Risk Assessment of Alternative Transport Modes for Hazardous Materials

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ABSTRACT

A computer-based system has been developed for the assessment of risks from process plants. In this paper, a brief description is given of the operation of this system and of its application to several types of projects, both existing and proposed, which involve the transportation of hazardous materials. The way in which it can be readily adapted makes it a vital tool in design and decision-making processes, replacing the older, cruder methods of assessment with one that provides a large amount of objective information which, when correctly applied, can minimize the effects of subjective errors. Its use in the estimation of absolute risk, both in terms of individual risk and of societal risk, is now at a significantly higher level of confidence compared with previous methods of limited scope. But it is in its application to comparative assessment of alternatives that it is proving itself to be a very powerful tool for all concerned, as there is now less reliance on subjective judgment.

Approximately 10 years ago, a series of major accidents in the European process industries, notably Flixborough (1974), Beek (1975), and Seveso (1976) provoked a major appraisal of the problems and how they should be dealt with. This culminated in 1982 in a council directive of the European Economic Community on the major-accident hazards of certain industrial activities (1). These stipulations are now required to be embodied in the laws and regulations of the member states. They include requirements for the technical appraisal of consequences that affect employees and the public, and therefore assume that the appropriate methodology is available.

HISTORICAL INTRODUCTION

During the last decade there has also been a significant development in the awareness and understanding of the effects of these accidents, and where knowledge has been lacking, major large scale experimental programs have been undertaken, principally in North America and Europe. This methodology is recorded in many papers and books and is the subject of frequent symposia and conferences concerned with loss prevention.

Development of Risk Assessment

In several places in the world, there are large concentrations of the process industries where large quantities of hazardous substances are manufactured and stored. In some of these locations, the resident population lives close by and is occasionally subjected to the effects of minor releases. But the major events that occur from time to time, (e.g., in Mexico City and Bhopal in 1984) indicate all too clearly the enormous problems of the coexistence of the process industries and the population and the necessity for assessment and control.

Some of these locations have mounted major exercises to assess the problem and to control future development. One such public authority, Openbar Lichaam Rijnmond, which covers the greater Rotterdam area of the Netherlands, has been very active in this respect. Based on the methodology as it was then developed, the COVO study was set up by them in conjunction with the local industry group. This examined the risks from 6 "objects" (selected storage installations that hold liquid nitrogen gas, chlorine, propylene, ammonia, acrylontrile, and a hydrodesulphurizer). The results of this exercise were published in 1981 (2) and the methodology that is used is displayed in detail through a standard classical treatment. The great extent of this study suggested that its widespread adoption would prove overwhelming and perhaps defeat its objective. Several more exploratory projects were subsequently undertaken in the Netherlands in an attempt to simplify the methods and increase the degree of computation.

It eventually became clear that the use of computers made simplification almost irrelevant in terms of dealing with such increasing complexity. At the same time, avoidance of simplification could remove the risk of accidentally eliminating some key events from the assessment. The Dutch government then sponsored the provision of an extensive computer package to bring all these methods together in their logical order. This work was undertaken by Technica, Limited in London, England and has taken some 15 man-years of effort to set up, test, and package. The result is the SAFETI package, which is currently being further extended and improved to permit it to deal with a wider variety of events, and with greater efficiency. It is going to prove impossible to model every scenario or possibility, but the intention is to enable adequate modeling to be available for the widest variety of cases.

The SAFETI Risk Assessment Package

It is only possible here to provide a brief summary of this package of computer programs. Its objective is to provide:

1. Ease of data input (it is interactive),
2. Reasonable speed of processing (dependent on machine),
3. Minimum loss of detail,
4. Variable level of data input/output to suit needs, and
5. Visibility of both intermediate and final results.

The outline flow sheet for the risk analysis is shown in Figure 1, and around this is assembled a series of independent programs that can be linked together through data files to subsequent programs in the chain. It is possible to see and check all these intermediate results, thus ensuring that errors are not introduced to be rolled forward. The programs model the various aspects of the analysis by using the best available and up-to-date methodology with importance attached to the validation of the selected methods.

