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Assessing the Risk and Safety in the Transportation of Hazardous Materials

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ABSTRACT

The transportation of hazardous materials is a broad and complex topic, which is made unmanageable by a morass of regulatory measures at several levels of government. Risk assessment methodologies provide the best means of helping community-level practitioners come to grips with local fears and perceptions. Current approaches to the development of risk assessment methods tend toward the relative rather than the absolute formulations needed by local authorities. The differences between these approaches are discussed. Although it is impractical to achieve a truly absolute risk- or safety-assessment model, an approach is suggested for a more realistic manner of determining an overall safety situation rather than simply risk-of-incident. By concentrating on the highway transportation mode for simplicity of analysis, a set of model formulations is developed that leads to a community safety assessment index. This index is, in turn, made up of a community preparedness index and a community risk index. The argument is made that risk assessment techniques as presently offered provide no distinction between these two means of measuring current safety (preparedness and risk), and do not distinguish between those variables within the control of communities and those beyond that control. A case study is presented for a hypothetical city, Newtown, New Guernsey, which illustrates how such a community assessment index might be calculated and how its results might be interpreted.

The transportation of hazardous materials is a broad and complex topic as a result of the varied legal and physical conditions that surround the subject and the many hazards to be encountered by moving vehicles. This complexity is increased appreciably by the many regulatory measures at the several levels of government and among sovereign countries. The lack of proper controls over hazardous materials transportation has created unreasonable risks to life, health, private and public property, and the natural environment--risks that can and do lead to catastrophic results, including the widespread dispersion of toxic gases, fire, and explosion.

All modes of transportation have been affected, and, in contrast to most other technological activities, hazardous materials transportation portends a greater risk for a greater number of persons. Given the volumes and frequencies with which hazardous materials are transported, risk assessment applications can provide both valuable insights into the solution of these problems and substantial safety improvements in regulations and management.

Government and industry have long recognized that U.S. economic and technical resources have limits; therefore, the application of risk assessment within the context of hazardous materials transportation is recommended to the regulator, the policymaker, and the entrepreneur.

MODAL CONSIDERATIONS

Although all transport modes have hazardous materials safety problems, bulk movements by highway are the most numerous, thereby creating the greatest exposure of populations to risk, on a general basis. Figure 1 shows that the highway mode accounted for most injuries caused by hazardous materials (except sulfuric acid) than did the rail mode; Figure 2

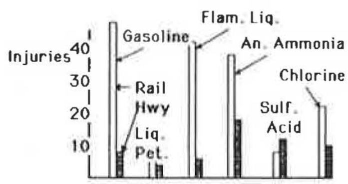

FIGURE 1 Bulk movements of hazardous materials: 1980-1981.

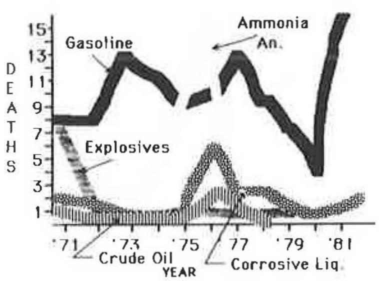

FIGURE 2 Deaths due to five highest commodities, highway mode.

shows that, except for 1976, gasoline carried by the highway mode accounted for the most deaths per year than any other hazardous material.

In 1977, of the 653 billion ton-miles of freight transported by trucks both inter-city and local, 74 billion ton-miles, or 11 percent, carried hazardous materials. Of the 5.7 million trucks in the United States, 6 percent, or 351,000, were in the service of hazardous materials. The typical 5-ton, single-unit truck traveled an average of 28 miles per trip, which accounted for 1.5 billion ton-miles in 56 million trips. The typical 18-ton tractor-trailer traveled an average of 98 miles per trip, this accounted for 3.6 billion ton-miles in 37 million trips, which represents 2.3 times more exposure to incidents. For these reasons, the following discussion relates chiefly to the highway mode, although conclusions are fully applicable to all modes.

