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**MODELING A REAL TIME DECISION
SUPPORT SYSTEM FOR HAZMAT
TRANSPORTATION IN A SUSTAINABLE
ORIENTED MOTORWAY ENVIRONMENT**

(Settore scientifico-disciplinare: MAT/09 RICERCA OPERATIVA)

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Abstract

The combined effects of economic globalization, development of transport systems and new communication techniques have had a profound influence on world development. The expansion of transport systems favors the increase of geographic mobility so that the existence of a complete highways network, adequately managed and maintained and with sufficient capacity, is essential for the good progress of the national economy.

The expansion of transport systems is coupled with the rise in land prices and the increase of air and noise pollution. In this development, we observe that dangerous goods are used in many processes in industries all over the world and this has been justified by the economic revenue which is generated by their use.

A dangerous good is any solid, liquid, or gas that can harm people, other living organisms, property, or the environment. They are often subject to chemical regulations. An equivalent term, used almost exclusively in the United States, is hazardous material (hazmat or HAZMAT).

Due to its nature, every production, storage, and transportation activity related to the use of HAZMAT has many risks for both society and the environment. HAZMAT are transported throughout the world in a great number of road shipments.

In spite of HAZMAT accidents being rare events, the commercial transport of HAZMAT can be catastrophic in nature and poses risks to life, health, property, and the environment due to the possibility of an unintentional release. In this scenario, a new factor has acquired more and more importance: sustainability.

As a consequence, it is necessary to integrate risk mitigation and prevention measures into transport management in order to avoid the risks turning into real events.

Three different topics are developed within the above framework.

- A business approach, named corporate sustainability, that creates long-term shareholder value by exploiting opportunities and managing risks deriving from economic, environmental and social developments.
- An assessment of risk and accident impacts related to dangerous goods transport with particular attention paid to HAZMAT on the road in a motorway environment.
- A DSS (Decision Support System) model for the management of the HAZMAT transportation.

Keywords: motorway, sustainable organization, balanced scorecard, hazardous material transportation, risk assessment.

Prefazione

Lo sviluppo avvenuto a livello mondiale negli ultimi anni, è stato fortemente condizionato da processi pervasivi e profondi quali quello di globalizzazione, di espansione dei mercati, di diffusione dei sistemi di trasporto e di nuova comunicazione grazie anche alle nuove tecnologie elettronico-informatiche introdotte.

Peraltro, il sistema trasportistico favorisce, con il suo evolversi, l'incremento della mobilità geografica ed il progresso delle varie economie nazionali. Ne discende, soprattutto nel caso del trasporto su "gomma" che è la modalità di gran lunga più usata, la necessità di sistemi stradali e reti autostradali di sufficiente capacità ma, nel contempo, adeguatamente gestiti ed oggetto di costante manutenzione.

L'espansione dei trasporti, oltre alle ripercussioni sui territori in termini economici, comporta un lento ma progressivo incremento del grado di inquinamento dell'aria ed ambientale più in generale. Peraltro, è riscontrabile nel modello di sviluppo appena descritto un impiego, sistematico e diffuso a livello planetario, di sostanze pericolose nei vari processi produttivi, sia per la loro indispensabilità nei processi stessi sia per i ritorni economici legati al loro utilizzo.

In funzione della natura di tali sostanze, lo stoccaggio e specialmente il trasporto di materiali pericolosi comporta dei rischi, spesso notevoli, di natura sociale ed ambientale. Secondo dati statistici, i rischi maggiori risiedono proprio nella fase di trasporto, che può avvenire secondo le tradizionali modalità terrestri, ("gomma", "rotaia"), marine ed aeree, con l'assoluta prevalenza delle prime.

Pur essendo contenuto il numero degli incidenti che avvengono, le ripercussioni ed i danni in caso di accadimento sono generalmente catastrofici per la perdita di vite umane, per i riflessi a livello di salute pubblica nonché ambientale. Ne derivano la necessità:

- di definire modelli di gestione che assicurino la sostenibilità economica, sociale e ambientale nel settore trasportistico ed in specie autostradale,
- l'importanza di poter valutare, individualmente e socialmente, il rischio associato al trasporto di merci pericolose, soprattutto su strada, al fine di definire idonei sistemi preventivi e di adeguato intervento in caso di accidentale rilascio delle sostanze stesse.

Tali studi e misure devono essere integrati nel sistema di gestione dei trasporti per far sì che i rischi si trasformino il meno possibile in eventi.

Al riguardo, nella presente tesi sono sviluppate le seguenti tre tematiche:

- un nuovo modello di sviluppo economico/manageriale, denominato "sostenibilità aziendale", che pur creando valore a lungo termine per l'azionariato

d'impresa, fornisce gli strumenti per rendere compatibile lo sviluppo stesso sotto il profilo economico, sociale, ambientale;

- un'adeguata valutazione sul rischio e sulle conseguenze possibili connesse al trasporto di sostanze pericolose su strada, analizzando il caso specifico autostradale;
- la definizione di un modello a supporto della presa delle decisioni che i vari responsabili ed operatori devono assumere nelle operazioni di gestione/intervento connesse al trasporto su gomma di sostanze pericolose.

Parole chiave: autostrada, organizzazione sostenibile, balanced scorecard, trasporto di sostanze pericolose, valutazione del rischio.

Dedica

A Tek, un caro vero amico che non c'è piú

Ai pochi sinceri Amici vicini e lontani

Citazioni

Dubium sapientiae initium

Cartesio

Rex eris...si recte facies

Orazio

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Chapter 1

Introduction

Economic analysis identifies comparative, rather than absolute, advantage as the basis of international trade. The *Law of comparative advantage* [60] is a principle that states that every nation, worker, or production entity has a production activity that incurs a lower opportunity cost than that of another nation, worker, or production entity, which means that trade between the two can be beneficial to both if each specializes in the production of a good with lower relative opportunity cost.

This law is most often studied within the confines of international trade, but it also applies to labor and other types of production. Over the last century, the strong economic growth experienced was just based on international comparative advantage and it has been accompanied by gains in material welfare in all parts of the world [226]. Public services and goods have provided necessary inputs into private productive activities and modern states finance these inputs through taxes collected from the community.

The reduction and removal of barriers between national borders in order to facilitate the flow of goods, capital, services and labour and the process of transformation of local or regional phenomena into global ones have given life to globalization.

Globalization is a combination of economic, technological, sociocultural and political forces and it can be described as a process by which the people of the world are unified into a single society and function together. Moreover, economic globalization is the integration of national economies into the international economy through trade, foreign direct investment, capital flows, migration, and the spread of technology.

Nowadays, the combined effect of economic globalization, development of transport systems and new communication techniques has had a profound influence on the world development [178].

In this scenario, a new factor has acquired more and more importance: sustainability. Sustainability [167] is a systemic concept that relates to the continuity of economic, social, institutional and environmental aspects of human society. It is intended to be a mean of configuring civilization and human activity, so that, society, its members and its economies, are able to meet their needs and to express their greatest potential in the present but, at the same time, to preserve biodiversity and natural ecosystems.

Pursuing sustainable development, Governments face the challenge of dis-

cerning how best to balance the challenges and opportunities of growth and to decouple economic growth from environmental and social pressures.

Various schools of research in public policy (the literature on “governance” and its continental counterparts) are converging to focus on the growth of policy styles based on cooperation and partnership in networks, instead of on vertical control by the state [186].

Consequently, firms should not consider sustainable development as an additional requirement imposed by Governments, but as an overarching principle, which governs all the development processes. Sustainability requires new management approaches to improve policy coherence, to increase the role of knowledge in the formulation and implementation of policies, and to devise better communication between civil society and business [13].

For example, the timing of the replacement of equipment is dependent on factors like replacement costs, discount factors and differences in productivity, reliability and safety of existing and new equipment.

Although predictions related to these factors are normally subject to uncertainties, successful corporate sustainability leaders achieve long-term shareholder value by replacing old equipment and gearing their strategies and management to harness the market’s potential for sustainability products and services while reducing, if not avoiding, sustainability costs and risks.

Economic globalization favors the increase of geographic mobility involving the expansion of transport systems that is coupled with the rise in land prices and the increase of air and noise pollution. According to the life cycle theory, technological innovations are related to the development phase of a transport system (introduction, growth, maturity and decline).

Technological innovations can contribute to the reduction of emissions in the international transport sector, but it will be a long term process to generate significant results.

As a consequence, it is essential that there exists a complete highways network with sufficient capacity, but adequately managed and maintained and with the right ratio of technological innovations for the good progress of the sustainable national economy. In the development just described, we observe that hazardous materials are used in many processes in industry all over the world and this has been justified by the economic revenue which is generated by their use. A dangerous good is any solid, liquid, or gas that can harm people, other living organisms, property, or the environment. They are often subject to chemical regulations.

An equivalent term, used almost exclusively in the United States, is hazardous material (hazmat or HAZMAT). Due to its nature, every production, storage, and transportation activity related to the use of HAZMAT has many risks for both society and environment.

HAZMAT are transported throughout the world in a great number of road shipments. While HAZMAT accidents are rare events, the commercial transport of HAZMAT could be catastrophic in nature and poses risks to life, health, property, and the environment due to the possibility of an unintentional release. In order to avoid the risks turning into real events, it is necessary to integrate risk mitigation and prevention measures into the transport management. HAZMAT has received considerable attention since the 1980’s, mainly due to growing safety concerns in most developed countries, but in recent years HAZMAT has acquired new importance because of sustainability.

In this thesis, an original approach is developed on an idea of the author, who was also Director of Operations of S.p.A. Autovie Venete. This idea consists in making an attempt to encompass both professional experience and theoretical knowledge with application-oriented studies from disparate areas related to the commercial transport of hazardous materials.

S.p.A. Autovie Venete is an important Italian motorway concessionaire and safety is its main priority. Its operators manage HAZMAT transportation following different strategies and using different technologies to detect vehicles, to give the alarm and to properly intervene in case of accidents. Three different topics are developed within the above framework.

- A business approach, named corporate sustainability, that creates long-term shareholder value by exploiting opportunities and managing risks deriving from economic, environmental and social developments.
- An assessment of risk and accident impacts related to dangerous goods transport with particular attention paid to HAZMAT on the road.
- A DSS (Decision Support System) model for the management of the HAZMAT transportation.

Following this introduction, the work continues with Chapter 2, which briefly discusses different approaches for quantifying sustainability and the issues about environmentally sustainable transport.

We illustrate some important aspects such as the productivity effects of road investment, regulation and licensee motorways companies in Europe and in the Italian highways network, especially in the North-East. Furthermore, in Section 2.5 we examine more deeply the process of formulating an Sustainability Balanced Scorecard for a motorways concessionaire. Before doing so, the basic conventional approach of the Balanced Scorecard is outlined.

In this context, we developed an original idea to use the Balanced Scorecard model [129] for the specific sector of motorway concessionaires in order to estimate its corporate efficiency and to evaluate environmental and social performance. The core work presented is currently being published, as a scientific paper, by International Journal Of Environment And Sustainable Development [46].

Concession systems are in widespread use in the road sector in Europe: concessions differ from public contracts in the transfer of the responsibilities of operation that they entail [14]. The mission of most of concessions holders is just to plan, build, expand and manage a motorway network.

Chapter 3 covers aspects as hazard identification, risk evaluation (i.e. evaluation of the acceptability of the risk) and risk reduction, quantified risk assessment (QRA) and risk management.

In order to get a clearer understanding of hazardous materials transportation and to describe a community's/region's hazardous materials transportation risk problem, in Chapter 6 we present models for a quantitative risk assessment of HAZMAT on the road that takes into consideration the length of time in transit, the probability of a collision and the risk of population exposure in the event of an incident.

We also present a bibliographic survey on the hazardous material transportation and particular attention is paid to HAZMAT on the road. The core

work presented is currently being published, as a scientific paper, in the book *Advanced Technologies And Methodologies For Risk Management in the Global Transport Of Dangerous Goods* [47].

In the following Chapter 6, we present a methodology for assessment of HAZMAT transport risk in a motorway network and we also propose a methodology for assessment of the HAZMAT transportation risk in a motorway network sustainably oriented.

The model developed also assists decision makers to take the right policies to reduce the risk posed, due to the shipment of hazardous materials to life and environment. The final Chapter summarizes the findings and conclusions of this research work.

Chapter 2

Social responsibility and sustainability in motorway corporate governance

In this section, we propose a brief discussion of different approaches for quantifying sustainability. The investors have an investable corporate sustainability concept so that the corporate sustainability performance can be financially quantified [104].

2.1 Environmentally Sustainable

A growing number of investors are convinced that sustainability is a catalyst for enlightened and disciplined management. In effect, the development of sustainability is driven by the two following crucial success factors.

- The concept of corporate sustainability is attractive to investors because it aims to increase long-term shareholder value: since corporate sustainability performance can be financially quantified, the investors have an investable corporate sustainability concept.
- The sustainability leaders are increasingly expected to show superior performance and favorable risk/return profiles.

As this benefit circle strengthens, it will have a positive effect on the societies and economies of both the developed and developing world. Increasingly, investors are diversifying their portfolios by investing in companies that set industry-wide best practices with regard to sustainability [145].

What private and institutional investors need is a global, rational, consistent, flexible and, most important, investable index (like the Dow Jones Sustainability Index World) [48], to benchmark the performance of their sustainability investments.

Investors also need an independent and reliable index as a basis for derivatives and funds focused on sustainability companies [15].

With adequate market signals and incentives to modify behavior in line with sustainability, policy makers can secure more efficient resource use, which in turn

implies higher overall welfare and equity today and in the future. In particular, it is important to define sustainability indicators to anticipate the fickleness of human-environmental interaction.

The development of environmental indicators is dominated by the so-called Pressure-State-Response (PSR) model of the Organization for Economic Cooperation and Development (OECD) [159]. The PSR contains a set of indicators measuring:

- the anthropogenic pressure (P) on the environment,
- the state (S) of the environment resulting from such pressure, and
- the societal response (R) to ease the pressure.

Over the past 30 years, environmental policies and related reporting activities adopted by OECD countries have steadily evolved. This evolution has been largely driven by increased public awareness of environmental issues, their international aspects and their linkages with economic and social issues.

Initially the demand for environmental information was closely related to the definition and implementation of environmental policies and their effects on the state of the environment.

Over the years, policy priorities evolved, as did demands for reliable, harmonized and easily understandable information, not only from the environmental community but also from other public authorities, businesses, the general public, environmental non-governmental organizations and other stakeholders. At the same time, international activities and co-operation on the environment continued to grow.

The strength of the PSR is its ability to take into account the causal relationship between the state of the environment and human activity. Its major weakness, however, is the lack of sophistication of the mathematical and cognitive models representing the causal relationship. As a result, current indicator systems based on the PSR fail to consider contingencies in human-environmental interaction that make the future state of the system difficult to ascertain.

Recognizing the fickleness of human beings and nature will result in indicators very different from the traditionally developed ones. They can be identified in the following important areas of indicator development:

- a) indicators for the sustainability ecosystem impacts of production, which measure changes in production outputs and environmentally significant inputs [121];
- b) indicators of bounded carrying capacity, which use alternative scenarios of human-environmental interaction to specify the ecosystem-specific limits that societies might impose on industrial production [229];
- c) indicators of congruence between ecosystems, institutions and production, which measure the compliance between the functions of an ecosystem and the institutional rules governing its management [121];
- d) indicators of technological and institutional path dependence, which observe and potentially strengthen lock-ins in human-environmental interaction [193];

These development challenges imply that sustainability indicators should be considered more as tools for improving communication between different communities of experts on the sustainability of a particular system of human-environmental interaction, rather than as universal measures of sustainability [17].

2.2 Environmentally Sustainable Transport

In this section we consider sustainability, with its indicators, in the transport sector. In order to integrate and communicate knowledge in the assessment of the environmentally sustainable aspects of transport technologies and policies, it is necessary to adopt a systemic approach to environmental and transportation issues by pursuing four main objectives:

- designing harmonized methods to build environmental indices to be applied to the transport sector in the different countries;
- assessing the level of environmental sustainability of transport systems and exploring new transport scenarios;
- assembling scientific knowledge between disciplines and countries through common research projects, for discussion, congresses and exchange of scientists;
- disseminating the knowledge and the sustainability assessment tools among decision makers, consultants and the public, especially by high level teaching.

The core of this approach is to integrate the different environmental impacts of the transport system into sustainability indices or other reporting mechanisms, taking into account the physical and biological impacts and the public perception of the environment.

But it is also necessary to assess the level of sustainability of the transport system in the past, present and future times with a long term approach, to develop long-term scenarios based on possibilities and constraints, and to identify tools and strategies capable of achieving the scenarios themselves, in terms of transport technologies and policies [94]. Significant improvement can be achieved in the short to medium term in the environmental performance of current transport arrangements.

2.3 Aggregate productivity effects of Road Investment

In this section, we suggest some answers to these policy questions:

- Has the development of the transport sector been a driver of globalization?
- Does transport policy underrate its role to support international trade and foreign direct investment?

- Does transport policy action have substantial income effects by facilitating trade?
- Do transport infrastructure investments reduce international trade costs?
- Which domestic policies have strong trade cost reducing effects?

Knowledge about the productivity effects of infrastructures would allow more informed decisions to be taken on the overall budget allocation for infrastructure investment in general and transport infrastructure in particular. The strong role assigned to transport infrastructure investment as a vehicle for economic growth appears to be worth critical examination for at least two reasons.

1. There is no strong growth theory foundation for the hypothesis that an increase in transport infrastructure investment would lead to an immediate and lasting increase in growth rates of economic activity; rather, according to the exogenous growth theory, an increase in the investment rate (which does not necessarily result from an increase in transport infrastructure investment) leads to an increase in the income level.
2. There is no clear, empirical evidence that transport infrastructure investment leads to higher growth or even to a higher level of income.

Aschauer [14] started the discussion on the productivity effects of public investment followed by Gramlich [105]; moreover, Kopp [142] found large positive productivity effects being caused by public investment. Kopp reviewed the previous attempts to measure the macroeconomic effects of infrastructure investment which often suffer from an unresolved endogeneity problem and in this perspective he investigates the productivity effects of national road infrastructure investment in Western Europe.

Considering the i -th of n countries, the relation between economic growth and road infrastructure development is shown in (2.1). This relation, named *national production function* [223], shows that, omitting time subscripts, the countries which have relatively transport-intensive industries benefit from an increase in road infrastructure investment more than countries with relatively low transport intensity from an increase in road infrastructure investment:

$$Q_i = U_i F^i(K_i, H_i, L_i, T_i[G_i, V_i]) \quad (2.1)$$

where:

- n is a set of countries;
- Q_i is the production of gross output for each country i ;
- K_i is the non-transport capital stock for each country i ;
- L_i is the employment for each country i ;
- T_i is the transport services level for each country i ;
- U_i is the economy's technological level for each country i which is assumed to progress in a Hicks-neutral way;
- G_i is the services of road stock for each country i and
- V_i is the national stock of transport equipment for each country i .

An interesting aspect is that the production of gross output Q_i , for each of the i -th of n countries, depends on non-transport capital stock K_i , employment L_i

and transport services T_i . Transport services depend on the services of road stock G_i as well as the national stock of transport equipment V_i . Output also depends on the economy's technological level U_i , which is assumed to progress in a Hicks-neutral way.

Hicks-neutral is an attribute of an effectiveness variable in a production function [19]. The attribute is that it does not affect labor differently from the way it affects capital. The canonical example is the Solow model production function $Y = AF(K, L)$ [150]. There Y is output, L labor, K capital, F a production variable, and A represents some kinds of effectiveness variable. In $Y = F(AK, L)$ the effectiveness variable affects capital but not labor. In $Y = F(K, AL)$ it affects labor but not capital. These two cases can be described as Hicks-biased. In $Y = AF(K, L)$ it is Hicks-neutral.

Equation (2.1) represents the gross production function of the representative firm using the primary inputs, capital K_i , labor L_i and transport services T_i , as the only intermediate input.

The transport services are produced using road services G_i and the services of the vehicle stock V_i . The firms do not choose input G_i but the number of vehicles, which is V_i . From gross output function 2.1 taking logarithm and total differential yields

$$\frac{dQ}{Q} = \frac{dU}{U} + \frac{F_K K}{F} \frac{dK}{K} + \frac{F_L L}{F} \frac{dL}{L} + \frac{F_V V}{F} \frac{dV}{V} + \frac{F_G G}{F} \frac{dG}{G} \quad (2.2)$$

where:

F_j denotes the derivative of the production function with respect to input j ;

$\frac{F_j J}{F}$ are coefficients indicate production elasticities, i.e. the percentage increase of gross output if the input J is increased by one per cent.

Consequently, output elasticity with respect to road services is not directly observable and firms do not take input decisions with respect to road services. However, input decisions with respect to vehicles are not independent of the road services provided by the existing road capital stock. The output elasticity with respect to road services can be expressed relative to the elasticity with respect to vehicles:

$$\frac{F_G G}{F} = \left(\frac{\frac{F_G G}{F}}{\frac{F_V V}{F}} \right) \cdot \left(\frac{F_V V}{F} \right) = \phi \cdot \left(\frac{F_V V}{F} \right) \quad (2.3)$$

where the parameter ϕ equals the ratio of output elasticities of roads and vehicles and is expected to be positive because economies which are relatively transport-intensive probably are also relatively road-intensive.

The production elasticity of vehicles measures the transport elasticity of the national economy. Hence the parameter links the observed transport intensity of the economy to the indirect input road use.

It is important to point out that the production theory framework explicitly includes the modeling of national transport intensities and the fact that transport services depend on private capital investment and government investment in roads. The endogeneity bias is addressed by introducing an estimation

breakdown which combines national productivity effects with overall productivity effects for the country group as a whole, to make residuals of the estimation orthogonal to the explanatory variables.

Productivity is measured by the Toernquist productivity index [41]. Index numbers try to avoid deficiencies of partial cost indices. They aim at indicating the ratio between output variables and a bundle of inputs. The most frequently used productivity index is just the Toernquist index. The Toernquist total factor productivity index is defined in its simpler logarithmic form as follows, comparing two entities, s and t :

$$\begin{aligned} \ln TFP_{st} &= \ln \frac{OutputIndex_{st}}{InputIndex_{st}} \\ &= \ln OutputIndex_{st} - \ln InputIndex_{st} = \\ &= \frac{1}{2} \sum_{I=1}^N (\omega_{it} + \omega_{is}) (\ln y_{is} - \ln y_{it}) - \frac{1}{2} \sum_{j=1}^K (\nu_{jt} + \nu_{js}) (\ln x_{jt} - \ln x_{js}) \quad (2.4) \end{aligned}$$

where:

- y denotes outputs, indexed by i ,
- x denotes inputs, indexed by j ,
- ω denote the shares of goods in i in total real output,
- ν denote the shares of inputs j in total costs.

The productivity effects depend on the sign of the ratio of vehicle stock to the road stock elasticity of production.

Kopp [143] calculated the expression for the national growth rate of productivity and developed an empirical analysis including western European countries for which data were available. The largest gaps in the data were found for transport infrastructure investment, and for the real value of vehicle stock.

The countries in the sample were Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom. Moreover, Kopp shows that investment in road infrastructure indeed has positive macroeconomic productivity effects, even if the results of the paper [143] do not justify as a general conclusion that national road infrastructure investment levels should be increased.

In conclusion, the fixed effects panel data analysis shows that transport infrastructure has a positive effect on macroeconomic productivity. The variance of road infrastructure investment in the panel explains, however, only a small part of the macroeconomic productivity development.

2.4 Regulation and licensee motorway companies

In this section we present the lines of policy in Europe to develop a sustainable transport. We also propose an overview of the application of motorway concession contracts in Europe and specifically in Italy, of the difficulties currently

encountered by the European and Italian road administrations in the utilization of the concession option and of the public-private partnership in the motorway field with its key-factors of success.

2.4.1 The development of Build-Operate-Transfer

The search for a new way to promote and finance infrastructure projects led to the introduction of a technique originally used in the 19th and 20th centuries, known as concessions.

Concessions were used in many parts of the world to develop infrastructure. The Suez Canal is one of the many examples of a privately financed concession and this method was also used to build canals, railroads, tram-ways, water works, electric utilities and similar projects in both industrialized and less-developed countries.

The Build-Operate-Transfer (BOT) formula adds to the old system of concessions, providing new possibilities [107] for reducing or eliminating the direct financial burden which states would otherwise bear. The objective is to transfer as much borrowing risk as possible to the private-sector promoter and the project itself. Therefore the BOT promoter must finance the project entirely or partially.

Financing is made available on the strength of the project's projected revenue stream and its other assets, including the promoter's quality. Normally the lenders would have limited or no recourse to the promoter or shareholder of the promoting company. BOT projects are part of the Public Private Partnership that have been adopted by various governments in recent years [113].

PPPs generally take the form of a long-term (e.g. 30 years) agreement between public and private entities. At the end of the concession the project is transferred back to the state or the public body. In the European countries, the public authorities of the member states often have sought the recourse of PPP arrangements to undertake infrastructure projects, in particular in sectors such as transport, public health, education and national security.

At European level, it was recognized that recourse to PPPs could help to put in place Trans-European networks, which had fallen very much behind schedule, mainly owing to a lack of funding. As part of the Initiative for Growth, the Council has approved a series of measures designed to increase investment in the infrastructure of the Trans-European transport network and also in the fields of innovation, research and development through forms of PPPs.

According to Halkias et al.(2007) [110], the key benefits of PPPs are the following.

- Infrastructure created through PPP can improve the quality and quantity of basic infrastructure such as water, energy supply, telecommunications and transport.
- Value for money PPP projects deliver greater value for money compared with that of an equivalent asset procured conventionally. The combination of design, construction and operation outweigh the higher cost of finance. PPP focuses on the procurement process of the whole life cost of the project not simply on its initial construction cost. It identifies the long term costs and assesses the suitability of the project.

- Transfer the risk of performance of the asset to the private sector. The private sector only realizes its investment if the asset performs according to its contractual obligations. As the private sector will not usually receive any payment until the facility is available for use, the PPP structure encourages efficient completion on budget and without defects.
- Buildings and services which would not otherwise be affordable can be under a PPP and this is a major benefit that helps public authorities to take a long-term strategic view of the services they require over a long period.
- The concept helps to reduce public debt and frees up public capital to spend on other public services.
- Innovation and best practice. The expertise and experience of the private sector encourages innovation, resulting in reduced cost, shorter delivery times and improvements in the construction and facility management processes. Developing these processes aids best practice.
- Repairs and maintenance-assets and services will be maintained at a pre-determined standard over the full length of the concession.
- Enable investment decisions to be based on fuller information as it requires a defined analysis of project risks by both the public sector and the lenders at the outset.
- The tax payer benefits by avoiding paying higher taxes to finance infrastructure development.
- The government or public authority still retains strategic control of the overall project and service.
- The process can assist in the reform of the public sector.

From a theoretical viewpoint, the main justification for the adoption of a PPP is the possibility of exploiting the management qualifications and the efficiency of the private sector without giving up quality standards of outputs, thanks to appropriate control mechanisms from the public party.

This result is achieved by setting up complex contractual arrangements with private sector operators where the public sector acts as *principal* and the private operator as *agent*. In *principal-agent* relationships, the most complex issues are the following:

- the precise definition of the tasks assigned to each party;
- the measure of the agent's performance;
- the extent to which the principal can control and monitor the agent's performance for the whole duration of the contractual relationship.

The definition of the tasks assigned to each party is the subject of the risk allocation between the two parties: well designed PPPs redistribute the risk to the party that is best suited to control and or bear the risk. The measure of the agent's performance and the extent to which the principal can control

and monitor the agent's performance are subject to the objectives set by the principal.

Social objectives play a major role in the incentives of the players and they are linked with the quality of the output. The extent to which the principal can control and monitor the agent's performance varies in the various stages of the contracting.

During the tendering phase, the best way to ensure that output quality is at least comparable with what would be expected in case of in-house public provision is to clearly set out quality standards and indicators, so that the private party is aware of such contractual requirements when submitting the offer.

During the building phase, reliance on past experience and use of accurate output indicators are the only means of control of the public entity in the building stage of any PPP contract.

At the operational phase, the greater the risk allocated to the private party, the smaller is the public involvement in the operation phase. The public sector however can use output indicators to monitor the private agent's performance. Therefore PPPs can be successfully applied only where service quality can be clearly specified, measured and guaranteed through performance indicators.

2.4.2 The Transport White Paper

We all know that mobility is essential to Europe's prosperity and to the freedom of movements of its citizens. But transport is a key policy area which not only determines how efficiently and at what cost goods and people move around the world and in Europe particularly, but also has a major impact on a series of other areas such as energy and environmental policy and, of course, on the operation of the Single Market which underpins the economy.

We must take into consideration the question: is mobility an intermediate good or a final one?

There is evidence that mobility of intermediate as a good: minimize mobility subject to a desired level of personal, production and consumption exchanges to be assured. But there is also evidence of mobility as a final good: maximize mobility subject to a desired level of congestion, emissions, safety, energy. The key issue remains the reconciliation of *mobility* and *sustainability*.

In the Transport White Paper (TWP) [70] and in keeping with the sustainable development strategy adopted by the European Council in Gothenburg in June 2001, the Commission proposes some 60 measures aimed at developing a European transport system capable of shifting the balance between modes of transport, revitalising the railways, promoting transport by sea and inland waterways and controlling the growth in air transport. The 2001 TWP suggested these lines of policy to solve the problem:

- transport demand management = trying to decouple economic growth from transport growth;
- modal shifts from road and air transport to rail, sea and inland waterways;
- better and smarter infrastructure charging
- new technologies for reducing energy consumption and negative transport side-effects like emissions and accidents

Sustainable transport is serving Europe's prosperity through building the single enlarged market (and making it operational) and increasing economic and social cohesion. A single transport market is to be built and maintained along three lines of policy:

- technical interoperability;
- market access liberalization;
- physical network interconnection.

Other 2001 Transport White Paper (TWP) lines of policy:

- Consumer protection;
- Europe in the global transport setting.

Modal shift is essential for reducing the environmental impact of transport.

2.4.3 The Revised Transport White Paper

The changes in scenario to be considered in the revision are:

- European Union is welcoming its 27th member state;
- globalization phenomena - both positive and negative, such as global warming - are winning ground;
- concern about security problems due to terrorism is growing;
- constraining all transport activities;
- new powerful Information Technologies are available.

Moreover, road transport is mostly responsible for congestion (mainly in urban and metropolitan areas), air pollution, transport casualties and transport energy consumption.

As a consequence, the TWP need a revision to be able to guarantee a better sustainable mobility: the revision must consist in a change in focus from managing transport demand and supply (decoupling and modal shift) to addressing negative side effects.

A modest modal shift can reduce road congestion: a 5% decrease in road traffic through modal shift would get a more than proportional reduction (10-20%) in road congestion, accidents, fuel waste, and so on.

We do not need any dramatic change or any punitive policy against cars and trucks. In this scenario the role of motorways concessionaires is as a cornerstone of every transport system with Concessions as

2.4.4 Regulation and licensee motorway companies in Europe

The first directive on the public works contracts of 1971 gives the definition of the concessions of public works. Currently the Green Paper (2004) [111] on the public-private partnership (PPP) refers to contractual agreements formed between a public agency and private sector entity that allow for greater private sector participation in the delivery of transportation projects proposing broad lines of "forms of cooperation between public authorities and the world of business which aim to ensure the funding, construction, renovation, management or maintenance of an infrastructure or the provision of a service".

The Green Paper also explains how to face the challenge for the Internal Market to facilitate the development of PPPs under conditions of effective competition and legal clarity.

The diversity of the concession systems introduced by the various European road administrations deals with the respective roles of the concession company and the public authorities. In particular, in the risk sharing between concession authority and Concession Company, various situations exist:

- risks borne by the governmental concession authority;
- risks borne by the concession company, but substantially supported/ limited;
- risks taken by the concession company.

The issue of risk sharing represents one of the major difficulties for road administrations when setting up concession projects [89]. There are also differences with respect to concession company selection criteria [67].

The criteria most frequently quoted by road administrations are:

- the amount of the public subsidy required,
- the credibility of the financial arrangement,
- the technical quality of the project,
- operating strategy and price policy, and
- the reputation of the concession company (the inclusion of a construction company amongst its shareholders, etc.).

The introduction of an agency, an autonomous public, or semi-public or private entity in the context of a concession or franchise arrangement, frequently has the primary advantage of making it possible to impose a management discipline [85].

Finally, a toll system can just serve to optimize utilization of the transport network (traffic spread, intermodal sharing of traffic load, etc.). In this case, however, charge systems must meet a number of different and sometimes contradictory objectives [16] such as, for example:

- marginal cost charging;
- cost recovery;

- maximised profit.

Formulas for determining toll charges also differ throughout Europe (“price cap” method in Italy, traffic band method or availability payment in the United Kingdom, etc.). Each of these formulas corresponds to a particular level of risk sharing, and it is consequently of genuine interest for all concession authorities in this regard [37].

The notion of toll a system is often confused with concession and private financing: in a toll system the user is charged and not the tax payer [35]. Moreover the European situation differs from American one where there are so few toll motorways (“toll road” or “turnpike”) and mainly built and operated by public authorities [180].

2.4.5 Regulation and licensee motorway companies in Italy

Before the Second World War, in 1921, the word “Autostrada” was used for the first time in Italy in the Puricelli relation, which presented a plan for a new kind of road, and it was translated literally in other languages as “Aautoroute”, “Aautopistas”, “Aautobahn” [38].

In 1922 the first highway was opened (Milano - Laghi): from the Second World War and after the end of the reconstruction, in 1955 law 463 states that highways should finance themselves with a public contribution of between 20% and 36%, a contribution updated to 52% in 1961 with law 729 but with an unexpected income that should be given to the government after the 5th year and financial costs fixed at 6.5%.

New highways (3600 km) were opened by 1970 and with law 492 in 1975 the construction of new highways was forbidden. In Italy, the prohibition of construction of new highways was partially abrogated in 1978 and legal limits slowed down new construction.

The construction of a toll motorways network in Italy started in the 50s, and was undertaken partly directly by A.N.A.S. (Azienda Nazionale Autonoma delle Strade), the State Department for toll and non-toll motorways, and partly under the terms of franchise contracts.

Franchise’s costs were assessed by means of the so-called “Piano Finanziario”, the financial plan (PF henceforth) which was to be presented at the beginning of the concession period, and included a detailed forecast for all costs and revenues for the whole period of the concession.

The object of the franchise contract is usually the motorway maintenance and the provision of motorways services. In some cases, the franchise contract has also included the construction of new motorways or the enlargement of existing ones. Nowadays, motorways services are provided in Italy by about 20 different concession holders, with the exact number depending on the used definition of “motorway” used.

Mostly for historical reasons, concession holders are very different in nature and size, whatever working definition of size and nature is adopted. During the 90s, a radical reform of the sector was undertaken.

The two most important changes relate to the ownership of the franchises and the regulatory framework. As to the change in ownership, many franchises were privatized, i.e. changed from governmental or public ownership or control

to private enterprise, with the most evident example being the privatization of Autostrade (now A.S.P.I. - Autostrade per l'Italia), which took place in 1999.

However, this was not the only change of ownership for motorway concessionaires in recent years: the number of privately owned franchises increased from 2 in 1992 (or 8, according to the working definition of private ownership) to 12 in 2003 (16, respectively).

The other important change refers to the reform of the regulatory regime: the new regulatory framework was defined in December 1996 with the CIPE Directive, which concluded a process that lasted several years.

This Directive provided for the renegotiation of all the existing franchise contracts. The new contracts had to adhere to the principles laid out in the Directive, amongst which the main ones are the price regulation based on a price cap formula, a X offset productivity factor and grants that the price level follows any change in productivity, the cost observation based on the PF. We should consider also that cost observation basis is provided by the franchise at the beginning of the franchise contract and being part of the contract itself. In addition, the PF is meant to be valid for the whole period of the concession and has to be updated only in special circumstances. The price cap mechanism (2.5) has been introduced as new regulatory framework:

$$\left[\frac{\sum_i p_i^t q_i^{t-1}}{\sum_i p_i^{t-1} q_i^{t-1}} - 1 \right] \cdot 100 \leq \Delta RPI - X + \beta \Delta Q \quad (2.5)$$

where:

ΔRPI	is the expected change in the Retail Price Index;
X	is the offset productivity factor and grants that the price level follows any change in productivity;
ΔQ	is the composite quality index (in % variation);
β	is a scaling positive factor;
p_i^t	is the (per Km) price paid by a vehicle of type i in year t ;
p_i^{t-1}	is the (per Km) price paid by a vehicle of type i in year $t - 1$;
q_i^t	is the total number of Km price traveled by vehicles of type i in year t ;
q_i^{t-1}	is the total number of Km price traveled by vehicles of type i in year $t - 1$.

It is important to notice that to avoid reducing the power of the incentives to cost reduction, the X factor should be set equal to expected rather than realized productivity gains and this feature of price cap regulation, with the related fact that the X factor is predetermined for a given number of years, differentiate this form of regulation from *rate of return* (ROR) regulation, where, at least in principle, prices follow closely realized costs.

The initial price of tolls has been the result of the initial conditions in the concession, so that it has been set on an individual basis and the variation ΔT of toll of motorways is calculated with the Price Cap Formula (2.6).

$$\Delta T \leq \Delta P - \Delta X + \beta \Delta Q \quad (2.6)$$

where:

- ΔP is the next year expected inflation;
- ΔX is the capital remuneration;
- β is the value related with the quality of the highways in the last 5 years;
- $\Delta Q = (I_{pav})(0.60) + (I_s)(0.40)$;
- $I_{pav} = (I_{a1})(0.60) + (I_{a2})(0.40)$;
- I_{a1} is the roughness;
- I_s is the number of accidents;
- I_{a2} is the regularity.

The Price Cap Formula adopted in the new contracts is applied to the prices charged by the concessionaire to each vehicle belonging to a given class for each Km traveled on the motorway. An interesting aspect is that the capital remuneration ΔX is different in the following cases:

- future investment plan (uncertain in income and time of construction);
- objective of productivities variation (different for each licensee);
- expected variation in demand (new alternative).

The price cap formula limits the increases of a Laspeyres index of these prices to the rate of inflation, adjusted for expected productivity gains and changes in the quality of services provided [65].

The Laspeyres Index is a price index following a particular algorithm. It is calculated from a set (“basket”) of fixed quantities of a finite list of goods. It is assumed that we know the prices in two different periods. Let the price index be one in the first period, which is then the base period. Then the value of the index in the second period is equal to this ratio: the total price of the basket of goods in period two divided by the total price of exactly the same basket in period one. As for any price index, if all prices rise the index rises, and if all prices fall the index falls.

2.5 An Application of the Balanced Scorecard to Motorway System Performance Assessment

In this section we describe how the balanced scorecard model, originally developed for use in the private sector, could be adapted for use in a modern motorway concessionaire to estimate its corporate efficiency and to evaluate environmental and social performance. We also propose a re-modulation of the tariff adjustment formula and a system to appreciate quality in a motorway environment.

2.5.1 Performance indicators

Performance indicators can be defined as variables whose purpose is to measure changes in a process or a function. Indicators used by the principal must be

clearly defined, accessible and transparent. Indicators may be quantitative or qualitative.

For example, the cost and the time taken to achieve a particular item are quantitative indicators. By contrast, the users' perception of his or her satisfaction is essentially qualitative in nature.

For comparison purposes, it is necessary to find some way of placing some quantitative value on such qualitative indicators. A common response to the need to quantify indicators is the use of ranking scales in which, for instance, a person's satisfaction with a process, activity or situation, might be ranked on a scale ranging from very happy, through happy, indifferent and unhappy to very unhappy. Such ranking scales must be set up at the time that indicators are identified and introduced to the overall monitoring and evaluation system. When selecting performance measures to evaluate a road network, the following should be taken into account:

- they should be truly representative of the quantities and characteristics that they are intended to represent;
- they should be verifiable: in other words, it should be possible to check that the values of the data or indicators presented are reported accurately;
- they should provide information that can be used by decision-makers. This will often mean that they are presented quantitatively;
- the information must be available in time to influence decisions;
- they should be linked into systems that allow feedback of information into the decision-making process.

Other issues that should be considered when selecting performance measures to evaluate a road network include the following.

- Forecastibility: is it possible to compare future alternative projects or strategies using this measure?
- Clarity: is it likely to be understood by transportation professionals, policy makers and the public?
- Usefulness: Does the measure reflect the issue or goal of concern? Is it an indicator of condition, which could be used as a trigger for action? Does it capture cause-and-effect between the agency's actions and conditions?
- Ability to diagnose a problem: Is there a connection between the measure and the actions that affect it? Is the measure too aggregate to be helpful to agencies trying to improve performance?
- Temporal effects: Is the measure comparable across time?
- Relevance: Is the measure relevant to planning and budgeting processes? Will changes in activities and budget levels affect a change in the measure that is apparent and meaningful? Can the measure be reported with a frequency that will be helpful to decision makers?

The preferred approach for regulating quality of service is for the regulator to specify and monitor performance outputs rather than inputs (for example to specify an indicator of drinking water quality rather than the treatment methodologies and equipment to be used to achieve the desired water quality). Regulating outputs promotes innovation and efficiency improvements - but only if the service provider also has an incentive to reduce costs. As a result, this approach goes hand-in-hand with other regulatory mechanisms, such as the price cap approach to tariffs (which motivates cost savings).

Specifying and monitoring a limited number of outputs helps to minimize regulation and avoid costly and bureaucratic regulatory practices and interference in day-to-day operations. The ultimate purpose of measuring performance in the road sector is to improve transportation service for customers and this is the reason that an increasing importance is given to it by transportation agencies. In the road sector, performance measures have long been used as part of pavement management and bridge management systems. Now many agencies are extending the process to applications in construction and maintenance systems, operations and safety, and administrative structures and processes.