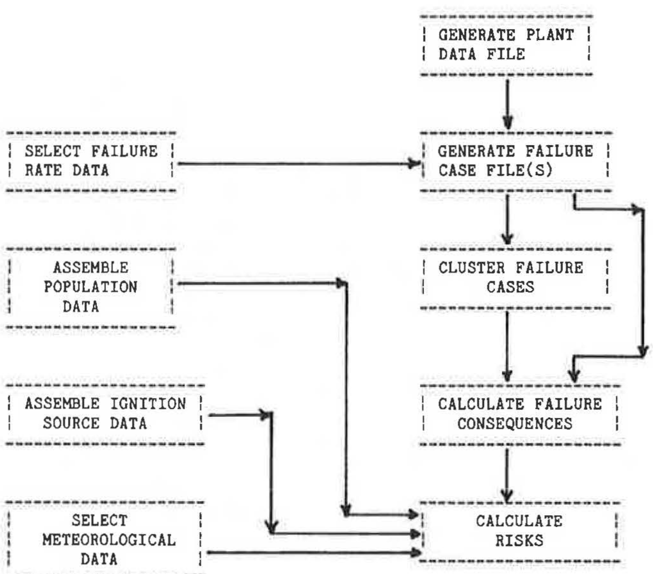

FIGURE 1 Overall flowscheme for risk analysis.

To support an assessment, a wide variety of data files is required. Many of these are held in background files, where data such as physical properties or toxic parameters can be stored and accessed as required. Others may be more specific to a project and would include, for instance, population distribution, ignition source distribution, and meteorology.

The basic requirement of the analyst, in using data from either a coarse- or full-scale hazard and operability study (HAZOP), is to generate an events file for failures. These are described by a label, their location relative to grid coordinates, the material escaping, the rate of release generated from hole size and operating conditions, and the corresponding frequency. To overcome the problem of there being a continuum in hole size in real situations, the events are characterized by a few equivalent discrete failures (EDFs)--each with the appropriate probability of occurrence. A further simplification that is incorporated is the use of clustering, or the grouping together of events of approximately similar size into one event with a combined probability of occurrence. This can be done automatically by the program under guidance from the analyst, and a revised list of EDFs then generated. Checks have shown that little accuracy is lost in this process but the gain in time is considerable. Program usefulness is enhanced by the routine use of default values to be replaced by the analyst whenever possible.

The next stage is the consequence analysis in which a heavy gas dispersion model is a key feature. The one used is that of Cox and Carpenter (3). Toxic effects can then be predicted as the probability profile for certain identified levels of (acute) toxicity. Flammable effects are similarly predicted for certain levels of thermal radiation or overpressure, for a variety of effects, [e.g., pool fires, jet flames, Boiling Liquid Expanding Vapor Explosions (BLEVEs)].

At the final stage, these profiles can be turned into impact terms by using predetermined algorithms that link human impact with dosage received as calculated by the programs.

The principal results can be displayed as

1. Degrees of consequential effect (without the probability determined);
2. Individual risk rates (fatalities per person per year) displayed either geographically by a coded matrix, or as iso-risk contours derived from this; and
3. Societal risk (F-N) curves that display the frequency (F) of killing N or more people as derived from the large number of events and probabilities that the analyst has generated and the program computed. It is possible to produce these results for selected parts of the plant or for the whole and, in this way, the package becomes a very powerful tool for comparative work. The resolution that is normally adopted is the use of a 100 m-by-100 m grid square as part of a matrix that covers an overall area of 20 km by 20 km.

The SAFETI Package Used for Transportation

The only fundamental difference when applied to transportation risks is that the source is no longer fixed, but could be anywhere along the route, be it pipeline, highway, railroad, or river. To admit this type of event, a modified events program is available, LINEDF. By inputting nodes or coordinates of locations where the route changes direction, this program will create a series of notional sources at approximately 100-m intervals, and will allot grid coordinates and proportional failure (f) rates (based on the input f/km/yr). The clustering technique means that the basic events are calculated in one group, and not repeated for each location or notional source. Special high (or low) risk locations can easily be identified, (e.g., grade crossings) and different failure rates input for these. Thus, it is possible to provide quite high resolution data for the overall computation of over-extended routes. If the overall route length becomes excessive, (i.e., it could run outside the 20 km-by-20 km area of concern), the "cell" size can be changed to, for example, 200 m by 200 m, allowing the overall area to be increased to 40 km by 40 km. This loss of precision is relatively small, but it will increase in degree if the cell size is further increased.

