Risk Assessment of the Transportation of Hazardous Substances Through Road Tunnels

M. Considine

ABSTRACT

Quantitative information on the risks to the public and the possible damage to tunnel structures from incidents involving the transport of hazardous substances is derived. Four United Kingdom road tunnels with differing characteristics were chosen. The road traffic in hazardous substances was reviewed and scenarios involving the transport of such substances, which may cause damage to the tunnel or harm to its occupants, were constructed. The frequency of such events and their consequences were assessed for the tunnels and for open roads. Societal risk tables were constructed to examine (a) free access to and (b) total exclusion (and rerouting) of all hazardous materials from the tunnels. In all cases examined the risks associated with a policy of diversion of hazardous substances proved to be higher at the bottom end of the societal risk spectrum than those associated with free access to the tunnel. In the majority of cases this trend was reversed at the top end of the societal risk spectrum. Flammable liquids conveyance was found to account for more than 70 percent of the risks. It emerged that structurally all of the tunnels studied exhibited a high degree of resilience and that the chance of tunnel collapse proved very remote.

Wilson drew attention to the need for risk assessment of the transport of hazardous substances through road tunnels in the United Kingdom when he made the following observations (1,p.180):

> Hazards of dangerous goods in tunnels is another problem area. Some of the larger tunnels under rivers in the UK are toll tunnels, and by-laws as to their use are the responsibility of the local authority. The D.Tp. [Department of Transport] approves such by-laws, but has no power to prevent a local authority from adopting by-laws more rigorous than any transport regulations, if it so wishes. Some of the by-laws appear to be unduly restrictive, notably in respect of the banning of certain radioactive traffic and yet half a dozen tanker vehicles of petroleum spirit in one convoy, [Author's note: The toll tunnels in fact have never taken six tankers in convoy and only release one batch of three once the preceding batch has cleared the tunnel.] under escort, will often be seen during the day when the tunnel appears to be congested. It is also possible for the local authority not to consider the broader issue: that to prevent a particular load of dangerous goods from proceeding by the quickest route to its destination may in certain cases lead to a higher probability of the goods being involved in a serious accident, because of the extra length of journey, perhaps via a bridge and through congested urban districts.

Because of these issues the Department of Transport commissioned a risk assessment to provide quantitative information on risks to the public and possible damage to tunnel structure from incidents involving the transport of hazardous substances.

Four tunnels were identified as suitable case studies. Two of the tunnels had been in existence for a number of years, the third was approaching the final stage of construction, and the fourth was still at the early design stage when the study commenced. The tunnels were specifically selected to cover a wide range of factors likely to influence risk levels in anticipation that specific features that have a strong beneficial or detrimental influence on risk levels would be identified. The main features of the four tunnels are summarized in Table 1.

The study was broken down into a number of stages:

1. A review of traffic in hazardous substances was to be concerned with the general pattern of hazardous substances traffic in the United Kingdom and to focus in particular on traffic using the tunnels and possible diversionary routes,
2. Identification of possible accident scenarios for the various categories of hazardous substances both within a tunnel environment and on the open road,
3. Assessment of the consequences of the various accident scenarios with regard to risk to human life and the possible effects on the structure of each of the tunnels,
4. Evaluation of the frequencies of hazardous events, and
5. Combination of traffic levels, accident frequencies, and consequences in order to determine the risks to people from hazardous substances traffic using the tunnel and diversionary routes.

In the following sections each of these aspects is considered in more detail.

TABLE 1 Main Tunnel Features

	Tunnel			
Feature	1	2	3	4
Length (m)	1030	1483	1436	650
No. of tubes/lanes per tube	2/2	1/2	1/2	2/3
Lane width (m)	3.65	2.41	3.65	3.65
Headroom (m)	5.1	4.72	5.03	5.1
Maximum gradient (%)/length in tunnel	-	2.7/640	4.3/500	0.4/500
Hilliness (m/km)	-	20	31	4
Curvature (degrees/km)	-	83	12	0
Ventilation system	Longitudinal	Semitransverse	Semitransverse plus section of longitudinal	Longitudinal
Construction	Submerged section	Driven tube	Driven tube	Cut and cover

Note: Dashes indicate information unavailable.