An important observation from the 1997 OCDE [182] report was that much less emphasis must be put on quantitative analysis, compared to qualitative assessment of the purposes served by the road programme and whether these reflect the views of the public. The objective is to widen the views of road managers and planners in order to reflect the vision of an integrated transport system. Furthermore, in an OECD review of performance indicators for the road sector [183], the authors observed that in the past, the expectations for road administrations were fairly straightforward. The dominant objective was to deliver services to the public at minimum cost.

However, road agencies are now expected to meet service level targets at reduced costs and to develop mechanisms for customer feedback. In general, road agencies now operate in an environment in which there is a much greater emphasis on customers. Meeting customers' needs drives business for the public sector as well as private sector agencies. That focus on customers has made the assessment of agencies' performance more complex and has been a trigger for the study and application of objective performance measurement.

It is interesting to note that the use of performance measurement is considered useful not only for reporting to the public but also for communicating with the public. In the literature, performance measures are needed to evaluate the state of assets, which is a first step in developing priorities and allocating resources amongst competing priorities. Consequently, performance measures have been called the "backbone" of asset management systems to be used for planning and programming.

In the modern era of sustainability, performance measurement is also seen as key to measuring progress on that front. Transportation systems are recognized for the benefits they provide to the economy in terms of access and mobility but are also recognized as putting pressure on our environment. Widely held policy goals are to make progress toward sustainability while increasing economic prosperity and quality of life. In order to understand whether our systems are becoming more or less sustainable, measurement of performance against related indicators is necessary [109]. However, the type of performance measures used and the implementation practices vary significantly between jurisdictions.

OECD [183] has selected 15 performance indicators for road agencies, which

were tested in various countries and are the following:

- average road user costs;
- level of satisfaction regarding travel time and its reliability and quality of road-user information;
- protected road-user risk;
- unprotected road-user risk;
- environmental policy/programme;
- processes in place for market research and customer feedback;
- long-term programmes;
- allocation of resources to road infrastructure;
- quality management/audit programmes;
- forecast values of road costs vs. actual costs;
- overhead percentage;
- value of assets;
- roughness;
- state of road bridges;
- satisfaction with road system.

In order to compare and understand why particular indicators are used and the reasons for their values, the indicators have to be viewed in the perspective of the role of the road agencies - Concessionaire/Operator for a BOT project - in the road transport system. The key issues facing the road transport system and road agencies include (8):

- decreasing road budget;
- demand for greater transparency in performance;
- separation of the production and administration;
- change to customer focus instead of “expert knows best” attitude;
- demand for greater efficiency in operation;
- demand for better results and quality;
- demand for more co-ordination and co-operation across the transport sector;
- demand for performance improvements to be implemented more rapidly than in the past;
- new management aspects, demand for an open and broad understanding of the mobility problems facing society;

- demand for more data and more efficient management.

In Figure 2.1 the conceptual model of a BOT within the road transport system is presented. The Concessionaire allocates to the road operator the tasks relative to operation and maintenance of the road project defined in the Concession Contract. The road operator will be responsible for producing the required level of service and quality standards as defined in the Concession agreement.

Figure 2.2 presents the conceptual model of road operator performance. The performance indicators in a road BOT project, are a tool enabling:

- the effectiveness of the operation and maintenance to be measured;
- an achieved result to be gauged or evaluated in relation to a set objective.

The risk allocation between the involved parties - Grantor/Concessionaire - as reflected in the Concession Contract is predominant in order to define the tasks allocated to each party. Furthermore it should be kept in mind that the different players, i.e. the Grantor, Concessionaire and the user have different views, when choosing the indicators.

The increase of the level of service was one prime objective in state expectations for the developments of motorway concession projects in EU. The level of service has a direct impact on safety, uninterrupted operation, maintenance of the motorway and the structures (bridges, tunnels) and users' satisfaction.

Theoretically, the level of service should be defined narrowly, specifically and without forethought. For instance, it could be resolved through a measure of the number and rate of unresolved service requests and complaints or through an indicator of reliability measured by the functioning time - the number of days in a month or year when the service is functioning.

For almost all the concession projects performance requirements regarding the level of service were inserted in the concession contracts.

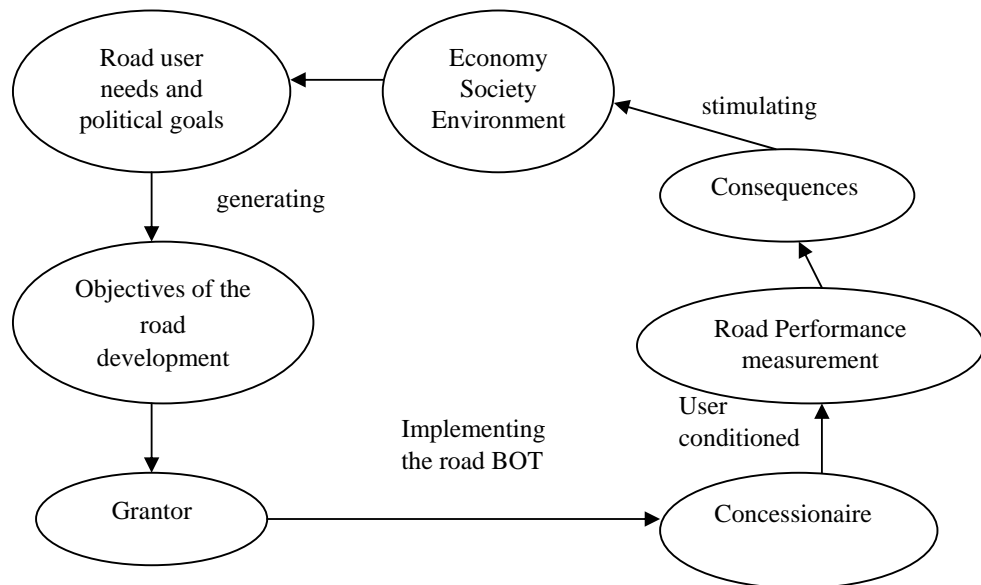


Figure 2.1: Conceptual model of a BOT within the road transport

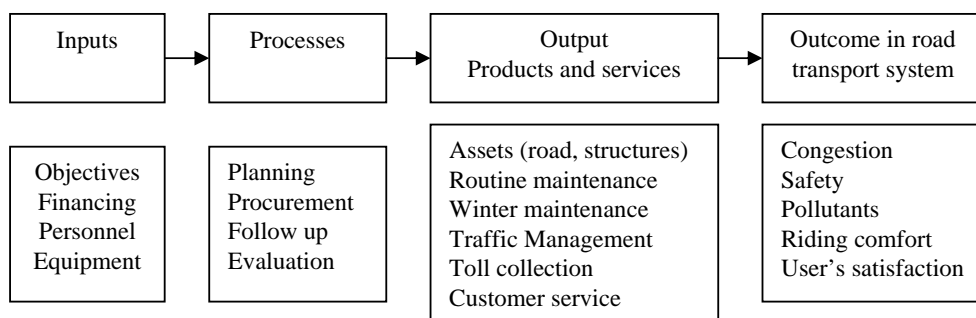


Figure 2.2: Model of a road operator performance

Dimension	Agent	Operator	Road user
Accessibility and mobility	Average road user costs		Level of satisfaction regarding travel time
Safety	Enforcement	Technical enforcement	Behavior
Environment	Legal framework	Environmental policy / programme	
Program development	Establish long term programs	Allocation of resources to road infrastructure Quality management /audit program	
Program delivery		Forecast values vs. actual costs	
Program performance	Value of assets	Roughness State of road bridges	Satisfaction with road system

Table 2.1: Taxonomy of performance indicators

2.5.2 What is the Balanced Scorecard

The balanced scorecard is a strategic management system that links performance measurement to strategy using a multidimensional set of financial and non financial performance metrics. The term “balanced scorecard” refers to the frameworks first described by Kaplan and Norton in 1992 [129] and in 1993 [130] and further expanded in *The Balanced Scorecard* (1996) [131] and *The Strategy-Focused Organization* (2001) [132]. In practice, many managers use the term “balanced scorecard” to refer to any set of financial and non financial measures that link performance indicators to corporate objectives. The four perspectives in the balanced scorecard in Figure 2.3 represent four key components of creating and sustaining corporate value.

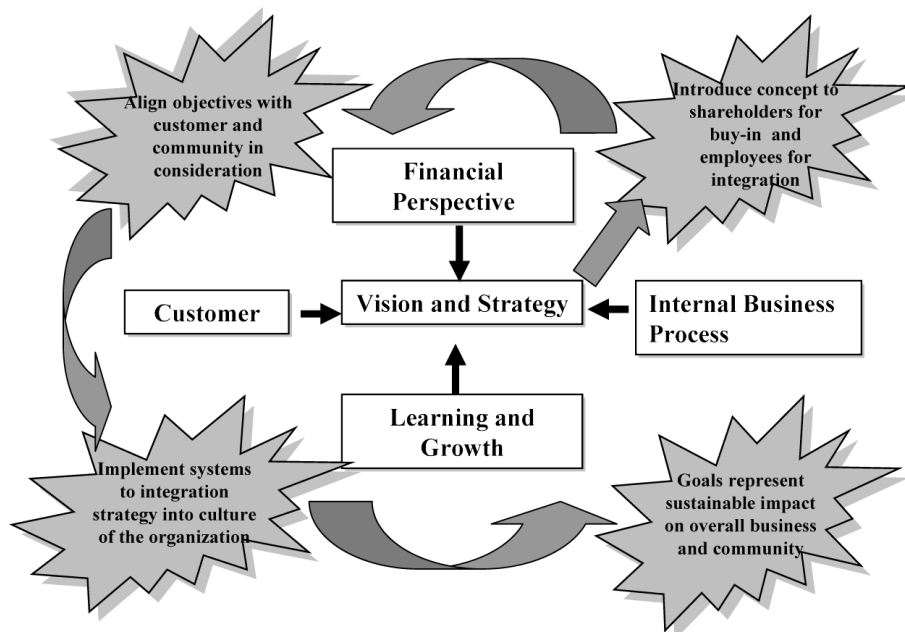


Figure 2.3: Adapted from “The Balanced Scorecard”, Kaplan and Norton, HBS Press, 1996

In addition to the balance achieved by including both financial and non financial performance indicators, the balanced scorecard helps managers to improve corporate decision making and accountability by including both leading and lagging measures of performance [63].

2.5.3 Problem Formulation

A performance measurement system is a tool for implementing strategic planning and achieving continuous improvement at all levels of an organization: the balanced scorecard is an integral part of business planning and strategy.

The state of practice related to transportation performance measurements is developing rapidly in the European Community and all over the world. There is an abundance of material on the subject that describes the theory, offers

recommendations for performance measurement programs, and documents experiences of agencies building and implementing their own programs. Interest is growing in enhancing management processes by including performance measurements as a core component.

When developing performance measurement programs, the literature emphasizes that outcome measures should be included, where these relate the activities an agency undertakes to its strategic goals. Data constraints must be considered and performance measurements should be implemented only when it is feasible to collect the data necessary to generate them.

The number of measures included should also be limited to those that are really important to an agency. This will simplify data collection and reporting and increase the likelihood the measures will be understood by the public sector, the private operator and the users.

In road authorities around the world, common performance measurements include:

- system condition and preservation
- safety
- accessibility and
- traffic conditions-mobility.

In many cases a user satisfaction index is reported which may be estimated from customer surveys. Protection of environment and sustainability are also cited as an important goal for most transportation agencies, public or private, around the world, and there is a common desire to be able to measure performance in this regard. A balanced scorecard identifies performance improvement opportunities/targets and highlights the need for business redesign or enterprise processes. Now, we will begin to develop the application of the balanced scorecard approach to a company from the motorway sector. In order to do this, the first step of our framework is to propose our vision in Figure 2.4 for S.p.A. Autovie Venete (AV): *Corporate Social Responsibility is a way of doing business which goes beyond mere financial results.*

In the North-East of Italy, Autovie Venete was established in 1928 in Trieste to design and build the highway from Trieste to Fiume (Rjeka -HR) and in 1965 it started the design and realization of the Trieste-Udine-Venezia Motorway, in operation since 1966. Now, the concessionaire manages about 200 Kilometers of motorways near the border with Slovenia and Austria [A4 (Venice-Triest), A23 (Triest-Udin), A28 (Portogruaro-Pordenone-Conegliano)].

Due to the changes in the countries near Italy (Slovenia, Croatia, Hungary, etc.), since the middle of 90's the traffic has increased with an unusual trend and the motorway, designed and realized for a different level of service, has become less comfortable and safer for users. The concessionaire has planned to invest a large amount of money in the network upgrade in the near future from two to three lanes in the stretch from Venice to Villesse. The construction phases will predictably induce the risk of traffic congestion: then the realization of Intelligent Highways and Intelligent Transport Systems become necessary to support the management in making decisions on traffic control, especially during emergencies and unusual conditions.

According to Vogelsang [232], AV has to state its own commitment to sustainable development through environmental protection, social responsibility and economic progress.

Consequently, AV should define a strategy to achieve these goals and to create a future that engages stakeholders, leverages core competencies and creates superior shareholder and societal value [140]. Finally, AV must develop value-



Figure 2.4: Adapted from "The Strategy-Focused Organization", Kaplan and Norton, HBS Press, 2001

based codes and Corporate Social Responsibility strategies and link them to its own mission, vision and values.

2.5.4 Solution approach

The mission of AV is to provide, ensuring **safety** and **mobility**, a **primary service** which is by nature deeply connected to its impact on society and the **environment** in which it operates. These factors will put the issues of *social and environmental responsibility* at the top of Group companies' agendas, which combine public service provision with the goals of creating value and meeting all stakeholders' requirements [174]. Moreover, the **quality** of the company's strategy and management and its performance in dealing with opportunities and risks deriving from economic, environmental and social developments can be quantified and used to identify and select leading companies for investment purposes [34]. Consequently, in AV Corporate Sustainability must be an investable concept and its performance shall be crucial in driving interest and

investments in sustainability to the mutual benefit of investors [149].

Then, the Concessionaire needs to begin to invest in improving behavior models according to commitments derived from signing up to the United Nations Global Compact projects, which aim to promote corporate social responsibility with the ultimate goal of building a more sustainable and non-discriminatory global economy [124]. The **new mission** shall be to meet the infrastructure needs for the mobility of people, goods, materials and information: it is necessary to work vigorously to integrate different historic businesses into a new corporate culture including the Strategic Plan for Corporate Social Responsibility. According to Marrewijk [164], this plan in particular must contemplate:

- minimizing environmental impact;
- guaranteeing transparency with the investment community;
- ensuring the motivation of human resources (H.R.);
- ensuring the involvement of H.R. in the continuous improvement of the Company;
- maintaining a close relationship with customers;
- guaranteeing customer satisfaction.

There is an opportunity for a new approach named "Sustainable Value Added - Measuring Corporate Contributions to Sustainability beyond Eco-Efficiency" [93]. With it, it is possible to measure corporate contributions to sustainability called Sustainable Value Added. Value is created whenever benefits exceed costs.

Current approaches to measure corporate sustainable performance take into account external costs caused by environmental and social damage or focus on the ratio between value creation and resource consumption. Environmental goals are drivers for long-term growth in profitability as they reduce releases to the environment and rate of waste generation, and improve energy efficiency per unit of production [162].

The concept of strong sustainability requires that each form of capital is kept constant. As Sustainable Value Added is inspired by strong sustainability, it measures whether a company creates extra value while ensuring that every environmental and social impact is in total constant.

Therefore, it takes into account corporate eco- and social efficiency as well as the absolute level of environmental and social resource consumption (eco- and social effectiveness). As a result, Sustainable Value Added considers simultaneously economic, environmental and social aspects.

The overall result can be expressed in any of the three dimensions of sustainability. But a Sustainable Organization of this kind is also in reality a Learning Organization [196], as described in the following model in Figure 2.5. In addition, we propose that AV has to integrate Sustainability into the Core Elements of Business just using a balanced scorecard. Leading indicators are generally thought of as input or process indicators that link more closely to operations, while lagging indicators relate more to outcomes achieved through the management of leading indicators. However, leading and lagging indicators should be thought of as a continuum, or as a part of a complex flow of causes and effects.

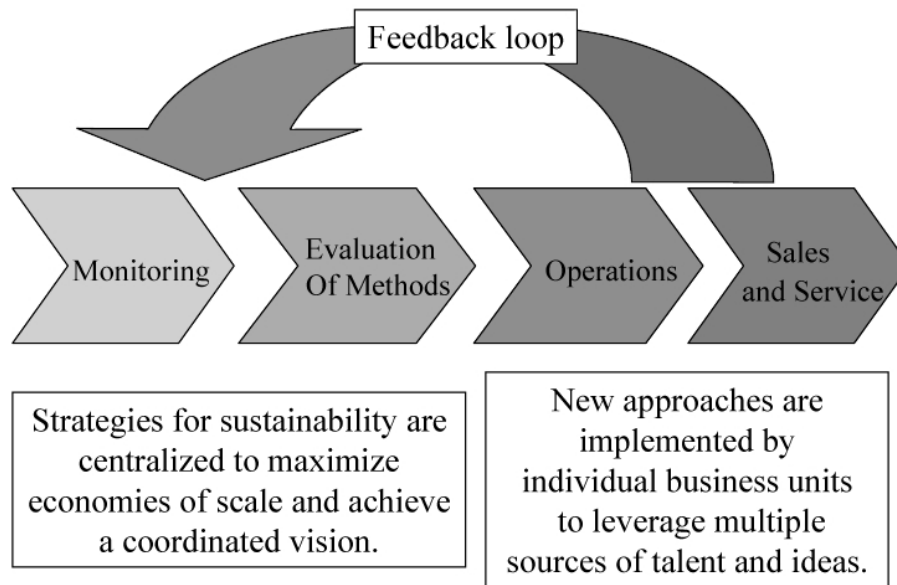


Figure 2.5: Model for Sustainable Organization

For example, a facility's toxic emissions are a lagging measure of process efficiency, and also a leading indicator of environmental costs. Employee turnover is a lagging measure of employee benefit expenditures, but a leading measure of recruitment and training costs.

To more effectively determine performance measures, managers must understand the causal links between actions that create organizational capabilities and the impact of those actions on operational performance, customer value, sustainability performance, and financial performance. The four perspectives of the balanced scorecard connect, through chains of cause and effect, learning and growth actions impact, internal business process outcomes, internal business process actions impact, and both customer and financial outcomes.

According to Epstein [73], developing social and environmental balanced scorecard measures helps environmental health and safety (EH&S) managers identify the key performance factors that link their department work to the company's strategic objectives and leading companies recognize the critical importance of systematically and pro actively managing corporate, social and environmental impacts.

There is no rule for the right number of measures to include in a balanced scorecard, although including too many of them tends to distract from the pursuit of pursuing a focused strategy. Generally, a complete balanced scorecard contains three to six measures in each perspective. A rich set of potential measures reflects the complexity of business today.

The measurement mix should be a combination of leading/lagging, financial/no financial, external/internal, strategic/tactical, process/product, people/technology, and input/output measures. Measures chosen for the scorecard should be:

- quantifiable, in either absolute or percentage terms;

- complete;
- controllable.

“Complete” in the sense that the measure sums up in one number the contribution of all elements of performance that matter; for example, profitability is a summary measure of revenue generation and cost control. “Controllable” in the sense that employees in the organization can actually influence improvement in the measured factor.

Finally, for the motorway concessionaire we propose the following Aim and Objectives and the customized balanced scorecard in Table 2.2 and 2.3.

Aims: Safe Motorways, Reliable Journeys, Informed Travellers, putting customers first, working together in dynamic teams and partnerships, encouraging learning, innovation and flexibility, delivering effective services that provide value for money, building trust by acting with honesty and fairness.

Objectives: to deliver a high quality service to all customers by improving road safety, making journeys more reliable through better network management and information, respecting the environment, to ensure more effective delivery through better working relationships, to implement best practice and innovative solutions to improve service now and in the future, to be an efficient firm with effective business processes and resource management systems.

Table 2.2: Balanced Scorecard proposed for a motorway concessionaire

Financial and Customer perspectives
(in italic the motorway specific factors)

FINANCIAL		CUSTOMER	
Environmental	Social	Environmental	Social
<ul style="list-style-type: none"> • <i>environmental saved</i> • fines/penalties • EH&S cost (% of sales) • % proactive vs. reactive expenditure • increase in relative % of proactive expenditures • % <i>environmental costs direct -traced</i> • capital investments • energy costs • disposal costs • <i>recycling revenues</i> • <i>revenues from "green" products</i> • operating expenditures • education in cost of debit • <i>cost avoidance from environmental actions</i> • <i>reduce costs in terms of life and money of the consequences of accidents</i> 	<ul style="list-style-type: none"> • philanthropic contributed • workers compensation costs • employee lawsuits • employee benefits • legal actions/costs • training budgets • reduction in hiring costs • revenue from socially positioned products • increased sales from improved reputation • <i>reduce costs in terms of life of the consequences of accidents</i> 	<ul style="list-style-type: none"> • cause-related marketing • green products • <i>product safety</i> • % recalls • customer returns • unfavourable press coverage • % products reclaimed after use • % stakeholder communications • product life • <i>functional product eco-efficiency</i> 	<ul style="list-style-type: none"> • <i>customer perceptions</i> • % of cause-related events supported (cancer, Aids) • community support (parks, safety, recreation, etc.) • % community meetings • <i>customer satisfaction</i> • social report requests • % product recalls • customer group demographics • <i>understand more in depth the needs of the users</i> • <i>respond to the needs with adequate services</i>

Table 2.3: Balanced Scorecard proposed for a motorway concessionaire

Internal and Learning perspectives
(in italic the motorway specific factors)

INTERNAL BUSINESS PROCESSES		LEARNING and GROWTH	
Environmental	Social	Environmental	Social
<ul style="list-style-type: none"> • % LCAs performed • % material recycled • % waste to landfill • % certified suppliers • % accidents spills • % audits /year • % <i>truck miles</i> • % office supplies recycled • internal audit scores • <i>energy consumption</i> • % facilities certified • % of product remanufactured • packaging volume • non product output • % supplier audits / year • <i>fresh water consumption</i> • <i>greenhouse gas emissions</i> • <i>air emissions</i> • <i>water emissions</i> • <i>vehicle fuel use</i> • <i>habitat changes due to operations</i> 	<ul style="list-style-type: none"> • % <i>employee accidents</i> • % lost workdays • % days work stoppages • hours overtime work • average work week hours • warranty claims • minority business purchases • % plant tours / visitors • % <i>non-employee accidents</i> • certifications • % suppliers certified • % supplier violations • <i>environmental quality of facilities</i> • <i>observance of international labour standards</i> • % <i>safety improvements projects</i> • % <i>solutions to avoid crashes and accident</i> • % <i>solutions for a better and safer mobility</i> 	<ul style="list-style-type: none"> • % of employees trained • training programs / hours • reputations per surveys • inclusion in "green" funds • employee complaints • community complaints • shareholder complaints • unfavourable press coverage • violations reported by employees • % of employees with incentives linked to environmental goals • % of functions with <i>environmental responsibilities</i> • <i>Management attention to environmental issues</i> • % of employees using car pools 	<ul style="list-style-type: none"> • workforce diversity (age, gender, race) • management diversity • % internal promotions • employee volunteer hours • average length of employment • % involuntary discharges • employee education • % family leave days • employee benefits • salary gaps between genders / races • employee satisfaction • "quality of life" programs • % of employees owning company stock • % applicants / job openings • employees with disabilities • employee grievances • <i>workforce equity</i>

2.5.5 Quality factors of the Italian Motorway System

In subsection 2.4.5 we presented that the tariffs of the Italian Concession motorway system are governed by the so called price-cap principle. In practice, until 2006 the system was based on the following formula:

$$\Delta T \leq \Delta P - X + \beta \cdot \Delta Q \quad (2.7)$$

where:

ΔT	is the weighted average change;
ΔP	is the planned rate of inflation;
X	is the expected productivity rate;
$\beta \Delta Q$	is the element of the tariff change that depends on the quality of the service;
β	is a positive or null coefficient and
ΔQ	is the percentage change of the quality indicator Q .

In January 2007 the Italian Government adopted a change by introducing a new tariff formula defined as follows:

$$\Delta T = \Delta P - X + K (+Y) \quad (2.8)$$

where:

ΔT	is the annual percentage change of the tariff;
ΔP	is the planned rate of inflation;
X and K	are two new parameters that take into account the return on invested capital as well as operating and infrastructure building costs vis--vis investments;
Y	is a quality factor.

It must be underlined that this change may be traced to the scope of a wider change of the entire regulatory framework governing the concession contracts that has been unilaterally changed by the Italian government. This change entails unsustainable costs for Concessionaires and this, in turn, has led to a claim against the Italian State and a regulatory uncertainty which currently affects the entire Italian toll motorway system.

2.5.6 Re-modulation of the tariff adjustment formula

Among the proposals submitted submit by Italian concessionaires to the Ministry for Infrastructure and Transport and A.N.A.S. (the granting body of Italian tolled motorways) there is as an alternative to the legislative intervention which is today being disputed. This alternative could be a re-modulation of the tariff system aimed at correcting certain quality parameters as well as the introduction of a specific penalty system, both useful to optimise the infrastructure's operation. According to [202], the proposal provided for:

- the introduction of a new quality parameter I_t relating to the *efficiency of toll stations* through the introduction of a new addend $\beta_1 \Delta Q_1$;

- the setting up of a penalty system related to minimum technical standards and relative procedures required to guarantee an adequate degree of motorway efficiency. The penalty system, which would be external to the tariff formula, is structured in such a way as to enable amounts collected from penalties/tickets to lead to reduced annual tariff increases.

In this way tariffs would be adjusted according to the following formulas:

$$\Delta T \leq \Delta P - X + \beta \cdot \Delta Q + \beta_1 \Delta Q_1 \quad (2.9)$$

or, after the new formula introduced in 2007, and assuming the existing $\beta \cdot \Delta Q$,

$$\Delta T \leq \Delta P - X + K + \beta \cdot \Delta Q + \beta_1 \cdot \Delta Q_1 \quad (2.10)$$

and

$$\Delta T_{eff} = \Delta T - \Delta T^* \quad (2.11)$$

where ΔT is the tariff increase to be adopted in the year in the absence of a penalty system. The *actual tariff increase* ΔT_{eff} to be imposed on users, under the new penalty system, is given by deducting the tariff decrease due to penalties ΔT^* from ΔT .

Both the tariff re-modulation as well as the introduction of the penalty system are aimed at directly tying the work of the motorway operator to observance of defined quality standards as described by the new quality factors.

In practice a virtuous mechanism is triggered, where the operator's aim of generating a profit coincides with the user's right to always have the best quality of infrastructure available: in fact, the operator's greatest tariff returns are directly related to effective observance of quality standards and efficiency.

2.5.7 Service quality

What we are proposing is the introduction of a quality indicator capable of measuring the smoothness/fluidity of toll collection operations at toll stations. We consider the greatest amount of time that is lost by users occurs at toll gates that do not have a telematic toll payment system (i.e, Telepass). Overall increased efficiency at toll stations may be achieved by reducing user build-up at non-Telepass gates in favour of Telepass gates. This is a form of toll-collection that has much higher service performance levels - approx. 1,600 transits/h on the one hand and increasing the hours of operation of non-Telepass gates on the other hand.

2.5.8 The Q_1 quality indicator and the β_1 coefficient

The index Q_1 is proposed as a measurement of the smoothness of toll station operations. It is calculated on the basis of aggregated data such as:

- annual exit transits from toll stations belonging to the network operated under concession broken down by type of payment;
- the number and type of exit lanes;
- the number of hours of operation of non-Telepass dedicated exit lanes, excluding night time (22.00-6.00), for the 12 months being examined (from July to June of the following year).

Through an understanding of this data, a historical series of dedicated non-Telepass exit lanes (i.e. manual lanes manned by a toll collector) may be assembled in an aggregate form for each concessionaire. In order to determine the smoothness/fluidity index of toll stations Q_1 we first calculate the average hourly flow per non-Telepass lane according to the relationship between the total number of annual transactions with non-Telepass dedicated payment (TA_{noTLP}) and the cumulative number of annual hours of operation of the non-Telepass dedicated payment lanes (OOO_{noTLP}):

$$I_s = FMO_{noTLP} = \frac{TA_{noTLP}}{OOP_{noTLP}} \quad (2.12)$$

We then define the maximum hourly capacity of non Telepass dedicated payment lanes CMO_{noTLP} :

$$CMO_{noTLP} = 350 \text{transits/h} \quad (2.13)$$

We then calculate the index of smoothness/fluidity of toll stations Q_1 through the following equation:

$$Q_1 = 100 \cdot \left(1 - \frac{FMO_{noTLP}}{CMO_{noTLP}} \right) \quad (2.14)$$

The value of the proposed β_1 coefficient is calculated on the basis of the value Q_1 as described below:

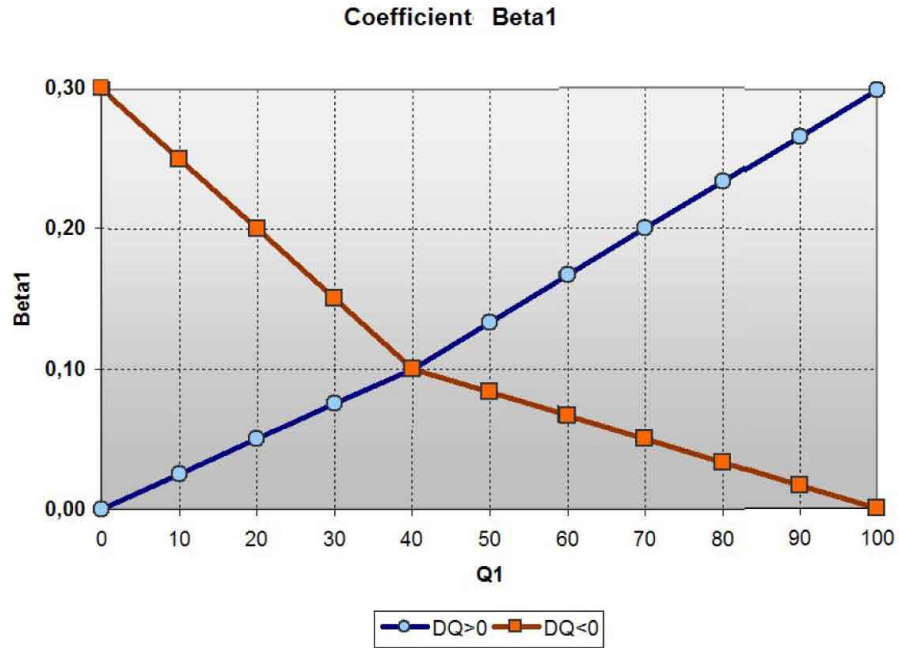


Figure 2.6: Model for determining coefficient β_1

- the first element, ΔT_1^* , is related to the penalties that are imposed once non-respect of a predefined standard has been notified and not been rectified, as well as any blocks related to adverse weather (for example snow);

- the second element, ΔT_2^* , is related to the number of signals of non-respect of predefined standards that are observed per motorway stretch at the end of each year by each individual concessionaire company.

In order to determine the annual change ΔQ_1 the following equation has been proposed:

$$\Delta Q_1 = \frac{Q_i - \bar{Q}_{i-1}}{\bar{Q}_{i-1}} \quad (2.15)$$

where \bar{Q}_{i-1} is the average of the Q_1 quality indicators over the last three years. In the absence of the necessary historical series and in order to immediately start an experimental application of the formula, data from the year that has just ended shall be compared with that of the previous year during the initial transitional phase; this shall be done until the aforesaid three year historical series is built.

2.5.9 A penalty system and the Annual Monitoring Programme

2.5.9.1 A penalty system

The proposal entails the introduction of a penalty system, connected to certain technical standards of reference that are useful to optimise the motorway's degree of efficiency. This penalty system is separate from the tariff formula, and may be able to transform amounts that are collected for penalties into a non-increase of tariffs. In this way, the penalty system attached to the tariff increases would turn amounts that are collected from penalties directly into a benefit for motorway users, without passing through the Grantor.

The total amount of penalties is transformed into a tariff rate ΔT^* on the basis of *vehicles * tolledkm* during the same period. This rate is deducted from the tariff adjustment ΔT so as to obtain the actual increase ΔT_{eff} to be imposed on users during the year of reference:

$$\Delta T_{eff} = \Delta T - \Delta T^* \quad (2.16)$$

The tariff reduction ΔT^* only holds for the reference year and is not added to that of the following years. Accordingly, once the year that is subject to the reduction has ended, the tariff that is applied shall no longer take into account the reduction that was made, and therefore the tariff change to be applied shall be calculated against the full tariff ΔT (without the reduction) matured during the previous year.

The penalty system requires an initial three year test period in order to assess the actual consequences of its adoption. In this regard, in order to guarantee consistency with the financial planning of concessionaire companies, a maximum cap to the tariff reduction is set at ΔT_{max}^* and equal to 0.5% of the unitary tariff for the first three years of application of this penalty system. Effective with the third year of adoption, the results of the test period shall be assessed. If the average penalties imposed shall have exceeded eighty percent of the plafond (average penalty in the three years > 0.4% of the tariff) this plafond shall be increased to 0.8%.

The value of the tariff decrease ΔT^* is calculated as the sum of two elements: The value of the proposed β_1 coefficient is calculated on the basis of the value Q_1 as described below:

- the first element, ΔT_1^* , is related to the penalties that are imposed once non-respect of a predefined standard has been notified and not been rectified, as well as any blocks related to adverse weather (for example snow);
- the second element, ΔT_2^* , is related to the number of signals of non-respect of predefined standards that are observed per motorway stretch at the end of each year by each individual concessionaire company.

We therefore have:

$$\Delta T^* = \Delta T_1^* + \Delta T_2^* \leq \Delta T_{max}^* \quad (2.17)$$

2.5.9.2 The Annual Monitoring Programme

Controls relating to respect/alignment with reference standards must be carried out according to procedures described in a Annual Monitoring Programme. This Programme must be prepared by the Grantor in agreement with concessionaire companies and shall concern motorway stretches not affected by works. All notices shall be sent to the concessionaire company which shall be invited to take part in the assessment. The Annual Monitoring Programme shall be updated on an annual basis and shall include:

1. a list of those elements that are subject to the assessment, with an explicit definition of:
 - the field/scope of application;
 - the parameters to be measured;
 - the standard of reference (benchmark);
2. an indication of the motorway's network breakdown into stretches for each concessionaire company. Each stretch shall have to be no longer than 80 km. Every notice of non-alignment shall need to refer to a specific stretch of the motorway network;
3. an indication of the Grantor's staff that is authorised to carry out the checks as well as an indication of the Concessionaire company's staff authorised to take part in the checks;
4. the number of planned annual checks shall be the same for each concessionaire company. The minimum number of annual checks is set at 4 checks/year. The Grantor shall have the right to increase the number of checks. In consideration of the possible widening of the motorway network, checks may be carried out over a number of days.

2.6 Balanced Scorecard, Deming Cycle and Customer Satisfaction

One key goal of all businesses is to achieve a continuous and high level of customer satisfaction in the delivery of services and/or products. Such satisfaction is believed to be the basis of long term profitability and business growth.

In the sphere of motorway-based system services, customer satisfaction is dependent on how system development projects evolve to build operational product systems and services that satisfy the perceived and actual customer need and associated system and service requirements. Ultimately, successful customer satisfaction depends upon the depth of “through-life” understanding about the business needs and associated user requirements for a future system, and the ability to communicate those requirements to the system developer. In addition, customer satisfaction and confidence depends upon the level of system assurance offered throughout the system development lifecycle. Requirements problems without understanding inevitably lead to poor customer-supplier relationships, unnecessary re-works, and overruns in cost and/or time so that the excellent construction of a motorway (or any other relevant project) is not sufficient on its own for achieving a successful operation and the public recognition. The provision of high level services is a necessity and these services are capable of highlighting the advantages of the project and justifying the benefits arising from the payment of toll by the users.

As a consequence, Customer Satisfaction is the “key” factor for the success operation of a modern tollway and the management of a motorway must develop a complete methodology for achieving continuous improvement of the services provided to the users.

Customer satisfaction is dependent upon many factors that are associated with the business need, the development project and resultant system product quality. Ultimately the customer is looking for added value to benefit the business operations within a defined time frame but at an affordable price; hence the customer priority is for an overall successful business.

The system supplier perspective is to deliver a system within the agreed cost plans to satisfy the customer requirements, thus contributing to the supplier’s profit and reputation; hence the supplier’s priority is for a successful project. These different perspectives are typically controlled through inflexible and formal contract management arrangements in the pursuit of a successful project for both customer and supplier.

The cornerstone of such “success” involves an appropriately rigorous and long-term approach to “quality” by customers and suppliers. A Model of Customer Satisfaction and its Components is presented in Figure 2.7. To develop a new methodology we can start from the cycle of W. Edwards Deming which proposed that business processes should be analyzed and measured to identify sources of variations that cause products to deviate from customer requirements. He also recommended that business processes be placed in a continuous feedback loop so that managers can identify and change the parts of the process that need improvements. The diagrams in the Figure 2.8 illustrates this continuous process, commonly known as the PDCA cycle for Plan, Do, Check, Act and the Continuous Learning Spiral.

PLAN : design or revise business process components to improve results.

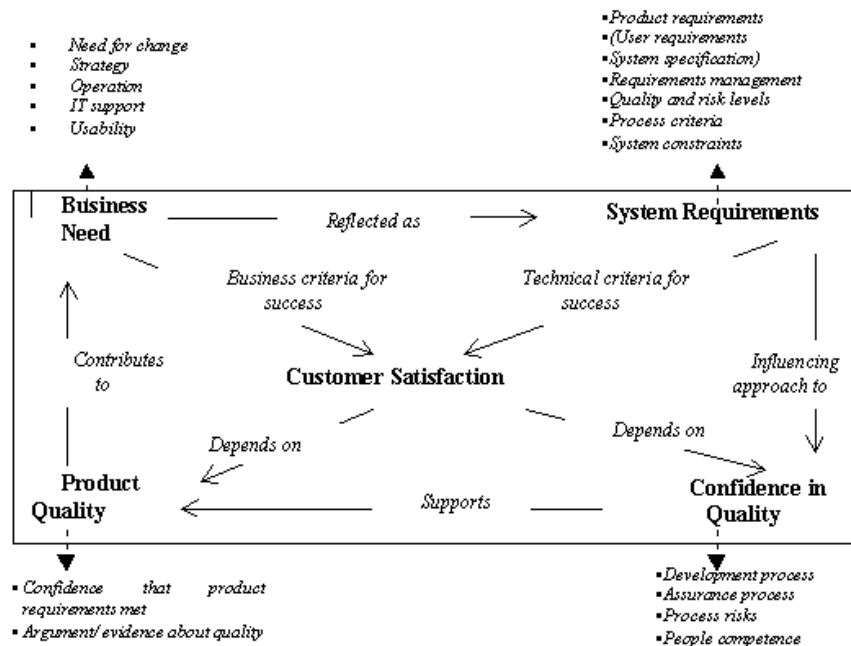


Figure 2.7: Model of Customer Satisfaction and its Components

DO : implement the plan and measure its performance.

CHECK: assess the measurements and report the results to decision makers.

ACT : decide on changes needed to improve the process.

Deming’s focus was on industrial production processes, and the level of improvements he sought were on the level of production. In the modern post-industrial company, these kinds of improvements are still needed but the real performance drivers often occur on the level of business strategy. Strategic deployment is another process, but it has relatively longer-term variations because large companies cannot change as rapidly as small business units. Still, strategic initiatives can and should be placed in a feedback loop, complete with measurements and planning linked in a PDCA cycle.

According to [171], the new methodology that we want to develop can be called “Continuous Learning Spiral” and it must be supported by both a balanced scorecard and a range of advanced and complete adjusted tools to the characteristics of the project. These tools are instruments for analysing data and market research, but also evaluation models of the economic impacts by the provision of new or existing services to the users of the motorways.

The main stages of this methodology could be:

- 1 - the recognition of the motorways users, their main trip characteristics and their socio-economic needs;
- 2 - the planning of new services covering the fundamental users

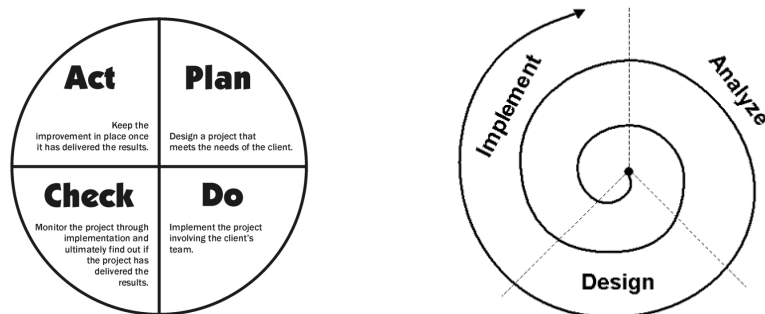


Figure 2.8: Graphical representation of the Deming Cycle and Continuous Learning Spiral

needs or adjusting the existing services according to the newly developed conditions;

- 3 - the provision and the support of these services to be known to the users and their recognition by the users and
- 4 - the evaluation of the perceived benefit of these services by the users.

As it is outlined in the caption of Figure 2.8, the procedure is continuous and this is the main element of the success of this approach. The stages are known internationally, but it may be the first time that they have been used in combination and completed for the planning and the evaluation of the provided services by a modern sustainable motorway [110]. In the following paragraphs, a short description of the main principles for each stage and all the supporting tools are presented.

In the following subsection we present an analysis of the stages of the methodology.