ESTIMATION OF RISKS

Risk can be estimated quantitatively if it is possible to assign quantitative values to the probability of an occurrence and the consequences of that occurrence. The probability of unlikely events can be estimated in a number of ways. In some cases the event results from a combination of other events that occur with greater frequency; then the subject event can be estimated statistically by combining the probabilities of the subevents that contribute to its occurrence. In other cases statistical extrapolation techniques permit the estimation of the probability of unlikely events on the basis of the largest values of such events previously experienced. In the procedure proposed in this paper, the known relationships between hazardous conditions (e.g., on highways) and hazardous materials transportation incidents are used.

Relative and Absolute Risk

Most approaches to risk assessment today are of the relative variety, that is, a numerical assessment by which one route or even one mode can be evaluated against another. The end result of such an assessment is that Route A can only be stated as being better or worse than Route B or safer or less safe than Route B.

Absolute risk is a direct measure of hazard, that is, an estimate of the numbers of persons who might be killed or injured, the dollar amount of potential economic loss, or the physical extent (quantitatively expressed) of possible environmental and ecologic damage. Although this approach is the most desirable one--it is the most useful and comprehensible to nonacademic, nonstatistically oriented persons--it is difficult to achieve. Nevertheless, a risk measure that tends toward the absolute is desirable, one that provides the practitioner with a feel for the condition of safety in which the community finds itself as a result of exposure to potential catastrophe.

A recent survey (1) of attitudes among those practitioners who have the greatest need for a usable means of assessing risk (including 400 municipal administrators, 2,500 fire and police chiefs, and 100 drivers of highway tank vehicles revealed not only the dearth of information, knowledge, and training among such interested parties, but the overwhelming need, expressed as interest and desire, for a usable means of assessing local community risk or levels of safety in relation to the movement of hazardous materials vehicles in or near those communities.

Current Practice and Definitions

Risk is defined as "the chance of injury, damage, or loss." The word "chance" can be translated as "probability," which can be turned into a numerical value. Risk is also defined as "hazard."

Previous definitions of risk and earlier risk models are described in a Kansas State University Study (2) in the section entitled, Risk--The Threat to a Community. The model in this case then becomes a series of logical steps to follow, which are intended to lead to better decision making. Risk level is subjectively categorized as high, medium, and low.

The definition of risk in hazardous materials transportation safety considerations has been accepted as the product of the probability of a hazardous materials accident and the consequences of that accident. Consequences are usually expressed as effects on either population or property. Then population risk plus property risk equals total risk. The probability that an accident will occur has usually been defined as the accident history of the roadway segment under study.

Another study (3) includes in its calculations "traffic density, proximity of transportation route to population density, environment, property, and manufacturing and storage establishments," and "forms of threat," defined as fire, explosion, and toxic release.

EVALUATING PROBABILITY

An evaluation of the "probability of injury, damage, or loss" in hazardous materials transportation should not, however, be based entirely on past accident figures or rates. Instead, the evaluation should be based on (a) the current, identifiable hazards and conditions presented to the hazardous materials vehicles on any given facility, (b) hazards inherent in the vehicles used to transport hazardous materials, and (c) hazards reflected in the condition and capability of specific drivers.

Researchers have consistently attempted to approximate true probability (i.e., in terms of percent of a whole) and this requires the use of previous accident data. However, previous accident data do not help in predicting future accident experience. This is an "incorrect assumption" (3) about unchanging conditions of roadway environment; vehicle characteristics; capabilities and conditions; and driver qualifications, training, and temperament. Therefore, the best estimate of probability of occurrence is a subjective assessment of real and apparent hazards.

This method has been approached in a study (3) in which the "fault tree" methodology (from systems-safety engineering) is proposed. In this regard, the number of potential faults in the system would have to be assessed. If faults are equated with hazards, this approach provides a more realistic method of assessing probability, and one that relates more directly to the capabilities and knowledge of practitioners in local communities.

The systems engineering approach requires that hazards be identified not only in the roadway environment element of the human-machine-environment system, but also in the driver (the human) and the vehicle aspects. Severity, or consequences, should be a separate aspect of risk.