TRAFFIC IN HAZARDOUS SUBSTANCES

Some idea of the percentage of freight traffic that may fall within the hazardous substances category can be found in "Transport Statistics Great Britain 1971-1981" (2). Typically, of the 1200 to 1500 mte of freight moved annually by road approximately 5 percent is classed as petroleum products, 3 percent as chemicals, and 1 percent as fertilizers. Of a total of 80 000 to 100 000 mTekm approximately 5 percent is due to the movement of petroleum products, 6 percent to chemicals, and 1 percent to fertilizers.

The most comprehensive and widely reported UK survey of dangerous goods is that carried out by Wilson from the Department of Transport. This survey is reviewed in detail by Hills et al. (3,4). In 1973 the Department of the Environment sent questionnaires to 679 industrial companies, 70 to 80 percent of which were affiliated with the Chemical Industries Association (CIA). They were asked to provide details of their bulk transport for the single month of April 1973, which was considered a reasonably typical month. An analysis of the replies by the Home Office suggested that the petroleum figures represented a complete picture and that about 80 percent of the bulk figures for chemicals were covered in the survey.

This exercise revealed that about 34 mte of dangerous goods are transported in bulk per annum. Of this 34 mte, approximately 26 mte were flammable liquids (23 mte petroleum) and 1.1 mte flammable gases.

The survey provided information on the type of load delivered and, in terms of tonnage, petroleum represented approximately 70 percent of all dangerous goods carried by road. The survey also provided a breakdown of the number of loads carried--approximately 25 million per annum. The breakdown into classes of materials allowed average load sizes to be derived for each class.

Taking account of the difference in average load sizes and average journey lengths per tonne for each type of material then at an "average" roadside location, based on the 1973 survey, the proportion of vehicles carrying hazardous goods that passed would be as follows:

Percentage	Material
56	Gasoline
8	Other flammable liquids
3	Flammable gases
3	Toxic gases
3	Other gases
19	Corrosives
3	Toxic solids and liquids
5	Flammable solids

A number of spot surveys in hazardous substances traffic were reviewed and all showed similar breakdowns in material classes.

Unpublished work by Clifton showed that tanker traffic would typically represent about 0.35 percent of total traffic. Surveys of Tunnels 1 and 3 in the study indicated that about 0.1 and 1 percent, respectively, of the total traffic would be tankers. It could also be inferred that tankers as a percentage of total traffic in Tunnels 2 and 4 (for which specific surveys were unavailable) would also be approximately 0.1 and 1 percent, respectively.

All the surveys related to goods transported in bulk and therefore provided no information on packaged goods. The surveys also conformed more or less to accepted definitions of dangerous goods. There may be many materials such as foam furniture or plastics, which in a fire may generate large volumes of toxic fumes and smoke that would be potentially lethal in a confined environment.

It was recognized that statistics generated from such surveys are unlikely to apply with any degree of reliability to regions other than those where the surveys were conducted. Some regional patterns have been discerned (4), but the degree of detail is still insufficient to permit the prediction of dangerous goods traffic flows for all roads. In particular hazardous goods traffic on routes close to a production or storage installation will be severely influenced by the presence of such an installation and may be quite different from the "typical" traffic flows derived previously.

IDENTIFICATION OF ACCIDENT SCENARIOS

The various mechanisms for causing harm to people or damage to tunnel structures and the possible routes whereby such harm could be realized in relation to the transport of hazardous substances were identified using the techniques of fault- and event-tree analysis. Such techniques involve the systematic decomposition of an event into combinations of subevents (fault-tree analysis) or the consideration of all possible outcomes of a single initiating event (event-tree analysis).

Such means revealed that the most important mechanisms by which people or tunnel structures could be affected by the various classes of hazardous substances were

1. Contact with toxic material (inhalation or dermal contact) or asphyxiant (inhalation). The number of people at risk would, in the case of a toxic liquid spill, depend on the extent of liquid pool spread (for possible dermal contact) and (for inhalation) the area affected by toxic vapors at concentrations sufficient to cause injury or death. For toxic gases and finely dispersed solids and also for asphyxiants, only the latter factor would be of relevance.
2. Fire. Fire can affect both tunnel structures and people. For a given fire the damage to a tunnel

would be determined by the temperature that the walls attained and the length of time they were exposed to that temperature. Occupants of a tunnel can be affected not only by the high temperatures generated within the tunnel but also by the effect of toxic combustion products from the fire.