2.6.1 Know your Customers and Learn from them

The aim of this task is to record and subsequently to analyse the main demographic and socio-economic characteristics, which are dominant at a specific time period and influence directly the trip generation of the potential motorway Tollway users. The continuous recording and analysis of the trips generated in a motorway can lead to the definition of the special characteristics of these trips and allows the creation of a user group with similar needs and behaviours. Various different categories can be used today by a motorway management combined with in depth analysis of the user needs for each category, contributing significantly to the development of adjusted services for achieving the satisfaction of these needs and ensuring the substantial acceptance by the users. The main supporting tools of this procedure are Road Side and Telephone Surveys, which have as targets the following:

- to define Users Profile and Users Groups;
- to know the Trip Purpose and Frequency of Use;

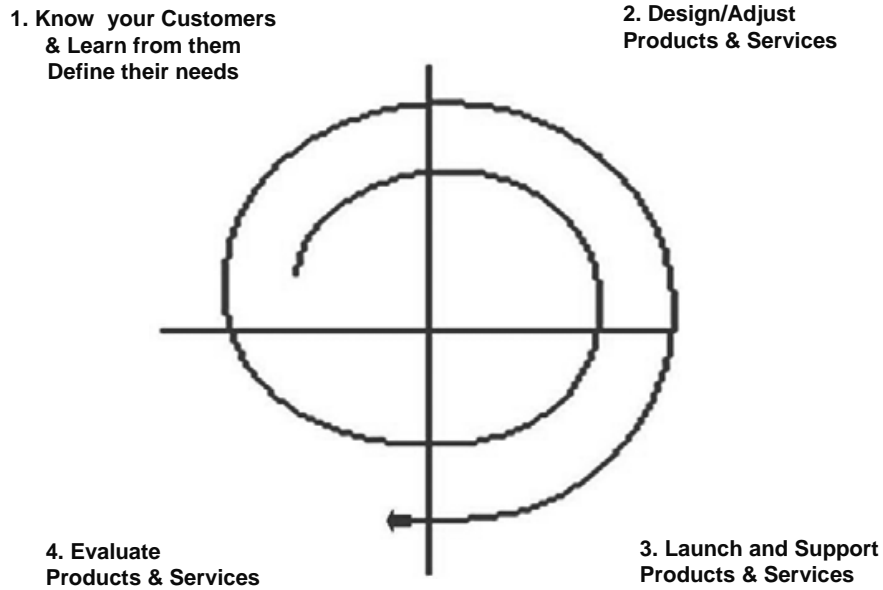


Figure 2.9: Graphical representation of the approach

- to know the Common routes and Value of Time;
- to identify the Professional and Income Status;
- to obtain User's Feedback for the Tollway;
- to measure the Level of Understanding for Products and Services.

Equally significant is the recording and analysis of the requests and suggestions made by the motorway's users, who point out possible small defaults of the provided services, significant improvements, and proposals for new useful services. For this reason, the company must develop a consistent and automated management system for user comments and complaints which constitutes a significant source of information for planning the new services.

2.6.2 Design/Adjust products and Services

For any new service planned or for any existing service modified it is crucial to examine its influence on the existing services and on the overall performance of the company. For this reason, high attention must be to the analytical recording of attributes of these services, and to the recognition of the relationships and interfaces (direct and indirect) of each of these characteristics with other services provided by the motorway or to the overall performance of the company. In this perspective several different scenarios of implementation are developed. These scenarios, with the support of complete models, are examined in terms of feasibility and effectiveness. In this manner, identifying the real consequences of each change or new service is possible and the justification of the decision pursued by the company is also available.

2.6.3 Launch and Support Products and Services

The success of a new service or the adjustment of an existing service mainly depends on the manner in which it is provided to the users of the motorway. It also depends on the efficiency of the support provided to each stage of provision of this service.

It can be mentioned that the successful operation of a new subscription scheme substantially depends on the completeness and the level of the information given to the users of the motorway regardless of whether they are already subscribers or not. This information is developed with data that arises from the analysis of the trips characteristics (stage 1 of the methodology) and it is focused on groups of users who are potential users of the specific subscription scheme.

Hence, the informative documents for this subscription scheme are distributed on determinate days and hours and from specific toll plazas which are used by those users. Specific research and measures are carried out during each campaign and afterwards of its completeness in order to evaluate its effectiveness. These measures provide significant remarks. These remarks are used for both the adjustment of the current campaigns and the planning of new ones.

Except for the subscription schemes, the subject of the campaigns must be all services provided by the motorway as well as issues directly or indirectly connected to its operation such as: Traffic Safety, Beautification, Signage and Guidance along the motorway, Tunnel Operation, etc. The support provided to the users that intend to use a new service contributes to the success of the new service.

An essential function is provided by Customer Support Centers and an excellent organized Call Center, which pays special attention to providing complete support to the users for each service provided to them. In this case the users' requests for support are recorded thanks to CRM software and they are regularly analyzed to indicate useful remarks for the future campaigns of the company.

2.6.4 Evaluate Product and Services

It is necessary to implement a complete evaluation of each service or product that is provided to the users of motorway. The results of this evaluation are compared with the expected results provided from models that were being used in stage 3 of the present methodology. The data necessary for this evaluation are collected and evaluated. This is a substantial monthly task that is carried out by the company and its external partners. A company using new techniques such as "data mining" and integrated systems "reporting" can carry out several processing such as:

- the evaluation of the operation of each provided service in comparison with the observed use from the users;
- the recording and the evaluation of the effects of each service on the total company's revenues and on the traffic volumes along the motorway to know the Trip Purpose and Frequency of Use;
- the determination of the interaction among the provided services;

- the definition of parts of the provided services that need to be improved to identify the Professional and Income Status;

Except from the evaluation of the data provided by the operation of the motorway, a substantial information reference for the acceptance and the perceived use of the services by the users are the Road Side Surveys and the regular telephone surveys to users. These surveys record the users' level of satisfaction, their perceived benefit from each provided service and essential proposals for improvement of these services is recorded.

2.7 Conclusions

This part of the thesis describes the problem and proposes a solution to perform the objective of a Sustainable Value Added in a Strategic Plan for Corporate Social Responsibility in the sector of Build-Operate-Transfer, road operators and motorway concessionaires in particular.

The European Union objective of reducing by half injuries and casualties on the Trans-European road network (TERN) is a real challenge for the different member states and road operators.

The continuous increase of traffic urges the development of systems that improve road safety and network fluidity and optimize the use of infrastructures in time and space. In that context, ICT for Cooperative Systems promise to substantially increase road quality, safety and efficiency, and to reduce the environmental impact of road transport.

Ethics are not a substitute for a fundamentally sound business strategy, and so it is important to provide value-added tools for companies to help them manage all aspects of sustainable and socially responsible business practices as in the road and motorway sector.

In order to perform the objective of a Sustainable Value Added in a Strategic Plan for Corporate Social Responsibility, it is very important to define the roles of technological progress, resource substitution, alternate capital valuation, better provision and pricing mechanisms of public goods in enhancing the productivity of existing assets.

It is also essential to discover the key features and principles of sustainable development by examining emerging needs, available capitals, and productivity capacities of each environment.

Business has a responsibility, beyond its basic responsibility to its shareholders, to a broader constituency that includes its key stakeholders: customers, employees, government and the people of the communities in which it operates.

Organizational ethics, values and Corporate Social Responsibility initiatives are becoming increasingly important value drivers in corporations and have implications right across the organization in area such as transportation.

The state of practice related to transportation performance measurements is developing rapidly in the European Community and all over the world. There is an abundance of material on the subject that describes the theory, offers recommendations for performance measurement programs, and documents experiences of agencies building and implementing their own programs. Interest is growing in enhancing management processes by including performance measurements as a core component.

When developing performance measurement programs, the literature emphasizes that outcome measures should be included, where these relate the activities an agency undertakes to its strategic goals.

Data constraints must be considered and performance measurements should be implemented only when it is feasible to collect the data necessary to generate them.

The number of measures included should also be limited to those that are really important to an agency.

This will simplify data collection and reporting and increase the likelihood the measures will be understood by the public sector, the private operator and the users.

In road authorities around the world, common performance measurements include:

- system condition and preservation;
- safety;
- accessibility and
- traffic conditions-mobility.

In many cases a user satisfaction index is reported which may be estimated from customer surveys. Protection of environment and sustainability are also cited as an important goal for most transportation agencies, public or private, around the world, and there is a common desire to be able to measure performance in this regard.

The Balanced Scorecard model can really to be useful to estimate corporate efficiency and to evaluate environmental and social performance in a motorway company.

It is so possible to improve Financial Benefits, to reduce Operating Costs, to enhance Brand Image & Reputation, increased Sales & Customer Loyalty, to increase Ability to Attract and Retain Employees, to reduce Regulatory Supervision.

Chapter 3

Hazardous Material

The scope and format of this chapter cover the following aspects:

- hazard identification;
- risk evaluation (i.e. evaluation of the acceptability of the risk) and risk reduction;
- quantified risk assessment (QRA);
- risk management (concerning the measures in place to eliminate, prevent, detect, control and mitigate major fire and explosion hazards, and their associated performance standards); and
- emergency arrangements.

In order to the scope, we introduce some important concepts about Hazardous Materials: in section 3.1 the definition and the classification of HAZMAT are given. Section 3.2 presents product, process, risk perception concepts. In section 3.3 we present hazard, risk, safety and accepted risk concepts. Section 3.4 describes the steps of risk analysis in detail.

3.1 HAZMAT Classification

HAZMAT category consists of dangerous goods and hazardous substances. Figure 3.1 shows this composition.

HAZMAT are divided into classes on the basis of the specific chemical characteristics producing the risk. According to the US Department of Transportation, a hazardous material is any substance or material capable of causing harm to people, property, and the environment [192].

There are nine major hazardous material classes:

- Class 1 - Explosives (dynamite, caps)
- 2 - Gases (propane, anhydrous ammonia, chlorine, oxygen)
- 3 - Flammable Liquids (gasoline, oil, tars, diesel, kerosene)
- 4 - Flammable Solids (plastics, asphalt shingles)
- 5 - Oxidizing Substances (peroxides)

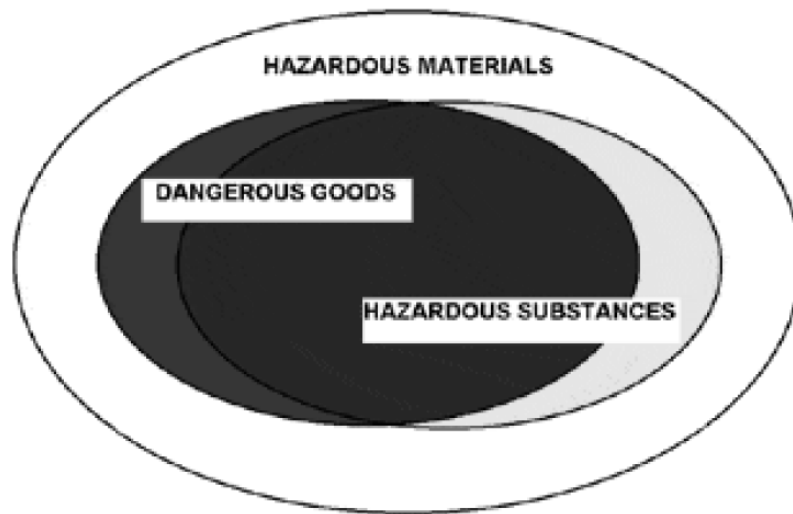


Figure 3.1: HAZMAT composition

- 6 - Poisonous and infectious substances (herbicides, pesticide)
- 7 - Radioactive materials
- 8 - Corrosives (acids)
- 9 - Miscellaneous (PCB's, dangerous wastes)

As described above dangerous goods may be radioactive, flammable, explosive, toxic, corrosive, biohazardous, an oxidizer, an asphyxiant, a pathogen, an allergen, or may have other characteristics that render it hazardous in specific circumstances.

Most countries regulate hazardous materials by law, and they are subject to several international treaties as well. Persons who handle dangerous goods will often wear protective equipment, and metropolitan fire departments often have a response team specifically trained to deal with accidents and spills. These teams train with different organizations at a variety of specialized locations.

In Italy, the “Nuclei NBCR (Nucleare, Batteriologico, Chimico e Radioattivo)” of “Corpo Nazionale dei Vigili del Fuoco” has a specialized Training Institute oriented to deal with accidents and spills. the “Nuclei NBCR” has the most important emergency site in Mestre (Venice), near the A4 motorway (Trieste-Venezia).

Persons who handle or potentially come into contact with dangerous goods as part of their work are also often subject to monitoring or health surveillance to ensure that their exposure does not exceed occupational exposure limits.

Laws and regulations on the use and handling of hazardous materials may differ depending on the activity and status of the material. For example one set of requirements may apply to their use in the workplace while a different requirements may apply to spill response, sale for consumer use, or transportation.

3.1.1 HAZMAT Placard

As hazardous materials can come in various forms, ranging from radioactive to explosive, it is important to be aware of what you are transporting when operating a courier service or heavy good vehicle.

Title 49 of the United States Code of Federal Regulations (49 CFR) also known as the Federal Motor Carriers Safety Regulations (FMCSR) [90] requires the use hazardous materials placards when shipping hazardous materials cargo and dangerous goods in the United States.

EU, Canada, Mexico and many other countries have similar regulations that also require the use of these placards that bear a UN/NA number on railway cars, trucks, shipping containers etc.

Mitigating the risks associated with hazardous materials may require the application of safety precautions during their transport, use, storage and disposal.

HAZMAT placards are essential when works involving hazardous materials are taking place. Equally, HAZMAT placards are vital when transporting hazardous materials.

If you do not make it directly apparent that you are working with, or are transporting, hazardous materials, you may not only be liable to personal litigation, but you may also be found criminally negligent and face a stretch in jail.

Each country has its own particular legislation and standards for HAZMAT placards, and so it is important to be aware of those which affect you when dealing with hazardous materials.

3.2 Product and Process

Human existence involves exposure to many hazards. Natural disasters such as floods and earthquakes cost thousands of lives every year all over the world. Since the industrial revolution also technical hazards, such as airplane crashes, train derailments, tunnel fires and industrial accidents disrupt society on a regular basis.

Long ago people tried to guard themselves from natural hazards with relatively simple methods, for example by building their houses on high grounds to protect them against floods.

As society changed protection systems were built, such as dams and dikes. Later new technological inventions, for instance nuclear power plants and aviation, and their accompanying hazards were introduced.

Other developments such as population growth and growing levels of production, consumption and transportation have lead to an increase of hazards and the consequences of the accidents.

Nowadays large amounts of money are spent to protect society against these disasters. However, in decision- and policymaking these expenditures on safety have to compete with other public interests, for instance public health and the development of new infrastructure.

Between its discovery and its elimination, every product passes through many different steps throughout its history: conception, design, feasibility studies, market studies, manufacturing, distribution, use, and elimination, the ultimate step, where from functional product, it becomes a waste product.



Figure 3.2: Class 1 Explosives



Figure 3.3: Class 2 Compressed Gasses



Figure 3.4: Class 3 Flammable Liquids



Figure 3.5: Class 4 Flammable Solids and Class 5 Oxidizers



Figure 3.6: Class Class 6 Poisons and Class 7 Radioactive Materials



Figure 3.7: Class 8 Corrosive Liquids and Class 9 Miscellaneous

For example, the chemical industry uses numerous and often complex equipment and processes. Moreover, in the fine chemical industries (including pharmaceuticals), the plants often have a multi-purpose character, that is, a given plant may be used for different products [68].

3.2.1 Product Safety

Risks exist linked to handling or using a product during the steps of conception, design, feasibility studies, market studies, manufacturing, distribution, use, and elimination [112].

This enters the negative side of the balance between benefits and adverse effects of the product and, consequently, its sustainability. Even if the public is essentially concerned with the product risks during its use, risks are also present during other stages, that is, manufacture, transportation, and storage.

For pharmaceutical products, the major concerns are secondary effects. For other products, adverse effects are toxicity for people and/or for the environment, as well as fire and explosion. Whatever its form, once a product is no

longer functional, it becomes a waste product and thus represents a potential source of harm.

Therefore, in order to guarantee sustainability, important decisions have to be made during product design in order to maximize the benefits that are expected from the product and to minimize the negative effects that it may induce. These decisions are crucial and often taken after a systematic evaluation of the risks.

Commercialization is strictly regulated by law and each new product must be registered with the appropriate authorities. The aim of the registration is to ensure that the manufacturer knows of any properties of its product that may endanger people or the environment and is familiar with the conditions allowing its safe handling and use, and finally safe disposal at the end of the product's life.

Thus products are accompanied by a Material Safety Data Sheet (MSDS) that summarizes the essential safety information as product identity, properties (toxicity, eco-toxicity, physical chemical properties), information concerning its life cycle (use, technology, exposure), specific risks, protection measures, classification (handling, storage, transportation), and labeling [141].

3.2.2 Process Safety

If, for example, we consider a chemical process, we must do it in an extensive way, including not only the production itself but also storage and transportation. This includes not only the product, but also the raw material.

Risks linked with chemical processes are diverse: product risks include toxicity, flammability, explosion, corrosion, etc. but also include additional risks due to chemical reactivity. A process often uses conditions (temperature, pressure) that by themselves may present a risk and may lead to deviations that can generate critical effects [195].

The plant equipment, including its control equipment, may also fail. Finally, since fine chemical processes are work-intensive, they may be subject to human error. All of these elements, that is, chemistry, energy, equipment, and operators and their interactions, constitute what we call process safety.

3.2.3 Risk Perception

According to European Statistics on Accidents at Work (ESAW) 2001 [83], about 4.8 million accidents at work resulted in more than 3 days as average of absence from work in the 15 Member States of the EU at that time .

Every year, about 5500 people are killed in the workplace across the European Union, with another 4.5 million accidents resulting in more than 3 days absence from work (amounting to around 146 million working days lost). These accidents are estimated to cost the EU about 20 billion.

The problem affects all sectors of the economy and is particularly acute in enterprises with less than 50 workers, that is another sustainability problem [108]. Due to accidents at work, around 5% of people were forced to change their job or place of work or reduce their working hours. 0.2% stopped working permanently. Between 1998 and 1999, it is estimated that work-related accidents cost the EU 150 million working days per year.

A further 350 million days were lost through work-related health problems. Together, the total bill was 500 million days per year. Accidents and occupa-

tional diseases can give rise to heavy costs to the company. For small companies particularly, occupational accidents can have a major financial impact.

Prevention of accidents has more benefits than just reducing damages. Preventing work accidents, occupational injuries and diseases not only reduces the costs, but also contributes to improving company performance.

Despite some incidents, the chemical industry presents good accident statistics. A statistical survey of work accidents shows that chemistry is positioned close to the end of the list, classified by order of decreasing lost work days.

For example, we can take into consideration in Figure 3.8 the accidents at work in different industries in Switzerland, from the statistics of the Swiss National Accident Insurance (2005). Further, these accidents only constitute a

Activity	Work accidents for 1000 insured
Construction	185
Wood	183
Mining	160
Metallurgy	147
Cement, glass, ceramics	130
Food	113
Rubber, plastics	95
Machinery	72
Transport	66
Energy	59
Textile, clothes	50
Offices, administration	46
Paper, graphics	45
Chemistry	37
Electricity, fine mechanics	33

Figure 3.8: Accidents at work in different industries in Switzerland, from the statistics of the Swiss National Accident Insurance (2005).

minor part due to chemical accidents, the greatest part consisting of common accidents such as falls, cuts, and so on that can happen in any other activity. Another instructive comparison can be made by comparing fatalities in different activities.

Here we use the Fatal Accident Rate index (FAR) that gives the number of fatalities for 10^8 hours of exposure to the hazard. Some activities are compared in Figure 3.9. This shows that even with better statistics in terms of fatalities, industrial activities are perceived as presenting higher risks.

This may essentially be due to the risk perception [218]. The difference in perception is that for traveling or sporting activities, the person has the choice as to whether to be exposed or not, whereas for industrial activities exposure to risk may be imposed [151]. Industrial risks may also impinge on people who are not directly concerned with the activity. Moreover, the lack of information on these risks biases the perception. Under European Union directives, employers have responsibilities for the safety and health of their workers. Directive 89/391 provides the general framework for health and safety management, risk

Industrial activities	FAR	Non industrial activities	FAR
Coal mining	7.3	Alpinism	4000
Construction	5	Canoe	1000
Agriculture	3.7	Motor bike	660
Chemistry	1.2	Travel by air	240
Vehicle manufacturing	0.6	Travel by car	57
Clothing manufacturing	0.05	Travel by railway	5

Figure 3.9: Some values of the FAR index for different activities.

identification and prevention. The Directive has been implemented in national legislation that may include additional requirements.

Employers are required to assess risks and take practical measures to protect the safety and health of their workers, keep accident records, provide information and training, consult employees and co-operate and co-ordinate measures with contractors. A hierarchy of prevention is set including:

- Avoid risks;
- Combat risks at source;
- Adapt work to the worker;
- Replace the dangerous with the non-dangerous; and,
- Give collective measures priority over individual measures.

Companies should ensure the safety and health of workers in every aspect related to their work. Therefore, employers should take the necessary measures for the safety and health protection of workers, including the prevention of occupational risks and the provision of information and training, and provide the necessary organization and means.

The Dangerous Goods Safety Management (DGSM) legislation (especially Part 3 of the Regulation 2001) [214], identifies specific risk control issues associated with the storage and handling of dangerous goods and combustible liquids that occupiers must address. If you are the occupier of a premises where HAZMAT or combustible liquids are present, you must identify the hazards from those materials and assess the resultant risks to people, property or the environment. The risk assessment must take into account the likelihood and magnitude of such injury or damage. Hazard identification and risk assessment can be simple and straightforward or highly complex.

For example, the storage of only one or two classes of dangerous goods at retail outlets where handling is limited to placing the goods on shelving for display is a relatively simple case and the hazard identification and risk assessment for the activity should be simple. By contrast, a major warehouse or chemical manufacturing plant handling a large range of HAZMAT and combustible liquids is likely to require detailed investigations of hazards and risks, involving people who have specialist knowledge of:

- the dangerous goods and combustible liquids;

- the processing of those materials; and
- the work practices employed in connection with those materials.

3.3 Hazard Identification and Risk Assessment Process

According to the European Federation of Chemical Engineering (EFCE) [96], in this section we summarize the definitions of hazard, risk and safety. As the risk assessment forms the basis for implementing control measures to achieve an acceptable level of risk, in this section we also provide a step-by-step process to guide the person or persons carrying out a hazard identification and risk assessment for HAZMAT. It can be used at any premises where HAZMAT are stored or handled. The flow diagram in Figure 3.10 provides a helpful summary of the process.

3.3.1 Hazard

Hazard is a situation that has the potential to cause harm to human, environment and property. Thus, hazard is the antonym of safety. As an example, for the chemical industry, the hazard results from the simultaneous presence of the three following elements.

- A threat stemming from the properties of processed substances, chemical reactions, uncontrolled energy release, or from equipment.
- A failure that may be of technical origin or stem from human error, either during the operation or during process design. External events, such as weather conditions or natural catastrophe may also be at the origin of a failure.
- An undetected failure in a system as non - identified hazards during risk analysis, or if insufficient measures are taken, or if an initially well - designed process gradually deviates from its design due to changes or lack of maintenance.

A hazard identification technique appropriate to the complexity of the installation, the stage of the installation in its lifecycle and the scale and nature of the hazards on the installation should be employed, for example [222]:

- Hazard and operability study (HAZOP) [139];
- Failure Modes and Effects Analysis (FMEA) [23];
- Safety reviews [44];
- Industry standard or bespoke checklists [127];
- Job safety analysis [84]; and
- Human error identification methods [138].

The hazard identification should be based on suitable reference information, for example:

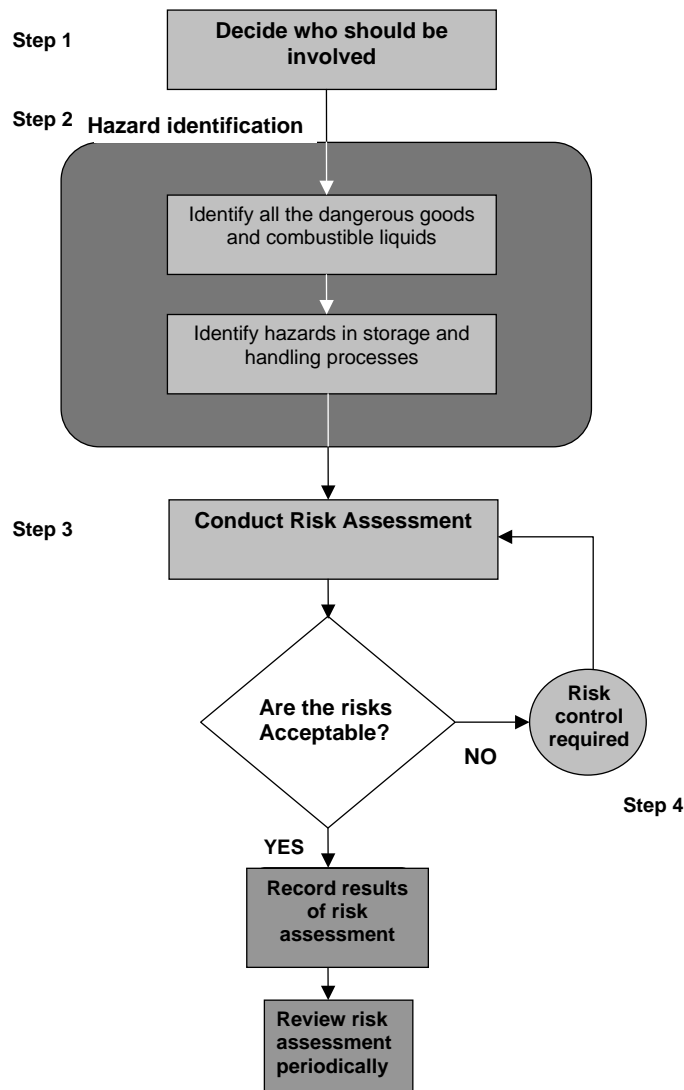


Figure 3.10: Hazard identification and risk assessment process

- Process Flow Diagrams (PFDs) [6];
- Piping and Instrumentation Diagrams (P&IDs) [50];
- Layout plans [122];
- Equipment lists [51];
- Process data sheets [66]; and
- Operating and maintenance philosophy [54].

The hazard identification methods presented above are all based on strongly systematic procedures [222] used by a risk analysis team. Obviously, the com-

position of the risk analysis team is of primary importance for the quality of the work.

Here the professional experience of the participants plays a key role, since the objective of the analysis is to identify events that have not yet occurred.

The work of the team must be traceable, even by persons who did not participate to the analysis. Thus, it is necessary to also document the hazards that were not considered as critical.

In the check list method, the systematic is provided by the check list itself. With the FMEA, the systematic is provided by the division of the system into elements and the failure modes considered.

In the HAZOP study, the systematic stems from the division of the plant into nodes and lines, then the systematic application of the keywords. With the decision table method, the systematic is inherent to the table. For the FTA and ETA, the systematic is given by the tree and the logical ports.

Another important method is based on the Hazard Risk Assessment Matrix that provides a systematic method for assigning a hazard level to a failure event based on the severity and frequency of the event [59]. An example of this matrix is presented in Figure 3.11. The hazard level consists of one number and one

Frequency of Occurrence	Severity			
	(1) Catastrophic	(2) Critical	(3) Marginal	(4) Negligible
(A) Frequent	1A	2A	3A	4A
(B) Probable	1B	2B	3B	4B
(C) Occasional	1C	2C	3C	4C
(D) Remote	1D	2D	3D	4D
(E) Improbable	1E	2E	3E	4E

Risk Categories:





 High	 Serious	 Medium	 Low
--	---	--	---

Figure 3.11: The Hazard Risk Assessment Matrix

letter. The number represents the severity of the event. The numbers represent:

- 1 - Death, system loss, or irreversible environmental damage;
- 2 - Severe injury, occupational illness, major system damage, or reversible severe environmental damage;
- 3 - Injury requiring medical attention, illness, system damage, or mitigatable environmental damage;
- 4 - Possible minor injury, minor system damage, or minimal environmental damage.

The letter of the hazard level represents the Frequency of Occurrence. The letters represent:

- A - Expected to occur frequently;
- B - Will occur several times in the life of an item;

- C - Likely to occur sometime in the life of an item;
- D - Unlikely, but possible to occur in the life of an item;
- E - So unlikely, it can be assumed occurrence may not be experienced.

As can be seen from the Figure 3.11, each hazard level is associated with a risk category. Risk categories assist risk-management team members in differentiating credible high-hazard threats that may result in loss of life and property from less probable risks, therefore aiding management in risk vs. cost decisions.

3.3.1.1 Failure Modes and Effects Analysis

In order to illustrate a hazard identification technique, we can take the example of the FMEA, or Failure Modes and Effects Analysis [23]. FMEA is a systematic approach to identify failure modes that could either directly result in, or contribute significantly to, the identified accident scenario by a multi-discipline team familiar with the process.

The Failure Mode and Effect Analysis (FMEA) is based on the systematic analysis of failure modes for each element of a system, by defining the failure mode and the consequences of this failure on the integrity of that system.

It was first used in the 1960s in the field of aeronautics for the analysis of the safety of aircraft. It is required by regulations in the USA and France for aircraft safety. It allows assessing the effects of each failure mode of a system's components and identifying the failure modes that may have a critical impact on the operability safety and maintenance of the system.

It proceeds in four steps:

- the system is to be defined with the function of each of its components;
- the failure modes of the components and their causes are established;
- the effects of the failure are studied, and
- conclusions and recommendations are derived.

The failure modes and failure causes are identified initially and are used as the starting point for the FMEA. Each cause is evaluated for adequate design safety and potential effect on the system. A qualitative ranking is determined by considering both the severity and frequency of occurrence.

Critical areas of the process are identified and studied to determine the possibility of a major incident. Management can then use this information to control the potential risk, and avoid the accident scenario.

A block flow diagram of the FMEA process is given in Figure 3.12.

The following terms are used in the FMEA process:

- Line No. - consists of an "Operation/Item" number and a single letter identifying the "Failure Cause" (e.g., 1A, 1B, 2A...).
- Operation/Item - the operation or item of concern in the scenario.
- Failure Mode - the potential problem.
- Failure Cause - events that cause the failure mode.

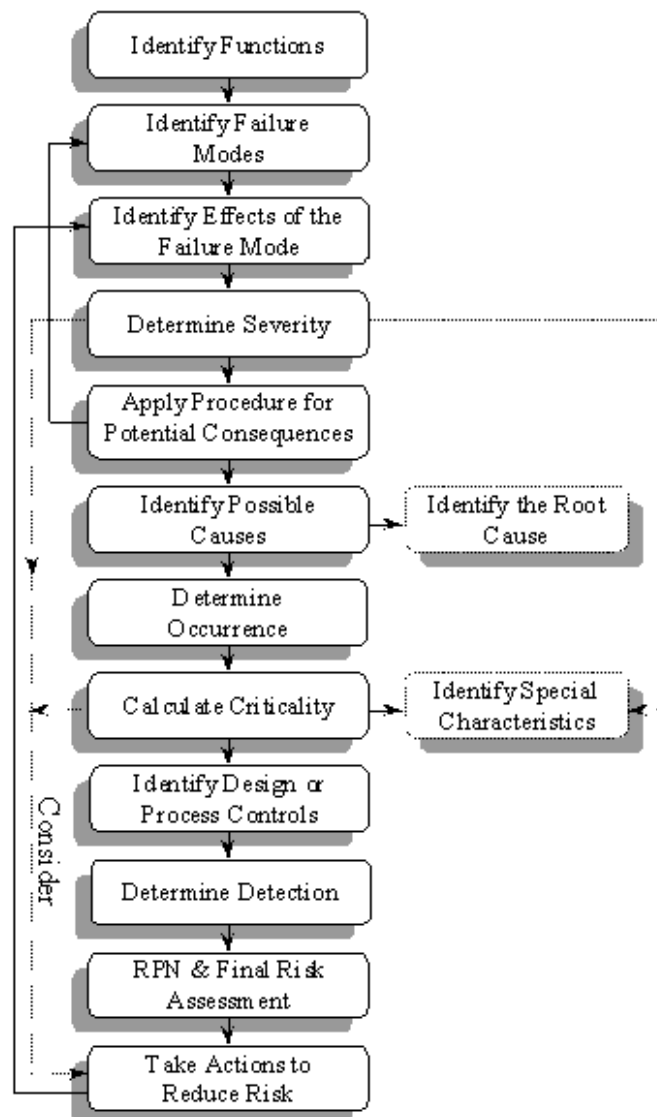


Figure 3.12: The FMEA process

- Potential Effects - potential effects of the problem in the system or sub-system. The potential Effects column lists the consequences of the Failure Mode.
- Design Safety - those features of a system that will prevent the Failure Mode from occurring. Any deficiencies in Design Safety will be reflected in the Recommendation column.
- Hazard Category - an assessment of the hazard risk of the operation. In this analysis, we have used the MIL-STD-882B, "Hazard Risk Assessment Matrix."

- Recommendations - recommended corrective actions. Deficiencies in the Design Safety are corrected by implementing the recommendations in the Recommendation column.

One important point in this type of analysis is to define clearly the different states of the working system, to ensure that it is in normal operation, in a waiting state, in emergency operation, in testing, in maintenance, and so on. The depth of decomposition of the system into its components is crucial for the efficiency of the analysis.

3.3.1.2 The HAZard and OPerability analysis

In order to illustrate another hazard identification technique, we can take the example of the HAZOP, or HAZard and OPerability analysis [166]. This is a structured technique in which a multi-discipline team performs a systematic study of a process using guide words to discover how deviations from the design intent can occur in equipment, actions, or materials, and whether the consequences of these deviations can result in a hazard.

The Hazard and Operability Study (HAZOP) was developed in the early 1970s by Imperial Chemical Industries (ICI) [139], after the Flixborough incident [211]. It is derived from the Failure Mode and Effect Analysis, but specially adapted for the process industry in general, and in the chemical industry in particular. It is essentially oriented towards the identification of risks stemming from the process equipment. It is particularly well suited for the analysis of continuous processes in the steady state, but can also be used for batch processes.

The first steps of the risk analysis, of scope definition, data collection, safe conditions definition, are the same as for other methods. Using the process and instruments design (PID) and the Process Flow Diagram (PFD) as basic documents, the plant is divided into itnodes and *lines*. For each of these divisions, a design intention is written that precisely summarizes its function.

For example, a feed line could be defined as: the line A129 is designed to feed 100 kg hour⁻¹ of product A from Tank B101 to reactor R205. Then in a kind of guided brainstorming approach, using predefined guidewords applied to different parameters of the design intention, the process is systematically analyzed.

These guidewords are listed below:

- Design Intent - the way a process is intended to function.
- Deviation - a departure from the design intent discovered by systematically applying guide words to process parameters.
- Guide Word - simple words such as "high" pressure, "high" temperature, "leak" etc. that are used to modify the design intent and to guide and stimulate the brainstorming process for identifying process hazards.
- Cause - the reason why a deviation might occur.
- Consequence - the results of a deviation.
- Safeguard - engineered systems or administrative controls that prevent the causes or mitigate the consequences of deviations.

- Hazard Category - an assessment of the hazard risk of the operation.
- Recommendations - recommendations for design changes, procedural changes, or for further study.

Guide words for flow in a chemical process include High Flow, No/Low Flow, Reverse Flow, Misdirected Flow, High Pressure, Low Pressure, High Temperature, Low Temperature, High Contaminants, Leak and Rupture. For processes utilizing explosives, the guide words include electrical initiation, ESD spark, Impact shock, Friction, Impingement, Incompatibilities, Explosive shock, Thermal ignition, Propagation, Personnel Injury, Environmental contamination, Equipment damage and Product damage.

There is some redundancy in the guidewords, for example, a temperature may be too high due to over - heating. This, again, is intentional and allows ensuring a comprehensive analysis. In cases where batch processes are to be analyzed by the HAZOP technique, additional guidewords concerning time and sequencing, for example, too early, too late, too often, too few, too long, or too short may also be added. It is then verified that the deviation generated by applying the guideword to a parameter is meaningful.

For example, reverse flow may be meaningful, but it would hardly be the case for reverse temperature. If the generated deviation has no sense, it is skipped and the next deviation is generated with the next guideword. For traceability of the thoroughness of the analysis, it may be marked as not applicable, n.a. For the meaningful deviations identified by the procedure described above, the possible causes for triggering the deviation are systematically searched.

As an example, possible causes for no flow may be an empty feed tank, a closed valve, an inadvertently open valve to another direction, a pump failure, a leak, and so on. In this context, it may be useful to indicate the logical relationship between the causes, such as where simultaneous failure of several elements is required in order to trigger the deviation. This is of great help for the assessment of the probability of occurrence.

The effects are searched in order to allow the assessment of the severity. These results are documented together with the risk evaluation and, where required, with risk - reducing measures in a hazard catalog, as presented in figure 3.13. The analysis is performed on the totality of the nodes and lines defined by the division of the plant. This allows checking the comprehensiveness of the analysis. The HAZOP technique, as its name indicates, is not only devoted to identification of hazards, but also to the identification of operability issues. In this frame, the hazard catalog also provides a list of possible symptoms for the early identification of abnormal situations and remedy. Then it becomes an efficient tool for process design, especially for the design of automation systems and interlocks.

The results of the HAZOP analysis are the team's recommendations, which include identification of hazards and the recommendations for changes in design, procedures, etc. to improve the safety of the system. Deviations during normal, startup, shutdown, and maintenance operations are discussed by the team and are included in the HAZOP. A block flow diagram of the HAZOP process is given in Figure 3.14 and a more detailed schema in Figure 3.15.

Company:		Unit:								Id.-Nr.:	
Product:		Process dated:								Date:	
Author:											
#	Hazard	Causes	Effects	S1	P1	Action	S2	P2	Resp.	Status	Remarks

Figure 3.13: Example of Hazards Catalogue with deviation causes effects and actions decided by the team as well as their status.

3.3.2 Risk

Risk is a concept that denotes the precise probability of specific eventualities. Technically, the notion of risk is independent from the notion of value and, as such, eventualities may have both beneficial and adverse consequences.

However, in general usage the convention is to focus only on potential negative impact to some characteristic of value that may arise from a future event. There are many definitions of risk that vary by specific application and situational context. One is that risk is an issue, which can be avoided or mitigated (wherein an issue is a potential problem that has to be fixed now.) Risk is described both qualitatively and quantitatively. In some texts risk is described as a situation which would lead to negative consequences.

Qualitatively, risk is proportional to both the expected losses which may be caused by an event and to the probability of this event. Greater loss and greater event likelihood result in a greater overall risk. Frequently in the subject matter literature, risk is defined in pseudo-formal forms where the components of the definition are vague and ill-defined, for example, risk is considered as an indicator of threat, or depends on threats, vulnerability, impact and uncertainty.

It is possible to identify three main categories of risk.

- Specific Risk: very frequent or continuous events, with small damages.
- Conventional Risk: quite frequent events, with damages of medium intensity against one or more people (mostly injuries).
- Potential Risk - relevant accident: caused by rare events with very large consequences and high damages.

In engineering, the definition of risk often simply is:

$$\text{Risk} = (\text{probability of an accident}) \times (\text{losses per accident})$$

or in more general terms:



Figure 3.14: A block flow diagram of the HAZOP process

Risk = (probability of event occurring) \times (impact of event occurring)

According to Stoessel [222], risk is defined as a measure of loss potential, and damage to the environment or persons in terms of probability and severity. An often-used definition is shown in (3.1) that risk is the product of severity time probability:

$$Risk = Severity \times Probability \quad (3.1)$$

In fact, considering risk as a product is somewhat restrictive: it is more general to consider it as a *combination* of the terms, severity and probability, that characterize the effects, that is, consequences and impact of a potential accident and its probability of occurrence.

This also means that the risk is linked to a defined incident scenario. In other

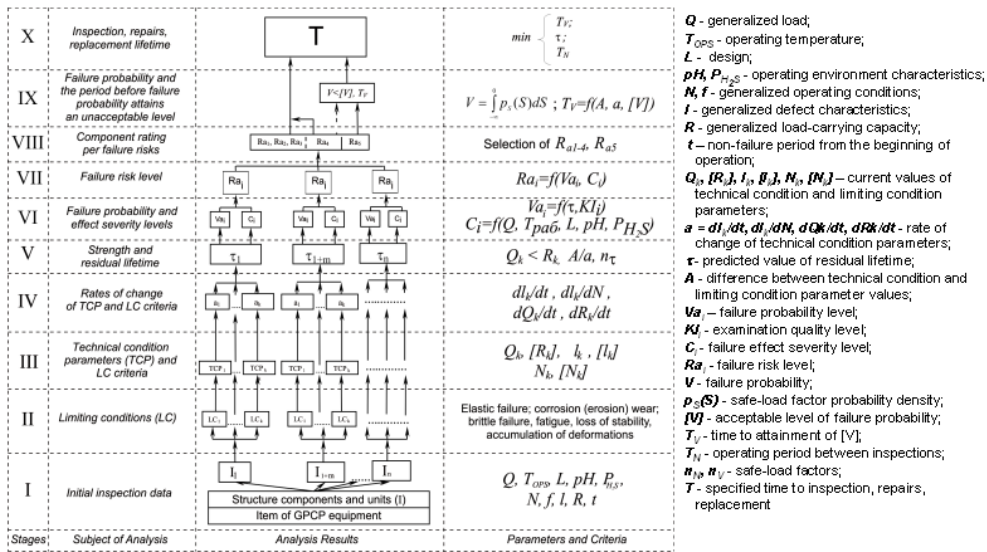


Figure 3.15: An example of a detailed model of analysis

words, the risk analysis will be based on scenarios that must first be identified and described with the required accuracy, in order to be evaluated in terms of severity and probability of occurrence.

In statistics, risk is often mapped to the probability of some event which is seen as undesirable. Usually, the probability of that event and some assessment of its expected harm must be combined into a believable scenario (an outcome), which combines the set of risk, regret and reward probabilities into an expected value for that outcome.