TRANSPORTATION OF HAZARDOUS MATERIALS

A variety of modes of transportation exists for hazardous materials. The major risks tend to be associated with the scale of operation, so they are likely to be dominated by bulk transportation, where individual packages are of around 20 te or greater, and can be in multiplicity. But in some modes, the tank size can be large, (i.e., 10,000 te or more) and, hence, the scale of risk can be large. However, it must be remembered that risk is measured fundamentally as the probability of the frequency of incident and the scale of consequences, so it is quite possible for the largest releases to be associated with very small probabilities of occurrence. The SAFETI package can draw this feature out very clearly.

Modes

The four principal modes for bulk transport are highway, railroad, pipeline, and waterborne. In the case of highway transport, single loads of 10-25 te move under various constraints of time or route. With railroad transport, the routes are more restricted, and many other operating constraints can exist. Unit loads can reach 100 te and, in Europe, full train loads of up to 1500 te can be carried. In North America, mixed train loads with several thousand tonnes of hazardous chemicals are not uncommon. Water transport varies from small unit loads, often on barges moving in canal systems, up to bulk carriers moving loads in one or more large refrigerated tanks from one end of the world to the other. In these three modes, the presence at any location of the hazardous material in tanks is usually of a transient nature, as the vessel or vehicle passes. For most of the time it will not be present. There are some locations, however, where it may be present for extended periods such as during loading or unloading operations, or when in marshalling yards, locks, or vehicle parks.

In contrast, the material will always be present in a pipeline at all locations through which it passes. Due account of these factors is taken in assessing the failure frequencies for each location.

Failure Frequencies

In certain cases, a suitable failure history or data bank exists from which one may reinterpret the local failures as assessed for local circumstances. For example, a very wide range of accident data exists for shipping in harbors and estuaries around the world. This can be studied and broken down into the constituent rates attributable to a variety of causes and, by comparison with the local conditions, a rate for the local conditions can be estimated. This can be expressed as collisions (groundings or strikings) per 1 km of each transit. From this, it is possible to estimate the rate across each 100-m cell or square, and to subsequently assess the corresponding frequencies for loss of containment either in small or large releases. Reliable data also exist for buried pipelines that run across country, and the methodology followed here is similar.

The problems of highway and railroad transport are less easy to process. With trucks, it is usually necessary to examine overall road accident statistics classified according to type of vehicle (when heavy goods vehicles/trucks would be the most relevant), type of highway (motorway, divided highway, etc.) and location (intersections, circles, tight bends, etc.). Generally inadequate data exist, but an overall figure for accident frequency per kilometer can nevertheless be derived in many cases. Again, a probability of tank puncture or rupture has to be estimated to provide a frequency for loss of containment. In this case, it is particularly important to examine the assessed rate to ensure that it is consistent with the basic data from which it was derived. In the case of railroad transport, many countries have negligible history of serious accidents to liquefied gas rail tank cars, and reliable statistics directly assessed from these are usually not available. However, there is usually a large amount of data on collisions and derailments and the types of location, and it is from these that a series of rail tank car failure rates has to be assessed for a variety of locations, plain track, marshalling yards, switches and similar track hazards, and grade crossings. As a typical example, one of the 100-m cells could contain the grade crossing, for which one can assess an overall accident rate as the rate for plain track plus that for a grade crossing of the particular type that exists at that location.

Failure Modes and Source Term

Loss of containment, following an accident, could involve a small leak from, or a puncture of, the containment vessel of varying size, shape, and position, or perhaps even a catastrophic rupture. Each type of accident requires careful study of past accidents to provide a realistic estimate of the size and rate of release of hazardous material. With the unlimited range that is possible, use is made of equivalent discrete failures (EDFs) to enable the problem to be modeled realistically. Two or three typical EDFs with a combined frequency corresponding to that estimated are often adequate for the accuracy required.

Because the amount of vapor produced at different stages of the release is a key data requirement, the fate of all liquid and vapor that issues from the container must be established with reasonable accuracy for each EDF. This is especially true for the first stage, where an instantaneous release and the initial stage of a continuous release are both likely to produce the greatest rates of vapor generation. Most large instantaneous releases are of finite duration taking perhaps up to a minute to occur. In these cases, however, one would experience a rapidly expanding vapor cloud during that time, which is not being subjected to any significant wind forces because of its relatively high expansion velocities. In these cases, the release rate of material cannot be used as the source term of the gas dispersion model--instead, the formation of the initial expanded cloud at the stage when wind forces begin to move it must be considered as the source term. Some of the phenomena involved are to be seen very clearly in the films of the heavy gas dispersion trials at Thorney Island in the United Kingdom and discussed at the Symposium in 1984 (4). However, the original source was a tent holding some 2000 m^3 of relatively quiescent gas at ambient temperature. In the real accident situation, such relative stability would never exist.