3. Explosion. Blasts can cause both damage to the tunnel and injury to people. Three types of explosion needed to be accounted for. They are, in decreasing order of severity, (a) detonation of solid explosives, (b) fast deflagrations of flammable vapor and air mixtures, and (c) physical explosions resulting from the sudden release of energy stored in compressed gases or explosions from the bursting of a vessel subject to an internal explosion.

4. Contact with corrosive or cryogenic material. The most common materials would be corrosive or cryogenic liquids that on contact may cause damage to the tunnel and injury to people.

The most likely routes by which such harm could be realized were identified as

1. Release of material (i.e., containment is breached);
2. Explosion within a container;
3. Load catches fire; and
4. Load explodes.

ASSESSMENT OF CONSEQUENCES

The determination of hazard areas for incidents on the open road is well within the domain of conventional risk assessments of chemical plants and there are numerous examples of such applications (5-7) reported in the literature. In analyzing the consequences of incidents within road tunnels such models are not generally applicable and there is a need to resort to models specifically developed to take account of such an environment. The development of such models formed a significant fraction of the whole study. The various models that are needed for a full consequence analysis are discussed next.

Pool Spread

The qualitative features of pool spread are well known. A spill spreads under the action of gravity; the rate of spread is dependent on the roughness of the underlying surface and the density of the liquid. When the pool reaches a certain height, the minimum pool height, this spreading ceases. For volatile liquids there will be simultaneous evaporation of the pool as it spreads. The computer code SPILL (8) has been developed to handle such situations and is set up to deal with the axially symmetric problem. An adaptation of such a model was developed for application to the essentially two-dimensional spreading that occurs when the entire width of the road is covered with liquid.

Dispersion

Vapor dispersion in the open air was evaluated using the dense gas codes DENZ (9) and CRUNCH (10). The dispersion of material released inside a tunnel will be dominated by the ventilation arrangement for the tunnel. For quasi-instantaneously formed vapor clouds [e.g., the sudden release of the entire contents of a liquefied petroleum gas (LPG) cylinder] the equations used in the DENZ code (9) were adapted to account for the essentially two-dimensional spreading that occurs when the heavy vapor completely fills the width of the tunnel. As a simplification, the ventilation was assumed to act to create a wind along the tunnel with the cloud advected at the tunnel ventilation velocity. For prolonged releases the approach adopted in the CRUNCH code (10) was used with a suitable modification for air entrainment based on an analogy (11,p.423) with methane layers flowing in mine roadways.

Explosions

For a given size explosion in the open, the overpressure-distance relationship can be obtained from a standard trinitrotoluene (TNT) curve (12) that relates peak side-on overpressure to scaled distance [(actual distance/mass of TNT)$^{1/3}$]. At some distance from the center of the explosion this approach has been found to be useful not only for condensed-phase explosives but also for fast deflagrations in vapor clouds provided that in the latter case the energy generating the blast wave is related to the explosion energy of an equivalent mass of TNT. Damage levels to property and injury to people were correlated with overpressure as described elsewhere (9). In general, physical explosions do not constitute a significant hazard in the open.

The degree of confinement provided by a tunnel precludes a straightforward application of these approaches in determining explosion damage levels. For high explosives, test results have indicated that an explosion in a tunnel leads to a pressure pulse that propagates along the tunnel with much less attenuation than in the open. In determining damage to tunnel structures both peak overpressure and impulse must be taken into account, and damage in large structures correlates better with mean pressures than with transient peak pressures.

Empirically derived correlations (13) were employed to predict overpressure and impulse as a function of distance from the center of the blast, charge size, and tunnel cross-sectional area.

In the confined environment of a tunnel the blast wave associated with the sudden depressurization of a gas or liquefied gas (e.g., as might arise from the sudden failure of an LPG vessel) may, in some cases, have the potential to cause damage to tunnel structures. The computer code GASEX2 (14) was used to calculate pressure-time histories for such events.