Thus, in statistical decision theory, the risk function of an estimator $\delta(x)$ for a parameter θ , calculated from some observables x , is shown in (3.2) and defined as the expectation value of the *loss function* L ,

$$R(\theta, \delta(x)) = \int L(\theta, \delta(x)) f(x|\theta) dx \quad (3.2)$$

3.3.3 Safety

Safety is a quiet situation resulting from the real absence of any hazard. Absolute safety (or zero risk) does not exist for several reasons: first, it is possible that several protection measures or safety elements can fail simultaneously; second, the human factor is a source of error and a person can misjudge a situation or have a wrong perception of indices, or may even make an error due to a moment's inattention.

3.3.4 Security

In common language, security is a synonym of safety. In the context of this thesis, security is devoted to the field of property protection against theft or incursion.

3.3.5 Accepted Risk

The accepted risk is a risk inferior to a level defined in advance either by law, technical, economical, or ethical considerations. The risk analysis, as it will be described in the following sections, has essentially a technical orientation.

The minimal requirement is that the process fulfills requirements by the local laws and that the risk analysis is carried out by an experienced team using recognized methods and risk-reducing measures that conform to the state of the art. It is obvious that non-technical aspects may also be involved in the risk acceptance criteria. These aspects should also cover societal aspects, that is, a risk benefit analysis should be performed.

3.4 Risk Analysis

A risk analysis is not an objective by itself, but is one of the elements of the design of a technically and economically efficient process. In fact, risk analysis reveals the process inherent weaknesses and provides means to correct them.

Thus, risk analysis should not be considered as a *police action*, in the sense that, at the last minute, one wants to ensure that the process will work as intended.

Risk analysis rather plays an important role during process design. Therefore, it is a key element in process development, especially in the definition of process control strategies to be implemented.

A well-driven risk analysis not only leads to a safe process, but also to an economic process, since the process will be more reliable and give rise to less productivity loss. That is risk analysis is very important for the sustainability.

3.4.1 Steps of Risk Analysis

There are many risk analysis methods, but all have three steps in common:

- 1 - search for hazards,
- 2 - risk assessment, and
- 3 - definition of risk-reducing measures.

If these three steps are at the heart of the risk analysis, it is also true that performing these steps requires preliminary work and other steps that should not be bypassed. By systematically in the sector studying past incidents, several causes can be identified. Thus, the risk analysis must be well prepared, meaning that the scope of the analysis must be clearly defined; data must be available and evaluated, to define the safe process conditions and the critical limits. Then, and only then, the systematic search for process deviations from the safe conditions can be started. The identified deviations lead to the definition of scenarios, which can be assessed in terms of severity and probability of occurrence. This work can advantageously be summarized in a risk profile, enhancing the major risks that are beyond the accepted limits. For these risks, reduction measures can then be defined. The residual risk, that is, the risk remaining after implementation of the measures, can be assessed as before and documented in a residual risk profile showing the progress of the analysis and the risk improvement. These steps are reviewed in the next subsections.

3.4.2 Scope of Analysis

The scope of the analysis aims to identify the process under consideration, in which plant it will take place, and with which chemicals it will be performed. The chemical reactions and unit operations must be clearly characterized. In this step, it is also important to check for interface problems with other plant units. As an example, when considering raw material delivery, it can be assumed that the correct raw material of the intended quantity and quality is delivered from a tank farm. Thus, it can be referred to the tank farm risk analysis, or the tank farm is to be included in the scope of the analysis. Similar considerations can be made for energy supply, to ensure that the appropriate energy is delivered. Nevertheless, loss of energy must be considered in the analysis, but it will be assumed that if nitrogen is required, nitrogen will be delivered. This allows checking for non-analyzed items in a whole plant, completing the analysis. Appropriate consideration should be given to the various hazardous inventories on an installation, for example for fire and explosion events:

- process oil/gas/condensate;
- process additives (e.g. methanol);
- fuels (e.g. diesel, aviation fuel) and lubricants;
- bottled gas;
- explosives and detonators;
- chemicals; and
- ordinary combustibles.

Appropriate consideration should be given to the potential for release of the down hole annulus gas inventory for gas-lifted wells. The various potential causes or initiating events should be identified. For example, in spite of external as helicopter crash, ship collision and extreme weather, causes in the fire and explosion events can have as internal causes:

- incorrect equipment or material specification;
- defective material or equipment;
- pressure outside design limits;
- temperature outside design limits;
- vibration;
- corrosion;
- erosion;
- human error;
- external loading; and
- impact.

3.4.3 Key Factors for a Successful Risk Analysis

The risk analysis represents an important part of the process know how. It may be useful to describe the risk - reducing measures together with the status, such as new, accepted, rejected, implemented, and so on. In order to a successful risk analysis the quality of a risk analysis is very important; it depends essentially on three factors:

- the systematic and comprehensive hazard identification;
- the experience of the risk analysis team members;
- the quality and comprehensiveness of the data used during the analysis.

As a consequence the hazards catalog cannot be a static document, but a part of the process documentation at the same level as the operating mode and mass balances. The hazard catalog then becomes a management tool and a living document, which must regularly be updated and accompany the process throughout its life.

3.4.4 Safety Data Collection

The required data must be collected prior to the risk analysis. This can be done gradually during process development as the knowledge on the process increases. The data can be summarized on data sheets devoted to different aspects of the process. They typically should encompass the following:

- involved chemical compounds,
- chemical reactions,
- technical equipment,
- utilities,
- operators.

In order to be economic and efficient, the data collection is accompanied by their interpretation in terms of risks. This allows adapting the amount and accuracy of the data to the risk. There are many different sources for safety data, such as Material Safety Data Sheet (MSDS), databases, company databases, and reports. Great care is required, when using MSDS, since experience has shown that they are not always reliable.

The safety data used in risk analysis can be grouped into different categories, described in the following subsections. The data should be provided for raw material, intermediates, and products, as well as for reaction mixtures or wastes as they are to be handled in the process. Missing data, important in risk analysis, may be marked with a letter *I*, to indicate that this information is missing or as a default by a letter *C*, if its value is unknown but judged to be critical.

3.4.4.1 Physical Properties

Physical properties such as melting point, boiling point, and vapor pressure, as well as densities and solubility in water, are especially important in case of a release, but also give important restrictions to the process conditions. For instance, the melting point may indicate that the contents of a stirred vessel solidify below this temperature.

This gives a lower limit to the heating or cooling system temperature, which would forbid using an emergency cooling system. In a similar way, the vapor pressure may define an upper temperature limit if a certain pressure level is not to be surpassed. Densities may also indicate what the upper and lower phase in a mixture is. Solubility in water is important in case of spillage.

3.4.4.2 Chemical Properties

The chemical properties allow summarizing observations or experiences made during process development or previous production campaigns. The following characteristic chemical properties should be identified during the risk analysis: acidity, auto-ignition temperature, pyrophoric properties, reaction with water, light sensitivity, air sensitivity, and storage stability. Further, impurities in the product may affect the toxic and ecotoxic properties of substances or mixtures.

3.4.4.3 Toxicity

The odor limit compared to other limits may indicate an early warning of a leak. The maximum allowed work place concentration (**MAC**), is the maximum allowed average concentration expressed in mgm^{-3} of a gas, vapor, or dust in air in a workplace, which has no adverse effects on health for an exposure of 8 hours per day or 42 hours per week for the majority of a population.

Since it is an average, **maintaining the concentration below this value does not guarantee no effects**, since the sensitivity may differ within a population. On the other hand, a short-term exposure to a concentration above **MAC** does not imply consequences on health.

A distinction is made between acute toxicity and chronic toxicity. For acute toxicity, the following indicators may be used.

- Lethal dose LD_{50} : gives the concentration that caused 50% of fatalities within 5 days in an animal population exposed once to the concentration. It may be an oral or dermal exposure and is expressed in $mgkg^{-1}$ of organism with a specification of the test animal used.
- Lethal concentration LC_{50} : is the concentration in air that caused 50% of fatalities within 5 days in a test in an animal population exposed to this concentration. It is through inhalation and is expressed in $mgkg^{-1}$ of organism with a specification of the test animal used.

The LD_{50} and LC_{50} for humans would be more directly applicable but, for obvious reasons, only very sparse data are available:

- The toxic dose lowest (TDL_o oral) is the lowest dose that induced diseases in humans by oral absorption.

- The toxic concentration lowest (TLC_o oral) is the lowest concentration in the air that induced diseases in humans by inhalation.

More qualitative indicators are also useful: absorption through healthy skin, irritation to skin, eyes, and respiratory system, together with sensitization with the following indicators: carcinogenic, mutagenic, teratogenic, reprotoxic, and so on. These properties can be summarized by indication of a toxicity class.

To judge the effect of short-term exposure, such as during a spillage, the short-term exposure limit (e.g. IDLH), must be known. The different levels given by the Emergency Response Planning Guidelines (**EPRG**), issued by the authorities as for example the American Department of Energy and the Department of Transport, may also be used in this frame.

The use of carcinogenic material should be avoided as far as possible, by replacement with non-toxic or at least less toxic substances. If their use cannot be avoided, appropriate technical and medicinal measures should be applied in order to protect the workers from their effects. Among such measures, the reduction of the exposure in terms of concentration and duration as well as a medical follow-up may be required. The exposure can be limited by using closed systems, avoiding any direct contact with the substance, or personal protection equipment. Moreover, the number of exposed operators should be limited.

3.4.4.4 Ecotoxicity

In instances of spillage or release, not only humans may be concerned, but the damage may also affect the environment. The following data are required:

- biological degradability, bacteria toxicity (IC_{50}),
- algae toxicity (EC_{50}),
- daphnia toxicity (EC_{50}),
- fish toxicity (LC_{50}),

The Po/w , that is, the distribution coefficient between octanol and water, indicates a possible accumulation in fat. Malodorous or odor intense compounds should also be indicated. The symbol (LC_{50} means lethal concentration for 50% of a test population. The symbol (EC_{50} means efficiency concentration for mobility suppression of 50% a test population. The symbol IC_{50} means inhibition concentration for 50% of a population in a test for respiratory suppression.

3.4.4.5 Fire and Explosion Data

The most common property in the assessment of fire hazards is the flashpoint that is applicable to liquids or melts, and is the lowest temperature at which the vapor above the substance may be ignited and continue to burn. The reference pressure for the flashpoint is 1013 *mbar*.

The combustion index is applicable to solids and gives a qualitative indication about combustibility, ranging from one to six. *Index1* corresponds to no combustion and *Index6* to a violent combustion with fast propagation. From *Index4*, the combustion propagates through to the solid.

The self-sustaining decomposition is a phenomenon whereby the decomposition is initiated by a hot spot, and then propagates through to the solid with

a velocity of some millimeters to centimeters per second. The decomposition does not require oxygen, so it cannot be avoided by using an inert atmosphere. Electrostatic charges may provide an ignition source for the explosion of a gas, vapor, or dust cloud. Electrostatic charges can accumulate only if a separation process is involved.

Since this is an often - occurring phenomenon as soon as a product is in motion, separation processes are common in chemical processes, during pumping, agitation, pneumatic transport, and so on. Charge accumulation occurs when the conductivity is too low to allow charge relaxation.

This may lead to an electrostatic discharge that may ignite an explosion if present at the same time as explosive atmosphere. For this to occur the concentration of combustible must be in a given range and oxygen must be present. In order to assess such situations, the explosion characteristics are required.

Explosion limits indicate in which concentration range a mixture of combustible substance can be ignited. There are two limits, the lower explosion limit (LEL), below which the concentration is too low to produce an explosion and the upper explosion limit (UEL), above which the oxygen is in default and no explosion occurs. Further, the explosion is characterized by the maximum explosion pressure and its violence by the maximum pressure increase rate.

In order to decide if an explosion can be ignited, the minimum ignition energy (MIE) is required. The shock and friction sensitivity of a solid is also an important parameter, especially when it is to be submitted to mechanical stress during processing.

3.4.4.6 Interactions

The reactivity of chemicals used in a process must be assessed, since these chemicals may become in contact in a desired way or accidentally during the process. These interactions are usually analyzed in a triangular matrix where the desired and undesired reactions are marked at the intersection of each row and column.

Beside chemicals or mixtures, the different fluids (i.e. heat carrier), waste streams, and construction materials must also be considered. An example of such a matrix, summarizing the safety data and the interactions, is represented in figure 3.16. Once the safety data have been collected and documented, they must be evaluated with regard to the process conditions in terms of their significance for process safety. With the interpretation of the safety data, the process conditions that provide safe operation and the limits that should not be surpassed become clear. This defines the critical limits of the process, which are at the root of the search for deviations in the next step of the risk analysis. This task should be performed by professionals having the required skills. Practice has shown that it is advantageous to perform, or at least to review, the interpretation with the risk analysis team. This ensures that the whole team has the same degree of knowledge and understanding of the process features.

3.4.5 Search for Deviations

During this step, the process is considered in its future technological environment, that is, the plant equipment, the control systems including the operators,

					LIKELIHOOD				
					"Unheard of in the drilling industry"	"Has occurred a few times in the drilling industry but not in the Company"	"Has occurred a few times in the Company"	"Has occurred several times a year in the Company"	"Has occurred several times a year on Facility"
					A	B	C	D	E
					Remote	Rare	Unlikely	Possible	Likely
C O N S E Q U E N C E S	Safety	Environment	Damage						
	Zero Harm	No Effect	Zero Damage	0	No Effect	0	0	0	0
	Minor injury, no lost time.	Slight Effect	Slight Damage	1	Negligible	1	2	3	4
	Minor Injuries: Restricted Work Case or Lost Work Case <4 days.	Minor Effect	Minor Damage	2	Minor	2	3	4	5
	Major Injuries, Permanent Partial Disability or Lost Work Case >4days	Localised Effect	Local Damage	3	Moderate	3	4	5	6
	1-2 Fatalities (or Permanent Total Disabilities)	Major Effect	Major Damage	4	Major	4	5	6	7
Multiple Fatalities (or Permanent Total Disabilities)	Massive Effect	Extensive Damage	5	Massive	5	6	7	8	

Figure 3.16: Interaction matrix, also called hazard matrix, summarizing the safety data of chemicals involved in a process.

and the delivery of raw material. The utilities are included in the critical examination of deviations from normal operating conditions. Here the following fields may be distinguished:

- deviations from operating mode, which are a central part in batch processes;
- technical failures of equipment, such as valves, pumps, control elements, and so on, which represent the central part of the equipment-oriented risk analysis;
- deviations due to external causes, such as climatic impacts (frost, flooding, storms);
- failure of utilities, especially electrical power or cooling water.

With continuous processes, different stages must be considered: steady state, start up and shut down, emergency stops, and so on.

The methods for search of hazards can be classified into the following three categories.

- 1 - Intuitive methods, such as brainstorming,
- 2 - Inductive methods, such as check lists, Failure Mode and Effect Analysis (FMEA), event trees, decision tables, Analysis of Potential Problems (APP). These methods proceed from an initial cause of the deviation and construct a scenario ending with the final event. They are based on questions of the type: "What if ?"

- 3 - Deductive methods, such as the Fault Tree Analysis (FTA) that proceeds by starting from the top event and looking for failures that may cause it to happen. These methods are based on questions of the type: “How can it happen?”

The triggering mechanism to make a real threat out of a potential threat is called the cause. Each potential threat can have several potential causes, which should be listed. The possible consequences of a triggered event are referred to as the effects. This description of hazard causes and effects build an event scenario.

The listing of the hazards in a table with an identifier, a short description a list of possible causes and the consequences, makes up the hazard catalog. An example of such a hazard catalog was presented in figure 3.13.

The table may also contain risk assessment, a description of risk-reducing measures, assessment of residual risk, and who is responsible for the action decided on. This is of great help for the follow-up of the project.

3.4.6 Risk Assessment

Risk assessment connotes a systematic approach to organizing and analyzing scientific knowledge and information for potentially hazardous activities or for substances that might pose risks under specified circumstances [71].

Risk assessment can be qualitative or quantitative. Qualitative risk assessment regards the identification of possible accident scenarios and attempts to estimate the undesirable consequences [106].

Quantitative Risk Assessment (QRA) tries to assess the risk in terms of the value of some indicators to be used to actively manage risk, to identify and prioritize technology needs and decision making and, finally, to evaluate regulatory alternatives [29, 133].

The deviation scenarios found in the previous step of the risk analysis must be assessed in terms of risk, which consists of assigning a level of severity and probability of occurrence to each scenario. This assessment is qualitative or semi-quantitative, but rarely quantitative, since a quantitative assessment requires a statistical database on failure frequency, which is difficult to obtain for the fine chemicals industry with such a huge diversity of processes.

The severity is clearly linked to the consequences of the scenario or to the extent of possible damage. It may be assessed using different points of view, such as the impact on humans, the environment, property, the business continuity, or the company’s reputation.

In order to allow for a correct assessment, it is essential to describe the scenarios with all their consequences. This is often a demanding task for the team, which must interpret the available data in order to work out the consequences of a scenario, together with its chain of events.

The probability of occurrence (P) is linked to the causes of the deviations. It is often expressed as frequency (f), referring to an observation period (T) often of one year:

$$P = f \times T \Rightarrow f = \frac{P}{T} \quad (3.3)$$

A probability of 0.01 is equivalent to an occurrence of 1 incident in 100 years. There are two approaches for the assessment of probability:

- the qualitative approach, based on experience and using analogies to similar situations;
- the quantitative approach, based on statistical data obtained from equipment failure databases [151].

These data were mainly gathered from the petrochemicals industry and bulk chemical industry, working essentially with dedicated plant units.

For the fine chemicals and pharmaceutical industries, where the processes are carried out in multi-purpose plants, this approach is more difficult to use. This is because the equipment may work under very different conditions from process to process, which obviously has an impact on its reliability.

The quantitative analysis must be based on a method, to allow identification of the interaction between different failures.

To get a better idea of the probability, a semi-quantitative approach consists of listing the logical relationships between the different causes. This allows identifying if the simultaneous failure of several elements is required to obtain the deviation and gives access to a semi-quantitative assessment. Severity and probability of occurrence of an event form the two coordinates of the risk profile.

The fault tree analysis is an example of a method on which is based the quantitative analysis. The fault tree analysis (FTA) is a deductive method, whereby the top event is given and the analysis focuses on the search of the causes that may trigger it. The principle is to start from the top event and identify the immediate causes or failures. Then each of these failures is again considered as an event and is analyzed to identify the next generation of causes or failures. In this way, a hierarchy of the causes is built up, where each cause stems from parent causes as in a generation tree. Such a tree may be developed to infinity; nevertheless, the depth of the analysis can easily be adjusted to function as the objectives of the analysis. In most cases, the depth of the analysis is adjusted to allow the design of risk - reducing measures. For example, in the analysis of a chemical process, when a pump failure is found, it is not useful to find out what caused the pump failure. For the process safety, it may be more appropriate to provide a back - up pump or to increase the maintenance frequency of the pump. Thus, in general the analysis is stopped at the failure of elementary devices as valves, pumps, control instruments, and so on.

A special feature of the FTA is that different events are linked by logical relationships as in figure 3.17. One possibility is the logical “AND” , meaning that two parent events must be realized simultaneously in order to generate the child event. The other possibility is the logical “OR” meaning, whereby only the realization of one parent event is sufficient to generate the child event. It becomes clear that the realization of an event behind an “AND” gate is less likely to occur than events behind an “OR” gate. This allows for a quantification of the fault tree. The probability of occurrence of an event C depending on the simultaneous realization of two events A and B, that is, behind a logical gate “AND”, is the conditional probability of A AND B:

$$P_C = P_A \cdot P_B \quad (3.4)$$

Since probabilities are comprised between zero and one and should be low figures, the conditional probability usually becomes extremely small.

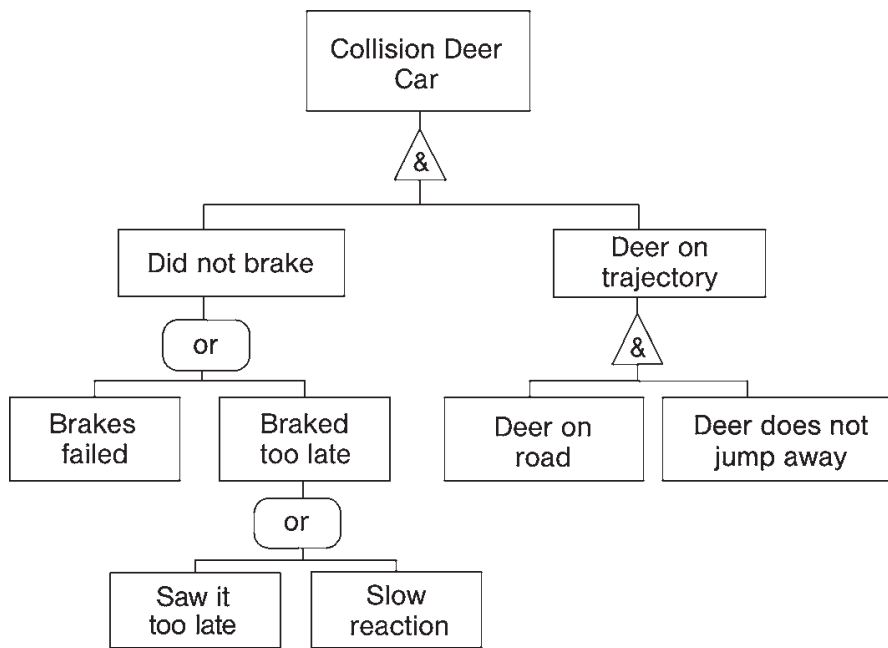


Figure 3.17: Example fault tree analysis for the collision of a car with a deer.

In other terms, an “AND” gate strongly reduces the probability of the occurrence of an event and it is advisable to design a safety system in order to provide such “AND” relationships before the top event.

The probability of occurrence of an event C , where only the realization of one parent event from A or B is required (behind an “OR” gate), the probability is the sum of probabilities of all parent events:

$$P_C = P_A + P_B - P_A \cdot P_B \quad (3.5)$$

In this expression, the subtraction of the product of probabilities takes into account the fact that the simultaneous realization of both events is still taken into account in the realization of individual events. This correction is usually very small, since individual probabilities are small.

In this way, the fault tree can be quantified, which makes this technique very powerful for the reliability analysis of protection systems. The prerequisite is the availability of statistical reliability data of the different devices and instruments that is often difficult to obtain for multi-purpose plants, where devices can be exposed to very different conditions when changing from one process to another. Nevertheless, if the objective is to compare different designs, semi-quantitative data are sufficient.

In spite of the deductive method fault tree analysis (FTA), there is the event tree analysis (ETA) that is an inductive method. It starts from an initial event and searches for the different possible effects and it is especially useful for studying the scenario of what may happen after the initial event when developing emergency plans.

Starting from the initial event, one searches for consecutive events, until the system reaches a final state. These different generations of events are represented

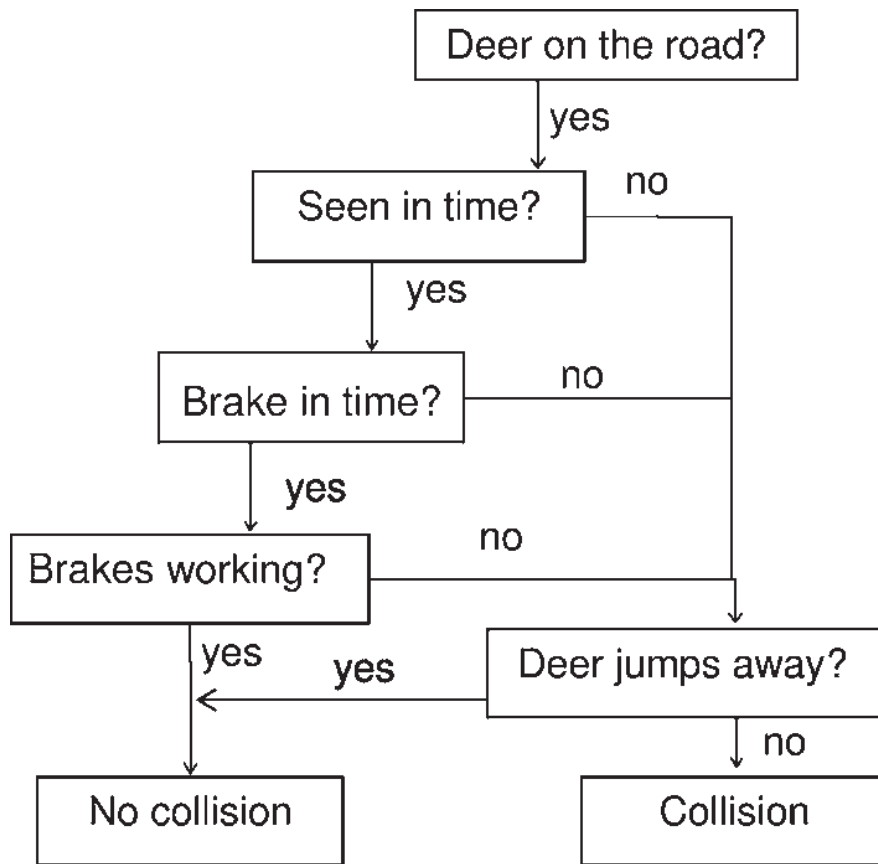


Figure 3.18: Event tree for the collision of a car with a deer.

as a tree. An example, again based on the collision of a car with a deer, is represented in figure 3.18. The vertical lines leading from one event to the next are related in a logical “AND” relationship and the corresponding probabilities must be multiplied. Horizontal lines indicate a logical “OR” relationship and the corresponding probabilities must be added. Thus, the tree can be quantified for the probability of entering one or the other branch after an event is known. Thus, it allows assessing quantitatively the effects of different possible chains of events and focuses the measures on the avoidance of the most critical chains. Often, it is useful start the analysis using the decision table method. It consists of logically combining all possible states of each element of a system and outlining the consequences on the entire system and it can be applied to a part of a system or to an operating mode. The combinations are analyzed by Boole’s algebra that gives the analysis a strong logical backbone. A part of such a decision table is shown in figure 3.19, an other time by the example of the collision of a car with a deer. It is the most powerful method for analysing combinations of failures, exhaustive in this respect. Nevertheless, the combinations rapidly become so numerous that it is difficult to retain an overview of the system by this method. Thus, it has a more academic character.

Deer on the road ?	No	Yes	Yes	Yes	Yes	Yes	Yes	...
Driver sees it in time ?	No	No	No	No	No	No	No	...
Brake in time ?	No	No	No	No	No	Yes	Yes	...
Brakes fails ?	No	No	No	Yes	Yes	No	No	...
Deer stays on road ?	No	No	Yes	No	Yes	No	Yes	...
Collision ?	No	No	Yes	No	Yes	No	No	...

Figure 3.19: Decision table for the collision of a car with a deer.

frequent				
moderate				
occasional				
remote				
unlikely				
almost impossible				
	negligible	marginal	critical	catastrophic

Figure 3.20: Example risk diagram with the accepted risk in white, non-accepted risk in dark gray, and conditionally accepted risks in light gray.

3.4.7 Risk Profiles

Risk assessment is not an objective by itself, but represents the required step for the risk evaluation. This is the step whereby it is decided if a risk is acceptable, or if it should be reduced by appropriate measures. This is usually done by comparing the risk to acceptance criteria defined in advance. This can be done graphically by using a risk diagram or risk matrix, as the example presented in figure 3.201.2. The numbers characterizing the different scenarios can be placed into the matrix, thus allowing a visual risk evaluation. Such a risk diagram must comprise two zones corresponding to the clearly accepted (white in figure 3.20 and clearly rejected risks (dark gray in figure 3.20. Often a third zone (light grey in Figure 3.20 is also used. This third zone corresponds to risks that should be reduced, as far as reasonably applicable measures can be defined, the decision being based on technical and economical considerations. This practice corresponds to the As Low As Reasonably Practicable (ALARP) [169]. The borderline separating the white zone from the others is called the protection level: this is the limit of accepted risks and represents an important decision for

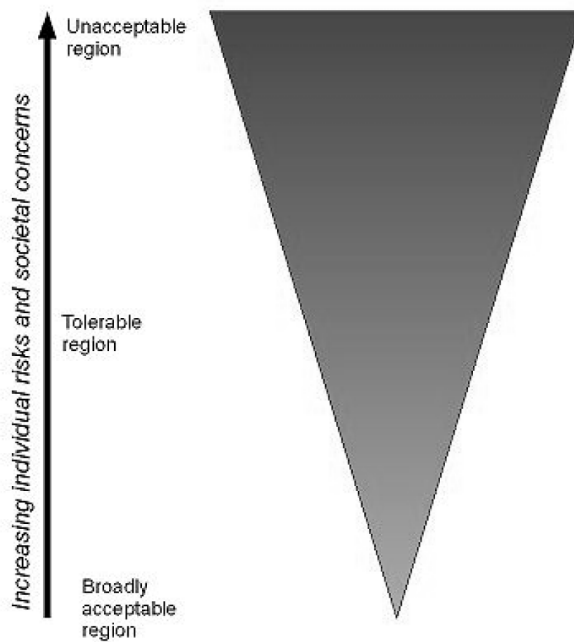


Figure 3.21: ALARP Carrot Diagram.

the risk policy of a company.

The term ALARP arises from UK legislation, particularly the Health and Safety at Work etc. Act 1974, which requires “Provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health”. The phrase So Far As is Reasonably Practicable (SFARP) in this and similar clauses is interpreted as leading to a requirement that risks must be reduced to a level that is As Low As is Reasonably Practicable (ALARP).

The key question in determining whether a risk is ALARP is the definition of reasonably practicable. This term has been enshrined in a UK case law in 1949 (the case of *Edwards v. National Coal Board*). The ruling was that the risk must be insignificant in relation to the sacrifice (in terms of money, time or trouble) required to avert it: risks must be averted unless there is a gross disproportion between the costs and benefits of doing so. Including gross disproportion means that an ALARP judgment in the UK is not a simple cost benefit analysis, but is weighted to favour carrying out the safety improvement. However, there is no broad consensus on the precise factor that would be appropriate.

Outside the UK the ALARP principle is often not used; instead standards and ‘good engineering practice’ are adhered to, and legislation tends to require absolute levels of safety.

Where the ALARP principle is used, it may not have the same implications as in the UK, as “reasonably practicable” may be interpreted according to the local culture, without introducing the concept of gross disproportionality. So called carrot diagrams are often used to display risks. They are called carrot diagrams, because they have an elongated triangle in the centre, which looks

Category	1. Negligible	2. Marginal	3. Critical	4. Catastrophic
Life/health in company	Injury, ambulant treatment	Injury requiring hospitalization	Injury with long-term disability	Fatality
Life/health outside company	No effect	No effect	First aid cases	Severe injury
Environment	No effect	Only on-site effects, effect on water treatment plant	Pollution outside site, recovery within 1 month	Long-term pollution of water, soil
Property	Not significant	Production line to be repaired	Loss of production line	Loss of plant
Business continuity	Not affected	Production stopped over 1 week	Delivery to customers must be interrupted several weeks	Business interruption more than 1 month
Image	No report outside company	Report in local media	Report in national media	Report in international media

Figure 3.22: Example assessment criteria for the severity.

like a carrot, and indicates the high (reducible) risks at the top and the low (insignificant) risks at the bottom.

The region in between is sometimes called the ALARP region; however this is misleading because the ALARP principle applies to all regions. A better name is the “Tolerable Region”, because risks in this region can sometimes be tolerated, if they cannot practically be reduced, in return for the benefits provided by the system or installation that causes the risks. It is unable to show the improvement of a risk situation especially with high severities, since such a situation often remains with high severity and low probability, even if additional measures are defined. On the other hand, too precise a matrix is not useful for risk evaluation and may lead to tedious discussions during its assessment.

The criteria mentioned in figure 3.22 and in figure 3.23 are given as an example of a possible practice, but as a part of the *company’s risk policy*, they must be defined for each company with respect to its actual situation.

3.4.8 Quantified Risk Assessment

It is important to realize that decision making about risks is very complex and that not only technical aspects but also political, psychological and societal processes all play an important role.

In this complex decision making process a clear identification of the risks and the effects of risk reducing measures is very useful. From a technical point of view the extent of the risks and the effects of risk reducing measures can be

Category	Frequency	Definition/Examples
Frequent	Several times in a week	Hazards occurring at each batch if no measures are taken, e.g. charging powders in flammable solvent, exposure during handling of liquid or solid chemicals, ignition effective electrostatic discharge (if nothing is done against charging)
Moderate	Once or twice a month	Pump failure, failure of data acquisition, weighing error, wrong set point setting
Occasional	Several times a year	Imprecise communication between production, e.g. tank farm, failure of utilities, failure of a motor, explosive mixture after a failure
Remote	Once a year	Wrong piping connection after repair, mix-up of chemicals, programming error of control system, leakage at reactor or tank jacket, total power failure in the site
Unlikely	Once in 10 years	Simultaneous failure of redundant level control, e.g. LAH and LAHH, leak at flange
Almost impossible	Once in 100 years or more	Undiscovered failure of self controlling data acquisition, simultaneous failure of multiple technical safety measures, heavy earthquake, aircraft impact

Figure 3.23: Example assessment criteria for the probability.

quantified in a quantitative risk assessment (QRA).

Typically, QRA presents Risk Results in terms of

- Individual risk (fatalities);
- Individual risk (Health and Injuries);
- Societal Risk (group Risk);
- Environmental risk;
- Economic risk (not necessarily a regulatory issue).

It is therefore that the QRA can provide a basis for the rational decision making about risks. In literature on quantitative risk assessment generally four phases are distinguished.

1. Qualitative analysis: in this step the system and the scope are defined, and the hazards and failure modes and scenarios are identified and described.
2. Quantitative analysis: the probabilities and consequences of the defined events are determined. The risk is quantified in a risk number or graph as a function of probabilities and consequences.
3. Risk evaluation: with the results of the former analysis the risk is evaluated. In this phase the decision is made whether the risk is tolerable or not.

4. Risk control and risk reduction measures: dependent on the outcome of the risk evaluation measures should be taken to reduce the risk. It should also be determined how the risks can be controlled (for example by inspection, maintenance or warning systems).

Risk measures play an important role in communicating the whole risk assessment process. A risk measure is defined as a mathematical function of the probability of an event and the consequences of that event. This risk measure forms the basis for evaluation of risks by the decision-makers. With limits or standards an acceptable risk level is set. Finally the risk measure can be used as an instrument to show the effect of risk reducing actions.

The risk measures are categorized in sections based on the consequences they consider:

- Individual risk
- Societal risk

3.4.8.1 Individual Risk and Individual Risk Measures

The first measure is the individual risk (IR). For example IR is used by the Dutch Ministry of Housing, Spatial Planning and Environment (VROM). It is defined as the probability that an average unprotected person permanently present at that point location, would get killed due to an accident at the hazardous activity [29].

$$IR = P_f \cdot P_{d|f} \quad (3.6)$$

where:

- P_f is the probability of failure;
- $P_{d|f}$ is the probability of dying of the individual in the case of failure, assuming the permanent unprotected presence of the individual.

The IR is thus a property of the place and as such useful in spatial planning. A slightly different definition, in which the actual presence of the individual is considered, is used by Dutch Technical Advisory Committee on Water Defences (TAW) and by Bohenblust [27] to describe the actual personal risk.

An overview of measurements to express the individual risk is given by Bedford and Cooke [21]. Apart from the individual risk as mentioned above four other expressions are described. The *loss of life expectancy* shows the decrease of life expectancy due to various causes. The *delta yearly probability of death* computes the intensity at which a given activity is performed (at suitable units) in order to increase the yearly probability of death by 10^{-6} . The *activity specific hourly mortality rate* reflects the probability per time unit of dying while engaged in a specified activity. An example is the Fatal Accident Failure Rate (FAFR) which gives the number of fatalities per 1000 hours of exposure to a certain risk. A variant is the death per unit activity, which replaces the time unit by a unit measuring the amount of activity. The risks of travel by car, train or aeroplane are often expressed in the form of the number of deaths per kilometer traveled.

The assessment of risks is the essential first step in the effective management of such risks throughout the life-cycle of an installation. It informs the selection of risk reduction measures and the establishment of appropriate performance standards for those measures. The assessment is an on-going process to ensure that, as changes to an installation occur, for example fire and explosion risks are maintained ALARP. The events selected should be a representative and sufficient set for the purposes of risk assessment. The basis for selection of the representative set of events should be explained. This should include consideration of such factors as:

Table 3.1: Factors for selection of the representative set of events for the purposes of risk assessment

Initial release	Event outcome
leak size	ignition characteristics (timing/location)
leak duration	wind direction and speed ventilation conditions
composition of hydrocarbon phase (gas/liquid/two-phase)	protective systems (eg deluge) operate or fail
leak location and leak orientation	personnel distribution
cause of release process conditions ESD/blowdown operates or fails installation operating regime	

The selection of the representative set of events should have regard to the nature of releases which have occurred and the basis for selection of representative hole sizes or release rates should be explained and should be appropriate to the characteristics of the installation.

3.4.9 Risk Reducing Measures

If the risk linked to a scenario falls into the non-acceptable zone, it must be reduced by appropriate risk-reducing measures. These are usually classified following two viewpoints:

- the action level;
- the action mode.

The action level can be elimination of the hazard, risk prevention, or mitigation of the consequences. For the action mode, different means can be used: technical measures that do not require any human intervention, or organizational measures that require human intervention and are accompanied by procedural measures defining the operating mode of the measure. Eliminating measures are

the most powerful since they avoid the risk, meaning that the incident can simply not occur or at least they strongly reduce the severity of the consequences of an eventual incident. For a chemical process, eliminating the risks can mean that the synthesis route must be changed avoiding instable intermediates, strongly exothermal reactions, or highly toxic material. The choice of the solvent may also be important in this frame, the objective being to avoid flammable, toxic, or environmentally critical solvents. Concerning runaway risks, an eliminating measure aims to reduce the energy in such a way that no runaway can take place.

Preventive measures provide conditions where the incident is unlikely to happen, but its occurrence cannot be totally avoided. In this category, we find measures such as inventory reduction for critical substances, the choice of a continuous rather than a batch process leading to smaller reactor volumes, and a semi-batch rather than a full batch process providing additional means of reaction control. Process automation, safety maintenance plans, etc. are also preventative measures. The aim of these measures is to avoid triggering the incident and thus reducing its consequences. In the frame of runaway risks, a runaway remains theoretically possible, but due to process control, its severity is limited and the probability of occurrence reduced, such that it can be controlled before it leads to a critical situation. Mitigation measures have no effect on triggering the incident, but avoid it leading to severe consequences. Examples of such measures are emergency plans, organization of emergency response, and explosion suppression. In the frame of runaway risks, such a risk may be triggered but its impact is limited, for example, by a blow down system that avoids toxic or flammable material escaping to the environment.

Technical measures are designed in such a way that they require no intervention, nor need to be triggered or executed. They are designed to avoid human error (in their action, but not in their design). Technical measures are often built as automated control systems, such as interlocks or safety trips. In certain instances, they must be able to work under any circumstances, even in the case of utility failure. Therefore, great care is required in their design, which should be simple and robust. Here the simplification principle of inherent safety, the KISS principle (Keep It Simple and Stupid), should be followed. Depending on the risk level, they must also present a certified high degree of reliability. This is described in the international standard IEC 61511 (International Electrotechnical Commission) that advises on the different Safety Integrity Levels (SIL) with the required reliability as a function of the risk.

Organizational measures are based on human action for their performance. In the fine chemicals and pharmaceutical industries, reactor-charging operations are often manual operations and the product identification relies on the operator. In this context, quality systems act as support to safety, since they require a high degree of traceability and reliability. Examples of such measures are labeling, double visual checks, response to acoustic or optical alarms, in process control, and so on. The efficiency of these measures is entirely based on the discipline and instruction of the operators. Therefore, they must be accompanied by programs of instructions, where the adequate procedures are learned in training. During the risk analysis, the measures must be accurately described to establish terms of reference, but no detailed engineering must be done during the analysis. It is also advisable to define a responsible person for the design and establishment of these measures.

risk measures Risk measures play an important role in communicating the whole risk assessment process. A risk measure is defined as a mathematical function of the probability of an event and the consequences of that event. This risk measure forms the basis for evaluation of risks by the decision-makers. With limits or standards an acceptable risk level is set. Finally the risk measure can be used as an instrument to show the effect of risk reducing actions.

The risk measures are categorized in sections based on the consequences they consider:

- Individual risk
- Societal risk

3.4.10 Residual Risk

This is the last step of risk analysis. After having completed the risk analysis and defined the measures to reduce risks, a further risk assessment must be carried out to ensure risks are reduced to an accepted level. The risks cannot be completely eliminated: risk zero does not exist, thus a residual risk remains. This is also because only identified risks were reduced by the planned measures. Thus, the residual risk has three components:

- the consciously accepted risk;
- the identified, but misjudged risk, and
- the unidentified risk.

Thus, a rigorous and consciously performed risk analysis should reduce both of the last components. This is the responsibility of the risk analysis team. Hence, it becomes obvious that risk analysis is a creative task that must anticipate events, which may occur in the future and has the objective of defining means for their avoidance. This may also be seen in opposition to laws that react on events from the past. Therefore, it is a demanding task oriented to the future, which requires excellent engineering skills. At this stage, a second risk profile can be constructed, in a similar way to that shown in subsection 3.4.7. This allows the identification of the risks that are now strongly reduced and thus the measures, which require special care in their design, should perhaps be submitted to a reliability analysis.

It is a creative task to identify the hazards, but also to define risk - reducing measures. Thus, different professions must be represented in the team, including chemists, chemical engineers, engineers, automation engineers, and operators. When a new process is to be analysed, the experience gained during process development should be available to the team, hence members of the process development team must be represented in the risk analysis. The plant manager, who is the risk owner, takes a determining part in the analysis. The team leader or moderator is responsible for the quality of the analysis; caring for its thoroughness, for discipline in the team, and for the time management. In the choice of risk - reducing measures, the moderator drives the group toward efficient solutions. More generally, the group dynamics is important, so the participants should also be creative and open - minded. The moderator ensures that all opinions can be expressed, leading the team toward consensual solutions.