With many releases being of liquefied gas, low temperatures are usually involved. In cases where liquefied gas is held under pressure, or gas is stored under pressure, releases will be turbulent and entrain air. Initial release velocities will be very high, and only when they have fallen close to air velocities will a source develop for modeling. It may be at a high level, and if it is dense, it would fall back towards the ground with a tendency to spread in all directions as it flattens. It may alternatively be horizontal, and quite often in an accident, impingement and obstruction may occur. Extensive modeling of these and other factors is obviously out of the question, but when establishing one or perhaps a few typical sources, bias toward the most or least favorable situation should be avoided. Any bias ought to be directed toward the most likely situation. The use of two or three different sizes for EDFs is intended to reduce bias and spread the failure cases, so these cases require careful selection.

The fate of the liquid that has escaped and remains in the liquid phase also needs to be established. After release of liquefied gas, the liquid phase will be at or below its boiling point at atmospheric pressure. The smallest diameter droplets may remain as an aerosol, evaporating through mixture with the warmer air but the more massive drops will tend to rain out, when they will fall on the relatively warmer ground, or water. In transportation accidents, this is of great importance. In highway accidents, they are likely to fall on impervious tarmac or concrete surfaces and will drain away via gutters and sometimes to sewers. In railroad accidents, they will fall on the ballast, a stone base that readily drains through and so presents a large wetted surface. Pipeline accidents are more likely to let the liquid fall back on soil or sand, perhaps wet but not impervious. In marine or canal accidents, it may fall on ship's steel structures or on jetties, or, more probably, into water where a massive heat sink exists for vaporization.

Thus, the scenario considered for each type of accident in the various modes of transport has a major bearing on the size, shape, and composition of the vapor clouds. It therefore has to be examined with care and appropriate data for the particular circumstances used for the source term in the gas dispersion model.

APPLICATIONS IN TRANSPORTATION

The SAFETI package has now been used for several applications in the transportation field. The objectives of these studies have varied widely and in the following sections, a brief description is given illustrating the way in which the package has proved helpful.

Pipeline Design

The selection of pipeline design and routing has traditionally been based on experience gained through previous projects and constrained by the design codes and regulations that apply to buried pipeline and by the availability of routes. Even so, many possible variations can be identified and features such as minimum capital cost or elimination of compressor stations have often been deciding factors in the final design. Risk was considered only in general terms and not quantitatively.

In using the SAFETI package, it has been possible to provide important guidelines on risk from the different schemes to assist in the selection process. This is becoming increasingly important as authorities and regulatory bodies give closer and more detailed attention to this aspect. As an example, the package can run through for each option, a complete iso-risk contour plot and, if population data exist, an F-N curve. The options considered are:

1. Selection of route;
2. Effect of isolation valve spacing on releases and on risk;
3. Operating pressure;
4. Line diameter;
5. Selection of vapor or liquefied gas line;
6. Effect of measures taken to reduce accident frequency (e.g., depth of burial, wall thickness, additional physical protection); and
7. Valve spacing and the use of automatic leak detection/shutdown systems.

(It should be noted that each of these options will change the capital and operating cost, and these costs can be estimated.)

It is therefore possible for a company that is considering using a pipeline from points A to B to be able to optimize its design and also assess the cost of various risk reduction measures. In addition, the overall level of risk, its geographic distribution, and its spectrum can be considered. As a result of such an exercise, it has been shown in one case, for instance, that it is preferable to strike a new route for a pipeline instead of using an existing corridor or way-leave. Two benefits accrued, (a) a shorter route was found, and (b) a very sparsely populated route was selected. In the comparative mode, great confidence can be placed in such results, and useful assistance is given to the problems that concern overall acceptability of risk to the local communities.

Comparison of Risks from Different Modes

Sometimes a company will be faced with the problem of moving a large quantity of hazardous material from one location to another, for example, between two manufacturing sites, or to a customer. The comparative economics of each mode of transport (highway, railroad, pipeline, etc.) are easy to establish. It should always be the case that in each mode, the safest means would be adopted, (e.g., route, container, operator practice, etc.). However, it has been difficult to be sure of the real comparison of risk levels that were associated with each mode. The SAFETI package now permits comparisons to be made, and furthermore, provides information on how safety might be further improved, and to what extent.