A simple model was developed to predict overpressures and impulses from the combustion of vapor clouds in a tunnel. The combustion processes were modeled on the basis of a planar flame front traveling along the tunnel. The expansion of the hot combustion products behind the flame will compress the air ahead forming a shock wave. At a given point along the tunnel, the pressure will rise to the shock pressure on arrival of the shock front and continue at this pressure until the flame arrives, when the pressure will fall to the flame pressure. The model used assumed a constant burning velocity leading to a constant flame velocity and shock velocity. At the completion of burning, subsequent pressures were modeled by a one-dimensional fluid flow code using the conditions at the end of combustion as input to the code. Studies of the response of tunnel structures to these loadings led to the following conclusions.

High explosive effects tended to be mitigated by the inability of some larger structural members in the tunnels to respond significantly to pressure loading on the short time scales indicated. Therefore, in spite of the relatively high overpressures created locally, serious structural failures were limited to two of the four tunnels considered. These failures were the roof and median wall of Tunnel 4 and the road support for Tunnel 3. These structural failures would be expected to be confined to the region within a few tens of meters of the detonation, although the damage would tend to be more widespread for Tunnel 3 than for Tunnel 4. The effects of the quantity of high explosive on tunnel damage did not worsen dramatically for increasing sizes of charge. In addition, widespread damage, due partly to blast and partly to thermal and missile loadings, to internal structures was expected. Some damage to some internal structures was expected in all cases considered.

The effects of rapid releases of pressurized liquids and vapors were generally not serious in spite of the relatively long duration of the impulse. This was because the peak pressures were quite low. The only exception to this was for Tunnel 3 where roadway failure appeared to be possible. Otherwise these loadings would not threaten the structural integrity of any of the tunnels. Damage to internal structures was likewise not predicted for the larger cross section cut-and-cover tunnels, although the extra confinement provided by the smaller bore-driven tunnels could allow some limited damage to particularly weak internal structures. The nature of the loading, combined with the lack of significant thermal effects and the implausibility of damaging missiles, ensured that any damage would be confined to the locality of the release.

The most damaging loads were those determined for the combustion of fuel and air mixtures that fill the entire tunnel cross section with a flammable mixture for appreciable lengths of the tunnel. The effects found were comparable to those determined for the TNT detonations. However, for large releases the damage would extend over a considerable length of tunnel, given the modeling assumptions made. For releases in the region of 10 to 200 kg of flammable vapor, the effects could be largely confined to perhaps 100 m or so of the tunnel length. Thus, 0.1 te of flammable vapor would provide a level of damage similar to that of 1 te of TNT, but over a greater tunnel length.

The hazards to people from an explosion were assessed on the basis of information made available by Eisenberg (15) and Baker (16). For condensed-phase explosions it was found that the longest hazard ranges arose from injury caused by direct blast damage, whereas for vapor cloud explosions damage related to impulse levels (i.e., secondary missiles and tertiary damage) was found to play a more important role.

Fires

Fires resulting from the ignition of hazardous substances may take on a number of forms including pool fires and vapor fires where volatile liquid spillages (such as gasoline) are involved and, additionally, for pressurized liquefied gas releases, torches, and fireballs.

The pool fire combustion mode will be by far the most important in terms of event frequency because this is the principal mechanism by which a pool of flammable liquid is consumed in a fire and, on the basis of the information in the second section, flammable liquids form the bulk of hazardous substances traffic.

For a pool fire in the open, thermal radiation will represent the chief hazard. Hazard ranges were evaluated for this situation using an approach described elsewhere (17).

A pool fire inside a tunnel will cause heating of the walls by radiation and convection from flames and hot gases. Significant damage may occur by thermal spalling of tile grout and concrete and it may be assumed that all fittings that are engulfed in the fire will be damaged. Both thermal effects from flames and hot gases and toxic effects of smoke and combustion products will represent a threat to people in a tunnel fire and will significantly hamper the approach of a fire-fighting force close to the seat of a fire.

A model was developed for predicting the temperature-versus-time profile along the length of a tunnel in the event of a fire. The model assumed that, downstream of the fire, flow in the tunnel could be approximated by a bulk one-dimensional unidirectional velocity, and the conservation equations for mass, momentum, and energy were solved. When a fire has been established it is probable that (at least for larger fires) its requirements will dominate the air flow.