COMMUNITY VULNERABILITY

The vulnerability of the community to potential explosion, fire, or other release of hazardous materials has recently come into consideration. Vulnerable is defined as that which is capable of being wounded or physically injured. In one risk study (2), vulnerability is used as the status of community preparedness. This definition requires that preparedness itself be suitably defined, but it is reasonable to assume that vulnerability relates directly to preparedness, among other factors.

Risk calculations must be separated from preparedness assessments, however. The purpose of assessing risk is, appropriately, for the selection of corridors of transport of hazardous materials and the selection of routes within those corridors. The definition of vulnerability does not equate entirely with preparedness. Preparedness should be defined in terms not included in the risk model, so that a community can assess its preparedness quite apart from the assessment of risk made by itself or, more probably, by some external agency.

The value of a community that assesses its state of overall safety lies in (a) the recognition of the degree to which it is, as a community, exposed to the hazard of catastrophe on a daily or weekly basis; and (b) the determination of its needs for improvement in preparation for a hazardous materials incident, from the emergency-response and evacuation standpoints.

In this regard, vulnerability cannot be set equal to, simply, Risk · Preparedness. Vulnerability (the capability of being wounded) should be evaluated in terms of variables such as state of emergency preparedness, public awareness, preparation for evacuation, readiness for evacuation, numbers of persons liable to be evacuated, and similar terms. The only justification for using the term "preparedness" in lieu of "vulnerability" is that "vulnerability" is a negative term that has shock value and therefore would not find support (or use) among grass-roots practitioners, whereas "preparedness" is a positive term and can be perceived as having clearer meaning.

A Proposed Community Safety Assessment Model

The two elements of an overall Community Safety Assessment model are community risk (CR) and community preparedness (CP).

CR is developed from a formulation of the risk level of a motor vehicle incident [RL (mvi)], the risk level of a hazardous materials incident [RL (hmi)], traffic volume level (Ltv), and community risk factors (traffic volume levels are given in Table 1.)

TABLE 1 Traffic Volume Levels

Level	Annual Average Daily Traffic
1	0–5,000
2	5–10,000
3	10–15,000
4	15–20,000
5	20–30,000
6	30–40,000
7	40–50,000
8	50–60,000
9	60–70,000
10	70,000+

$$RL(mvi) = Ltv \cdot (Ni \text{ or } Nr + Nhc + Nvc + Cp + Cm + Nrh + Ctc) \quad (1)$$

where

- Ni = number of intersections per mile,
- Nr = number of on and off ramps per mile,
- Nhc = number of horizontal curves per mile,
- Nvc = number of vertical curves per mile,
- Cp = condition of pavement (e.g., a Pavement Serviceability Index, to be based on AASHTO's Present Serviceability Index),
- Cm = condition of median (e.g., a scale of 1 to 10, with 1 = positive barrier, correctly chosen, correctly installed, and maintained; and 10 = no barrier, median width of 20 ft or less),
- Nrh = number of roadside hazards per mi (e.g., a scale of 1 to 10, with 1 = no roadside

hazards, 30-ft clear zone or smooth walls per barriers, and 10 = 20 primary hazards or 30 secondary hazards or a combination of the two), and

Ctc = condition of traffic control devices (signs, signals, markings) (e.g., a scale of 1 to 10, with 1 = excellent, and 10 = great number of devices in poor condition).

Then, the RL(hmi) can be expressed as follows:

$$RL(hmi) = RL(mvi) \cdot \{P(ex) \cdot 5.5 + P(fl) \cdot 2.5 + P(cg) \cdot 4.0 + P(c) \cdot 1.0 + P(p) \cdot 1.0\} \cdot Lv \cdot Ld \quad (2)$$

where

P(ex) = proportion of explosives vehicles in AADT (e.g., use percentage derived from random surveys; random surveys should cover 24 hr, each day of week, four seasons of year);
P(fl) = proportion of flammable liquids vehicles in AADT;
P(cg) = proportion of compressed gas vehicles in AADT;
P(c) = proportion of corrosives vehicles in AADT;
P(p) = proportion of poisons vehicles in AADT [the multipliers (5.5, 2.5, 4.0, 1.0, 1.0) were based on the approximate comparative impact of an incident];
Lv = vehicle level, including physical condition, how material is loaded, braking system, age of vehicle, condition of tires, and type of container--evaluation of the container is to be based on criteria of Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation. This evaluation is related also to available gauges and instruments within or on specific vehicles; and
Ld = driver level (including driver experience, accidents/violations history, training, awareness of regulations, awareness of emergency response actions, and knowledge of potential of material carried).