It is advantageous that the moderator has a sound industrial experience and, if possible, some experience in dealing with risks or in incident analysis.

3.4.11 Risk Management

Risk management is activity directed toward the assessing, mitigating (to an acceptable level) and monitoring of risks. In some cases the acceptable risk may be near zero. Risks can come from accidents, natural causes and disasters as well as deliberate attacks from an adversary. In businesses, risk management entails organized activity to manage uncertainty and threats and involves people following procedures and using tools in order to ensure conformance with risk-management policies.

The possibility of accidents requires the development of integrated safety management systems to implement mitigation activities, which seek the reduction of the vulnerability, and prevention activities, which try to reduce the hazard [147].

Theoretically, risk management activities can be oriented to deal with specific and defined risk and manage it optimally. Unfortunately, reality is far too complex and resources far too scarce to deal with each risk event individually, as often one hazardous event is linked or related to one or more other hazardous events. Some events triggered others.

As an example Pons et al., 2007 [197], urban degradation caused, e.g., by unplanned urban growth, bad construction practices, or immigration of people from the rural areas, tends to disturb the balance in the urban system, influences the interaction process between different hazards and vulnerabilities increasing vulnerability levels, and then creates new hazards factors.

The strategies include transferring the risk to another party, avoiding the risk, reducing the negative effect of the risk, and accepting some or all of the consequences of a particular risk.

In spite of these strategies the traditional risk management programs (e.g., health risk assessment) are focused on risks stemming from physical or legal causes (e.g. natural disasters or fires, accidents, ergonomics, death and lawsuits).

An advanced approach to risk management must to emphasize:

- Minimizing personnel exposure
- Minimizing quantities of hazardous materials
- "Safety by Design"
- Accurate procedures and standards
- Rigorous personnel training.

Proper risk management, as given in Figure 3.24 focuses on not only normal operations/conditions but also abnormal operations/conditions, equipment design, human factors, standard operating and contingency procedures, maintenance operations, and facility design and siting.

A possible approach to risk management focuses resources on addressing critical credible failure scenarios. This is accomplished by prioritizing operations/equipment based on perceived risk and material type and quantity, identifying and ranking

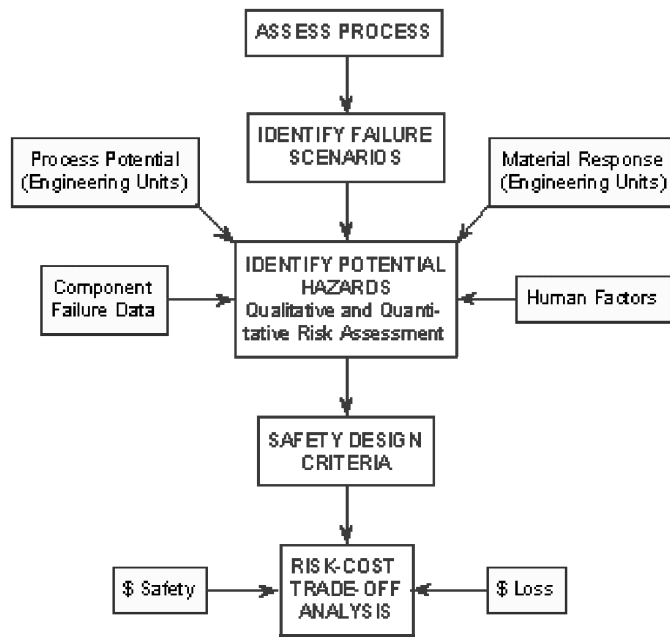


Figure 3.24: An example of proper risk management

potential hazards using qualitative methodologies, and then using quantitative methodologies to evaluate the critical scenarios. This type of review is known to industry as risk assessment or Process Hazards Analysis (PHA). These PHA services may be used independently or in conjunction with our explosive characterization, incident investigation, facility siting, and other analysis services. Process Hazards Analysis and Qualitative and Quantitative Risk Assessment techniques can be applied to processes to minimize potential hazards. In order to this scope, the Hazard Risk Assessment Matrix presented in Figure 3.11 can be very useful because it provides a systematic method for assigning a hazard level to a failure event based on the severity and frequency of the event. Finally, in Figure 3.25 there is a procedural schema that step-by-step arrives to emergency arrangements starting from hazard identification through Quantified risk assessment, Risk evaluation and reduction and Risk management.

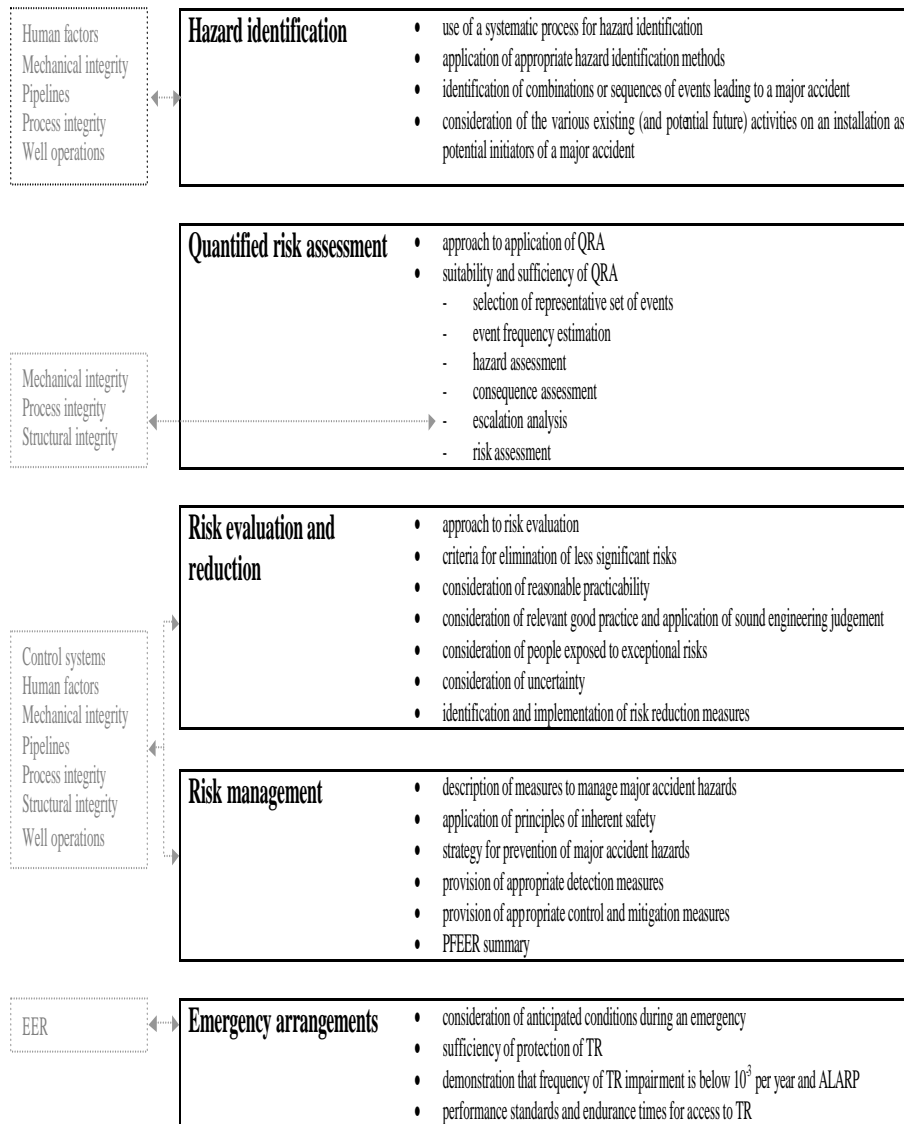


Figure 3.25: The problem of HAZMAT step-by-step

Chapter 4

Hazardous Materials Transportation

In this chapter, some important concepts are introduced about Hazardous Materials Transportation: Section 4.1 gives background informations.

Section 4.2 presents hazard and risk concepts in HAZMAT transportation and the main factor that differentiate HAZMAT logistic problems from other logistic problems. We also review different models of risk assessment.

Section 4.3 offers a high-level view of HAZMAT logistics literature. It describes how the transportation of HAZMATs can be classified according to the mode of transport, namely: road, rail, water, air, and pipeline. We propose a classification scheme that take into account the framework and the method of the former article by Erkut, Tjandra and Verter edit in 2007, completes it with the most recent literature. In Section 4.4 we cluster and discuss the papers available in the literature according to the proposed scheme.

4.1 Background Informations

In the last few years, logistics has become a strategic factor for development and competition. In fact, Research and Development activities have traditionally faced the management of Supply Chain and International Transport focusing on two main aspects: *speed* and *efficiency*.

However, several vulnerabilities have recently been highlighted under a safety and security viewpoint. The weakness of the logistic chains has become more evident with the beginning of the new millennium. Terrorist attacks, such as 11/09 in the USA have caused the introduction of new rules and procedures, which affect the overall logistics showing the vulnerability of the global economy.

As a consequence, nowadays, it is necessary to carry out an exhaustive research activity on the various typologies of risk, which may affect the supply chain. HAZMAT transport probably represents by definition the most vulnerable aspect in global logistics and transportation activities.

In Chapter 3 HAZMATs were defined and referred to any material whose transportation has the potential to cause harm to people, property or the environment. This category includes flammable liquids or gases, chemicals, toxic, explosives, radioactive, corrosive and nuclear materials.

Most of the 1.5 billion tons of HAZMAT transferred annually in the USA are flammable liquids. HAZMAT transportation is an important economic activity in industrialized countries due to the need to move a large number of HAZMAT shipments from production to consumption sites. With globalisation, these distances tend to increase as production sites are shift to countries with more favorable labour conditions.

As hazardous materials traffic originates and terminates at numerous locations throughout shipment network in the world, the HAZMAT transportation poses risks to life, health, property, and the environment due to the possibility of an unintentional release. While moving HAZMAT is necessary, authorities are increasingly concerned about the risks associated with these movements and the catastrophic consequences of possible accidents.

More than 300 million HAZMAT shipments are transported annually in the USA, and it is estimated that HAZMAT transportation accounts for 5% to 15% of the total number of shipments carried.

Although the possibility of an accident is relatively low ($10^{-8} \div 10^{-6}$ per vehicle-mile traveled) the catastrophic outcomes together with the large number of shipments and the longer distances they travel cause great concern to the authorities [4].

HAZMAT catastrophes occur primarily through either involvement of the transportation vehicle in an accident or leakage and activation of the HAZMAT carried. The combination of these two incidents of course, could have even more catastrophic consequences. The events above could result in human injuries and fatalities, environmental pollution and large economic costs.

As most hazardous materials are not used at their point of production and they are transported over considerable distances, HAZMAT transportation can be also classified according to the mode of transport, namely: road, rail, water, air, and pipeline, although some shipments are intermodal. Most countries regulate some aspect of hazardous materials.

The most widely applied regulatory scheme is that for the transportation of dangerous goods. The Committee of Experts on the Transport of Dangerous Goods of the United Nations Economic and Social Council issues Model Regulations on the Transportation of Dangerous Goods.

Most regional and national regulatory schemes for hazardous materials are harmonized to a greater or lesser degree with the UN Model Regulation.

As it was seen in Section 3.1.1, HAZMAT placards are essential when works involving hazardous materials are taking place. Furthermore, in the event of an accident, it is important for first responders to know the nature of the hazardous materials involved. Hence, vehicles transporting hazardous materials must display unified placards describing the class and the nature of the cargo. On the other hand, making HAZMAT vehicles easy to identify through placards exposes them to another kind of risk: sabotage or misuse as weapons of mass destruction or of convenience.

UN/NA numbers are required for the shipment of hazardous materials and some Hazard Identification Numbers have special meanings and indicate a particular hazard or combination of hazards. United Nations (UN) Numbers are four-digit numbers used world-wide in international commerce and transportation to identify hazardous chemicals or classes of hazardous materials. These numbers generally range between 0000 and 3500 and are ideally preceded by the letters "UN" (for example, "UN1005") to avoid confusion with other number

The ADR Hazard Identification Number HIN
(The Kemler Code)



The substance's UN Number

Figure 4.1: Example of The ADR Hazard Identification Number

codes.

UN numbers are assigned by a committee of the United Nations, the Economic and Social Council (ECOSOC) Committee of Experts (COE) on the Transport of Dangerous Goods which issues “Recommendations on the Transport of Dangerous Goods” (also called “the Orange Book” [227]).

UN Recommendations are not regulations, but are recommendations addressing the international transport of dangerous goods by sea, air, road, rail and inland waterways. These recommendations are reviewed, amended and updated biennially (every second year) by the UN COE and are distributed to nations throughout the world.

These recommendations serve as the basis for national, regional, and international transport regulations such as those prepared by the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO). The UN Recommendations are also used as a basis for the development of regional (e.g., North American Free Trade Agreement (NAFTA) and European Road and Rail regulations) and national transport regulations, including the U.S. Hazardous Materials Regulations.

Each country has its own particular legislation and standards for HAZMAT placards, and so it is important to be aware of those which affect you when dealing with hazardous materials.

For instance, in the U.S., hazardous materials carried in bulk are required to be marked before shipment by road, rail, or air. The authority that regulates this marking is the Department of Transportation, or DOT. The rules for placarding are contained in CFR (The Code of Federal Regulations) Title 49, sections 171 and 172 [49]. North American (NA) Numbers are identical to UN numbers. If a material does not have a UN number, it may be assigned an NA number; these are usually 4-digit numbers starting with 8 or 9 such as 9037 (or ideally, NA9037), the NA number for hexachloroethane.

Vehicles running under International ADR regulations will carry a three-digit Code, referred to as the *Kemler Code* (see Figure 4.1). This code will give the Fire and Rescue Service further information about the hazards involved in dealing with the material. The first figure of the Kemler Code indicates the primary hazard and the second and third figure generally indicate secondary hazards as indicated in Figure 4.2. Doubling of a figure indicates an intensification of that particular hazard. Where the hazard associated with a substance can be adequately indicated by a single figure, this is followed by a zero. An orange blank placard without any numbers indicates vehicle carrying dangerous load (drums, packages, etc.) or multi-load tanker.

If a hazard identification number is prefixed by letter 'X', this indicates that the substance will react dangerously with water. The international carriage

The first figure of the Kemler Code indicates the primary hazard:		The second and third figure generally indicate secondary hazards:	
		0	the hazard is adequately described by the first figure
2	gas	2	(flammable) gas may be given off
3	flammable liquid	3	fire risk
4	flammable solid	4	fire risk
5	oxidizing substance or organic peroxide	5	oxidizing risk
6	toxic substance	6	toxic risk
7	radioactive substance		
8	corrosive substance	8	corrosive risk
9	miscellaneous/environmental hazard	9	risk of spontaneous, violent reaction
X	reacts dangerously with water		

Figure 4.2: The Kemler Code

of HAZMAT has long been governed by established international agreements known, in the case of land transport, by the abbreviations ADR, RID or ADN. These rules were drawn up by international organizations which have a wealth of experience and knowledge in the field. They are updated at intervals to keep pace with technical progress and improve safety.

The European Union's approach is to transpose these rules via specific directives which are then applicable to national transport too, not just transport between Member States. Currently, the European Union has legislation for the transport of dangerous goods by road and by rail.

In Europe, the first directive adopted by the Council (in 1989) covered only very specific aspects such as the training of drivers.

The Maastricht Treaty explicitly established the competence of the European Community to deal with transport safety. Subsequently, the Commission suggested general legislation concerning the transport of dangerous goods in various modes, such as road or rail transport.

In order to avoid duplicating with the work carried out by international organizations, the Commission considered that Community legislation should be established on the basis of the following principles:

- uniform application of international agreements at EU and Member States level;
- elimination of obstacles to exchanges created by non-harmonized international standards;
- adoption of measures at Community level, to supplement those contained in the international agreements;

- coherence of Community legislation in this field with other EU policies.

The first Directive was the 94/55/EC from 21 November 1994 on the approximation of the laws of the Member States with regard to the transport of dangerous goods by road, usually called the ADR Framework Directive. This directive is intended to apply the requirements of the technical annexes to the ADR agreement uniformly to national road transport and to transport between Member States.

A second Directive is very similar to the ADR Framework Directive but applies to transport by rail: the Council Directive 96/49/EC of 23 July 1996 on the approximation of the laws of the Member States with regard to the transport of dangerous goods by rail ('RID Framework Directive').

As far as 'Class 2 gases' are concerned, the annexes to both these directives contain common requirements on the design of containers, the materials to be used depending on the type of the product to be transported, the maximum level to which containers should be filled and periodical examination.

As certain requirements of the ADR and the RID, concerning containers for category 2 Gases are less detailed than the requirements of national legislation, article 6.4 of each of these Framework Directives allow the Member States to retain their national requirements on the subject until such time as the reference to the European Standards for the construction and use are added to the annexes of the two directives.

An abstract of the Standardization Programme of CEN and the section of RID/ADR where the standards will be referred to is available.

The collection of legal instruments organizing the safe transport of dangerous goods is quite complex. Further information on EU legislation can be found on the Commission's Europa website.

The European Commission has initiated a proposal in order to regroup the Road and Rail Frameworks Directives under a single framework Directive dealing with Road, Rail and Inland Navigation transport of dangerous goods.

In the context of its global goal of improving safety in transport, the European Union has issued in 1999 the Directive 1999/36/EC to enhance safety with regard to transportable pressure equipment approved for the inland transport of dangerous goods by road and by rail. The Directive aims simultaneously to ensure the free movement of such equipment within the Community, including the placing on the market and repeated putting into service and repeated use aspects.

Directive 1999/36/EC is commonly referred to as TPED (Transportable Pressure Equipment Directive). In order to facilitate the use of the Directive, the Commission together with Member States' experts has elaborated TPED Guidelines, which may be found here. These will be completed as new Guidelines are adopted.

The European Agreement concerning the International Carriage of Dangerous Goods by Road, commonly known as ADR (from the french abbreviation *Accord européen relatif au transport international des marchandises dangereuses par route*), governs transnational transport of hazardous materials. Launched in Geneva on 30 September 1957 under the aegis of the United Nations' Economic Commission for Europe, it first took effect on 29 January 1968. The agreement was modified (article 14, paragraph 3) in New York on 21 August 1975, though these changes only took effect on 19 April 1985. A set of new Amendments

entered into force on 1 January 2007, and consequently, a fourth consolidated restructured version was published as document ECE/TRANS/175, Vol.I and II (ADR 2007).

The agreement itself is brief and simple, and its most important article is article 2. This article states that with the exception of certain exceptionally dangerous materials, hazardous materials may in general be transported internationally in wheeled vehicles, provided that two sets of conditions be met:

- Annex A regulates the merchandise involved, notably their packaging and labels.
- Annex B regulates the construction, equipment and use of vehicles for the transport of hazardous materials.

The Regulations covering the transport of dangerous goods are very different from those covering Supply. There are also separate arrangements for each of the four modes: Road, Rail, Air and Sea. These pages explore each of these in turn, looking at the situation in the UK and International transport.

4.2 Risk analysis of HAZMAT transportation

In Chapter 3, hazard and risk concepts were defined and it was seen that risk estimates are often used to evaluate the safety of an industrial plant, in order to find which additional safety measures can reduce the risk, or to support public authorities new plant siting in establishing new plant siting or emergency planning.

In this section, a survey of the mathematical models used to calculate the individual and societal risk in HAZMAT transportation is given.

4.2.1 Risk assessment of HAZMAT transportation

Risk assessments are an essential part of the process of integrating natural disaster programs with overall development objectives. These assessments identify sources of risk, vulnerable groups, and potential interventions.

Risk assessment allows policymakers to specifically define the objectives of the risk management programs and to establish vulnerability reduction targets.

Risk is characterized by two aspects: occurrence probability of an event and consequences of an occurring event. In the context of HAZMAT transportation, the undesired events are the accidents that could lead to a release of a HAZMAT.

According to Alp [10], “risk is a measure of the probability and severity of harm to an exposed receptor due to potential *undesired events* involving a HAZMAT whereas the exposed receptor can be a person, the environment, or properties in the vicinity”.

Harwood et al. (1989) [114] define risk on the basis of historical data, that is, as:

$$Risk = \frac{Events}{Exposure} \quad (4.1)$$

where: The strength of indicators as (4.1) is that they represent an integrated comprehensive measure of both frequency and severity of the past undesired

Exposure is an exposure measure, such as truck miles, and
Events is the weighted number of releases or vehicular accidents.
Here, the weight associated to an event expresses
the level of its severity.

events, and for this reason they are frequently used in literature to assess the risk.

On the other hand, the subjectivity, in defining the value of the weights that account for the severity of the events, is an unavoidable weakness of these indicators.

In addition, such indicators may be not suitable to assess the risk of potential future occurrences, in presence, e.g., of technological advances. Different studies tries to overcome this latter limitation (see, e.g., [18, 20, 26]).

As these studies are usually focused on releases that occur on the road or, in a lesser extent, along railways, they assesses the risk by taking into consideration different factors such as population density, facility type, material to be shipped and exposure.

The challenge is to convert these factors into quantitative values that allow to express the probability of a hazardous materials accident and a measure of the associated consequences (e.g. expected population exposure) to apply to the links of the road (rail) network so that the best (safest) routes can be determined.

QRA involves the following key steps:

1. hazard and exposed receptor identification;
2. frequency analysis; and
3. consequence modeling.

In addition, examination of risks on different types of exposed receptor is essential to cover different response characteristics in the risk assessment. Also, given the fact that public opposition is a function of perceived risks, perhaps more attention should be paid to quantifying and modeling of perceived risks.

Each step of QRA presents some difficulties. For example, the consequence modeling step requires as inputs the territorial distribution of the population exposed to the consequences of an accident. Differently, many past studies roughly assumed uniform population density along transport links.

4.2.2 Frequency analysis of HAZMAT transportation

According to [12], the frequency analysis involves:

- 1 - determining the probability of an undesirable event;
- 2 - determining the level of potential receptor exposure, given the nature of the event;
- 3 - estimating the degree of severity, given the level of exposure.

Each stage of this assessment requires the calculation of a probability distribution, with stage (1) and (2) involving conditional distributions.

As an example, [80], for each unit road segment, determine the joint probability of type of accident, release, incident, and consequence as follows.

Let it be:

- A the accident event that involves an HAZMAT carrier,
- M the release event,
- I the incident event,
- D the event of an injury to an individual.

Suppose that the consequence of the HAZMAT release is expressed in terms of the number of injuries. Then, using *Bayes' theorem*, we obtain the probability of an injury resulting from an accident related to the HAZMAT as:

$$p(A, M, I, D) = p(D|A, M, I) p(I|A, M) p(M|A) p(A) \quad (4.2)$$

where: Despite its simplicity, the above model already contains many of the

- $p(E)$ denotes the probability of the event E , and
- $p(E|F)$ denotes the associated conditional probability.

necessary elements for HAZMAT risk assessment. For example, Chow et al. (1990) [53] used a Bayesian model that includes multiple levels of event severity to predict severe nuclear accidents and to estimate the associate risks. Glickman (1991) [101] used a Bayesian model in the assessment of the risks of highway transportation of flammable liquid chemicals in bulk.

Furthermore, if S_{lm} denotes the number of shipments of HAZMAT of type m on the road segment l per year, then the product $S_{lm} \cdot p_l(A, M_m, I, D)$ corresponds to the frequency of the occurrence of the hazardous release event with consequence D for a person in the neighborhood of road segment l .

In assessing the risk, the literature makes a distinction individual and societal risks. Such a distinction is justified as, if few people are present around the hazardous activity, the societal risk may be close to zero, whereas the individual risk may be quite high.

4.2.3 Individual Risk Assessment

Individual Risk [177] defines the individual risk as the yearly death frequency for an average individual at a certain distance from the impact area. The analytical expression for individual risk are often mathematically complex and their value can only determined numerically.

As an example [153, 155] propose a model that requires the following high level variables to assess the individual risk:

- frequency of release,
- probability of final outcome given a release,
- wind probability,
- vulnerability.

We must take into consideration that a pipeline accident can take place everywhere along the pipeline route. a road tanker release can occur in any point along the road on which the tanker is traveling.

We should consider also a road tanker release can occur in any point along the road on which the tanker is traveling. As a consequence, a tanker or a pipeline conveying HAZMAT can be considered as a *linear risk source* equivalent to a great number of point-risk sources.

First, the point-risk source must be characterized by defining the release cases, i.e. by assigning:

- a hole size;
- a physical state of the outcome;
- a release rate;
- a release duration.

In addition, it is necessary to know:

- a likelihood of occurrence to the possible accidents which may occur during the transport;
- which have been chosen to classify all possible releases;
- the suitable meteorological conditions have to be chosen, given by the pairs “atmospheric turbulence class wind speed”.

Then, consequence models are used to calculate the spatial distribution of the physical effects of each pair “release case meteorological condition”, i.e.:

- concentrations if the hazardous chemical is a toxic one;
- thermal radiation and the overpressure of the blast if it is flammable.

The physical effects are then combined with proper exposure times to obtain the received doses which are converted in vulnerabilities, i.e. death probabilities of an average individual, through “probit” equations [234]. In this way, the *vulnerability distribution* around the risk point is assigned to each pair “release case-meteorological condition”: it is named *vulnerability map*.

Probability Estimates (probits) are just used to calculate the percentage of an exposed population that will suffer a certain type of consequence from a given magnitude of an adverse effect. They can be used to estimate the consequences of toxic exposures, thermal radiation from fires and overpressure from explosions. In mathematical terms “probit” is a straight line probability relationship developed to measure, for example, killing a certain proportion of the population, expressed as a standard deviation and related to a mean of 5. It has the advantage of being easily used without deep understanding of the underlying theory, provided suitable data is available.

Probit equations have the form:

$$Y = k_1 + k_2 \ln V \quad (4.3)$$

Where Y is the probit, which is related to the percentage of the population suffering the set consequence. k_1 and k_2 are constants which are determined

from historical data and V is the magnitude of the effect, for example the overpressure or thermal dose [151].

According to Bonvicini et al. (1998) [28], at a test area point (i.e. a point corresponding to a real location of a geographical site), the individual risk is given by the sum of the risks created at that point by all arcs of the linear risk source of the road).

In order to calculate the individual risk at point P due to an accident at point $Q(t)$, the vulnerability maps are combined with the probability of occurrence of different seasonal situations, weather conditions and wind directions to obtain the unit risk maps, whereas t is a curvilinear route abscissa.

Let $Q(t)$ the point risk source; then, at a generic point O of the unit risk map for the i th release case, the *unit risk* $R_{Q(t) \rightarrow O}$ is a parameter given by:

$$\bar{R}_{Q(t) \rightarrow O}(i) = \sum_{j=1}^{N_{seas}} x(j) \sum_{k=1}^{N_{met}} \int_0^{2\pi} P_{wind}(j, k, \vartheta) v_{Q(t) \rightarrow O}(i, k, \vartheta) d\vartheta \quad (4.4)$$

where:

- N_{seas} is the number of different seasonal situations;
- N_{met} is the number of different meteorological situations;
- P_{wind} is the probability density function of a given wind ϑ for a specified meteorological condition k and a seasonal situation j ;
- $v_{Q(t) \rightarrow O}$ is the vulnerability that a release i at $Q(t)$ creates at O when the is meteorological condition is k and the wind direction is ϑ ;
- $x(j)$ is the fraction of the year that tankers travel on the road in a given season (the symbol $x_V(j)$ is used in this case);
- is the fraction of the season during which the pipeline is active (the symbol $x_p(j)$ is used in this case).

Then, the unit risk maps are combined with proper frequency factors and translated along the route to describe the changes in the position where an accident can occur, i.e. the contributions of all point risk sources $Q(t)$ to the risk at P . Finally, they are summed for all release cases to obtain the global individual risk at P , IR_P :

$$IR_P = \sum_{i=1}^{N_{rel}} \left[\int_L f_{rel}(i, t) \bar{R}_{Q(t) \rightarrow P}(i) dt \right] \quad (4.5)$$

where:

- L is the road route;
- N_{rel} is the number of release cases;
- f_{rel} is the frequency of the i th release case.

Of course, the frequency f_{rel} of the i th release case has different expressions for the road in spite of other modal transports as, for example, the pipeline. The release case frequency for the pipeline is calculated as

$$f_{rel}(i, t) = \lambda_p(t) p_{\Phi}(i) p_I \quad (4.6)$$

where λ_p is the average release frequency (release $year^{-1} km^{-1}$).

The release case frequency for the road is given by

$$f_{rel}(i, t) = \lambda_R(t)p_{rel}p_{\Phi}(i)p_I p_V \quad (4.7)$$

where:

- λ_R is the average incident rate ($vehicle^{-1}km^{-1}$);
- p_{rel} is the probability to have a release once an incident has occurred;
- $p_{\Phi}(i)$ is the probability of the release of a particular size;
- p_I is the ignition probability (for flammable substances only);
- n_V is the number of yearly traveling tankers.

The release case frequency for the pipeline is calculated as

$$f_{rel}(i, t) = \lambda_p(t)p_{\Phi}(i)p_I \quad (4.8)$$

where λ_p is the average release frequency (release $year^{-1}km^{-1}$).

In order to perform the line integral of 4.5, it is necessary to represent the route as a polygonal curve of N_{seg} straight segments, each characterized by constant release frequency values.

With this hypothesis, 4.5 becomes

$$IR_P = \sum_{i=1}^{N_{rel}} \sum_{l=1}^{N_{seg}} f_{rel}(i, l) \left[\int_{Li} \bar{R}_{Q(t) \rightarrow P}(i) dt \right] \quad (4.9)$$

4.2.4 Societal Risk Assessment

Societal risk can be represented by means of $F(N)$ curves, where F is the frequency of all accidents capable of causing the death of N or more persons. Apart from the vulnerability maps defined for each release case meteorological condition, it is necessary to identify on a population map:

- the zones of rectangular shape, where people may be considered uniformly distributed with a density depending on the area being an urban, a sub-urban or a rural one;
- the roads, where people are linearly distributed;
- the aggregation centres, e.g., schools, hospitals, and commercial sites, where people can be considered as clustered. Furthermore, the probabilities of each category of people being indoor have to be assigned.

At the point risk source $Q(t)$, a scenario is given by the combination release case i -seasonal situation j -meteorological condition k -wind direction ϑ .

When an accident occurs at $Q(t)$, the number of fatalities $N_{Q(t)}^{scen}(i, j, \vartheta)$ due to each scenario is evaluated according to the following equation.

$$\begin{aligned}
N_{Q(t)}^{scen}(i, j, \vartheta) = & \\
& \sum_{m=1}^{n_L} \rho_{L_m}(j) \int_{L_m} \nu_{Q(t)}(i, k, \vartheta) [x_{L_m}(j) + (1 - x_{L_m}(j)) \alpha_{P, L_m}] dL_m + \\
& \sum_{n=1}^{n_A} \rho_{A_n}(j) \int_{A_n} \nu_{Q(t)}(i, k, \vartheta) [x_{A_n}(j) + (1 - x_{A_n}(j)) \alpha_{P, A_n}] dA_n + \\
& \sum_{o=1}^{n_C} \nu_{Q(t)}(i, k, \vartheta) [x_{C_o}(j) + (1 - x_{C_o}(j)) \alpha_{P, C_o}] N_{C_o}(j) \quad (4.10)
\end{aligned}$$

where:

- n_L is the number of lines on the population map;
- n_A is the number of rectangles on the population map;
- n_C is the number of points on the population map;
- ρ_{L_m} is the people densities corresponding to the m th line;
- ρ_{A_n} is the people densities corresponding to the n th rectangle;
- N_{C_o} is the number of persons in the aggregation centre o ;
- x_{L_m} is the fraction of people staying indoors on the generic line;
- x_{A_n} is the fraction of people staying indoors on the generic rectangle;
- x_{C_o} is the fraction of people staying indoors on the aggregation centre o ;
- α_{P-L_m} is the the mitigation factor deriving from being indoors on the generic line;
- α_{P-A_n} is the the mitigation factor deriving from being indoors on the generic rectangle;
- α_{P-C_o} is the the mitigation factor deriving from being indoors on the aggregation centre;
- $\nu_{Q(t)}$ is the vulnerability due to a release in the point risk source $Q(t)$ stored in vulnerability maps.

To perform the integration steps of 4.10, each vulnerability matrix is linearly interpolated obtaining a continuous function.

An efficient numerical algorithm based on the ‘‘circutation theorem’’ accelerates the surface integration that constitutes the slowest step of the procedure.

Each scenario of the point risk source has to be characterized by a number of fatalities $N_{Q(t)}^{scen}(i, j, \vartheta)$ and a frequency per unit length and unit angle, defined as

$$f_{Q(t)}^{scen}(i, j, \vartheta) = f_{rel}(i, t) x(j) P_{wind}(i, j, \vartheta) \quad (4.11)$$

In order to evaluate $N_{Q(t)}^{scen}(i, j, \vartheta)$ for a given scenario at a point risk source $Q(t)$, the population map is overlaid with the vulnerability maps, which are rotated to describe the changes in the wind direction.

Once $N_{Q(t)}^{scen}(i, j, \vartheta)$ and $f_{Q(t)}^{scen}(i, j, \vartheta)$ at point $Q(t)$ are known for each scenario, $F_Q(t)(N(i, j, k))$, i.e. the cumulative frequency function $Q(t)$ per unit length at point $Q(t)$ can be evaluated by taking into account all wind directions.

To simulate the change in the position where accidents can occur, the vulnerability maps are translated along the route, and for each route point $Q(t)$,

the evaluation of $F_Q(t)(N(i, j, k))$, along the route obtaining $F(N(i, j, k))$, and, for fixed values of N , and, for fixed values of N , to sum the integrated values for all combinations of release casemeteorological conditionseasonal situation, in order to obtain the final $F(N)$ curve.

As in the individual risk model, the route is represented by a polygonal curve of N_s straight segments, each characterized by constant release case frequency values.

For each segment l , the outlined calculus is performed, and eventually, the $F(N)_l$ curves are summed for constant N values to obtain the $F(N)$ curve for the whole route. An alternative way to describe the societal risk is the use of the so-called FN -curves [126], where F is the cumulative frequency of an accident with N or more either fatalities or evacuated people. Such FN -curve are drawn by computing, the probability that a group of more than N persons would be impacted due to an HAZAMAT accident, for each (reasonable) value of N .

Expressions from (4.5) to (4.10) allow to assess the risk in the assumption that just one type of accident may happen. However, more than one type of accident, release, incident, and consequence can occur during the HAZMAT transport activity. For example, a release of flammable liquid can lead to a variety of incidents such as a spill, a fire, or an explosion. To accommodate this, Erkut et al.(2005) [80] suggest to assess the risk as follows.

Let A , M , I , and C denote respectively the set of possible accidents, releases, incidents, and consequences that may occur on road segment l . Suppose that all consequences (injuries and fatalities, property damage, and environmental damage) can be expressed in monetary terms. Then, the hazardous materials transport risk associated with road segment l can be expressed as:

$$R_l = s_{lm} \sum_{a \in A} \sum_{m \in M} \sum_{i \in I} \sum_{c \in C} p_i(A_a, M_m, I_i, C_c) \cdot CONS_c \quad (4.12)$$

where $CONS_c$ is the possible c -type consequence.

In practice, researchers frequently neglect conditional probabilities and simplify the analysis by considering the expected loss (or the worst-case loss) as the measure of risk. The expected value is calculated as the product of the probability of a release accident and the consequence of the incident [161]. Hence the HAZMAT risk associated with a road segment l is expressed as

$$R_l = \sum_{m \in M} s_{lm} p(M_m) \cdot c_{lm} \quad (4.13)$$

where c_{lm} is the undesirable consequence due to the release of HAZMAT m on road segment l . This risk model is sometimes referred [82] to as the *technical risk*.

4.2.4.1 Security of HAZMAT transportation

The risk assessment methodologies introduced in the previous section may need reviewing in the next future due to the new concern for security in HAZMAT transportation.

The terrorist attacks in the USA in 2001 have focused attention on what other targets terrorists may choose. It was quickly recognized that HAZMAT vehicles could be desirable targets for terrorists, and certain HAZMAT vehicles were designated as *weapons of mass destruction*, see [2, 225].

Such concerns changed the way the HAZMAT industry operates. For example, the US Federal Government now requires HAZMAT truckers to submit to fingerprinting and criminal background checks [97].

The security issue, however, has not yet received much attention from the operations research (OR) literature. However, there is potential for OR studies, for examples:

- Rerouting around major cities - The risk of terrorist attacks made it very undesirable to route HAZMAT vehicles (particularly trains) through major population centres. In particular, [76] show that significant risk reductions are possible through rerouting, and [78] develop new methodology for routing with a catastrophe-avoidance objective.
- Changes in the modeling of incidence risks - The traditional risk assessment for HAZMAT assumes incidents are caused by traffic accidents or human error. We now know that there is a nonzero probability of a terrorist attack or a hijack. This fact increases the incident probabilities and requires a new way of modeling consequences since the impact may no longer be limited to the planned route. Furthermore, attack probabilities are unlikely to be uniform. For example, a tunnel, a bridge, or a *trophy building* are likely to have a higher attack probabilities than a remote and unpopulated area. In contrast, sparsely populated areas may be associated with a higher hijack probability. A hijacked vehicle's future route is unpredictable and special precautions may have to be taken to prevent it from having an incident in a densely populated area. As a result, traditional risk assessment-based route planning is no longer adequate. There are few papers on these subjects, but see [188] for probabilistic modeling of terrorist threats, and [118, 120] for incorporation of security concerns in route planning.
- Changes in route planning methodology - Past HAZMAT routing literature focuses on finding a minimum risk route. Unfortunately, the use of quantitative measures and selecting routes accordingly make the routes predictable by terrorists. To minimize the probability of a successful terrorist attack or hijacking, shippers should use alternative routes. A game theory approach can be applied determine the best way of either alternating the routes or switching from one to other ones en-route time to minimize predictability. In this context, video surveillance, global positioning systems and communication equipment installed on all HAZMAT vehicles allow the precise tracking of vehicles, but also allow the implementation of such real-time decision making (see, e.g., [97, 237]).

4.2.5 Risk management of HAZMAT transportation

The possibility of accidents requires a risk management process that involves set of crucial logistic decisions referring to, as an example, the organization of the emergency response operations. In fact, the logistical decisions on the routing of HAZMAT vehicles and the emergency response must be integrated [240].

HAZMAT routing constitutes a critical decision in mitigating the associated transportation risk. Rerouting of this traffic, especially toxic inhalation hazard

materials, away from populated areas has received considerable attention in recent years as a means of reducing risk.

However, rerouting on a route-specific basis is neither simple nor necessarily effective at reducing risk because of physical constraints in the configuration of the network and the possible need to increase the miles traveled by hazardous materials so as to avoid populated areas.

Well-defined HAZMAT response policies, procedures and risk management can allow to accurately identify the hazardous material, direct further response and minimize risks.

As a consequence, it is very important to define models to assess the risks relative to the transport of HAZMAT in a quantitative way. The models must evaluate simultaneously the consequences and the frequencies of occurrence of possible scenarios. This makes it possible to assess quantitatively the societal risk (if the distribution of the people liable to be exposed is at hand) and the individual risk.

It is also necessary the development of integrated safety management systems to implement mitigation activities, which seek the reduction of the vulnerability, and prevention activities, which try to reduce the hazard [148].

However, as the consequences of an accident involving hazardous materials can be enormous, researchers are whetted to model the risk associated with this shipment to propose various methods to design suitable routes that present interesting trade-offs between transportation costs and accident risks.

In addition to these concerns, recently the possibility of a HAZMAT incident deliberately caused by terrorists is raising even greater concern. While government agencies have attempted to address the problem with a number of measures and laws that differ from state to state, researchers focus on setting the necessary framework that aims at two complementary goals:

- to model risk parameters and develop methods for quantifying transportation risk and
- to efficiently formulate and solve the problem of routing HAZMAT, so that the risk is minimized without unreasonably increasing transportation cost.

This area of research has recently attracted more interest because of the development of advanced transport systems for sensing and communicating vehicle locations. These technologies provide the ability for real-time decision making in complicated networks. Further, the world-wide concern caused by terrorist activities highlights the need for safer living conditions in every aspect of human activity. Minimizing HAZMAT transportation risk serves this goal. Theoretically, risk management activities can be oriented to deal with specific and defined risk and manage it optimally. Unfortunately, reality is far too complex and resources far too scarce to deal with each risk event individually, as often one hazardous event is linked or related to one or more other hazardous events.

Some events triggered others. As an example, urban degradation caused, e.g., by unplanned urban growth, bad construction practices, or immigration of people from the rural areas, tends to disturb the balance in the urban system, influences the interaction process between different hazards and vulnerabilities increasing vulnerability levels, and then creates new hazards factors [56].

The hazardous materials risk management process involves a set of crucial logistical decisions referring to:

- the planning of the hazardous materials transportation;
- the organization of the emergency response operations.

The inherent interrelationships between the emerging hazardous materials logistical problems imply the integration of routing and emergency response logistical decisions in order to improve the effectiveness of the hazardous materials emergency response process. Public agencies have addressed the problem with series of regulations and safety measures; hazardous materials transported via:

- Rail (RID regulation applies);
- Road (ADR regulation applies);
- Sea (IMDG regulation applies);
- Air, in some cases (ICAO).

Researchers have striven to model the risk associated with shipment of hazardous materials to propose various methods to design suitable routes that present interesting trade offs between transportation costs and accident risks.

The key elements of risk management are divided into two phases: the pre-disaster phase and the post-disaster phase. The pre-disaster phase includes risk identification, risk mitigation, risk transfer, and preparedness; the post-disaster phase is devoted to emergency response and rehabilitation and reconstruction. In Figure 4.3 the key components of disaster risk management are divided into actions required in the pre-disaster phase and actions needed in the post-disaster period [157].