Trial runs of the model showed good agreement with the predictions of the Sandia National Laboratories for the quasi-steady-state temperature profile in the Caldecott tunnel fire (18).

Thermal radiation and smoke-integrated doses to people were evaluated assuming that at the onset of a fire there would be a delay period, during which the hazardous situation could be appreciated and evasive action formulated, followed by movement toward the tunnel exit at a brisk pace.

When a significant vapor cloud builds up before ignition a vapor fire is possible. The hazards from vapor fires, in which significant overpressures are not involved, will be dominated by the damage produced by flame contact. For release in the open, hazard zones may be approximated to the area of the unburnt cloud as determined by dispersion modeling, because it has been observed (19) that in such cases expansion on combustion will be predominantly upward. For a vapor fire in a tunnel the length of tunnel was estimated by determining the extent of the vapor cloud and then making allowance for volumetric expansion on combustion (by a factor of as much as 8). Because the duration of flame contact is short in a vapor fire, significant direct damage to the tunnel was not anticipated although subsequent burning of vehicles left in the tunnel would probably cause some spalling of the lining and damage to fittings.

Quasi-instantaneous and continuous releases of pressurized liquefied flammable gases will, when ignited almost immediately, burn as fireballs and torches, respectively. The determination of hazard areas from such events in the open is described elsewhere (5). These burning mechanisms are still incompletely understood and the extent of the flame zone for such events in the tunnel environment was evaluated assuming that it would occupy the same volume as it would in an open air event.

For fireballs, the duration of which is limited, damage would be akin to that from a flash fire, whereas for torches of prolonged duration damage would be more like that from a pool fire.

EVALUATION OF FREQUENCIES OF HAZARDOUS EVENTS

Previous studies (20,21), which examined hazardous material spills or load fires in road tunnels, adopted the approach of extrapolating accident data on tankers or heavy goods vehicles and applying a factor to represent the fraction of accidents that result in a material spill, leak, or fire.

In this study, data on hazardous material spills and fires were extracted primarily from the reporting of incidents by fire brigades. This information was accessed in two forms. In 1980 MacLean (22) reported a survey of chemical incidents collected from questionnaires returned by fire brigades. The survey covered some 336 incidents. Access to unprocessed data was also secured. These data were from county fire brigade special service call returns for England and Wales that cover the years 1979-1982 and yield information on approximately 1,000 road transport-related incidents.

Analysis of these data suggested that only 15 percent of tanker leaks and spills that were attended by the fire brigade were in fact due to road traffic accidents, and unpublished work by Clifton has shown that only 2 percent of all tanker fires are due to this cause. For these reasons, it was decided to derive event frequencies directly from the previously mentioned sources of reported spill and fire incident data.

Both sources suggested an overall spill probability of approximately 5×10^{-8} per vehicle-kilometer for tanker traffic. Tanker spill data also led to the conclusion that leakages and spills from liquefied gas carriers occurred no less frequently than from road tankers as a whole.

There is little doubt, however, that the stronger construction of liquefied gas carriers compared with most chemical and petroleum tankers would afford them greater resistance to impact damage (the likely route to larger spills) and an appropriate reduction factor was therefore applied to the frequency of large spills of liquefied gases.

Although, for all materials, the smaller spills would arise mostly from leaking flanges, fittings, and so forth, the larger tanker releases would almost certainly arise from accidents involving collisions, rollovers, or the like and it was anticipated that such spill frequencies would depend on road characteristics that reflect trends observed in the overall accident rates. Accordingly, for the larger tanker spills, an environmental factor that takes account of road characteristics was applied in assessing spill frequency.

The problem of determining spill frequencies from packages was exacerbated by inadequate information about the volume of traffic in packaged goods. In the study it was assumed that the volume of traffic in packaged goods for any particular class along a particular route would be proportional to the number of bulk carriers for that class of material. On this basis, packaged goods spill frequencies could be described in terms of bulk-carrier-kilometers.