Assessment of Existing Risks in Transportation

Many countries have large areas developed into petrochemical complexes to, from, and between which considerable quantities of hazardous materials are moved, or in which they are stored. In some cases, public housing is located close to either the complexes themselves or to the core arteries of transportation, resulting in exposure of the public to risk as a result of accidental release at any location.

Faced with this situation, Rijnmond has been examining these risks and their relative importance for a number of years. The first principal exercise of this examination was the COVO study of six objects in the area, basically six different types of static storage of hazardous material. By using the earlier models, iso-risk contours and F-N curves were produced. More recently DCMR, the environmental agency in Rijnmond responsible for this work, has sponsored an exercise into the assessment of risks in the Rijnmond area from transportation of liquid ammonia and liquid chlorine. The updated SAFETI package was used by Technica, Limited, for this work and, from the results, the iso-risk contours and F-N curves for the various routes and modes can be examined. Because there have been changes to parts of the overall model from the days of the COVO study, comparisons between the two will not always be relevant. This is one of the side-effects of improving and changing methodology, but the new package can partially overcome this by rerunning older data where necessary (as has been done for the 6 cases of the COVO study). The difference was shown to be insignificant.

The new transportation assessment, by comparison, can indicate the relative importance of size of unit load, total tonnage moved, route taken, etcetera. One particular difference comes in comparison with pipeline transportation, where the risks are not directly associated with tonnage moved but with line capacity.

GENERAL FEATURES IN APPLICATION

In the case of a specific site, one normally needs to use the air stability and wind statistics for the nearest meteorological station. This may be many kilometers away in perhaps totally different surroundings, so the use of such statistics may introduce some small statistical errors. Experience shows that the major differences may lie in the probabilities and directions for the lowest wind velocities because these are the least uniform over a large area. High velocities exhibit smaller random variations.

Meteorology

When dealing with transportation risks, distance from the meteorological station varies, and sometimes use can be made of two or more stations that are close to parts of the route that is being assessed. The point at which change is made from one set of data to another depends on a variety of factors, but one example is the use of a coastal and an inland station. The former's data will basically apply only to coastal areas, whereas the latter may change little from one inland location to another.

In the SAFETI package, each meteorological station used has its data reconstructed into day files and night files. The day file covers Pasquill categories A, B, C, and D, and the night file covers categories D, E, and F. There is a small mismatch when used opposite population day and night files that are more correctly considered as "normal working day" and "outside normal working day" files with the latter including nights and weekends. To split the files further would at least quadruple the number of calculations, even neglecting the seasonal change of the length of day, and it is not considered justified.

In the context of gas dispersion, it is worth remembering that if a quantified assessment of risk with probabilities is required, statistical meteorological data must be used. Until recently, this has only been based on the system developed by Pasquill around 1961, and described in his book (5) using observations of cloud cover and time of day to establish a stability category. It is axiomatic therefore that the gas dispersion model used employs the same stability typing system. Most models, especially of the box type do just this, but some of the newer and more elaborate models are based more on a description of the physics. For them, no suitable statistical data have existed, so they can only be used for the calculation of a few typical cases and not for overall estimation of risk. However, in the last few years, KNMI, the Dutch Meteorological Institute, has started collection of the newer data at selected stations, in parallel with the old. An added benefit will be the ability in due course to compare the two types of data also on a statistical basis.

Topography

One of the important constraints in applying dispersion models to releases is the assumption that the ground, both up- and downwind, is adequately flat and unobstructed. The effect of ground roughness can, in fact, be modeled for environmental-type releases, though it has to be given an average value, but it is not yet possible to ascribe different values for ground roughness to the terrain bordering a chemical plant or a transport route. But even more important, especially when a large proportion of such releases can produce dense vapor clouds is the effect of topography. Hills and valleys are well known for their ability to divert or channel dense clouds.

One might think that the very extensive flat ground in the Netherlands and Northern Belgium presents no problems, but the whole area is criss-crossed with dykes, canals, ditches, and embankments leading to bridges. The vertical height changes here are substantial relative to the depth of heavy gas clouds, so even releases in this region will be subject to substantial diversion and channeling. Releases in docks, rivers, and canals will all be similarly influenced by the combination of wind direction and the orientation of the obstruction. Some estimates of risk could therefore be pessimistic, especially for areas that are protected by canals or dykes.