Then

$$CR = RL(hmi) \cdot \{Pd = Na + V\$ + Ns\} \quad (3)$$

where

Dp = population density of impacted areas (e.g., from Census Bureau classifications in specific tracts, available to community representatives, on a scale from rural to heavily urbanized);
Na = number of hazardous materials actors (generators, receivers, storers); this requires a land-use survey--available records should not be relied upon;
V$ = dollar value of property affected; and
Ns = number of sensitive facilities (e.g., schools, hospitals, churches, nursing/old age homes, libraries, manufacturing facilities, and area of public concentration).

The CP element is formulated in the following manner:

$$CP = Ler + Lec \quad (4)$$

where Ler is the level of emergency response capability (e.g., training, equipment, communication, transportation, manpower, evacuation capability, response time, planning, and exercises). Public awareness and preparedness emergency services include fire services, police, health and hospitals, public works, and contract personnel. Lec is the enforcement and compliance level, including training level of personnel (police and fire); number of inspections, both fixed-facility and on highways; history of violations; history of releases and incidents; and penalty structure.

CP, when combined with CR, provides an overall community safety assessment (CSA) as can be seen in Equation 5.

$$CSA = CP/CR \quad (5)$$

The eventual value of CSA, as a product of CP and CR, will reflect the overall community safety situation relative to hazardous materials transportation. For instance, values between 1 and 5 for CP, with 5 as "best" condition, or highest CP level, and between 0.1 and 1.0 for CR, with 1.0 as "worst" condition, or highest CR level, offer the following CSA values: in the worst-case condition, CP = 1, CR = 1.0: CSA = 1; and in the best-case condition, CP = 5, CR = 0.1: CSA = 50.

If the variables introduced in the three elements of the CSA are given values that result in a CSA index of this configuration, the significance of CSA can be shown graphically, as in Figure 3. A "criticality value" would be chosen to represent unacceptable levels (to the community) of death, injury,

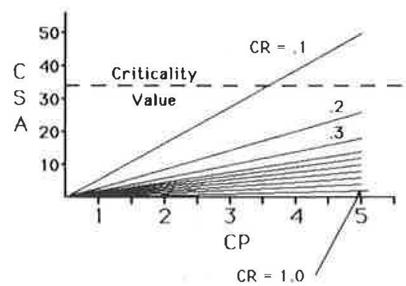

FIGURE 3 Community safety assessment (CSA = CP/CR).

and/or destruction in the event of an incident. If, for example, we set the criticality value of the CSA at 25, it is clear that a reduction of risk has a much greater effect on overall safety than does an increase in preparedness.

CASE STUDY: HYPOTHETICAL CITY OF NEWTOWN, NEW GUERNSEY

Newtown, N.G. (Figure 4), is a suburban town in a northeastern state, with a population of 15,000. It is bisected by an Interstate route (I-88), a U.S. route (US-44), and two state routes (NG-20 and NG-55). A railroad (P and G) also bisects the town and branches off into two lines close to the central business district (CBD).

Figure 4 shows the general hazardous materials risk situation of Newtown. Hazardous-materials-carrying vehicles in large numbers pass through the town close to the CBD, churches, schools, hospitals, and other sensitive facilities, and close to industry, much of which itself produces, stores, and/or utilizes hazardous materials. Thus, residential, commercial, industrial, institutional, govern-

