the selected situations, thereby reducing the data collection requirements considerably. Although not as comprehensive as a designated route system, this approach does have the virtue of being more flexible and more reflective of localized conditions.

In either case, it is clear that the analysis of regulations that would reroute railroad cars laden with hazardous materials is far from a simple task, and that it must be performed judiciously because of the potential public safety implications and economic ramifications.

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REFERENCES

1. T. S. Glickman. Rerouting Railroad Shipments of Hazardous Materials to Avoid Populated Areas. *Accident Analysis & Prevention*, Vol. 15, 1983, pp. 329–335.
2. P. R. Nayak, D. B. Rosenfield, and J. H. Hagopian. *Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads*. Report DOT/FRA/ORD-83/20. FRA, U.S. Department of Transportation, 1983.
3. J. P. Kelsall. Risk Reduction and Economic Efficiency in the Railway Industry. In *Dangerous Goods Movements*, J. H. Shortreed (ed.), University of Waterloo Press, 1985, pp. 107–122.
4. Toronto Area Rail Transportation of Dangerous Goods Task Force. *Final Report*, Toronto, Canada, 1988.
5. Delcan Ltd. *Rail Transportation of Dangerous Goods: Relationship Between Train Speed and Incidence and Severity of Accidents*. Toronto, Canada, 1987.
6. T. A. McClure, L. A. Brentlinger, V. J. Drago, and D. C. Kerr. *Considerations in Rail Routing of Radioactive Materials, with Emphasis on the Relationship Between Track Class and Train Accidents*. Technical Report BMI/OTSP-02, Battelle Memorial Institute, Columbus, Ohio, 1988.
7. A. E. Harvey, P. C. Conlon, and T. S. Glickman. *Statistical Trends in Railroad Hazardous Materials Transportation Safety 1978 to 1986*. Publication R-640, Association of American Railroads, Washington, D.C., 1987.
8. T. S. Glickman and D. B. Rosenfield. Risks of Catastrophic Derailments Involving the Release of Hazardous Materials. *Management Science*, Vol. 30, pp. 503–511.
9. F. F. Saccomanno, J. H. Shortreed, and M. Van Aerde. *Assessing the Risks of Transporting Dangerous Goods by Truck and Rail*. Institute for Risk Research, University of Waterloo, Waterloo, Ontario, 1988.
10. Ministry of Housing, Physical Planning, and the Environment. *The Risks for Transportation of Chlorine and Ammonia in the Rijnmond Area*. The Netherlands, 1985.
11. P. K. Raj and T. S. Glickman. Generating Hazardous Material Risk Profiles on Railroad Routes. In *Recent Advances in Hazardous Materials Transportation Research*, TRB State-of-the-Art Report 3, National Research Council, Washington, D.C., 1986, pp. 53–59.
12. Pickard, Lowe, and Garrick, Inc. *A Manual for Performing Transportation Risk Assessment*. Report PLG-0588. Newport Beach, Calif., 1987.
13. Arthur D. Little, Inc. *Risk Assessment for Gas Liquids From Santa Barbara County*. Public Draft, Santa Barbara, Calif., 1989.
14. J. W. Cashwell, K. S. Neuhauser, P. C. Reardon, and G. W. McNair. *Transportation Impacts of the Commercial Radioactive Waste Management Program*. Report SAND85-2715/TTC-0633, Sandia National Laboratories, Albuquerque, N. Mex., 1986.
15. International Institute for Applied Systems Analysis. *Interactive Risk Assessment for Chlorine Transportation in the Netherlands*. Draft Report, Laxenburg, Austria, 1988.
16. C. Haaland and T. Heath. Mapping of Population Density. *Demography*, Vol. 11, 1974, pp. 321–336.
17. *Review of the Selection of the Rail Route for Shipping Three Mile Island Debris*, Report SS-42-U1.1-57(r). Transportation Systems Center, Cambridge, Mass., Research and Special Programs Administration, U.S. Department of Transportation, 1989.
18. E. J. Barber and L. K. Hildebrand. *Guidelines for Applying Criteria to Designate Routes for Transporting Hazardous Materials*. Report FHWA-IP-80-15, FHWA, U.S. Department of Transportation, 1980.
19. *Guidelines for Selecting Preferred Highway Routes for Highway Route Controlled Quantity Shipments of Radioactive Materials*. DOT/RSPA/OHMT-89/01, Research and Special Programs Administration, U.S. Department of Transportation, 1989.
20. D. Kessler. Establishing Hazardous Materials Truck Routes for Shipments Through the Dallas-Fort Worth Area. In *Recent Advances in Hazardous Materials Transportation Research*, TRB State-of-the-Art Report 3, National Research Council, Washington, D.C., 1986, pp. 79–87.
21. Committee on Government Operations. *Promoting Safer Highway Routing of Ultrahazardous Cargoes: DOT Oversight*. Hearings in the House of Representatives, October 14 and 19, 1987.
22. S.-M. Chin and P. D. Cheng. Bicriterion Routing Scheme for Nuclear Spent Fuel Transportation. In *Transportation Research Record 1245*, TRB, National Research Council, Washington, D.C., 1989.
23. T. S. Glickman. A Methodology for Estimating Time-of-Day Variations in the Size of a Population Exposed to Risk. *Risk Analysis*, Vol. 6, 1986, pp. 317–324.
24. C. A. Geffen et al. *An Assessment of the Risk of Transporting Propane by Truck and Train*. Report PNL-3309, Battelle Pacific Northwest Laboratory, Richland, Wash., 1980.
25. W. B. Andrews et al. *An Assessment of the Risk of Transporting Liquid Chlorine by Rail*. Report PNL-3376, Battelle Pacific Northwest Laboratory, Richland, Wash., 1980.
26. R. Batta and S. S. Chiu. Optimal Obnoxious Paths on a Network: Transportation of Hazardous Materials. *Operations Research*, Vol. 36, 1988, pp. 84–92.
27. M. A. Turnquist. Routes, Schedules and Risks in Transporting Hazardous Materials. In *Strategic Planning in Energy and Natural Resources*, B. Lev et al. (eds.), Elsevier, 1987, pp. 289–302.
28. M. Henig. Shortest Path Problems with Two Objectives. *European Journal of Operations Research*, Vol. 25, 1985, pp. 281–291.

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