Both MacLean's survey (22) and the special service returns indicated that the frequency of packaged spills was about twice that of spills from bulk carriers making a total spill probability for packaged plus bulk goods of 1.5×10^{-7} per tanker-kilometer. The data also showed that, in terms of spills from "packages," liquefied gas spills were around four times less than would be anticipated from the fraction of hazardous substances falling into this category. This could be attributed primarily to the greater resistance of liquefied gas cylinders, compared with most other forms of packaging, to damage in a fall from a vehicle (a major cause of packaged goods spills).

The data also provided information on hazardous substances involved in fires. It was found that the frequency of load fires on tankers was about 10^{-8} per kilometer and that the frequency of load fires in packaged goods that merited attendance by the fire brigade was about 50 percent of that attributed to bulk tankers, making a total overall load fire probability of 1.5×10^{-8} per tanker-kilometer.

Although in only a limited number of cases were the quantities involved recorded, the special service returns did allow a breakdown of the probability of spill or load fire falling within a particular size range.

EVALUATION AND DISCUSSION OF RISKS

In determining societal risk levels, motorists and members of the general public were examined as separate groups. There can be merit in this distinction for putting overall risk levels into perspective.

Societal risks were evaluated by combining the frequency and consequences of all the various events described in the third and fourth sections. A knowledge of route lengths and tanker traffic allowed event frequencies expressed in terms of tanker-kilometer to be converted into events per year. Fatalities were determined on the basis of affected area (see the fourth section) and population density. In evaluating the number of motorists affected by a particular incident, due allowance was made for stationary traffic backing up behind an accident.

For each tunnel, societal risks were determined between two fixed locations assuming that (a) all hazardous substances were allowed free access to the tunnel and (b) all hazardous substances used the nearest convenient diversion routes around the tunnel.

Table 2 gives the ways in which various events typically contribute to the overall societal risk levels for all hazardous substance carriers using a tunnel route (Tunnel 1) and one of the corresponding diversion routes. Table 3 gives a comparison of the societal risks of road tunnels with those of an equivalent length of open road.

A number of features emerged from the societal risk expressions. For all of the the routes examined, the risks were found to be primarily associated with other road users; risks to the general public were typically an order of magnitude lower than were risks to motorists.

When the tunnels were considered by themselves it was found that in all cases the major contributors to the risks (always accounting for 70 percent over the whole societal risk spectrum) were incidents associated with flammable liquid (primarily petroleum spirit) fires. Clearly, then, the most effective way of controlling overall risk levels is to direct attention to reducing both the likelihood and the severity of such incidents.

If motorist risks in the tunnels are compared (Table 3), at least for the lower end ($N \geq 1$, $N \geq 10$) of the societal risk spectrum, the risks do not exhibit a strong dependence on tunnel design but reflect rather the density of traffic in hazardous materials passing through the tunnels. This behavior can be demonstrated by observation of the similarities between the risks for Tunnels 3 and 4 (for $N \geq 1$ and $N \geq 10$), which are of substantially different designs but assessed on the basis of similar levels of traffic in hazardous substances. This pattern is repeated in the risks from Tunnels 1 and 2, again of different designs but assessed as carrying similar traffic in hazardous materials. Indeed in each case the societal risks to motorists at the bottom end of the societal risk spectrum ($N \geq 1$ and $N \geq 10$) were remarkably similar to those of equivalent lengths of open road. The small differences can be explained as arising largely as a result of the effect of different environmental factors that themselves reflect those characteristics of a tunnel likely to affect accident rates. Tunnel accident rates are often lower than those for an equivalent length of open road. These observations can be summarized by the conclusion that for small casualty numbers the likelihood of a particular event, rather than its subsequent progression within a particular environment, is the predominant factor in determining risk levels.