A comprehensive risk management program addresses all these components: they are an integrated, cross-sector network of institutions addressing all the above phases of risk reduction and disaster recovery. Activities that need support are policy and planning, reform of legal and regulatory frameworks, coordination mechanisms, strengthening of participating institutions, national action plans for mitigation policies, and institutional development.

Pre-disaster phase				Post-disaster phase	
Risk identification	Mitigation	Risk transfer	Preparedness	Emergency response	Rehabilitation and reconstruction
Hazard assessment (frequency, magnitude, and location)	Physical/ structural mitigation works	Insurance and reinsurance of public infrastructure and private assets	Early warning systems and communication systems	Humanitarian assistance	Rehabilitation and reconstruction of damaged critical infrastructure
Vulnerability assessment (population and assets exposed)	Land-use planning and building codes	Financial market instruments (catastrophe bonds and weather indexed hedge funds)	Contingency Planning (utility companies and public services)	Clean-up, temporary repairs, and restoration of services	Macroeconomic and budget management (stabilization and protection of social expenditures)
Risk assessment (a function of hazard and vulnerability)	Economic incentives for promitigation behavior	Privatization of public services with safety regulation (energy, water, and transportation)	Networks of emergency responders (local and national)	Damage assessment	Re-vitalization for affected sectors (exports, tourism, and agriculture)
Hazard monitoring and forecasting (GIS, mapping, and scenario building)	Education, training and awareness about risks and prevention	Calamity Funds (national or local level)	Shelter facilities and evacuation plans	Mobilization of Recovery resources (public, multilateral, and insurance)	Incorporation of disaster mitigation components in reconstruction activities

Figure 4.3: Phases of risk reduction and disaster recovery

In ideal risk management, a prioritization process is followed whereby the risks with the greatest loss and the greatest probability of occurring are handled

first, and risks with lower probability of occurrence and lower loss are handled in descending order.

In practice the process can be very difficult, and balancing between risks with a high probability of occurrence but lower loss versus a risk with high loss but lower probability of occurrence can often be mishandled.

4.3 HAZMAT logistics literature review

The attention to HAZMAT research dates back 1980's, mainly due to growing safety concerns in developed countries (see, e.g., [22, 55, 99, 103, 128, 136, 137, 144, 190, 191, 194, 206, 213, 215, 217, 219, 228, 235]).

After a slight slow-down mainly caused by the difficulty of gathering accurate and relevant data, it has recently gained emphasis again (see, e.g., [9, 11, 25, 33, 39, 40, 61, 69, 74, 75, 77, 79, 118, 118, 134, 238]).

This renewed interest is also owed to two factors that have acquired more and more importance in the recent years: sustainability and equity. Sustainability is the long-term compatibility between the economic and the environmental and the social dimensions of development [15].

According to Keeney [136], Equity regards the public sensitivity to HAZMAT as the beneficiaries from these shipments are usually those who live near production facilities or the delivery points, yet also the populations living along HAZMAT routes are also exposed to transportation risks (see, e.g., [57, 137, 165]).

This lack of burden-benefit concordance is typical source of public opposition to hazardous material shipments. The shipment of spent nuclear fuel offers a good example of equity-based public opposition ((see, e.g., [52, 53, 87, 102, 172, 175, 179, 212, 215, 231]).

4.3.1 Special issues of journals

The following journal have had special issues either devoted or strictly related to HAZMAT transportation.

- *Management Science* published a special issue on Risk Analysis in 1984 (Vol. 30, No. 4) where five papers dealt with HAZMATs and hazardous facilities. This issue was followed by a number of special issues of refereed academic journals that focus on HAZMAT transportation or location problems [31, 98, 144, 219].
- *Transportation Research Record* published two special issues on HAZMAT transportation in 1988 (No. 1193) that included four papers [100, 116, 125, 204] and 1989 (No. 1245) that included six papers [3, 52, 114, 208, 210, 239].
- *Transportation Science* devoted an issue to HAZMAT logistics in 1991 (Vol. 25, No. 2) that contained six papers [101, 158, 160, 161, 200, 233].
- *Journal of Transportation Engineering* published a special section on HAZMAT transportation in the March/April 1993 issue that included four papers [115, 117, 146, 203].
- *INFOR* published a special double-issue on hazardous materials logistics in 1995 (Vol. 33, No. 1 and 2) with nine papers.
- *Location Science* published four papers included in a special issue dealing with HAZMATs in 1995 (Vol. 3, No. 3) [32, 57, 168, 173].
- *Transportation Science* produced a second special issue with seven papers on HAZMAT logistics in 1997 (Vol. 31, No. 3).

- *Studies in Locational Analysis* published a special issue on undesirable facility location in April 1999 (Vol. 12) that contained seven papers.
- *Computers & Operations Research* have published a HAZMAT logistics special issue in 2007 which contains results of the most recent research in the area in 13 papers.

4.3.2 Books

The following books are a good starting point for those who wish to familiarize with the terminology and the problem context.

1. *Transportation of Hazardous Materials* (1993) [176] - This book, edited by L. N. Moses and D. Lindstrom, Kluwer Academic Publishers, issues in Law, Social Science, and Engineering. It contains 18 articles presented at HAZMAT Transport '91, a national conference held at Northwestern University on all aspects of HAZMAT transport. While only a few of the articles use OR models and techniques, the book offers a multi-dimensional treatment of the subject and it is good reading for new researchers in the area.
2. *Institute for Risk Research (IRR), University of Waterloo, Toronto, Ontario, Canada* (1992) - Three books were produced by this Institute as a result of the First International Consensus Conference on the Risks of Transporting hazardous materials, held in Toronto, Canada in April, 1992.
 - Transportation of hazardous materials: Assessing the Risks* [205] - This book, edited by F.F. Saccomanno and K. Cassidy, contains 30 articles which are organized into five main chapters: Application of QRA models to the transport of hazardous materials; Analysis of hazardous materials Accident and Releases; Application of Simple Risk Assessment Methodology; Uncertainty in Risk Estimation; Risk Tolerance, Communication and Policy Implications.
 - Comparative Assessment of Risk Model Estimates for the Transport of hazardous materials by Road and Rail* [207] - This book, edited by F.F. Saccomanno, D. Leming, and A. Stewart, documents the assessment of a corridor exercise involving the application of several risk models to a common transport problem involving the bulk shipment of chlorine, LPG and gasoline by road and rail along predefined routes. The purpose of the corridor exercise was to provide a well defined transportation problem for analysis in order to examine the sources of variability in the risk estimates. Seven agencies in six countries participated in this exercise.
 - Risk and Responsibility* [152] - This book, edit by W. Leiss, and C. Chociolko, documents the controversies over how to manage health and environmental risks.
3. *Hazardous materials transportation risk analysis* (1994) [201] - This book, edited by Rhyne WR, Van Norstrand Reinhold, developes a quantitative approaches for truck and train and it explains the QRA methodologies and their application to HAZMAT transportation. It also provides an extended

example of a QRA for bulk transport of chlorine by truck and train. This detailed example explores every step of the QRA from preliminary hazards analysis to risk reduction alternatives. This book is a valuable reference for HAZMAT transportation risks, and it is intended for practitioners. It is not an OR book, but it provides useful information for OR research in HAZMAT transportation modeling and analysis.

4. *Guidelines for chemical transportation risk analysis* (1995) [43] - This book, edited by American Institute of Chemical Engineers, Center for Chemical Process Safety (CCPS) New York, completes two other books in the series of process safety guidelines books produced by CCPS: Guidelines for Chemical Process Quantitative Risk Analysis (CPQRA, 1989) and Guidelines for Hazard Evaluation Procedures (HEP, 2nd edition, 1992). It is intended to be used as a companion volume to the CPQRA and HEP Guidelines when dealing with a quantitative transportation risk analysis (TRA) methodology. This book offers a basic approach to TRA for different transport modes (pipelines, rail, road, barge, water, and intermodal containers). It can be useful to an engineer or manager in identifying cost effective ways to manage and reduce the risk of a HAZMAT transportation operation.
5. *Quantitative Risk Assessment of Hazardous Materials Transport Systems* (1996) [181] - This book, edited by M. Nicolet-Monnier and A.V. Gheorge, Kluwer Academic Publishers, contains a comprehensive treatment of the analysis and assessment of transport risks due to HAZMAT transport on roads, rail, by ship, and pipeline. It contains European case studies as well as a discussion of computer-based decision support system for HAZMAT transport problems. It is a useful reference book in the area.

4.3.3 Classification

The rest of this section deals mainly with the academic literature consisting of refereed journal articles. The number of papers published between 1982 and 2007s in this area of research has peaked in mid 1990s and has declined somewhat since 2004. In 2007 there is again a grow-up of the importance of the matter and of the number of articles. Given the large number of papers in these last twenty years, the articles deal with different aspects of the problem and can be classified as summarized in Tab. 4.1.

Table 4.1: Main subjects in HAZMAT transportations literature

1. Risk assessment	3. Combined facility location and routing
2. Routing	4. Network design

Most hazardous materials are not used at their point of production and they are transported over considerable distances. From this perspective HAZMAT transportation can be also classified according to the mode of transport, namely: road, rail, water, air, and pipeline, although some shipments are intermodal.

Risk assessment	Road	Jonkman et al. (2003), Nardini et al. (2003), Martinez-Alegria et al. (2003) ^G , Rosmuller and Van Gelder (2003), Abkowitz (2002) ^C , Fabiano et al. (2002), Gheorghe (2002), Kimberly and Killmer (2002), Saccomanno and Haastrup (2002) ^{tunnels} , Hollister (2002), Hwang et al. (2001), Abkowitz et al. (2001), Verter and Kara (2001) ^G , Efroymsen and Murphy (2000), ICF Consulting (2000), Leonelli et al. (1999), Zhang et al. (2000) ^G , Pet-Armacost et al. (1999), Cassini (1998), Mills and Neuhauser (1998), Cutter and Ji (1997), Groothuis and Miller (1997), Lovett et al. (1997) ^G , Pine and Marx (1997), Alp and Zelensky (1996), Ertugrul (1995), Sissell (1995), Chakraborty and Armstrong (1995), Erkut and Verter (1995a) ^U , Erkut and Verter (1995b), Moore et al. (1995) ^G , Spadoni et al. (1995), Verter and Erkut (1995) ^U , Gregory and Lichtenstein (1994), Macgregor et al. (1994), Hobeika and Kim (1993), Sandquist et al. (1993), Harwood et al. (1993), Abkowitz et al. (1992), Glickman (1991), Grenney et al. (1990) ^{DSS} , Kunreuther and Easterling (1990), Chow et al. (1990), Abkowitz and Cheng (1989), Ang et al. (1989), Harwood et al. (1989), Abkowitz and Cheng (1988), Hillsman (1988), Horman (1987), Keeney and Winkler (1985), Scanlon and Cantilli (1985), Pijawka et al. (1985), Kunreuther et al. (1984), Philipson, et al. (1983), Wilmot et al. (1983), Keeney (1980), Shappert et al. (1973)	
	Rail	Anderson and Barkan (2004), Barkan et al. (2007), Barkan et al. (2003), Fronczak (2001), Orr et al. (2001), Dennis (1996), Larson (1996), Glickman and Golding (1991), McNeil and Oh (1991), Saccomanno and El-Hage (1991), Glickman and Rosenfield (1984), Glickman (1983), Saccomanno and El-Hage (1989)	
	Marine	Douligeris et al. (1997), Roeleven et al. (1995), Romer et al. (1995)	
	Air	LaFrance-Linden et al. (2001)	
	Road + Rail	Brown and Dunn (2007), Milazzo et al. (2002), Bubbico et al. (2000), Neill and Neill (2000), Deng et al. (1996), Leeming and Saccomanno (1994), Purdy (1993), Saccomanno and Shortreed (1993), Saccomanno et al. (1989), Vanaerde et al. (1989), Glickman (1988), Swoveland (1987)	
	Road + Rail + Marine	Andersson (1994)	
	Road + Rail + Marine + Air	Kloeber et al. (1979)	
Routing	Local Routing	Road	Akgün et al. (2007), Boulmakoul (2006), Duque et al. (2005), Erkut and Ingolfsson (2005), Huang and Cheu (2004) ^{C,G} , Huang et al. (2003) ^{C,U} , Kara et al. (2003),

Table 4.2

Routing	Local Routing	Road	<p>Luedtke and White (2002)^{C,U}, Marianov et al. (2002), Frank et al. (2000), Erkut and Ingolfsson (2000), Leonelli et al. (2000), Zografos et al. (2000)^{DS}, Erkut and Verter (1998), Tayi et al. (1999)^M, Bonvicini et al. (1998), Marianov and ReVelle (1998)^M, Verter and Erkut (1997), Sherali et al. (1997)^M, Nembhard and White (1997)^M, Erkut and Glickman (1997), Jin and Batta (1997), Verter and Erkut (1997), Erkut (1996), Jin et al. (1996), Ashtakala and Eno (1996)^S, Beroggi and Wallace (1995), Boffey and Karkazis (1995), Erkut (1995), Moore et al. (1995)^G, Karkazis and Boffey (1995), Glickman and Sontag (1995)^M, McCord and Leu (1995)^M, Sivakumar et al. (1995), Beroggi (1994), Beroggi and Wallace (1994), Ferrada and Michel-haugh (1994), Patel and Horowitz (1994)^G, Lassarre et al. (1993)^G, Sivakumar et al. (1993), Turnquist (1993)^{M,S}, Wijeratne et al. (1993)^M, Lepofsky et al. (1993)^G, Beroggi and Wallace (1991), Miaou and Chin (1991), Gopalan et al. (1990a), Chin and Cheng (1989)^M, Zografos and Davis (1989)^M, Abkowitz and Cheng (1988)^M, Batta and Chiu (1988), Vansteen (1987), Cox and Turnquist (1986), Belardo et al. (1985), Saccomanno and Chan (1985), Urbanek and Barber (1980), Kalelkar and Brinks (1978)^M</p>
Routing	Local Routing	Road	
		Rail	Verma and Verter (2005), McClure et al. (1988), Coleman (1984), Glickman (1983)
		Marine	Iakovou (2001), Li et al. (1996), Haas and Kichner (1987)
		Road + Rail	Glickman (1988)

Table 4.2

Routing		Road + Rail + Marine	Weigkricht and Fedra (1995) ^{DSS}
	Local Routing and Scheduling (on Road)	Chang et al. (2005), Meng et al. (2005), Zografos and Androutsopoulos (2004) ^M , Zografos and Androutsopoulos (2002) ^M , Miller-Hooks and Mahmassani (2000) ^{S,T} , Bowler and Mahmassani, (1998) ^T , Miller-Hooks and Mahmassani (1998) ^{S,T} , Suljoadikusumo and Nozick (1998) ^{M,T} , Nozick et al. (1997) ^{M,T} , Smith (1987) ^M , Cox and Turnquist (1986)	
	Global Routing	Road	Carotenuto et al. (2007a,b), Diaz-Banez et al. (2005), Dell'Olmo et al. (2005), Akgün et al. (2000), Marianov and ReVelle (1998), Lindner-Dutton et al. (1991), Gopalan et al. (1990a,b), Zografos and Davis (1989)
		Marine	Iakovou et al. (1999)
Combined facility location and routing	Alumur and Kara (2007), Cappanera et al. (2004), Berman et al. (2000), Giannikos (1998) ^M , Helander and Melachrinoudis (1997), List and Turnquist (1998), Current and Ratick (1995) ^M , Jacobs and Warmerdam (1994), Boffey and Karkazis (1993), Stowers and Palekar (1993), List and Mirchandani (1991) ^M , List et al. (1991) ^U , Revelle et al. (1991), Zografos and Samara (1989), Peirce and Davidson (1982), Shobrys (1981)		
Network design	Erkut and Gzara (2007), Berman et al. (2007), Dell'Orco (2006), Floros et al. (2006), Erkut and Alp (2005), Verter and Kara (2005), Huang et al. (2005), Kara and Verter(2004)		

C: with security consideration; *DSS*: Decision Support System model; *G*: using GIS; *M*: Multiobjective; *S*: Stochastic; *T*: Time-varying; *U*: Survey/Annotated Bibliography

According to Erkut, Tjandra and Verter [80], we believe in a simple classification that can be useful in providing some structure to the rest of the chapter. One possible classification is that in Table 4.3.3.

Although we have offered this simple classification, it is fair to say that numerous papers deal with problems that lie at the intersection of the above areas and such problems are receiving increasingly more attention in the literature. Table 4.3.3 suggests that the HAZMAT transportation problems on highways received the most attention from the operations researchers. In contrast, HAZMAT transportation via air or pipeline, as well as intermodal HAZMAT transportation has received almost no attention.

4.4 Literature review of problems and models

In Tab. 4.3.3 we suggest a schematic classification of the academic literature of HAZMAT that now we review. Rather than giving a detailed separate presentation of each work, we outline the most relevant guidelines emerging from the

literature. We consider separately risk assessment, routing, combined facility location and routing, network design.

4.4.1 Risk Assessment for HAZMAT

Risk is an integral part of the hazardous materials transportation literature. The majority of articles are operations research studies for minimizing risk on a transport route. The risk equations in the OR studies tend to be relatively simple and are often variations on the release probability or the product of release probability and consequences.

Other articles focus on calculating risk as part of QRA studies. These latter articles are typically written by environmental, civil, and chemical engineers who incorporate demographic, meteorological, and chemical databases in calculating risk. These OR and QRA studies are focused on releases that occur on the road or along railways.

There is not a focus on transport-support activities, such as loading or unloading of containers. Although there are differences in the accident scenarios surrounding these two activities, many of the variables and associations and hence the general Bayesian network structures are the same.

The great majority of existing studies attempt to minimize or calculate the risk of potential future occurrences. The HAZMAT literature does not seem interested in modeling the past release incidents to determine the influence of the relevant variables.

One notable exception is a study by Burns and Clemen (1993) [36] in which various sociological, behavioral, and perceptual variables affect the impact of an HAZMAT release, was depicted using an influence diagram. From this perspective, the decision model suggested by Burns and Clemen is unique within the HAZMAT transport literature by virtue of its exploratory, statistical nature.

In general, this literature lacks a focus on data-driven analysis of outcomes relative to the influencing variables. A possible reason of this lack is owed to the fact that past data are not very reliable. Using general truck accident data for HAZMAT trucks overestimates the accident probabilities.

What makes matters worse is that there is no agreement on general truck accident probabilities and conflicting numbers are reported by different researchers.

Furthermore, applying national data uniformly on all road segments of similar type is quite problematic since it ignores hot spots such as road intersections, highway ramps, and bridges.

Researchers need to have access to high quality accident probability data and empirical or theoretical research that leads to improvements in the quality of such data should be welcome.

Brown and Dunn (2007) [33] describe a quantitative risk assessment approach for hazardous materials transportation that employs considerable statistical data from past incidents. They illustrate application of this method to evaluating distances to which the public should be protected immediately following an accidental release of toxic materials that pose an inhalation hazard. While this paper focuses on emergency response aspects of the problem, the framework that they describe has applications to societal risk estimation and routing optimization for a wide variety of hazardous materials.

Typically, accident and release probabilities have been estimated for a given road and area type using averaged values, which have limited sensitivity in specific situations (Harwood et al, 1993) [115].

Differently, some recent empirical works suggest the use of fuzzy logic to determine the accident frequency (see, e.g., Bonvicini et al, 1998) [28].

Additional exploratory work on accident probabilities is still needed. There is a lack of agreement [47, 82] on how HAZMAT transport risk should be represented. Risk is described at least from seven different perspectives:

- Accident or Release Probability [3]
 - Probability of a vehicular accident of the HAZMAT truck [5]
 - Probability of a vehicular accident that leads to release [115]
 - Probability of a release [72]
- Consequences [81]
- Consequence Probability [216]
 - Individual Risk [155]
 - Societal Risk ([86])
- Numerical Indices [199]
- Exposure and Product of Exposure [76]
- Expected Value [82]
- Variations on Expected Value [126]

However, as already described in Section 4.2 risk is usually assessed in terms of the following high-level variables:

- accident or release probability,
- consequence level,
- population count, and
- exposure amount, such as amount of HAZMAT transported.

Several authors whose risk equations are limited to these high level variables characterize their risk models as *simple* (see e.g. ReVelle et al., 1991, Current et al 1995) [57, 200]). More complex formulations (see e.g. Akgn et al. 2007 [9] for risk assessment include the above high-level variables along with variables such as

- wind probability or
- fatality probability, also known as vulnerability.

In turn, the latter variables are often specified in terms of sub-variables, or input parameters [58]. However, the numerical relationships of the sub-variables to the higher level variables or outcomes are not provided to the reader and are therefore not a discussion focus [155].

For example, Leonelli et al., 2000 [153] suggest that the release probability calls for the use of vehicle type and material type as sub-variables. However, they neither discuss or provide in the article the exact numerical relationship of vehicle type or material type to release probability.

4.4.2 Route Optimization for HAZMAT

In the following we briefly introduce some of the most relevant work dealing with route optimization, i.e. network design, combined facility location and routing, for HAZMAT relevant aspects mentioned in previous research studies. Karkazis and Boffey (1995) [135] focus on the damage induced to the population in case of an accident. In this research study attention is given to the dispersion of the HAZMAT through air. Therefore, the impact area is not defined by a given bandwidth, but is a function dependent on the type of material transported and the meteorological conditions at the moment of the accident.

Akgün et al. (2000) [8] consider the problem of finding a number of spatially dissimilar paths between an origin and a destination in a transportation network. A number of dissimilar paths can be useful in solving capacitated flow problems or in selecting routes for hazardous materials. In this research, a critical discussion of three existing methods for the generation of spatially dissimilar paths is offered, and computational experience using these methods is reported. As an alternative method, the generation of a large set of candidate paths, and the selection of a subset using a dispersion model which maximizes the minimum dissimilarity in the selected subset is proposed. Computational results with this method are encouraging.

Berman et al. (2000) [24] point out the possibility of a significant improvement via relocation of the existing specialized teams, currently stationed at the shipment origins.

Frank et al. (2000) [91] made research study that has considered a simplified approach to quantify risk. This research study focuses in the development of a spatial decision support system for the selection of route for the transport of HAZMAT within the United States of America. The element at risk considered is the population located in the impact area of the possible accident. The impact area is located alongside the route and it extends to both sides of the route up to a predefined bandwidth.

Leonelli et al. (2000) [153] introduce a methodology based on the quantification of individual and societal risk indexes for the selection of optimal route for the transport of HAZMAT. The hazard considered is the accident probability of a HAZMAT transport unit, and the population is considered as the element at risk, being affected in the case of an accident. The population value results from aggregating the population travelling on the transport network and the population located adjacent to the transport network. In a previous article Leonelli et al. (1999) [155] mention that the use of individual and societal risk can give an accurate indication of risk, however to calculate these values, a great amount of data and programming effort is required. Due to this, a number of other simplified risk quantification techniques have been adopted in other research studies some of these are mentioned above.

Zografos and Androutopoulos (2004) [238] consider the population as the element at risk. In this study the population located inside the impact area is assumed to have the same vulnerability value, namely one. The risk for the population is then defined as the product of the individual risk and the total population. The individual risk is assessed only on hazards, vulnerability, and element at risk. The previous results could be generalized assessing the individual risk on the basis of also the accident probability of a HAZMAT transport unit, and the population is considered as the element at risk, being affected in

the case of an accident as proposed by Leonelli et al. (1999).

Chang et al. (2005) [50] describe a method for finding non-dominated paths for multiple routing objectives in networks where the routing attributes are uncertain, and the probability distributions that describe those attributes vary by the time of day. This problem is particularly important in routing and scheduling of shipments of very hazardous materials. The method developed extends and integrates the work of several previous authors, resulting in a new algorithm that propagates means and variances of the uncertain attributes along paths and compares partial paths that arrive at a given node within a user-specified time window. The comparison uses an approximate stochastic dominance criterion.

Diaz-Banez et al. (2005) [64] study the problem of determining a path for a shipment of hazardous materials between a pre-specified origin-destination pair on the plane taking into account minimization of risks during the transportation and cost of the path. Given a source point a , a destination point b , a set S of demand sites (points in the plane) and a positive value I , the authors want to compute a path connecting a and b with length at most I such that the minimum distance to the points in S is maximized. They propose an approximate algorithm based on the bisection method to solve this problem and the technique reduces the optimization problem to a decision problem, where one needs to compute the shortest path such that the minimum distance to the demand points is not smaller than a certain amount r . To solve the decision task, Diaz-Banez, Gomez and Toussaint transform the problem to the computation of the shortest path avoiding obstacles. This approach provides efficient algorithms to compute shortest obnoxious paths under several kinds of distances.

Huang and Fery (2005) [119] study the determination of optimal routes for hazardous material transportation trying to find trade-off solutions among many conflicting objectives in the analysis, such as travel cost, population exposure, environmental risk or security concerns. The authors use as generalized objective the product of the different objective functions and solve a complex shortest path problem that often present several “efficient” solutions. A case study with 8 objective functions has been carried out on a road network in Singapore. A geographical information system is used to quantify road link attributes, which are assumed linear and deterministic for the sake of simplicity. The proposed algorithm derives four significantly different routes, which conform to intuition.

Meng et al. (2005) [170] propose a novel vehicle routing and scheduling problem in transporting hazardous materials for networks with multiple time-varying attributes. It actually aims to identify all non-dominated time-varying paths with fixed departure times at the origin and fixed waiting times at intermediate nodes of the paths for each given pair of origin and destination. Three kinds of practical constraints must also be respected: limited operational time period, limited service time, and limited waiting time window at each node. Based on the assumption of linear waiting attributes at a node, the proposed problem can be transformed into a static multiobjective shortest path problem in an acyclic network reconstructed by the space-time network technique. An efficient dynamic programming method is then developed.

Boulmakoul (2006) [30] analyzes the possible use of telegeomonitoring in HAZMAT transportation. The author proposes a telegeomonitoring system that uses a geographic information system to represent civil infrastructure (urban network, land use, industries, etc.) and a decision support systems technology to assess the risk and to evaluate the K -best paths that minimize transportation

risk. To this end, routing algorithms on graphs are extended to deal with fuzzy risk. In particular, the K -best fuzzy shortest paths.

Dell'Orco (2006) [62] proposes a model of flow propagation, assuming "packets" of vehicles and uniformly accelerated movement. Such an approach allows the author to propose a mesoscopic model of the HAZMAT vehicles movements that appears lifelike in the representation of outflow dynamics and easy polinomiale to solve.

Floros, Ziliaskopoulos and Chang (2006) [88] study the problem of routing hazardous material on a multimodal network with time-varying link travel times and intermodal options. The problem is formulated as a Dynamic Program and an intermodal/multimodal shortest path algorithm is modified to compute minimum risk paths by combining the available transport modes, while accounting for transfer delays and transportation costs. The algorithm is implemented on a test network to observe changes in the solution under different scenarios. Computational performance is evaluated on networks of different sizes and the algorithm's efficient running time makes it appropriate for use on realistic networks for both planning and real-time operations.

Akgn et al. (2007) [9] focus on the effects of weather systems on HAZMAT routing. They start by analyzing the effects of a weather system on a vehicle traversing a single link. This helps characterize the time-dependent attributes of a link due to movement of the weather systems. This analysis is used as a building block for the problem of finding a least risk path for HAZMAT transportation on a network exposed to weather changes. Several methods are offered to solve the under-lying problem, and computational results are reported. Two conclusions are drawn from this paper: (1) it is possible to determine the time-dependent attributes for links on a network provided that some assumptions on the nature of the weather system are made; (2) heuristics can provide effective solutions for practical size problems while allowing for parking the vehicle to avoid weather system effects. technologies (4) how to route waste residues to disposal centers. The model has the objective of minimizing both the total cost and the transportation risk.

Alumur and Kara (2007) [11] propose a new multiobjective location-routing model that is object of a large-scale implementation in the Central Anatolian region of Turkey. The aim of the proposed model is to answer to the following questions: (1) where to open treatment centers and with which technologies, (2) where to open disposal centers, (3) how to route different types of hazardous waste to which of the compatible treatment technologies (4) how to route waste residues to disposal centers. The model has the objective of minimizing both the total cost and the transportation risk. The model proposed is manageable for a realistic problem in the Central Anatolian region of Turkey. Given that the hazardous waste management problem is a strategic one that will be solved in-frequently, the authors believe that the computational effort is reasonable for problems with up to 20 candidate sites and that the application is a few orders of magnitude better than other applications in the literature. Most of the papers present applications for small problems such as with 10 or 15 generation nodes and with 3 or 4 candidate sites, whereas Alumur and Kara applied their model with 92 generation nodes and with 15 and 20 candidate sites. As another research direction, the authors suggest that they can include other objectives of the hazardous waste management problem in their model. For example, one can maximize the energy production after the incineration process. Differently,

one can minimize the risk due to the location of the treatment facility. When multiple objectives are considered, the model can be managed with different multi-objective solution techniques. Alumur and Kara propose a relatively simple multi-objective solution technique for ease of application. Apart from the different objectives, one can expand the mathematical model so that the locations of the recycling facilities and the corresponding routing strategies are also determined. Lastly, a multi-period version of the model can be used to schedule the processing of different types of waste. In this case, the compatibility constraint will gain more importance. That is, any new model should not allow wastes that are not compatible with each other to be transported or incinerated at the same time.

Berman et al. (2007) [25] study how undesirable consequences of hazardous materials incidents can be mitigated by quick arrival of specialized response teams at the accident site. They present a novel methodology to determine the optimal design of a specialized team network so as to maximize its ability to respond to such incidents in a region. They show that this problem can be represented via a maximal arc-covering model. They discuss two formulations for the maximal arc-covering problem, a known one and a new one. Through computational experiments, the authors establish that the known formulation has excessive computational requirements for large-scale problems, whereas the alternative model constitutes a basis for an efficient heuristic. The methodology is applied to assess the emergency response capability to transport incidents, that involve gasoline, in Quebec and Ontario.

Carotenuto et al. (2007a) [40] study the problem of managing a set of HAZMAT requests in terms of HAZMAT shipment route selection and actual departure time definition. For each HAZMAT shipment, a set of minimum and equitable risk alternative routes from origin to destination points and a preferred departure time are given. The aim is to assign a route to each HAZMAT shipment and schedule them on the assigned routes in order to minimize the total shipment delay, while equitably spreading the risk spatially and preventing the risk induced by vehicles travelling too close to each other. This HAZMAT shipment scheduling problem is modeled as a job-shop scheduling problem with alternative routes. No-wait constraints arise in the scheduling model as well, since, supposing that no safe area is available, when a HAZMAT vehicle starts travelling from the given origin it cannot stop until it arrives at the given destination. A tabu search algorithm is proposed for the problem, which is experimentally evaluated on a set of realistic test problems over a regional area, evaluating the provided solutions also with respect to the total route risk and length.

Erkut and Alp (2007a) [74] consider the problem of designating HAZMAT routes in and through a major population center. Initially, they restrict the attention to a minimally connected network (a tree) where we can predict accurately the flows on the network. They formulate the tree design problem as an integer programming problem with an objective of minimizing the total transport risk. Such design problems of moderate size can be solved using commercial solvers. Then they develop a simple construction heuristic to expand the solution of the tree design problem by adding road segments. Such additions provide carriers with routing choices, which usually increase risks but reduce costs. The heuristic adds paths incrementally, which allows local authorities to trade off risk and cost. Erkut and Alp use the road network of the city of Ravenna, Italy,

as a case study.

Erkut and Alp (Erkut et al. 2007b) consider an integrated routing and scheduling problem in HAZMAT transportation when accident rates, population exposure, and link durations on the network vary with time of day. They minimize risk subject to a constraint on the total duration of the trip and allow for stopping at the nodes of the network. The authors consider four versions of this problem with increasingly more realistic constraints on driving and waiting periods, and propose pseudo-polynomial dynamic programming algorithms for each version. They use a realistic example network to experiment with their algorithms and provide examples of the solutions generated. The computational effort required for the algorithms is reasonable, making them good candidates for implementation in a decision-support system. The en-route stops allow us to take full advantage of the time-varying nature of accident probabilities and exposure and result in the generation of routes that are associated with much lower levels of risk than those where no waiting is allowed.

Chapter 5

A Risk Analysis Model for HAZMAT Transportation on Motorway

In this section will be presented a model for the calculation of the Individual and Societal risk derived from transport of HAZMAT by road, and on motorway in particular.

5.0.3 What is the risk derived from transport of HAZMAT by road

Both historical evidence and provisional calculations have shown that the risks arising from the transportation of HAZMATs are often of the same magnitude of those ones due to fixed installations, and thus need to be taken into account with the same attention in order to keep them under control and to reduce them.

Among the different means used to transport hazardous materials, the road system represents an increasingly pressing problem due to the constant increase of the amount of HAZMAT shipments.

Transportation of HAZMAT on road actually represents a potentially high risk with regard to:

- the nature of the HAZMAT carried by trucks and the physiochemical events associated with these materials (radioactivity, explosion, toxicity, corrosion etc.)
- the nature, the localization and the density of the stakes (population, economic activities, buildings, networks, infrastructures, natural areas etc.)
- the characteristics and state of the roads (topography, layout, presence of tunnels etc.)
- the density of the traffic, and the environmental conditions (weather, natural events etc.)

HAZMAT type, quantity, itinerary and delivery time are not precisely known by the public authorities, the highway companies, the territorial collectivities, the population.

One of the main objectives of research in this field is to provide appropriate answers to the safety management of HAZMAT shipments, in collaboration with the principal parties involved in the goods transportation process.

5.0.4 How to characterize the risk in transport of HAZMAT by road

As presented in Section 4.4, research in this area focuses on two main issues:

1. to assessing the risk induced on the population by HAZMAT vehicles traveling on various segments of the road network;
2. to involve the selection of the safest routes to take.

A lot of work in risk assessment has already been done by modeling risk probability distribution over given areas, for example, by taking into account the risk related to the transported substance and the transport modality [1] as well as the environmental conditions [189].

Moreover, as useful tools, *map algebra* techniques from Geographic Information Systems (GIS) allow us to combine mathematically the concentration of HAZMAT releases into the environment with population distribution in order to estimate the risk when airborne contamination happens [236].

Given the incident probabilities on unit segments of a network, an analysis of different risk models associated to a route is given in [82]. In that paper, it is highlighted that one of the most popular risk model used by researchers and practitioners is the societal risk, this being the product between the incident probability per unit length and the incident consequence, which is evaluated as the population in the impact area.

One widely used assumption, based on the λ -neighborhood concept, is that the impact area is a circle centered in the incident location with a substance-dependent radius λ [20].

The main problem related to this issue is that of finding minimum risk routes while limiting and spreading the risk equitably over any zone. As a matter of fact, risk equity has to be taken into account whenever several HAZMAT shipments take place from a given origin to a given destination.

In this situation, the planning effort not only has to be directed toward minimizing the total risk, but also has to be devoted to distributing risk uniformly over all the zones of the geographical crossed region.

This concept is well defined by Keeney in [136], where a measure of the collective risk is determined with explicit reference to *equity*.

5.1 The Model and its Parameters

Motorway is a term for both a type of road and a classification or designation.

Motorways are *high capacity roads* designed to carry fast motor traffic safely. In the E.U. they are predominantly:

- dual-carriageway roads;

- with a minimum of two lanes in each direction;
- all have grade-separated access.

Motorways are comparable with North American freeways as a road type, and interstates as a classification.

The model derives from the application of the quantitative risk assessment methodology presented in Figure 5.1.

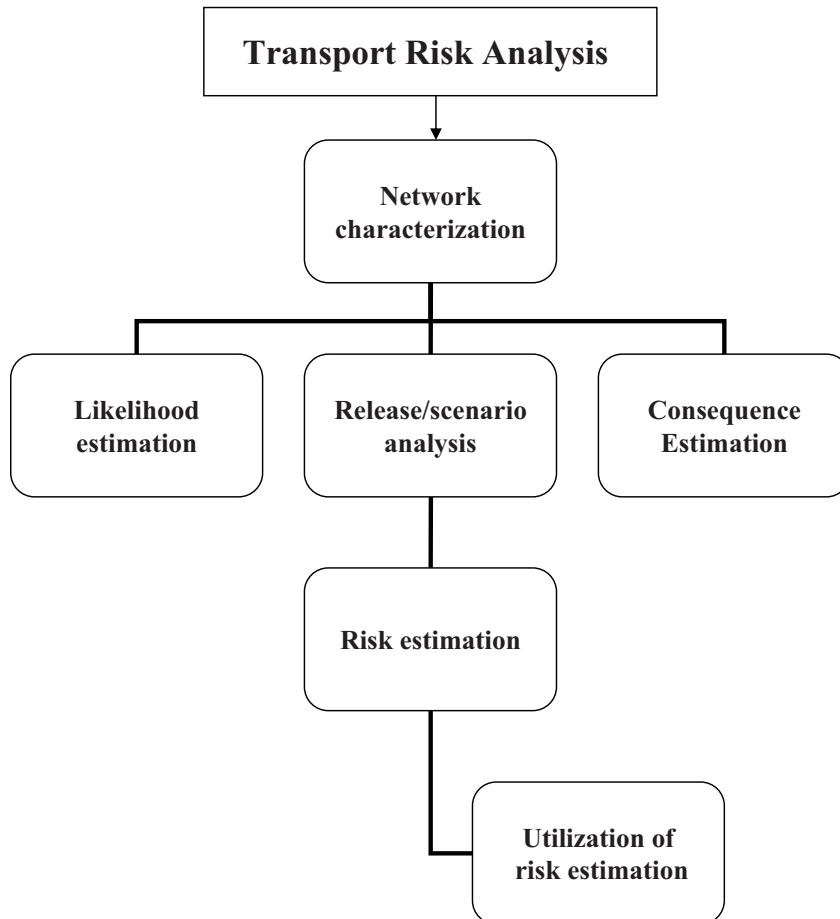


Figure 5.1: The Transport Risk Assessment Methodology

We must take into consideration the following cause-effect chain which can be associated to a vehicle transporting one or more dangerous substances i.e. HAZMATs:

1. the vehicle may be subject to a road accident (*accident*);
2. the accident may cause the release of material transported (*release*).
3. the release may cause a series events (*incident*).

- the incident has an effect in the area surrounding the point accident.

The model refers to damage to persons and in particular to death.

The model of risk assessment derived from road transport of HAZMAT is presented by a schematic representation in Figure 5.2. Risk assessment is typi-

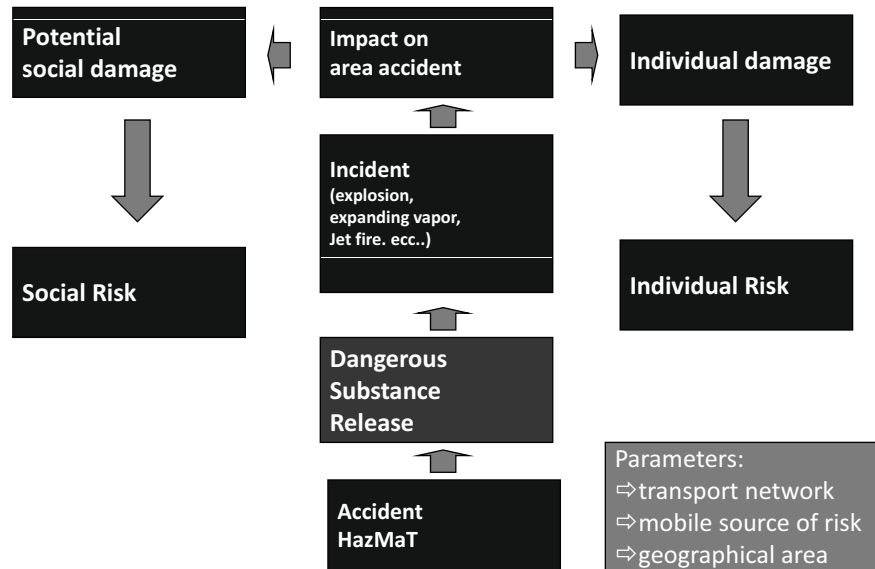


Figure 5.2: The Risk Assessment Model

cally structured as a process resulting from the interaction between:

- the transportation network (in this case motorway);
- the vehicle (or better the traveling risk source);
- the impact area.

5.1.1 QRA Model of HAZMAT Transportation by road

The main purpose of the QRA model is to assess the risks relative to the transport of HAZMAT in a quantitative way. The model evaluates simultaneously the consequences and the frequencies of occurrence of possible scenarios.

This makes it possible to assess quantitatively the *individual risk* and the *societal risk* (if the distribution of the people liable to be exposed is at hand).

A complete assessment of the risks due to HAZMAT by road would require to consider:

- all the possible weather situations;
- all the kinds of accidents, with
- all the types of vehicle partially or fully loaded.

Such an evaluation is completely impossible and some simplifications have to be introduced. The QRA model is based on the following steps:

- Choice of a restricted number of HAZMATs.
- Choice of some representative accidental scenarios implying those HAZMAT with their usual packagings.
- Identification of physical effects of those scenarios for an open air or a tunnel section.
- Evaluation of their physiological effects on road users and local population.
- Taking into account of the possibilities of escape/sheltering.
- Determination of the yearly frequency of occurrence for each scenario.

F/N curves and their expected values are the major outputs of the QRA model. They are defined as follows:

- *Frequencies / Gravity curves (F/N curves)*: stand for the annual frequency of occurrence F to have a scenario likely to cause an effect (generally, the number of fatalities) equal to or higher than N .
- *Expected value (EV)*: number of fatalities per year, obtained by integration of a F/N curve.