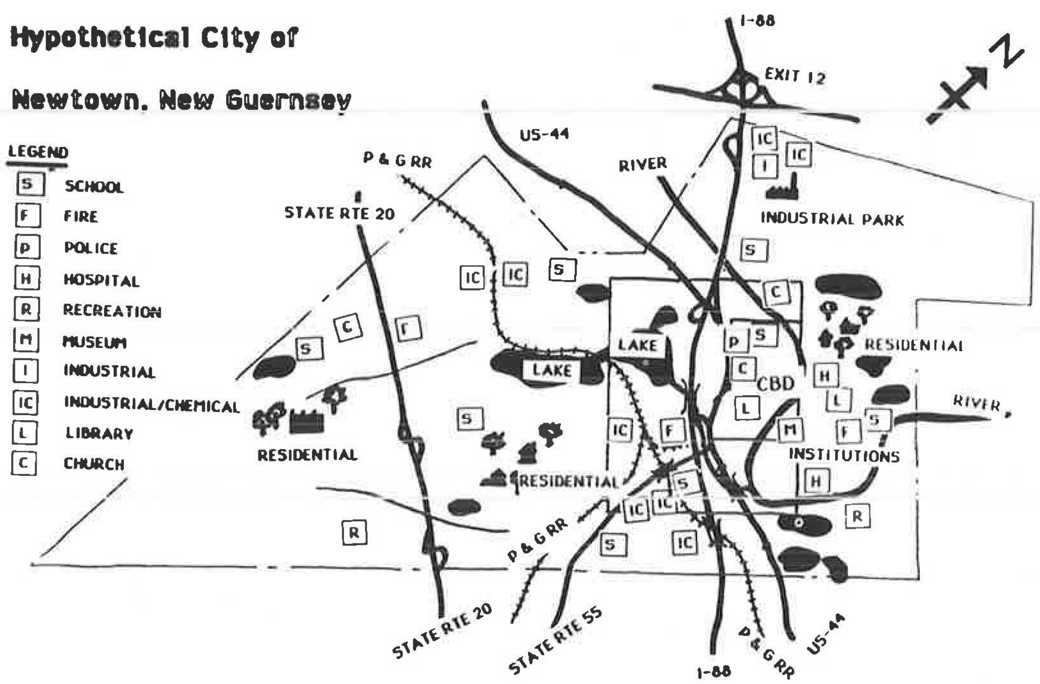

FIGURE 4 Map of Newtown, New Guernsey.

ment, and recreational (note streams and bodies of water) properties are exposed to risk.

Information from Observation

The following observations are made:

1. Newtown has a volunteer fire department, which does as well as it can to keep ready for emergencies. However, emergencies related to hazardous materials, (for which there is great potential in Newtown) are not easily confronted by volunteers. Training can never be adequate under such conditions; knowledge of the effects of and proper countermeasures for each of the many toxic chemicals is difficult to impart to part-time personnel. The Fire Chief has developed a more than adequate emergency plan, but his efforts are hampered by lack of personnel, appropriate equipment, and hydrants in strategic locations (such as within a reasonable distance of segments of I-88, which carries most of the hazardous materials vehicles).

2. Roads are heavily traveled by hazardous-materials-carrying vehicles (up to 119 tankers and 53 nontankers in a single 24-hour period). Thirty-six of these vehicles were carrying gasoline. The others ran the gamut of hazardous materials, including corrosives, flammable liquids and gases, poisons, combustible materials, oxidizers, and radioactive materials.

3. The industries within the city of Newtown use, receive, store, and ship materials such as oils, acetone and ethyl alcohol, pesticides, pigments and resins, lacquer, thinners, freon, antimony oxide, oxybisphenoxarsine, ketone, trichloroethane, toluene, and methylene chloride.

4. Accident information reveals that on I-88 alone some 25 commercial-vehicle accidents occur per year.

5. A major danger is that of hazardous materials spills that run off roads into the river, which interconnects with the many lakes and ponds seen in Figure 4. The P and G railroad has been asked by the Fire Chief not to park tanker cars on the overpasses precisely for this reason.

6. There is "incredibly heavy" traffic on the indicated roads--all of which (except for I-88) enter the city at street grade in the a.m. and p.m. peak hours. Tanker trucks thread through city streets and stop at diners.

7. There is a lack of hydrants and water lines along certain stretches of the highways.

8. An existing, continuing hazard that raises the risk factor considerably is the climbing lane on northbound I-88, which ends at the top of the upgrade. Just beyond that upgrade summit, out of sight of climbing trucks, other trucks pull off the road for repairs or rest periods. The area they pull off onto is in the shoulder--precisely in line with climbing trucks.