A comparison of motorist risks at the top end of the societal risk spectrum ($N \geq 100$), however, revealed a different trend. If the frequency for N

TABLE 2 Societal Risks from Tunnel 1 Route and Corresponding Diversion

Event	Route Section	Societal Risks (frequency of N or more fatalities per 10^6 years)					
		Motorists			Public		
		N = 1	N = 10	N = 100	N = 1	N = 10	N = 100
Tunnel							
Corrosive or toxic liquid release	Tunnel	5.8	–	–	–	–	–
	Open road	170	–	–	–	–	–
Flammable liquid release	Tunnel	45	15	15	–	–	–
	Open road	1,200	380	–	7	–	–
Liquefied gas release	Tunnel	1.6	0.61	0.44	–	–	–
	Open road	47	5.3	–	0.29	0.11	–
Toxic gas release	Tunnel	3.2	3.2	0.19	–	–	–
	Open road	57	21	0.66	6.5	1.8	–
Asphyxiant gas release	Tunnel	0.19	–	–	–	–	–
	Open road	6.6	–	–	–	–	–
Condensed phase explosion	Tunnel	0.04	0.04	0.02	–	–	–
	Open road	0.88	0.44	–	0.12	0.8	–
Total		1,600	420	16	14	1.9	0
Diversion							
Corrosive or toxic liquid release	Open road	420	–	–	–	–	–
Flammable liquid release	Open road	3,000	900	–	11	–	–
Liquefied gas release	Open road	110	13	–	0.44	0.17	–
Toxic gas release	Open road	130	50	1.6	19	2.7	–
Asphyxiant gas release	Open road	16	–	–	–	–	–
Condensed phase explosion	Open road	2.1	1.1	–	0.18	0.12	–
Total		3,700	960	1.6	21	2.9	0

Note: Dashes indicate negligible level of risk.

TABLE 3 Societal Risks of Road Tunnels Compared to Equivalent Lengths of Open Road

Tunnel No.	Category	Societal Risks (frequency of N or more fatalities per 10^6 years)		
		N = 1	N = 10	N = 100
1	Tunnel (motorists)	56	18	15
	Open road (motorists)	69	18	0.03
	Open road (public)	3.5	0.5	0
2	Tunnel (motorists)	59	34	23
	Open road (motorists)	100	31	0.05
	Open road (public)	11	6	0.06
3	Tunnel (motorists)	1,200	350	340
	Open road (motorists)	3,000	900	27
	Open road (public)	240	120	3
4	Tunnel (motorists)	1,400	350	41
	Open road (motorists)	770	200	4
	Open road (public)	41	13	1

$\geq$ 1 reflects primarily the level of traffic in hazardous substances, then any differences between the ratio of frequency for N $\geq$ 100 and N $\geq$ 1 can be attributed principally to the tunnel environment. These ratios are given in the following table.

Tunnel	Societal Risk Ratio (frequency $\geq$ 100/frequency $\geq$ 1)
1	0.27
2	0.39
3	0.28
4	0.03

These ratios follow the trend that would be anticipated from tunnel design: Tunnels 1 and 3 in many respects have similar characteristics (two tubes, two lanes, similar cross sections); Tunnel 4 has the lowest ratio that reflects its favorable characteristics for mitigating the impact of a particular event of short length--large cross section and good ventilation; Tunnel 2 has the highest ratio that reflects its unfavorable features of two-way traffic and small cross section.

A comparison with the open road ratios was even more revealing in that in all such cases the ratios fell below 1 in 100. Not surprisingly, it can be concluded that, for a given incident involving hazardous materials, the tendency toward high casualty numbers increases on moving from the open road to the confined environment of a tunnel and the particular design of tunnel can influence the level of increase.

When route comparisons were considered, it was found in all cases that at the lower end of the societal risk spectrum (N $\geq$ 1, N $\geq$ 10), use of the diversion routes presented higher levels of risk than did allowing free passage of hazardous substances through the tunnels. At the upper end of the societal risk spectrum the increased tendency toward higher casualty numbers for events in tunnels proved sufficient in the cases of Tunnels 1, 2, and 3 to offset the extra distances associated with the diversion routes.

In none of the examples was it considered that the absolute risks would necessarily be considered unacceptable when making comparisons with other activities of the oil and chemical industries (the prime sources of hazardous substance traffic on the road).

INFLUENCE OF EMERGENCY ACTION

In most risk assessments the actions taken by emergency services to reduce the impact of a major accident are largely discussed in qualitative terms because the effectiveness of such actions will vary from one situation to another, which makes quantitative assessment almost impossible. When examining risk figures, it is important to recognize that action by emergency services will not be fully accounted for and that absolute values of risks will therefore tend to be overestimates.

Despite the difficulties in incorporating emergency actions quantitatively into a risk assessment, qualitative discussion of these factors can nevertheless prove of value.