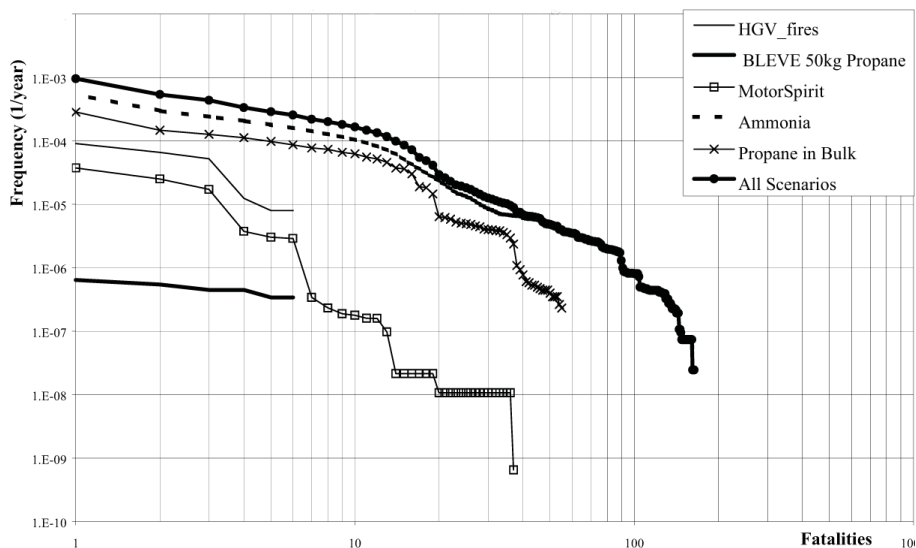


Figure 5.3: Example of $F(N)$ curve for a given route

5.1.2 Frequency evaluation of an hazardous event

For an effective approach to risk modeling, a proper evaluation of the expected frequency is the starting point. The frequency of an accident on the i -th road stretch can be expressed by the followings (?? and (5.2):

$$f_i = \gamma_i L_i n_i \quad (5.1)$$

$$\gamma_i = \gamma_0 \sum_{j=1}^6 h_j \quad (5.2)$$

where:

- γ_i is the expected frequency on i -th road stretch (accident km^{-1} per vehicle);
- L_i is the road length (km);
- n_i is the vehicle number (vehicle);
- γ_0 is the basic frequency (accident km^{-1} per vehicle);
- h_j is the local enhancing/mitigating parameters.

The frequency of an accident evolving according to a scenario S , on the i -th road stretch, can be expressed as in (5.3):

$$f_{i,S} = \gamma_i L_i n_i P_S P_I \quad (5.3)$$

where:

- P_S is is the probability of evolving scenarios of type S , following the accident initializer (i.e. collision; roll-over; failure etc.);
- P_I is the ignition probability for flammable substances involved in the accident.

In dealing with the magnitude of the accident, it seemed important to include both the motorists on the road and the off-route population. The number of fatalities N_S caused by the accident evolving according to a scenario S , on the i -th road stretch, can be calculated according to following equations:

$$N_S = N_{S1} + N_{S2} \quad (5.4)$$

$$N_{S1} = k (\nu A_{L,1}) \quad (5.5)$$

$$N_{S2} = D (A_{L,2}) \quad (5.6)$$

where:

- N_{S1} is the fatality number (fatalities);
- ν is the vehicle density on the road area (vehicle m^{-2});
- k is the average vehicle occupation factor;
- $A_{L,1}$ is the road lethal area (m^2);
- N_{S2} is the off-road fatality number (fatalities);
- $(A_{L,2}$ is the lethal area (km^2);
- D is the population density (inhabitants $\times \text{km}^{-2}$).

When considering the different concurrent scenarios y and j (i.e. toxic release and delayed ignition), in order to avoid overestimation, the total lethal area will be considered as

$$A_{L,t} = A_y + A_j - \left[A_y \cap A_j \right] \quad (5.7)$$

5.1.3 The transportation network characterization

We assume that the transport network, i.e. the motorway, can be considered as a set of arcs (*links*) and nodes (*nodes*). When performing the transportation *risk analysis* each link has to be characterized by some properties.

According to Leonelli et al. (1999) [155], let N_{link} a set of links of the motorway network and l a generic link. The “link properties” to take into account are the following.

1. The geographical position in the impact area; to do this a Cartesian reference frame X/Y with origin $O_{X/Y}$ has to be arbitrarily overlapped on the impact area.
2. The transportation network typology to which the link belongs (in this case the road network otherwise rail, inland waterway or pipeline).
3. The amount of the yearly shipments $N_{ship}(l, \nu)$ traveling on each link l of the motorway for each “vehicle typology” ν , i.e. on a specific conveyance means carrying a specific substance;
4. The incident frequency $\lambda_{inc}(l)$, expressed in events/(km.vehicle), for each road; this variable is generally a function of the route features, the traffic conditions, the environmental conditions, and driver status [86, 114]. The *release frequency* $\lambda_{rel}(l)$ of a traveling vehicle could be evaluated as the product of the incident frequency of the link and the release probability from the vehicle traveling on that link.

In the calculation procedures here presented each *link* has to be *straight* and each link must have *uniform* properties at all its points; this condition can easily be obtained without any loss in generality by adding fictitious nodes to the network.

In a motorway, each stretch is characterized by substantially rectilinear link from toll to toll station. As a consequence, it is possible to consider the access / exit points of the motorway as network nodes .

Since link properties can have considerable changes over the year, the calculation procedure will subdivide the year into smaller periods (N_{seas}), which we refer to as “seasonal situations” ($j = 1, N_{seas}$) and will assign different link property values for each season.

As an example, road shipments can be limited to daylight hours, or the incident frequency can be greater in fall and winter. In this way $\lambda_{inc}(l)$, $\lambda_{rel}(l)$ and $N_{ship}(l, \nu)$ become a function of the seasonal situation j too. They are marked, respectively, with:

$\lambda_{inc}(l, j)$	i.e. the probability of accident;
$\lambda_{rel}(l, j)$	i.e. the probability of release;
$N_{ship}(l, \nu, j)$	i.e. the amount of the yearly shipments;
$p_{wind}(i, k, \vartheta)$	i.e. the density of probability of wind direction

5.1.4 The vehicle or traveling risk source characterization

As already mentioned in Section 4.2, a transportation route can be viewed as a linear risk source, since a release can occur at each of its points.

This means that each of its points can be considered as a *point risk source*, or, in other words, the generic vehicle has to be considered as a traveling risk source.

Therefore, in transportation risk analysis the second step is the vehicle or traveling risk source characterization.

In order to perform this description, the concept of “vehicle typology” has to be introduced.

“Vehicle typology” is a certain kind of vehicle conveying certain kind of HAZMAT which could caused hazard if a release occurs during the transportation. For example, a truck tanker conveying ammonia is a kind of vehicle typology.

A generic “vehicle typology” ϑ and $N_{veh}(l)$ different typologies traveling on each link l are considered.

More pairs “link-vehicle typology” can be generally defined for each link, since more “vehicle typologies” can travel on it. For each traveling risk source the following parameter has to be evaluated:

- the release probability $p_{rel}(l, \nu)$ for each road “vehicle typology”, that is the probability of having a release once an incident has happened ($p(R|A)$). Vehicle construction standards are obviously different for different transportation modalities, and, for a single transportation mode, strongly depend on the features of the transported substance; in other words the release probability depends on the “vehicle typology”. Furthermore it can also depend on the link l , since, for instance, it can be greater on high speed than on low speed route segments.

It is worth noting that coupling the transportation characterization of road links with proper release probabilities allows us to calculate each $f_{rel}(l, \nu, j)$, i.e. is the frequency of having a release from a specified “vehicle typology” ν on a specified link (l) in a specified season (j). In fact it results in (??):

$$f_{rel}(l, \nu, j) = N_{ship}(l, \nu, j) \cdot \lambda_{inc}(l, j) \cdot p_{rel}(l, \nu) \quad (5.8)$$

In order to identify and quantify accidental scenarios referred to each traveling risk source the following parameters are required.

1. The transportation conditions for each substance, i.e., the temperature and pressure values at which the substance is stored in the transportation vehicle and the vehicle capacity.
2. The sizes of the equivalent holes which have been chosen to describe all possible releases from each “vehicle typology”. For each “vehicle typology” and for each rupture size a physical aspect of the outcome and a release rate, or a release quantity in case of instantaneous release, have to be evaluated. Each vehicle typology can lead to $N_{out}(\nu)$ final outcomes (i is the generic one).
3. The final outcomes to which each hole size of each “vehicle typology” typology can lead, that is if:
 - a toxic cloud arises;
 - an explosive one (BLEVE (Boiling Liquid expanding vapor explosion, UCVE (Unconfined Vapor Cloud Explosion));
 - a pool flame;
 - a jet-fire and so on.
4. The probability of having the final outcome i once a release has occurred, $P_{out}(i)$, i.e., the product of the probability of the release being of a specific equivalence size, once the release has occurred, and the probability of having final outcome, once the release of this specific equivalence hole has occurred.

Examples of vehicle characterizations can be found in [154, 220] and in Advisory Committee on Dangerous Substances (1991)[185].

5.1.5 The impact area characterization

The impact area characterization includes both the definition of some parameters which influence the release effects evaluation and the description of the population distribution.

5.1.5.1 Parameters influencing the effects evaluation

To perform the release effects evaluation it is necessary to define:

- some physical parameters, like the air temperature and air humidity; the average terrain roughness, the terrain typology, the grade of confinement and so on;
- meteorological conditions characterizing the impact area, given by N_{met} pairs “atmospheric stability classwind speed”, (the generic one is marked with k);
- the wind probability density distribution $p_{wind}(j, k, \vartheta)$, that is the wind rise in the impact area, for each meteorological condition k and seasonal situation j . The angle θ is used to mark a generic wind direction.

All the parameters influencing the effects evaluation can vary from zone to zone of the impact area, especially when considering very large areas, and the procedure takes into account these variations.

5.1.5.2 Population distribution

The distribution of the population on the impact area is an essential input for calculating societal risk.

The described procedure very accurately describes the people living in the impact area, and, furthermore, takes into account that people can be indoors at the occurrence of a release, being somewhat sheltered from the accident consequences.

A generic “population map”, which is an input to the procedures, is composed of zones, where people may be considered uniformly distributed, and of aggregation centres, where people are clustered.

Zones with uniform population density can have rectangular shape or can be linear; rectangular areas describe, for example, residential quarters where the off-route population is living, while linear zones represent the road network, on which motorists, which constitute the on-route people, are present.

The total number of rectangles and the generic rectangle are marked, respectively, with N_A and n ; the total number of lines and the generic line with N_L and m .

For each zone it is necessary to know the geographical position, the uniform population density (ρ_{A_n} , persons/m² for rectangles; ρ_{L_m} , persons/m for segments), and, for each zone, the fraction of people being indoors (x_{A_n} , for rectangles and x_{L_m} for segments).

Centres of particular interest from the risk analysis point of view, like schools, hospitals, commercial centres are better described as points in the impact area where people may be considered as clustered.

Properties of aggregation centres are the geographical position, the number of persons and their probability of being indoors.

The generic aggregation centre is marked, with o ; the total number of such centres with N_C ; the fraction of persons being indoors with (x_{C_o} ; and the total number of persons in each centre with P_{C_o}).

The population distribution can change dramatically over the year: for example, on-road population can be higher on day than on night; schools and commercial centres are empty during the night; schools are furthermore empty in summer; bathing villages have high population density only in summer.

To describe such changes the societal risk code can handle different “population maps”, one for each season: this means that the previously defined variables ρ_{A_n} , ρ_{L_m} , P_{C_o} , x_{A_n} , x_{L_m} and x_{C_o} are a function of the seasonal situation j .

AS there was inability to obtain data of a certain relevance and significance about the traffic and the population density on the traditional roads in the geographical reference, in this thesis only links that form the network are considered as linear zones.

Furthermore, as a motorways are high capacity roads with a minimum of two lanes in each direction, we consider each link as a pair of links.

Furthermore, we consider each carriageway of the two directions characterized by its specificity (i.e. traffic, building sites, geometric characteristics, etc..). Ultimately, we take into account the following:

ν	is a generic “vehicle typology” on each link l ;
$N_{veh}(l)$	is a different typologies traveling on each link l ;
$p_{rel}(l, \nu)$	is the the release probability for each “vehicle typology” i.e that is the probability for each traveling risk source of having a release once an incident has happened;
$f_{rel}(l, \nu, j)$	is the frequency of having a release from a specified “vehicle typology” on a specified link in a specified season;
$N_{out}(\nu)$	are the final outcomes foe each “vehicle typology” (i is the generic one);
$P_{out}(i)$	is the probability of having the final outcome once a release has occurred.

5.1.5.3 Preliminary input data evaluation

The procedures for evaluating individual and societal risks require the input data described above. Data usually have to be derived from very different sources, for instance:

- “population maps” can easily be constructed once census data are known;
- meteorological parameters can be derived from the data gathered at meteorological stations;
- accident frequencies and the final outcomes probabilities from data banks or open literature;

An exhaustive list of data sources about the link and vehicle characterization can be found in [43].

5.1.6 “Vulnerability Maps” construction

Input data are, among others, the “vulnerability maps”, whose construction is described in this section.

The vulnerability is the probability of suffering a certain typology of damage, which can be a minor injury, a major one or even a lethal one; in this thesis we well refer to the vulnerability as the probability of incurring death after a release has occurred.

As explained in Section 5.1.4, all the release cases that a “vehicle typology” can have are described by taking into account a discrete number of equivalent holes.

Each equivalence hole can produce different $N_{out}(\nu)$ final outcomes which can take place at all $N_{met}(j)$ meteorological conditions possible for the impact area.

This means that each “vehicle typology” produces different pairs “final outcome meteo condition”, the distribution of effects of which has to be evaluated using consequences models [224]. These effects can be, depending on the final outcome they refer to toxic gas concentrations, thermal radiations and blast over-pressures, and they have to be evaluated both outdoor and indoor.

An exhaustive discussion about this topic can be found in [43]. To perform these effects evaluations, each “vehicle typology” has to be considered as a point risk source at a generic point $Q(t)$, where t is a straight route abscissa drawn along the link.

Let us consider a Cartesian reference ξ/η with the origin $O_{\xi/\eta}$ at $Q(t)$ and ξ as the downwind direction, and an arbitrary grid on this reference, in order to evaluate the effects at its points. Combining these effects with proper exposure times the corresponding received doses are obtained, and doses are converted into vulnerabilities through *probit equations*.

In this way for each “outcome meteo pair” a vulnerability distribution around $Q(t)$ is obtained and stored in “vulnerability maps”. Probit equations give exactly zero vulnerability values only at infinite distance from the risk point source; since in reality there is no harm probability indeed at a finite distance from the accident location, vulnerability values less than a fixed limit value (equal to 1025 events/yr, for instance) can be considered as negligible. In Figure 5.4 a representation of a “vulnerability map” is given. For each “outcome meteo

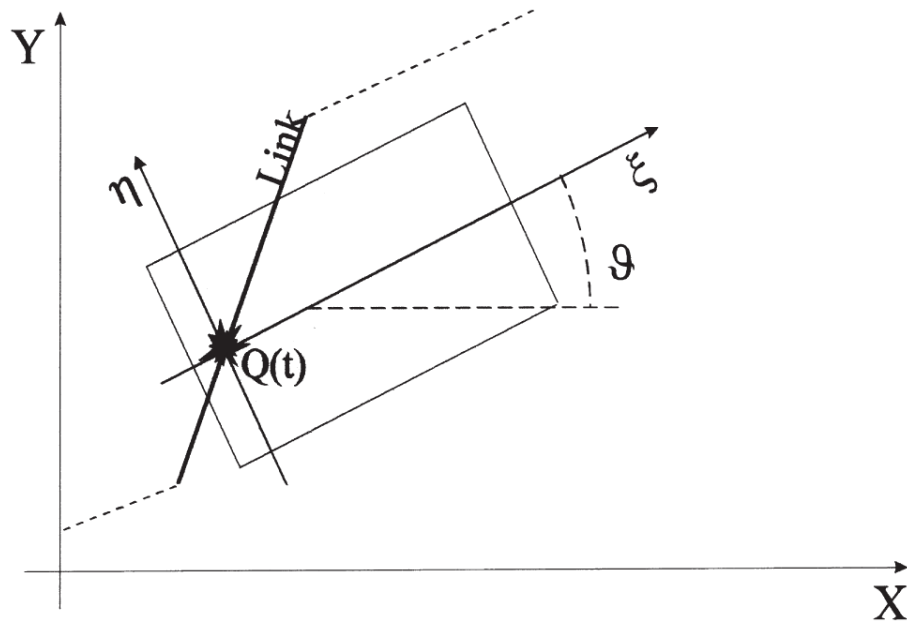


Figure 5.4: X/Y and ξ/η frames and “vulnerability map representation”

pair”, “vulnerability maps” do not depend on the population distribution, but only on the vehicle characterization and on the physical parameters of the impact area. As a consequence the total number of “vulnerability maps” for each “vehicle typology” is given by the product of $N_{out}(\nu)$ and $N_{met}(j)$.

Note that the grid on which the vulnerability is evaluated need not be the same for all “outcomemeteo pair”, and furthermore, it need not be regular. In order to handle the vulnerability as a continuous point function, vulnerability values in points not belonging to the grid are obtained through a linear interpolation procedure.

In a Motorway Services area both fixed plants and transportation networks involving hazardous materials can be present.

Risks on these areas due to both risk sources can be done with the procedures just presented.

Point risk sources can be really considered as very short linear risk sources, for instance, as links having a length of 1 m.

Therefore, special “vehicle typology” can be defined for these special links. For instance, referring to a petroleum pump and its storage plant of a Motorway Service Areas, each specific vessel storing a specific substance can be considered as a “vehicle typology”.

It means that, through some simple intuitive tricks, the evaluation at the same time of the risks of all risk source typologies can be performed.

5.2 HAZMAT transport on motorway: Individual Risk associated calculation

According to [126] individual risk (IR) is defined as the probability that an average unprotected person permanently present at that point location, would get killed due to an accident at the hazardous activity [29].

5.2.1 The single link single vehicle typology IR evaluation

It is very important to notice that IR is additive with respect to the risk source [42].

As a consequence the IR at a point P is given by the sum of the risks created there by each risk source $Q(t)$.

Furthermore each risk source $Q(t)$ creates at P a risk given by the risks due to each “vehicle typology” releasing a hazardous material at $Q(t)$.

Translating this concept in transportation risk analysis means that the risk of a single link is given by the sum of the risks created by all “vehicle typologies” traveling on that link, and that risk values of single links can be summed to give the risk of the whole network.

In addition, when evaluating individual risk, only the outdoor vulnerability has to be considered.

5.2.2 The “rotation algorithm” and the “unit risk map” construction

According to [155], the first step of the procedure is to evaluate the risk created on an impact area by a single “vehicle typology” ν travelling on a single link l .

Let the impact area represented by a vector or raster maps using Geographical Information System (GIS) software.

On the Cartesian plane X/Y (overlapped with the impact area) the examined link l is drawn and on this link a generic point risk source $Q(t)$ is considered which is the origin of the ξ/η plane where the vulnerability distribution has been evaluated, ξ being the downwind direction and θ the angle between X and ξ .

An intermediate variable called “unit risk” is evaluated for all area points around $Q(t)$.

In order to do this, a third Cartesian reference frame ξ'/η' is introduced, having its origin $O_{\xi'/\eta'}$ at $Q(t)$ and axes parallel to those of the geographical reference frame X/Y .

In ξ'/η' a grid is chosen automatically on the base of the smallest distance step of the “vulnerability map” grids related to the “vehicle typology” in examination.

On the points of the ξ'/η' grid an algorithm, called “rotation algorithm”, constructs the “unit risk map”.

First of all it is necessary to evaluate the vulnerability at a point S of the ξ'/η' frame due to a single “outcome meteo pair” (i, k) possible at $Q(t)$ in the seasonal situation j , but taking into account the wind probability density distribution $p_{wind}(j, k, \theta)$ for the meteorological case and seasonal situation in examination, that is taking into account the fact that the wind can blow in each direction θ) with different probability values.

To obtain this “wind direction averaged death probability”, the “vulnerability map” has to be rotated around its origin and the vulnerability $V_{Q(t)\nu \rightarrow S}(i, k, \vartheta)$, which the map assigns at the point coinciding with S at each rotation grade θ), has to be weighted with the wind probability.

Thus the integration of (5.9) must be performed:

$$\int_0^{2\pi} p_{wind}(j, k, \vartheta) \cdot V_{Q(t)\nu \rightarrow S}(i, k, \vartheta) d\vartheta \quad (5.9)$$

The co-ordinates of S in the ξ'/η' frame have to be converted into co-ordinates (ξ_s, η_s) of the “vulnerability map” reference scheme ξ/η for each rotation grade θ . The vulnerability at point (ξ_s, η_s) is $V_{Q(t)\nu \rightarrow S}(i, k, \vartheta)$ since the co-ordinates of S in the ξ/η frame depend on θ , it depends on θ too.

In the implemented numerical procedure the integration of (5.9) is performed with a fixed step Simpson rule [198] taking into account 360 possible wind sectors, each of amplitude equal to 1 degree.

Performing the calculation for all meteorological conditions a sort of wind direction and meteo averaged death probability is obtained for a single final outcome i and for each seasonal situation.

If this is done for all final outcomes possible at $Q(t)$, taking into account their final outcome probabilities once a release has occurred $p_{out}(i)$, the “unit risk” at point S during the season j for the “vehicle typology” ν is obtained.

The “unit risk” $UR_{Q(t) \rightarrow S}(j, \nu)$ due to the point risk source $Q(t)$ at a generic point S of the “unit risk” is defined by (5.10):

$$UR_{Q(t) \rightarrow S}(j, \nu) = \sum_{i=1}^{N_{out}(\nu)} p_{out}(i) \cdot \sum_{k=1}^{N_{met}} \int_0^{2\pi} p_{wind}(j, k, \vartheta) V_{Q(t)\nu \rightarrow S}(i, k, \vartheta) d\vartheta \quad (5.10)$$

Due to the finite dimensions of “vulnerability map”, non-zero “unit risk” values are surely confined inside a circumference centre in $Q(t)$ with radius r equal to the maximum “vulnerability map” dimension, that is to the maximum effect distance, of all “outcome meteo pairs” possible at $Q(t)$. A representation of the “unit risk map” is reported in Figure 5.5.

Once the “unit risk map” has been constructed, it is possible to evaluate the “unit risk” value at a generic point $P(X_P, Y_P)$ due to point $Q(X_Q, Y_Q)$ by simply overlapping the “unit risk map” on the impact area. Resorting to (5.11):

$$\xi' = X_P - X_Q \quad \eta' = Y_P - Y_Q \quad (5.11)$$

the co-ordinates of P in the X/Y frame (X_P, Y_P) are converted in co-ordinates on ξ'/η' frame (ξ'_P, η'_P) : the “unit risk” value at (ξ'_P, η'_P) represents the “unit risk” value at point P .

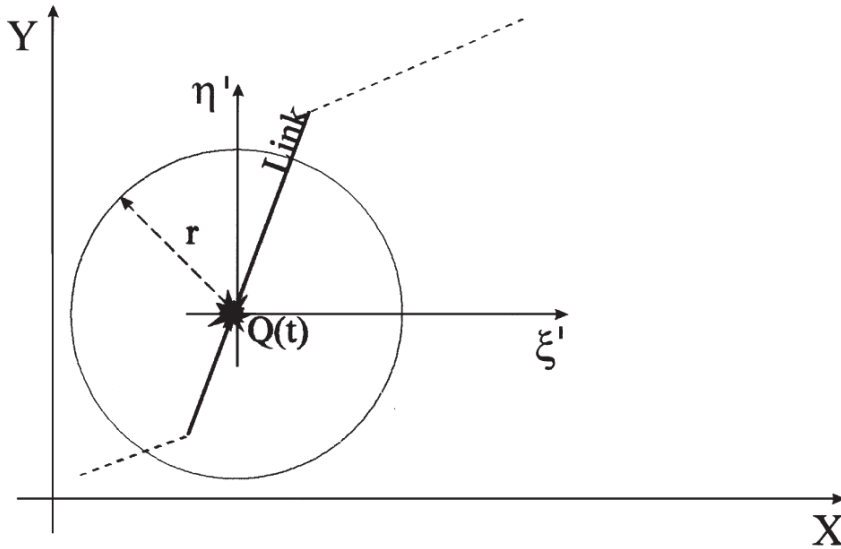


Figure 5.5: Unit risk map representation

5.2.3 The “translation algorithm”

Until now the vehicle has been assumed to be standing at $Q(t)$, as if it were a fixed storage vessel from which a release has occurred.

Thus the successive step is to describe the vehicle movement along the link l , since an accident can occur at each point of the link. This can be made by translating the “unit risk map” along the link.

This means making a linear integration along the route of the “unit risk” value created by $Q(t)$ at an area point P of the X/Y plane, that is evaluating the integral shown in (5.12):

$$\int_{L_l} UR_{Q(t) \rightarrow P}(j, \nu) dt \quad (5.12)$$

where L_l is the route of link l . The value of the integral evaluated in (5.12) represents the death probability at P having taken into account the fact that the vehicle is moving along the link.

In the numerical procedure the integration is performed by means of an adaptive step size Simpson rule, which automatically chooses the number of link points to be taken into account [198].

Once the distance d of point P from the link and the radius r of the “unit risk map” are known, the procedure can identify the segment ab of the link that contributes to the risk at point P , as shown in (5.6), and then it performs the linear integration (5.12) taking into account the ab segment only; in this way the time effectiveness is improved without reducing the accuracy.

By considering the release frequency of the “link vehicle pair” in examination and summing up at all seasons, the individual risk at P created by link l when

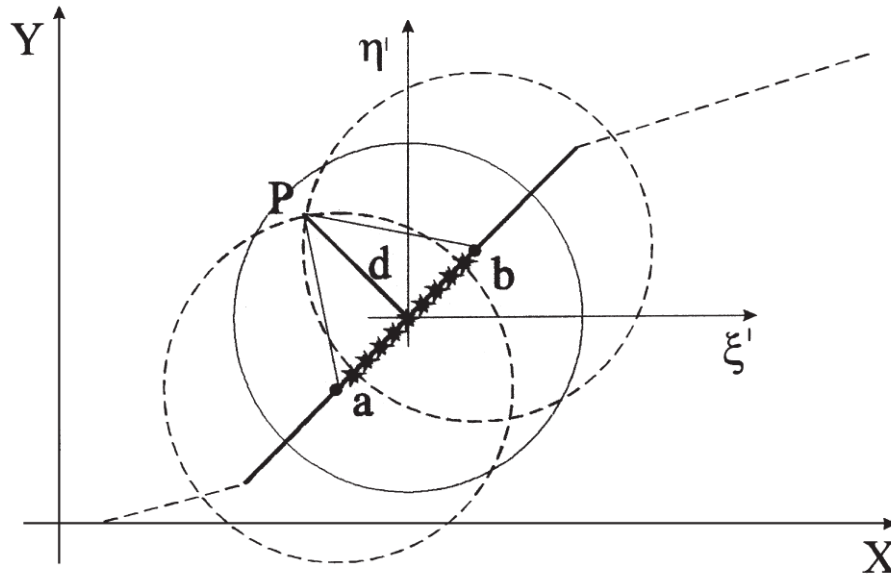


Figure 5.6: “Unit risk map” integration along the route

the “vehicle typology” ν is traveling on it is given; (5.13 is obtained:

$$IR_P(l, \nu) = \sum_{j=1}^{N_{seas}} f_{rel}(l, \nu, j) \int_{L_l} UR_{Q(t) \rightarrow P}(j, \nu) dt \quad (5.13)$$

5.2.4 The all links all vehicle typologies individual risk evaluation

The sum of $IR_P(l, \nu)$ values extended at all “vehicle typology” and all links gives the total individual risk created by the whole transportation network on a point P of the impact area. Its expression is detailed in (5.14):

$$IR_P = \sum_{l=1}^{N_{links}} \sum_{\nu=1}^{N_{veh}(l)} \sum_{j=1}^{seas} f_{rel}(l, \nu, j) \int_{L_l} \sum_{i=1}^{N_{out}(\nu)} p_{out}(i) \sum_{k=1}^{N_{met}} \int_0^{2\pi} p_{wind}(j, k, \vartheta) V_{Q(t)\nu \rightarrow S}(i, k, j) d\vartheta \quad (5.14)$$

5.3 HAZMAT transport on motorway: Societal Risk associated calculation

As noted in the previous Section 4.2.4 an alternative way to describe the Societal Risk (SR) is the use of the so-called $F(N)$ -curves [126], a powerful index of the risk created by a transportation network over an impact area.

Such $F(N)$ -curve are drawn by computing the probability that a group of more than N persons would be impacted due to an HAZAMAT accident, for each (reasonable) value of N .

F is the cumulative frequency of an accident capable of causing the death of N or more persons (in other cases N or more evacuated people).

To calculate $F(N)$ curves, is required , an accurate description of the indoor and outdoor population living in the impact area is required.

As with IR , SR too is additive with respect to the risk source.

Consequently, on an impact area created by a motorway network the SR is given by the sum of risks created on that impact area by each link of the network.

In addition, the risk due to a single link is given by the sum of the risks created by each “vehicle typology” traveling on it.

This leads to a procedure which calculates first the risk created by each “vehicle typology” on each link and then sums all these values.

As the SR is given by a curve, summing societal risk measures implies the sum of F values corresponding to the same abscissa values N .

5.3.1 The concept of “scenario”

The calculation procedure explained in this section is based on the concept of “scenario”. at the point risk $Q(t)$ on a generic link l a scenario is given by the combination:

$Q(t)$	point risk
i	final outcome
k	meteorological condition
j	seasonal situation
θ	wind direction

5.3.2 The “scenario fatalities and frequency”

Resorting to the “outcome meteo pair” introduced above, a scenario can be viewed also as a combination “ $Q(t)$ outcome/meteo pair (i, k) seasonal situation j wind direction θ ”.

That means to each scenario a “vulnerability map” is assigned, the one corresponding to the “outcome meteo pair” (i, k) of the scenario, and that all scenarios having the same “outcome meteo pair” refer to the same “vulnerability map”.

To evaluate the number of people involved in a scenario, the ξ/η frame of the correspondent “vulnerability map” has to be positioned on the impact area, with its origin at $Q(t)$ and the ξ axis positioned as to form with the X axis the exact angle θ of the scenario under examination.

Geographical information systems (GIS) provide an effective framework for estimating these risk parameters [56, 118, 120, 156, 163, 230, 236].

In this way the “vulnerability map” represents exactly the impact zone of the scenario, and the people involved in it are those of the “population map” elements belonging to the scenario impact zone.

The fatalities involved are given by the area integration over this impact zone of the product of the vulnerability at each point with the people density at this point, taking into account also the probability of being indoors.

By rotating the “vulnerability map” around $Q(t)$, all the scenarios referring to the same “ $Q(t)$ final outcome i meteo condition k seasonal situation j ” are taken into account.

A schematic representation of this procedure is shown in Figure 5.7. The

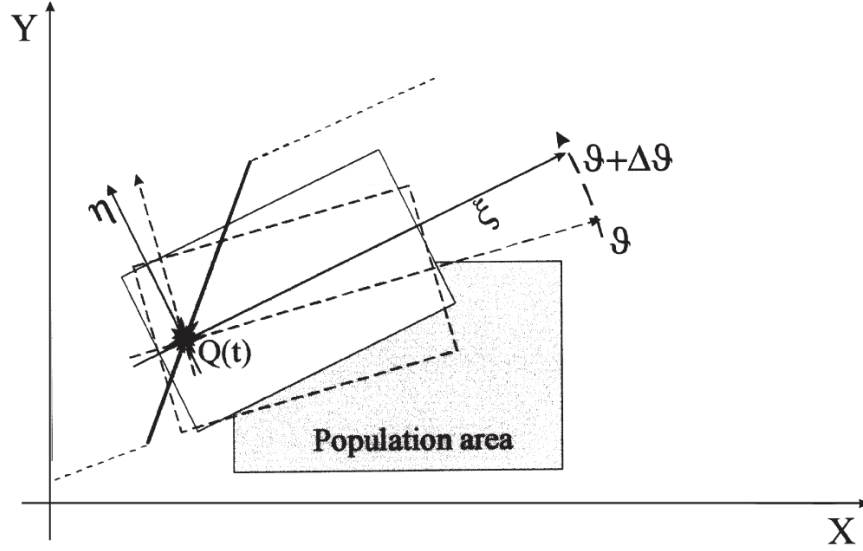


Figure 5.7: Overlapping of a “vulnerability map” with a “population map” element

number of fatalities $N_{Q(t),\nu}^{scen}(i, j, k, \theta)$ due to each scenario when an accident occurs at $Q(t)$ is evaluated according to the following (5.15):

$$\begin{aligned}
 N_{Q(t),\nu}^{scen}(i, j, k, \theta) = & \\
 & \sum_{m=1}^{N_L} \rho_{L_m}(j) \left[X_{L_m}(j) \int_{L_m} V_{Q(t),\nu}^{in}(i, k, \vartheta) dL_m + (1 - x_{L_m}(j)) \int_{L_m} V_{Q(t),\nu}^{out}(i, k, \vartheta) dL_m \right] + \\
 & \sum_{n=1}^{N_A} \rho_{A_n}(j) \left[X_{A_n}(j) \int_{A_n} V_{Q(t),\nu}^{in}(i, k, \vartheta) dA_n + (1 - x_{A_n}(j)) \int_{A_n} V_{Q(t),\nu}^{out}(i, k, \vartheta) dA_n \right] + \\
 & \sum_{o=1}^{N_C} P_{C_o}(j) \left[X_{C_o}(j) V_{Q(t),\nu}^{in}(i, k, \vartheta) + (1 - x_{C_o}(j)) u V_{Q(t),\nu}^{out}(i, k, \vartheta) \right] \quad (5.15)
 \end{aligned}$$

where $V_{Q(t),\nu}^{in}$ and $V_{Q(t),\nu}^{out}$ represent, respectively, the indoor and outdoor vulnerabilities; the meaning of the other symbols has already been explained in Section 5.1.5.2.

In Figure 5.7 the contributions to the number of fatalities of all the “population map” elements are taken into account in a different way.

In fact for those “population map” elements, like roads, where people are linearly distributed, a linear integration is performed using an adaptive step size Simpson rule [198]; while for rectangular zones, where population is uniformly distributed, a surface integration is made.

In the numerical procedure the performance of this surface integral represents the slowest step in evaluating (5.15); in order to accelerate this evaluation without reducing the accuracy, the procedure resorts to a mathematical theorem [198] which allows the quick calculation of surface integrals by performing first a line integration in the ξ direction and then to linearly integrate in the η direction the integral just obtained.

The linear integration in the ξ direction may be performed once for each “vulnerability map” with an adaptive step size trapezoidal rule [198]. First this evaluation is made for grid points and then, through a parabolic interpolation procedure, also for points not belonging to the grid.

In fact the use of a parabolic interpolation, rather than a linear one, avoids increasing the error due to the already performed linear interpolation of the vulnerability values in grid points to obtain vulnerability values in points not belonging to the grid. To warrant accuracy the evaluation of the “scenario fatalities” should be performed for all 360 wind directions considered and for each combination “ $Q(t)$ final outcome i meteo condition k seasonal situation j ”.

The “scenario frequency” is the frequency of having a number of fatalities equal to the “scenario fatalities” $N_{Q(t)l,\nu}^{scen}(i, j, k, \theta)$ it is defined by (ref)

$$f_{Q(t)l,\nu}^{scen}(i, j, k, \vartheta) = f_{rel}(l, \nu, j) \cdot p_{out}(i) \cdot p_{wind}(j, k, \vartheta) \quad (5.16)$$

It is worth noticing that the “scenario frequency” is a frequency per unit length and unit angle, expressed in events/(kmyrgrade).

Furthermore, since a scenario depends on an “outcome meteo pair”, the “scenario frequency” depends on the “release frequencies” defined for this “outcome meteo pair” for the seasonal situations in examination.

5.3.3 The “wind direction cumulated scenario frequency”

Once $N_{Q(t)l,\nu}^{scen}(i, j, k, \theta)$ and $f_{Q(t)l,\nu}^{scen}(i, j, k, \vartheta)$ are known for all scenarios referring to the same “ $Q(t)$ final outcome i meteo condition k seasonal situation j ” combination, it is necessary to evaluate for this combination the frequency of having N or more fatalities by taking into account all wind directions.

This frequency we call the “wind direction cumulated scenario frequency” and we indicate it as $F_{Q(t)l,\nu}(N(i, j, k))$.

Then for a selected number of values N^* of the number of fatalities N , those frequency values which refer to a scenario with fatalities equal or greater than N^* have to be summed to give the value of $F_{Q(t)l,\nu}(N(i, j, k))$ corresponding to N^* .

The following (5.17) is used to evaluate $F_{Q(t)l,\nu}(N(i, j, k))$:

$$F_{Q(t)l,\nu}(N(i, j, k)) = \int_0^{2\pi} \delta_{scen}^N(i, j, k, \vartheta) d\vartheta \quad (5.17)$$

where:

$$\begin{aligned} \delta_{scen}^N(i, j, k, \vartheta) &= f_{Q(t)l, \nu}^{scen}(i, j, k, \vartheta) && \text{for } N_{Q(t)l, \nu}^{scen}(i, j, k, \theta) \geq N^*; \\ \delta_{scen}^N(i, j, k, \vartheta) &= 0 && \text{for } N_{Q(t)l, \nu}^{scen}(i, j, k, \theta) < N^*. \end{aligned}$$

As a consequence of having evaluated the “scenario frequencies” for 360 wind directions, the integral in (5.17) is just a sum extended to all these wind directions.

5.3.4 The simulation of the traveling risk source

To simulate the change in the position where accidents can occur, the evaluation of $F_{Q(t)}(N(i, j, k))$ has to be performed for all points of the link in examination.

The evaluation of the line integral of $F_{Q(t)}(N(i, j, k))$ for each fixed number of fatalities N^* along the link allows a “cumulated link frequency” $F(N(i, j, k))_{l, \nu}$ to be obtained, as shown by (5.18):

$$F(N(i, j, k))_{l, \nu} = \int_{L_l} F_{Q(t)l, \nu}(N(i, j, k)) dt \quad (5.18)$$

In the numerical procedure, in order to reduce the number of link points $Q(t)$ to be analyzed, an adaptive step size algorithm can be conveniently used.

5.3.5 The societal risk reassembling procedures

In order to obtain the link $F(N)_{l, \nu}$ curve for the “vehicle typology” ν traveling on the examined link l , it is necessary to evaluate (5.18) for all the combinations “final outcome i meteorological condition k seasonal situation j ” possible for l , and then to sum them at constant N values.

The outlined $F(N)_{l, \nu}$ calculus is performed for each pair (l, ν) , and eventually the $F(N)_{l, \nu}$ curves are summed at constant N values to obtain the $F(N)$ curve for the whole network.

To make a précis of the whole procedure, the SR created by the whole network on an impact area is given by (5.19):

$$F(N) = \sum_{l=1}^{N_{link}} \sum_{\nu=1}^{N_{veh}(l)} \sum_{i=1}^{N_{out}(\nu)} \sum_{j=1}^{N_{seas}} \sum_{k=1}^{N_{met}} \int_{L_l} \int_0^{2\pi} \delta_{scen}^N(i, j, k, \vartheta) d\vartheta \quad (5.19)$$

being $\delta_{scen}^N(i, j, k, \vartheta)$ defined as in 5.16.

5.4 Tolerable or acceptable risk (ALARP)

The characterization of the objectives of safety and reliability involves the definition of acceptable levels of risk. This acceptability may be related to the possible consequences of adverse events in humans, on the environment or on the system object of the study, depending on the scope.

At international level, there is no uniformity of approach to the definition of criteria of acceptability of risk. The definition of criteria is associated to

economic considerations and social reality in which the source of risk will be placed reflecting the importance that is placed on issues of security. Below are briefly presented some of acceptability criteria commonly adopted as international standards.

We assume the following basic definitions

- Acceptable risk: a risk which everyone impacted is prepared to accept. Action to further reduce such risk is usually not required unless reasonably practicable measures are available at low cost in terms of money, time and effort.
- Tolerable risk: a risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.
- ALARP (As Low As Reasonably Practicable) principle: Principle which states that risks, lower than the limit of tolerability, are tolerable only if risk reduction is impracticable or if its cost is grossly in disproportion (depending on the level of risk) to the improvement gained.
- $F(N)$ curves: curves relating the probability per year of causing N or more fatalities F to N . This is the complementary cumulative distribution function. Such curves may be used to express societal risk criteria and to describe the safety levels of particular facilities.
- Societal risk: the risk of widespread or large scale detriment from the realization of a defined risk, the implication being that the consequence would be on such a scale as to provoke a socio/political response.

5.4.1 ALARP demonstration of requirements

As already mentioned in Section 3.4.8, ALARP stands for “As Low As Reasonably Practicable”, and is a term used in the analysis of safety-critical and high-integrity systems.

The ALARP principle is that the residual risk shall be as low as reasonably practicable (forms part of a Nuclear Safety Justification) is derived from legal requirements in the UK’s Health & Safety at Work Act 1974 and is explicitly defined in the Ionising Radiation Regulations 1999.

The ALARP principle is part of a safety culture philosophy and means that a risk is low enough that attempting to make it lower would actually be more costly than any cost likely to come from the risk itself.

This is called a tolerable risk. The ALARP principle arises from the fact that it would be possible to spend infinite time, effort and money attempting to reduce a risk to zero. It should not be understood as simply a quantitative measure of benefit against detriment. It is more a best common practice of judgment of the balance of risk and societal benefit.

The following factors are likely to be considered when deciding whether or not a risk is tolerable.

- Health and safety guidelines.
- The specification.

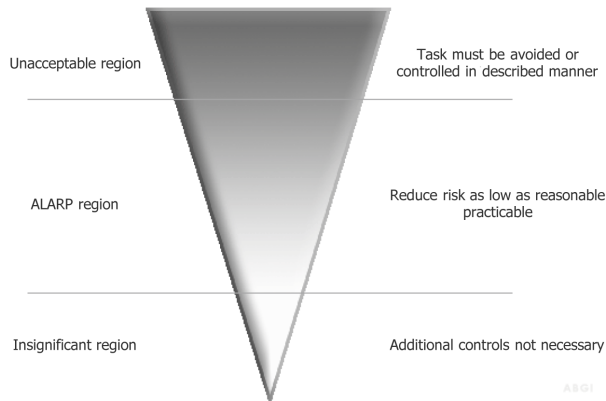


Figure 5.8: ALARP Diagram.