9. Since the state of New Guernsey has not adopted CFR 49, the Code of Federal Regulations rule that concerns the transportation of hazardous materials, no state, county, or city officials have any authority to control the movement of hazardous materials vehicles through Newtown.

Application of the CSA Model

Risk, Preparedness, and Safety Assessment Methodology

To assess the risk, preparedness, and safety values, it is necessary to recall Equation 1. As examples, traffic volumes and a simplified volume-level rating system are given as follows:

Road	AADT	Level
I-88	75,000	10
US-44	30,000	6
NG-20	24,000	5
NG-55	24,000	5

Estimated hazard values (Ni through Ctc), are given in Table 2. By normalizing all values to retain a span of 1 to 10, RL(mvi) is calculated to have a

TABLE 2 Hazard Values for Roads, Newtown, New Guernsey

Road	Ni-Nr	Nhc	Nvc	Cp	Cm	Nrh	Ctc
I-88	3	3	3	5	8	10	8
US 44	2	3	2	4	10	10	8
NG 20	2	5	2	3	10	10	6
NG 55	2	4	3	4	10	10	7

value between 8 and 4.5. Then CR = 0.7 (on a scale of 0.1 to 1.0), and CP = 2.5 (on a scale of 1 to 5). Then, the CSA = 2.5/0.7 = 3.6. If the CSA value is located on Figure 4, as shown in Figure 5, it is found to be well below the criticality value.

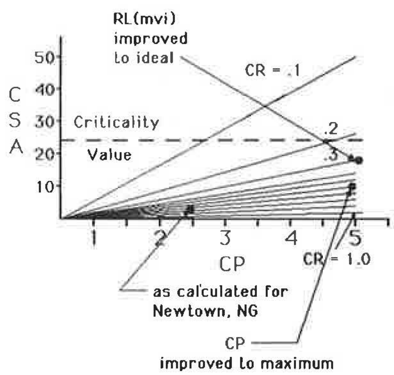

FIGURE 5 Newtown, New Guernsey: CP, CR, and CSA values.

Evaluation

The CSA value, at 3.6, is clearly below the agreed-upon criticality value of CSA = 25. The CSA value can be increased by increasing the CP value, decreasing the CR value, or both.

If it is assumed that CP can be improved to its maximum value (CP = 5), it is found that (as shown in Figure 5) it remains, at 7.14, well below the criticality value.

If it is then assumed that the RL(mvi) will be reduced by reducing the value of each of the hazard factors to 1, CR is reduced to .3.

This improves CSA to a value of 16.7, still well below the agreed-upon criticality value. Some options for added improvement can be considered, such as

- Rerouting all traffic;
- Rerouting hazardous materials vehicles;
- Shifting population;
- Shifting hazardous materials actors;
- Moving sensitive facilities;
- Reducing speed of traffic;
- Escorting (convoy) hazardous materials vehicles;
- Restricting hazardous materials vehicles to I-88, specific lanes, lower speeds, under escort, etc.; and
- Erecting protective walls, etc.

Other remedies may be available, but it is clear that preparedness in and of itself cannot reduce vulnerability, and therefore cannot significantly improve safety, yet, a high level of preparedness is absolutely essential.

The variables that are most difficult to improve in any existing situation are precisely those that can be avoided, prevented, or ameliorated in the planning stage: proximity of hazardous materials transport facilities and routes to concentrations of population, sensitive facilities, and hazardous materials industrial sites.

CONCLUSIONS

Risk/safety assessment methods that tend toward the acceptable, understandable (to community-level practitioners), absolute type can and must be developed. Theoretical, relative methods are neither comprehensible to nor usable by grass-roots practitioners. In addition, the need to separate risk assessments from vulnerability (or preparedness) assessments is quite clear.

Although greater detail and calibration of the method discussed here are necessary and desirable, the expressed needs are met for a usable methodology, and the desirability of improving community preparedness while at the same time improving the risk exposure situation of individual communities.

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