Emergency action can prove of most benefit in those instances in which there is a buildup in the hazard over a period of time. Under these circumstances there is time for the emergency services to reduce the hazard, to effect evacuation, and to advise the public of the hazard.

For incidents that occur on the open road and involve hazardous substances, the approach adopted by the emergency services (primarily the fire brigade) would be expected to be well rehearsed. The usual approaches when dealing with chemicals in incidents would be based principally on policies of containment, dilution, and cooling. In MacLean's survey (22) 98 percent of the 968 reported incidents involving chemicals were treated by one of more of these methods.

Emergency action would therefore be expected to play an important role in reducing the likelihood or severity of most of the incidents described in this paper. The degree of effectiveness of emergency action will not necessarily be the same on the open road as in a tunnel. On one hand, the confinement presented by the tunnel can pose greater problems of access, communications will often be more difficult, breathing apparatus may be required on more occasions, emergency equipment may be more likely to be damaged by the incident (particularly where fires are involved), and evacuation and escape will be more difficult. On the other hand, tunnels are usually well provided with emergency equipment, a degree of control of the hazard can be exercised under certain circumstances via the ventilation system and drainage system, some tunnels may be well supervised, and hazardous materials may be escorted by tunnel staff equipped to prevent the escalation of small incidents involving such materials into major incidents.

In assessing the effectiveness of emergency action some 18 incidents involving hazardous materials in tunnels were reviewed. Of particular interest was the lack of a clear policy on ventilation procedures in the event of a fire. All 12 of the incidents that carried information on ventilation aspects took place in tunnels that had either full or semitransverse ventilation or natural ventilation. It has been suggested (23) that the lack of control over axial flows makes such systems less desirable than reversible booster fans in controlling smoke flows for evacuation or fire-fighting policy. Nevertheless, in some cases in which it is necessary to approach a fire from the tunnel exit, there will be a dilemma between directing smoke flow away from fire-fighting activities or away from possible occupants of vehicles trapped behind the fire.

In 3 of the 12 incidents the ventilation was deliberately switched off or left off and in 2 of these incidents smoke severely hampered operations. In 7 of the remaining incidents the ventilation was boosted to full capacity (at least in the exhaust mode). Ventilation produced significant improvements where the fire was of only moderate proportions but could not cope with the smoke produced by a large fire at its peak. In 2 of these 7 incidents fire was responsible for partial failure of the ventilation system.

Two of the incidents took place in naturally ventilated tunnels and, despite attempts in one of the incidents to induce ventilation by way of a partable blower, smoke severely hampered rescue and fire-fighting operations.

In general, the speed of arrival of fire fighters (tunnel operators or fire brigade) was found to be quite good (in many instances less than 5 min) and, where present, tunnel fire fighters played a useful role, particularly in smaller incidents or in controlling the initial stages of development of a fire.

Evacuation and escape from the tunnel and the prevention of further entry both proved effective means of reducing the number of casualties and this is illustrated by reference to the Nihonzaka fire in which 231 vehicles were initially behind the fire in the tunnel and, although major tunnel damage occurred over a length of more than 1 km, fatalities were kept down to only seven (most of these resulting from the initial collision).

CONCLUDING REMARKS

An examination of the risks associated with the policies of allowing free access and total exclusion of hazardous substances through road tunnels has been described.

For the four tunnels selected as case studies differences were observed both in the absolute levels of risk and in the relative risks among tunnels and between tunnels and diversion routes. These differences demonstrate the desirability of examining each particular case on its merits.

A number of areas in which further examinations would be desirable were identified in the study. In addition, there is latitude for extending the work to evaluate forms of control other than free access or total exclusion and to incorporate the economic aspects of incidents involving hazardous substances into the process of policy formulation.

To conclude, the study has shown the technique of risk assessment to be a powerful tool for aiding the formulation of policies for the transport of hazardous substances through road tunnels. Many of the issues raised in the introduction were resolved, enabling future policy makers to consider quantitative information on levels of risk when making decisions.

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The views represented in the paper are those of the author and do not necessarily reflect those of the Safety and Reliability Directorate, the Department of Transport, or the Welsh Office.