Toxicology

For approximately 15 years, attempts have been made progressively to improve the assessment of risk from releases of the more common toxic gases, such as ammonia and chlorine. At the outset, most quantitative information on the dosage necessary to cause lethal effects came from standard reference books, together with a few old references of experimental work or observations. From 1975-1979, the U.S. Coast Guard developed a vulnerability model that includes probit equations for these gases, for example, equations that indicated the probability of death for a given concentration and duration of exposure. These are really based on limited and often old animal test data, so the Institution of Chemical Engineers in England embarked on a critical study of the underlying evidence (6). The Rijnmond authority, aware of the criticism of some of the equations, has also considered the evidence available and revised some equations for their own use (7). The Atomic Energy Control Board of Canada also conducted a review for ammonia (8). The problems are still extensive, despite this fresh look at the better quality experimental data, but there is a little hope of some further animal test data in the near future.

The dispersion models almost invariably tend to produce average concentrations of vapor rather than instantaneous concentrations. This is clearly demonstrated in the test data obtained where the concentrations are anything but steady even if the release was steady and continuous. Griffiths and Megson (9) have suggested that the toxic effects are underestimated by using this average from the model. The true comparison that should be made is between the varying concentration predicted by the model and the cumulative dosage this represents. This may be less pessimistic but, unfortunately, it is not a practical result of dispersion models in current use.

Lower Flammable Limits

A similar problem affects the estimation of true short-duration flammable limits. The majority of dispersion models cannot provide this information, only time-averaged values, so invariably factors have to be applied. Various modelers differ in this respect, ranging typically from using 0.5 x (LFL) to 0.1 x (LFL). The uncertainty is clearly shown in the data from China Lake (10).

RESULTS

The conclusions reached in the various transportation projects so far processed through the SAFETI package have been very wide-ranging. At the design or proposal stage, considerable objective information was obtained that led to positive changes in the design or proposal. For instance, the transportation problem is essentially one of moving material from point A to point B. A wide variety of routes could be taken in between the points, but at locations A and B, this is not always possible. The prime objective would be to increase the separation of population and route, but overall distance and the hazardous nature of some routes introduce problems. Quite often the older type of superficial comparison is not at all easy. By using this computer package, it has been possible to make good-quality comparisons and so make meaningful decisions. By making stepwise changes, the benefit to be derived from each change can be assessed.

In the case of pipelines, the introduction of automatic sectionalizing valves can produce as much benefit as moving the pipeline further away from a center of population. Line diameters can be changed, and even the alternatives of vapor and liquefied gas can be examined. A design team could complete a full examination of all its options and propose a lowest risk pipeline in a few days.

For examinations of existing transportation problems, it is also possible to make more meaningful comparisons by using risk contours and F-N curves, of modes that superficially, at least, appear totally dissimilar. Furthermore, it is also possible, by using the ability to input failure data and populations in 100-m cells, to improve the resolution of the results and so highlight many of the smaller problems and hazards that might otherwise be missed. An example here has been where a route contains a turn of 90 degrees at the same time as hazards and populations change. The old manual calculation method gave no more than a very crude estimate of average risk. The iso-risk contour that can now be calculated and drawn shows clearly the degree of risk intensification on the inside of the bend. Even when the amount of tonnages moved differs, comparisons can still be made on a per tonne basis (except for pipelines). And the effect of any proposed time scheduling of shipments can be closely examined as, for instance, the effects of restricting railroad transport of chlorine in the Netherlands to night time, except for local movement at the chlorine site.

CONCLUSIONS

The computerized risk analysis package for process plants can be very effectively used also in the transportation area. Some simple adjustments are necessary but do not present excessive difficulty.

In the comparative mode, for example, comparing routes or mode of transport used, it is proving to be a very powerful aid to the decision maker, be he the operator, designer, or regulatory authority. Results in this mode can be treated with a high degree of confidence because many of the subjective judgments that have been included in the data input are common to all the variants being compared, and provided best available data are used, the potential errors become insignificant in comparison.

In the absolute mode, there is a major benefit in the ability to examine the assumptions made in a practical time scale so that the potential for error can be better assessed. In this way, overall accuracy is probably enhanced, although it still may not be as high as when the package is used for comparisons.

The transportation projects examined thus far have all benefited from the ability to examine a large number of alternatives or options, far more than would normally have been attempted manually. It is believed that by using this system, the amount of guesswork involved in decision making can be significantly reduced.

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