- International standards and laws.
- Suggestions from advisory bodies.

Another factor that comes into the ALARP principle, is the cost of assessing the improvement gained in an attempted risk reduction. In extremely complex systems, this can be very high, and could be the limiting factor in practicability of risk reduction.

Determining that a risk has been reduced to ALARP involves an assessment of the risk to be avoided, of the sacrifice (in money, time and trouble) involved in taking measures to avoid that risk, and a comparison of the two. This is a Cost Benefit Analysis. The meaning and value of the ALARP tolerability risk triangle show in Figure 5.8(see figure 1 above) is that the triangle represents increasing levels of “ risk for a particular hazardous activity, as we move from the bottom of the triangle toward the top”. The triangle can be divided into three broad regions:

1. The zone at the top represents an *unacceptable region*. For practical purposes, a particular risk falling into that region is regarded as unacceptable, whatever the levels of benefit associated with the activity. Any activity or practice giving rise to risks falling in the uppermost region would, as a matter of principle, be ruled out unless the activity or practice can be modified to reduce the degree of risk so that it falls in one of the regions below, or there are exceptional reasons for the activity or practice to be retained.
2. The zone at the bottom represents a broadly *acceptable region*. Risks falling into the region are generally regarded as insignificant and adequately controlled. Regulators would not usually require further action to reduce risks unless reasonably practicable measures are available. The levels of risk characterising this region are comparable to those that people regard as insignificant or trivial in their daily lives. They are typical of the risk from activities that are inherently not very hazardous or from hazardous activities that can be, or are, readily controlled to produce very low risks. Nonetheless the UK government HSE would take into account

that duty holders must reduce risks wherever it is reasonably practicable to do so or where the law so requires it.

3. The zone between the unacceptable and the broadly acceptable region is the tolerable region¹. Risks in that region are typical of the risks from activities that people are prepared to tolerate in order to secure benefits, in the expectation that:
 - the nature and the level of risks are properly assessed and the results used properly to determine control measures,
 - the residual risks are not unduly high and kept as low as reasonably practicable (ALARP),
 - the risks are periodically reviewed to ensure that they still meet ALARP criteria.

5.4.2 Individual Risk

The individual risk (IR), as used by the Dutch Ministry of Housing, Spatial Planning and Environment (VROM), is defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity $IR = P_f \cdot P()_{d|f}$.

To limit the risks, there are many criteria such as ALARA, Risk Matrix, AFR (Annual Fatality Risk), AIR (Average Individual Risk) and AI (Aggregated Indicator) etc.

The tools used to demonstrate ALARP will vary depending on the levels of risk. However, the measures in place to prevent or limit major accidents should be described in the safety report and be at least to “Relevant Good Practise”.

The assessor will need to focus on these measures to be satisfied they do represent good practice etc. The regulator will regard relevant good practice to have met the (AMN) All Measures Necessary requirement when:

- the societal risks can be shown (subject to uncertainty) to be acceptable, e.g. by use of an approximate risk integral (ARI) or other societal risk methodology; and
- no group, or individual, is subject to relatively high individual risks that are not ALARP.

Risk assessment techniques range from a simple qualitative approach to a detailed quantitative assessment. Fully quantified risk assessments are very costly and time consuming exercises, and there is within the chemical industry resistance to adopt such practices. One method which may help to bridge the gap between purely qualitative and full QRA approaches is to use a risk matrix. This type of approach has been widely used by many operators in their Control of major accident hazards (COMAH) safety reports.

Risk is interpreted as the combination of consequence (severity) and likelihood (frequency). Both these are minimum requirements of COMAH safety reports. A risk matrix enables this combination to be represented graphically. It is a reasonably quick and easy method to visualize the spread of risk and consequently is commonly used during (or after) hazard identification studies (such as a HAZOP), to screen hazards or to conduct a simple risk analysis. The

Likely > 10⁻²	Intolerable	Intolerable	Intolerable	Intolerable	Intolerable
Unlikely 10⁻⁴ - 10⁻²	Tolerable (Intolerable if Fatality >10⁻³)	Tolerable (Intolerable if Fatality >10⁻³)	Intolerable	Intolerable	Intolerable
Very Unlikely 10⁻⁶ - 10⁻⁴	Tolerable	Tolerable	Tolerable	Tolerable	Intolerable
Remote 10⁻⁸ - 10⁻⁶	Broadly Acceptable	Broadly Acceptable	Tolerable	Tolerable	Tolerable
	Single Fatality	2-10 Fatalities	11-50 Fatalities	50-100 Fatalities	100+ Fatalities

Figure 5.9: ALARP Risk Matrix Limits.

main advantage of the matrix is its easy representation of different risk levels, and the avoidance of more time consuming quantitative analysis where this is not justified.

The basis for the risk estimate is usually qualitative, although it can be quantitative (for either the consequences or the frequencies or both). The matrix, as illustrated in Figure 5.9, typically comprises a square divided into a number of boxes, with each box representing a different underlying risk level. Another approach suggested by the UK's Health & Safety Executives Methodology and Standards Development Unit (MSDU) is to use a non cumulative fn (frequency, numbers of people killed) plot to visualize the spread of risk and guide the proportionality to be used for examining risk reduction options.

The HSC suggested, moreover, to assume what level of risk to "acceptable" to 10^{-6} / year and the values 10^{-4} and 10^{-3} / year what level of risk to themselves "not acceptable", respectively, for the operators concerned and for the population.

5.4.3 Societal Risk

Societal risk reflects the societys point of view. In this perspective, risks having low hazard and high consequence are taken into account.

For individual and societal risk, the unit of risk is the loss of life/yr. Societal risk is generally expressed by $F(N)$ (sometimes indicated as $f - N$ or $F - N$ curves).

When the frequency of events which causes at least N fatalities is plotted against the number N on log log scales, the result is called $F(N)$ or $F - N$ curves. If the frequency scale is replaced by annual probability, then the resultant curve is called $f - N$ curve ($\log f = a + b \log N$). $F(N)$ curves are constructed based on

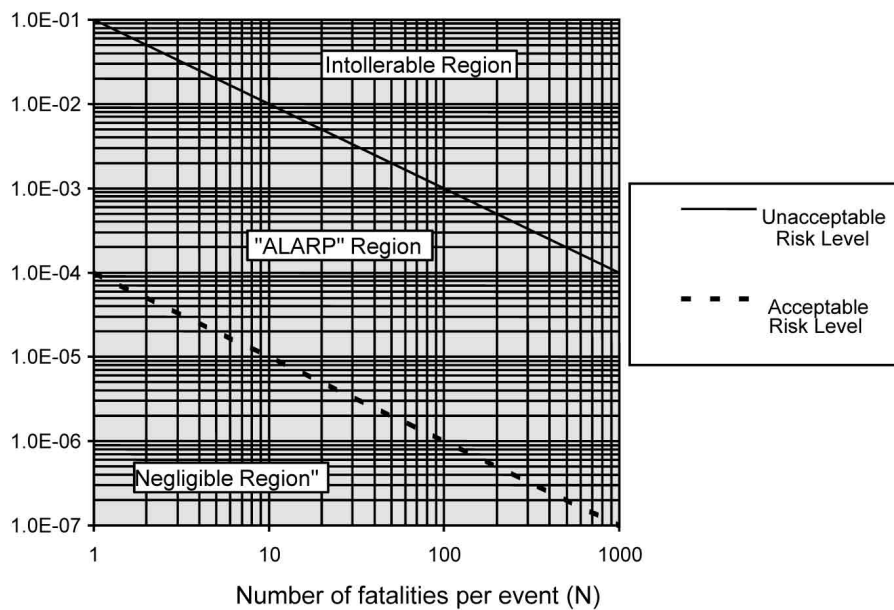


Figure 5.10: Curves $F(N)$ in the United Kingdom

historical data in the form of number of landslides and related fatalities. They in fact represent current situation i.e. the situation we live now.

$F(N)$ curves form the basis of developing societal acceptability and tolerability levels. The $F(N)$ curves can be constructed for various geographical units such as country, province, state etc. The number of landslides and related fatalities within the considered geographical unit determine the acceptability and tolerability criteria.

The General Guidelines for Tolerable Risk Criteria Establishment presume incremental risk from a hazard to an individual should not be greater than the one which is exposed to in everyday life of a person. The incremental risk from a hazard should be reduced wherever reasonably practicable (ALARP Principle). If the possible life loss is high, the risk should be low. Individuals tolerate higher risks than they regard as acceptable, when they are unable to control or reduce the risk due to financial or other limitations. Higher risks are likely to be tolerated for existing slopes than for planned projects. Tolerable risks are higher for natural slopes than engineered ones. If the slope is under monitoring or risk mitigation measures are implemented, tolerable risk approaches to engineered slopes. Tolerable risks depends on countrys experience with landslides.

As to assess the acceptability of individual risk is necessary to compare the size (number) of that risk with the thresholds, to determine if the societal risk is acceptable it is necessary is to compare the curve $F(N)$ obtained from analysis of risk (usually rectilinear) by the curves $F(N)$ threshold reported in the figures below. In particular, in Figure 5.10 are shown the curves $F(N)$ which identify the three areas of risk (acceptable, not acceptable ALARP) in the United Kingdom. [126].

We can identify the following possibilities:

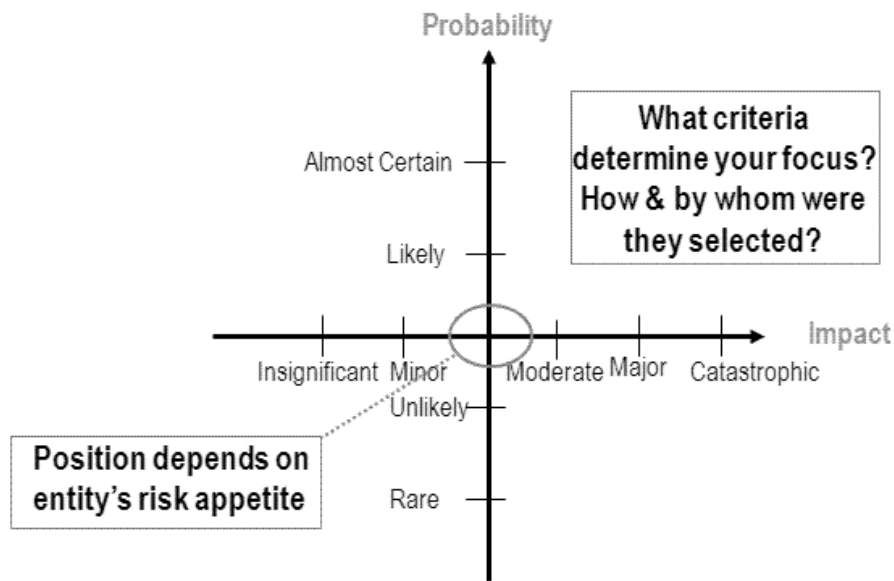


Figure 5.11: How were establish and select Risk Assessment Criteria

- societal risk is acceptable if the curve $F(N)$ is calculated entirely below the curve $F(N)$ straight out that the threshold of acceptable risk;
- risk ALARP if the curve $F(N)$ is calculated entirely below the curve $F(N)$ straight out that the threshold of risk is not acceptable and partially or entirely above the curve $F(N)$ which defines the threshold acceptable risk;
- risk is not acceptable if the curve $F(N)$ is calculated in part above the curve $F(N)$ straight out that the threshold of risk is not acceptable.

5.4.4 Perceived risk

In the model for calculating the IR and the SR discussed above we assume that the company is neutral to risk, i.e. events with equal likelihood (product of probability for damage) are considered equivalent.

This means that, for example, a single incident that causes hundreds of deaths is equivalent (or equally undesirable) to 100 accidents causing the death of each individual, and this because in both cases the number deaths is the same and therefore the two events are perceived by society in the same way.

However, it is widely believed that an event characterized by low probability but high consequences (LPHC) is the most undesirable features of a high probability but low consequences (HPLC), although the expected consequences of the two events are the same.

Therefore, many “decision makers” tend to show an aversion to risk when they have to make decisions about LPHC events such as accidents in the transport of dangerous goods. The Figure 5.11 shows the subjectivity in determining the risk assessment criteria depending on the perception of the risk.

The Figure 5.12 shows the probability of an event occurring based on the number of deaths caused from the same depending on the propensity to take risks:

- the solid line indicates a neutral position toward the risk (events with equal probability for product damage, are considered equivalent);
- the dotted line indicates a position of risk aversion (the population is more adverse events with low probability and high damage, but very rare events are more easily accepted).

The change of perception depends on the probability of occurrence and can be described by a correlation function, shown for the first time by Starr (1969) [221]: when the events are very familiar, objective risk and perceived match.

When the events are less frequent, there is a perception in excess, and when the events are extremely rare, the perception is failing. In order to incorporate the propensity to take risks with the models of risk, a simple way is to use an exponent α to be applied to the values of the consequences or vulnerabilities.

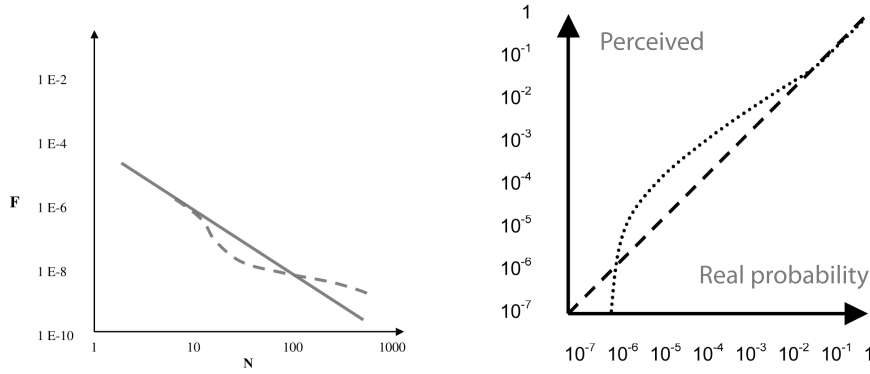


Figure 5.12: Examples of Perceived Probability

The previous model is modified as in (5.20) for IR and as in (5.21) for SR to take into account the perception of risk.

Individual Risk

$$\begin{aligned}
 IRP = & \sum_{i=1}^{N_{links}} \sum_{\nu=1}^{N_{veh}(l)} \sum_{j=1}^{N_{seas}} f_{rel}(l, \nu, j) \cdot \int_{L_l} \sum_{i=1}^{N_{out}(\nu)} p_{out}(i) \cdot \\
 & \cdot \sum_{k=1}^{N_{met}(j)} \int_0^{2\pi} p_{wind}(j, k, \vartheta) \cdot V_{Q(t)\nu \rightarrow s}(i, k, \vartheta)^\alpha d\theta \quad (5.20)
 \end{aligned}$$

Societal Risk

$$N_{Q(t)_{i,\nu}}^{scen}(i, j, k, \vartheta) = \sum_{m=1}^{N_l} \rho_{L_m}(j) \left[\int_{L_m} V_{Q(t)_{i,\nu}}(i, k, \vartheta)^\alpha dL_m \right] + \sum_{n=1}^{N_a} \rho_{A_n}(j) \left[\int_{A_n} V_{Q(t)_{i,\nu}}(i, k, \vartheta)^\alpha dA_n \right] + \sum_{0=1}^{N_C} P_{C_0}(j) [V_{Q(t)_{i,\nu}}(i, k, \vartheta)^\alpha] \quad (5.21)$$

whereas for $\alpha=1$ the model is neutral to risk, for $\alpha>1$ the model is with risk aversion and for $\alpha<1$ you have the model with propensity to take risks. The higher the value of α , the higher the calculated risk.

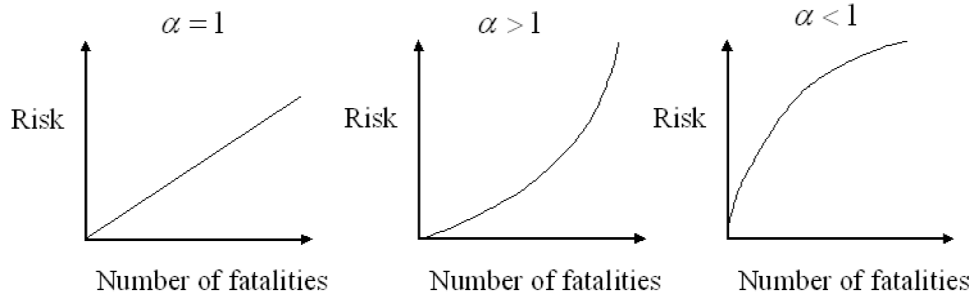


Figure 5.13: Relationship between risk and number of victims according to the type of willingness to take risk

According to [209], the main factors influencing the acceptability of risk and in particular its perception are:

- the number of people participating in dangerous;
- the comparison with the natural mortality;
- the real or supposed benefit resulting;
- the voluntary nature of risks;
- the irreversibility of the consequences;
- the geographical location of the source of danger with respect to receptor;
- the inherent characteristics of individuals, in particular the cultural level and social status.

The nature of subjectivity that characterizes the perception of risk does not permit the application of mathematical models, or at least objective, that will uniquely define the distance between real risk and perceived risk.

The only instrument that is normally used is a sample survey conducted by sociologists and psychologists in which you are asked to evaluate, through questionnaires or oral interviews, to give an opinion on the perceived seriousness of a given event.

Finally, we will have a vision of how the event object of investigation is perceived by the population. Therefore, we can estimate the distance between real risk and objective and in addition find α (enabling the transition from a calculated risk that received the population).

Chapter 6

A Real Time DSS for HAZMAT Transportation in a sustainable oriented motorway environment

In this chapter, some important concepts are introduced about Hazardous Materials Transportation by road. Section 6.1 gives background informations and introduces the problem and the proposed solution related to a series of obligations to which must meet motorway companies under the ADR, civil protection agencies and managers of road infrastructure. Section 6.2 presents the proposed real-time monitoring system as the basis for assessing the risk derived from the HAZMAT transport. In Section 6.3 a brief presentation of the system architecture is offered and a simulation of the application of the risk assessment model and corresponding values are carried out in Section 6.4. Finally, Section 6.5 summarizes results and conclusions.

6.1 The *en-route* HAZMAT

Today, a great amount of Hazardous Materials are carried “on the road” and this fact can be very important for the continuance of strong and effective national and international economies.

Hazardous material transportation on road represents a relevant risk for the people, their properties and the environment. Sustainability in HAZMAT transportation on road has often been addressed as the requirement to include integrated risk analysis as well as prevention measures in the distribution planning activities of the transportation companies.

In all these processes road pavement can play a crucial role, but many aspects still need answers on this topic. For example to test Hot Mix Asphalt chemical resistance and the assessment of relationships in order to estimate how much a transported fluid can be dangerous depending on mix characteristics (effective porosity, etc.).

On the other end, quantification of risk of the “en-route” hazardous materials

accidents is difficult because probabilities for traffic accidents are low and those involving hazardous materials are even lower.

The *en-route* hazardous materials (*involuntary*) accidents have low probability: Gheorghe [95] estimate as a typical accident rate the value of 3.0×10^{-6} accidents/vehicle-km.

Nevertheless, the potentially catastrophic impacts attributed to such incidents and the large number of hazardous shipments raise serious fears to all stakeholders involved in and affected by the HAZMAT process i.e. governmental authorities, carriers, the local societies and social groups, and shippers.

Yet some risk is imposed on the population living along the major highways, who are asked to assume the risk with no clear benefits to them. For this reason, if the same main route segment is selected for shipments from multiple origins, the objection of people living along this route would increase considerably.

These people are likely to prefer alternate routings that would spread the risks. Public opposition to HAZMAT shipments has increased in recent years, due to fears of terrorist attacks on HAZMAT vehicles.

6.1.1 European Road HAZMAT Transport Legislation

The principal step of Legislation on road of carriage of dangerous goods are presented in the following paragraph.

- Commission Directive 2006/89/EC of 3 November 2006 adapting for the sixth time to technical progress Council Directive 94/55/EC on the approximation of the laws of the Member States with regard to the transport of dangerous goods by road (Text with EEA relevance).
- Council Directive 94/55/EC of 21 November 1994 on the transport of dangerous goods by road ('ADR framework directive'). The first general directive covering land transport was Directive 94/55, commonly known as the "ADR framework directive". This directive makes the provisions of the ADR agreement uniformly applicable to road transport nationally and between Member States, adopting in particular the technical annexes to the ADR agreement. These annexes set standards for the classification, packaging and labeling of dangerous substances and the construction of vehicles used to transport them.
- Council Directive 95/50/EC of 6 October 1995 on uniform procedures for checks on the transport of dangerous goods by road. This provides for a common list of points to be checked and the issuing of a copy of the report on the road check carried out. This is for the information of any authorities carrying out a second road check, either in the same Member State or another one.
- Council Directive 96/35/EC of 3 June 1996 on the appointment and vocational qualification of safety advisers for the transport of dangerous goods by road, rail and inland waterway. Under this directive "the activities of which include the transport or the related loading or unloading of dangerous goods by road, rail or inland waterway, (must) each appoint one or more safety advisers". Since this definition includes loading and unloading activities, it is also applicable to port undertakings which carry

out these operations for the different modes of land transport. The role of safety advisers is to help prevent the risks which these activities entail to individuals carrying out the work, other persons of the environment. The directive also stipulates that the job of safety adviser may be done by an individual from outside the undertaking or by an employee already engaged on other duties. The Commission sets great store by this directive, given the importance of the human factor in the risk of accidents and the part to be played by the safety adviser.

- Directive 2000/18/EC of the European Parliament and of the Council of 17 April 2000 on minimum examination requirements for safety advisers for the transport of dangerous goods by road, rail or inland waterway. With this directive Member States shall take all necessary measures to ensure that safety advisers for the transport of dangerous goods are examined in such a way that they satisfy these minimum requirements.
- Directive 98/91 of the European Parliament and of the Council, relating to motor vehicles and their trailers intended for the transport of dangerous goods by road, and amending Directive 70/156/EEC relating to the type-approval of motor vehicles and their trailers (OJ L11 of 16 January 1999). This directive is concerned with the type-approval of motor vehicles used to carry dangerous goods. It incorporates the technical requirements laid down by the ADR agreement and provides for the issuing of an EU certificate to facilitate vehicle registration in the various Member States.
- Council Directive 1999/36/EC on transportable pressure equipment. This is concerned with receptacles and tanks used to transport Class 2 gases. The proposal seeks to introduce a system of EU conformity markings for new equipment and EU markings for periodic inspections, with a view to free transport and use, including refilling, in all Member States of the European Union.
- During 2004-2005 the Commission carried out an evaluation of its policy in the field of the transport of dangerous goods. The work was done by an external group of consultants. Final Report on the Evaluation of EU policy on the Transport of Dangerous Goods since 1994. Launched an impact study on a possible European directive to improve intermodal transport security. The study was commissioned in December 2004 to a consortium chaired by Det Norske Veritas (DNV) Consulting and identifies risks, possible security measures including a cost benefits analysis, a transport infrastructure plan and possible EU coordination. The final report was published on 1 December 2005. It does not contain the opinion of the European Commission.

6.1.2 Problem definition

Transport steps are linked by many important cultural and social progress that have made this area more and more strategic for the development of contemporary society.

Transport networks and their supporting infrastructure assure efficient and safe mobility of persons and transport of goods in the EU, and represent the largest part of the built environment.

In Italy about 80% of road traffic is represented by the delivery of goods, and the overall trend in Europe seems to predict an increase of 30% within 2010.

About 18% of this freight traffic is currently represented by HAZMAT Transport, but a clear awareness of HAZMAT Transport world flows on road and on the other transport modes - as well as of the related security and safety aspects - is not present yet, at least from a social and economic point of view.

Intelligent Transportation System technologies has also made possible the gradual reduction in journey times and thus opening up new economic horizons, with the conquest of markets wider.

The freedom gained by the ease of movement, however, had a cost in terms of environmental impact, quality of life and safety.

The risk is that the increasing demand for current and especially future can make that cost is no longer sustainable.

In addition, several thousands of trucks HAZMAT circulate within European roads on daily basis. They utilize urban roads, rural roads, highways, tunnels and long bridges and in some case they are not allowed in some of them.

The risks connected to the operation and maintenance remains one of the major issues regarding the European transport systems. Safety and security of these systems is of major concern to society.

The transport of hazardous materials is a specific concern which can be associated with approximately 8% of all European shipments.

However, the actual accident risk and impact is not calculated. In addition, when, due to unforeseen events (traffic jams, accidents, etc.), they need to change route, they do not have any particular guidance on the safest alternative nor are consequences of road choice to the business chain and societal risk calculated.

Safety and security are especially crucial here, as these shipments not only present an additional inherent hazard potential in case of accidents, but also present an opportunity for intentional misuse to criminals and terrorists.

As a consequence, accident prevention and consequence mitigation are becoming a common practice at large manufacturing (e.g. chemical companies) and service firms (e.g. transportation of dangerous goods).

The benefits of improving safety performance and reduced costs associated with potential accidents or pollution risks are compelling.

However, most such efforts are still being carried out as special programs or projects, layered on top of ongoing business operations (e.g. production, storage, transportation, etc.).

Recent experience shows that the full benefits of accident and pollution prevention and consequence mitigation will only be realized when such activities are fully integrated into a core approach or into the company core business practice.

In view of the increasing concern in transportation security, there is an urgent need to review and improve, if necessary, the way trucks carrying HAZMATs are being routed on urban and suburban road networks.

Routing of such vehicles should not only ensure the safety of travelers in the network, but should also consider the risk of the HAZMAT being used as weapon of mass destruction.

In Italy, according to [45], HAZMATs transport by road requires constant monitoring (tracking and tracing) of vehicles cargo handled. This requirement

involves a series of obligations to which must meet companies under the ADR, civil protection agencies and managers of road infrastructure.

As a consequence, motorways concessionaires must adopt real-time systems to monitor HAZMATs carried and to support the decisions on the transport (MAS Monitoring - Alarm - Alerts).

6.1.3 The proposed solution

We propose an innovative real-time decision support system (DSS) model for monitoring and routing of HAZMAT Vehicles, aiming at solving the above stated problems.

Such systems should aim to calculate and evaluate in real time the individual and societal risk related to the transit of HAZMAT on the motorway network.

Then, they should allow:

- a monitoring in real-time means of the means transporting HAZMAT;
- a risk assessment derived from the carriage;
- the alert and notification of emergencies;
- a reporting anomalies for a subsequent planned intervention.

As outlined in Section 5.1.3, in a motorway, each stretch is characterized by substantially rectilinear link from toll to toll station. As a consequence, routes for HAZMATs transport shall be considered as a linear type source of risk consisting of a number of points that are also source of risk.

This substantially increases the computational load required to obtain the final measure of risk. Consequently, according to [230] GIS-systems need to use through the overlapping of the layer and the query space.

6.2 The real-time monitoring

Real-time monitoring system is the basis for assessing the risk derived from the HAZMAT transport. The main objective of monitoring phase is to collect by sensors a set of data to be input into the model for calculating the risk.

GPS technology it is not possible to precisely locate vehicles carrying dangerous goods because the vehicles not at all have this technology on board.

Furthermore, it is not possible to access the data location for the absence of agreements or technological infrastructures that enable the data transfer between the vehicle and the motorway's concessionaires.

Nevertheless, the identification of vehicles can only be done through the use of vision systems (cameras), positioned at the toll station and along the motorway.

These systems make it possible to identify the tank cars and tank container carrying HAZMAT and the substance transported through reading the ADR Hazard Identification Number (HIN) (Kemler Code) with the materials UN number on placards.

Consequently, we can still determine the link of the motorway traveled by the generic trucker in spite of the exact position, moment to moment, of the vehicle. So, for every stretch (link) of motorway we can identify the *dynamic data* (which vary over time) such as:

- the presence on link of vehicles carrying HAZMAT;
- the types of substances carried;
- the weather conditions (wind direction, wind speed, rain, snow, fog, ice, atmospheric stability, etc.);
- the traffic conditions (vehicle flow);

as well as *static data* (which do not vary over time) such as:

- characteristics and type of road (the presence of curves, number of lanes, etc.);
- distribution and population density nearby the link;
- services and infrastructure around it.

In the calculation procedures that we present each link is considered straight and have uniform properties along its entire length. These conditions can be obtained easily without loss of generality, adding fictitious nodes to the transport network.

In the case of the motorway network, characterized by substantially rectilinear road stretch from toll to toll, it is possible to consider the nodes as points of access / exit of the motorway.

6.2.1 Risk Assessment derived from HAZMAT transport

In order to assess the individual and societal risk derived from the HAZMAT transport, we reference to the model discussed previously in Section 5.1 adapted to real-time event. In particular, we take into account the following:

1. N is a set of links (the road stretches of motorway);
2. l is a generic link of the motorway network;
3. ν is a type of hazardous substance;
4. $\lambda_{inc}(l, j^t)$ is the accident frequency calculated through historical analysis [114] expressed in *events/(vehicle * km)*. This size can be amplified or diminished to change some values that can be static (e.g. for the tortuous path, the slope, the number of lanes and the presence of a tunnel or a bridge) or dynamic (in particular the weather, the flow and vehicle speed, and the presence of work) that depends on the type of road in particular the geometry of the route, traffic conditions and weather conditions [86].
5. $N_{veh}^t(l)$ is a different typologies (ν) traveling on each link l at moment t ;
6. $N_{type}^t(l, \nu)$ is the number of vehicles carrying the dangerous substance ν currently in transit on the link l at instant t ;
7. $p_{rel}(\nu)$ the release probability due to the accident ($P(R|A)$) that depends on the characteristics of the vehicle transporting the hazardous substance ν (mechanical strength, possible internal partitioning, presence of double walls and insulation) and the type of accident where the vehicle is involved;

8. $N_{out}(\nu)$ is the number of all types of effects caused by different types of HAZMATs released since the accident for a given type of substance ν (as e.g. jet fire, pool fire, flash fire, fireball, BLEVE (boiling liquid expanding vapor explosion), UVCE (unconfined vapor cloud explosion));
9. $P_{out}(i)$ is the probability $P(X|R, A)$ of a type of effects once a release i has occurred;
10. $C_{met}^t(l)$ is the weather condition on the link l (wind speed and atmospheric stability) at instant t ;
11. $\vartheta^t(l)$ is the current direction of the wind on the link l at instant t ;
12. n the generic rectangular area of rectangular N_A areas (for each area are known the uniform population density (ρ_{A_n} [persons/m² for rectangles], the geographical position);
13. m is the generic linear zone of the total linear number N_L (for each zone are known the is the population density ρ_{L_m} [persons/m] and the geographic location);
14. o is the generic aggregation of the total number of such centres N_C ; the fraction of persons being indoors (x_{C_o} and the total number of persons in each centre P_{C_o}) are known;
15. $V_{Q(x) \rightarrow S}(i, C_{met}^t(l), \vartheta^t(l))$ is the measure of vulnerability in S given the incident in $Q(x)$ which depends on the result i , the weather condition C_{met} and the wind direction ϑ on the link l at the moment t ;
16. α is the perception of risk ($\alpha=1$ risk-neutral, for $\alpha>1$ risk aversion and for $\alpha<1$ propensity to take risks) given as input to the system and depends on the “decision maker” willingness to risk.

6.2.2 IR Assessment

In Sections 4.2 and 5.1.4 the individual risk was presented additive with respect to the source of risk and therefore risk to themselves at a point P is given by the sum of the risks posed by individual $Q(x)$.

As a result each source of risk $Q(x)$ produced in P is a risk given by the possible release of each vehicle carrying HAZMAT ν in $Q(x)$.

The relative risk to a single *link* is the sum of the risks arising from all vehicles $N_{type}^t(l, \nu)$ that are currently in transit on that *link*. This measure of risk, related on the individual *link*, can be added on all the *link* to obtain the total risk of the network.

6.2.2.1 Unit risk

As the model is in real time, its purpose is to calculate the risk in time at any moment. Consequently, is not necessary to take into account the probability density of the wind $p_{wind}(j, k, \vartheta)$ and that the wind can blow from all directions with different values of probability, because the weather conditions and wind direction data are instantly measurable at the moment t .

As a consequence, there is no need to rotate the map of vulnerability around the origin $Q(x)$ weighed at each step of rotation for the probability that the wind blow in that direction.

To evaluate the vulnerability at any point P related to a single triplet - final outcomes i - weather condition $C_{met}^t(l)$ - substance transported ν is sufficient overlap the map of vulnerability and the Cartesian system ξ / η (in which the origin coincides with the source of risk $Q(x)$ and the axis ξ coincides with the wind direction whereas ϑ is the angle between ξ and X) on the system X/Y and in particular to the system ξ' / η' origin in $Q(x)$ and with axes parallel to the reference Cartesian general X/Y .

This is the *unit risk map*.

The evaluation of *unit risk map* is even simpler using a GIS software (e.g. MapInfo) because it is sufficient to overlap the layer of the map of vulnerability directed in accordance with the direction of the wind on the link at instant t on the layer of the motorway network.

We make the previous result for each possible final ν relative to the substance that is in transit on *link* l , obtaining (6.1).

$$\text{UR}_{Q(t) \rightarrow S}^t(\nu) = \sum_{i=1}^{N_{out}(\nu)} p_{out}(i) \cdot V_{Q(x)\nu \rightarrow S}(i, C_{met}^t(l), \vartheta^t(l)) \quad (6.1)$$

6.2.2.2 Total Unit Risk on link

So far, the vehicle was considered as stationary in $Q(t)$. The next step is to describe the vehicle traveling on the (*link*) as a traveling source of risk to which assimilate the possible accidents that can happen in any point of the l .

In addition, previous expression is modified as in (6.2), considering the relative frequency of the possible HAZMAT release for the vehicle carrying the substance on the ν (*link*) l .

$$\text{IRP}^t(l, \nu) = f_{rel}(l, \nu, j^t) \cdot \int_{L_l} \text{UR}_{Q(x) \rightarrow P}^t(\nu) dt \quad (6.2)$$

whereas:

$$f_{rel}(l, \nu, j^t) = \lambda_{inc}(l, j^t) \cdot p_{rel}(\nu) \quad (6.3)$$

and where L_l is the *link* and $\int_{L_l} \text{UR}_{Q(t) \rightarrow P}(j, v) dt$ is the translation of *unit risk map on link*.

It is also important to notice the following:

- the frequency of release is a static data as result of historical data analysis;
- j^t means the current season (frequency analysis of release may refer to different time periods, i.e. “seasons”, to take into account of its seasonal phenomena so we must use the data on the current season in which it is carrying out the calculation of risk).

6.2.2.3 Total Unit Risk

Finally, adding the individual risks calculated in the previous paragraph on all vehicles that are dangerous through the *link* ($N_{type}^t(l, \nu)$) and all *link* in order to obtain the individual risk to be attributed to the point P as in (6.4).

$$\begin{aligned} \text{IRP}^t = & \sum_{i=1}^{N_{links}} \sum_{v=1}^{N_{veh}^t(l)} N_{type}^t(l, v) \cdot f_{rel}(l, v, j^t) \cdot \\ & \cdot \int_{Ll} \sum_{i=1}^{N_{out}(v)} p_{out}(i) \cdot V_{Q(x)v \rightarrow S}(i, C_{met}^t(l), \vartheta^t) \end{aligned} \quad (6.4)$$

Taking into account the perceived risk (6.5) is obtained.

$$\begin{aligned} \text{IRP}^t = & \sum_{i=1}^{N_{links}} \sum_{v=1}^{N_{veh}^t(l)} N_{type}^t(l, v) \cdot f_{rel}(l, v, j^t) \cdot \\ & \cdot \int_{Ll} \sum_{i=1}^{N_{out}(v)} p_{out}(i) \cdot V_{Q(x)v \rightarrow S}(i, C_{met}^t(l), \vartheta^t)^\alpha \end{aligned} \quad (6.5)$$

6.2.3 Societal Risk Assessment

As individual risk, the societal risk is additive with respect to the source of risk.

Consequently, on an area of the motorway network under consideration we can determine the societal risk adding the risks arising from individual *link* of the network whereas the risk due to a single (*link*) is the sum of risks due to all vehicles transporting HAZMATs currently in transit on that route of the motorway.

As noted in the previous Section 4.2.4 an alternative way to describe the Societal Risk (SR) is the use of the so-called $F(N)$ -curves [126], a powerful index of the risk created by a transportation network over an impact area.

The curves $F(N)$ report values of the cumulative (per year) frequency F which, as a result of all possible accidents, we have seen in the damage of a reference area not less than N (and therefore a number of deaths greater than or equal to N units).

Therefore, add societal risks means the addition of frequencies F for the same abscissa value of N .

For each scenario, defined by:

- final outcomes i depending on the substance ν ;
- *point source* $Q(x)$;
- current weather conditions on the *link* l $C_{met}^t(l)$;
- current direction of the wind on the *link* $\vartheta^t(l)$;

- current season j^t ;

We start with the map of vulnerability ξ/η describing the impact or exposure map for a scenario; we overlap the map of vulnerability on population map.

The number of possible deaths is from integrating on the product between each point in vulnerability and population density at that point.

As in the Individual Risk case, it is not necessary to rotate the map of vulnerability around $Q(x)$ in order to weigh up all the scenarios that refer to the same $Q(x)$, to the same final outcome i , to the same weather conditions $C_{met}^t(l)$, but to different wind directions ϑ diverse.

Only the actual scenario at moment t is evaluated, scenario for which the following parameters:

- $C_{met}^t(l)$
- $\vartheta^t(l)$
- j^t

are fixed at the moment t in which risk is assessed.

Number of deaths for each scenario is given in (6.6).

$$N_{Q(t)l,\nu,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t) = \sum_{m=1}^{N_l} \rho_{L_m} \left[\int_{L_m} V_{Q(x)\nu}(i, C_{met}^t(l), \vartheta^t) dL_m \right] + \sum_{n=1}^{N_a} \rho_{A_n} \left[\int_{A_n} V_{Q(x)\nu}(i, C_{met}^t(l), \vartheta^t) dA_n \right] + \sum_{0=1}^{N_c} P_{C_0} [V_{Q(x)\nu}(i, C_{met}^t(l), \vartheta^t)] \quad (6.6)$$

Taking into account the perceived risk we get in (6.7).

$$N_{Q(t)l,\nu,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t) = \sum_{m=1}^{N_l} \rho_{L_m} \left[\int_{L_m} V_{Q(x)\nu}(i, C_{met}^t(l), \vartheta^t)^\alpha dL_m \right] + \sum_{n=1}^{N_a} \rho_{A_n} \left[\int_{A_n} V_{Q(x)\nu}(i, C_{met}^t(l), \vartheta^t)^\alpha dA_n \right] + \sum_{0=1}^{N_c} P_{C_0} [V_{Q(x)\nu}(i, C_{met}^t(l), \vartheta^t)^\alpha] \quad (6.7)$$

Frequency of the scenario

$$f_{Q(t)l,\nu,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t) = f_{rel}(l, \nu, j^t) \cdot p_{out}(i) \quad (6.8)$$

6.2.3.1 Societal Risk derived from traveling risk source

As when we calculate the individual risk, for the societal risk is necessary to consider a possible incident that may occur with equal probability in any of the generic links l taken into account.

Therefore, for a given value of N^* deaths in the field of N , the values of the frequencies related to the scenarios of each of the *point source* $Q(x)$ ($f_{Q(t)l,v,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t)$) with a number of deaths of at least N^* must be added together to obtain the value of $F(N(i, j^t, C_{met}^t(l), \vartheta^t))_{l,v,t}$ related to N^* .

$$F(N(i, j^t, C_{met}^t(l), \vartheta^t))_{l,v,t} = \int_{L_l} \delta_{scen}^N(i, j^t, C_{met}^t(l), \vartheta^t)_t dLl \quad (6.9)$$

$$\delta_{scen}^N(i, j^t, C_{met}^t(l), \vartheta^t)_t = \left\{ \begin{array}{l} f_{Q(t)l,v,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t) \text{ if } N_{Q(t)l,v,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t) \geq N^* \\ 0 \text{ if } N_{Q(t)l,v,t}^{scen}(i, j^t, C_{met}^t(l), \vartheta^t) < N^* \end{array} \right\} \quad (6.10)$$

6.2.3.2 Total Societal Risk

Next step is to calculate the total curve $F(N)_{l,\nu,t}$ at moment t , on the *link* l related to the vehicle ν .

To perform this is necessary evaluate $F(N(i, C_{met}^t(l), \vartheta^t(l)))_{l,\nu,t}$ of previous step for each type of final outcome i adding the amount so found for values of N constants, given the current weather conditions on the link $C_{met}^t(l)$ and the the current season j^t .

Last step of the procedure, finally, is to determine the curve $F(N)$ of the network always adding to values of N different constants $F(N)_{l,\nu,t}$ for all (*link*) l and all vehicles carrying dangerous goods that are going on generic (*link*).

$$F(N)_t = \sum_{i=1}^{N_{link}} \sum_{v=1}^{N_{veh}^t(l)} N_{type}^t(l, \nu) \cdot \sum_{i=1}^{N_{out}(\nu)} \int_{L_l} \delta_{scen}^N(i, j^t, C_{met}^t(l), \vartheta^t) \quad (6.11)$$

6.2.4 Emergency Alert and Notification Systems

After completing the calculation of individual and societal risk on the motorway network at the generic instant t , we must take into consideration whether these measures of risk are acceptable and possibly, if they were not, notify the situation through messages warning to take appropriate action[187]. As example, in Figure 6.1 are shows the levels of Risk Tolerability in Great Britain.

For example, if the societal risk is unacceptable, “*crisis manager*” can choose to implement policies of homogenization and dilution of risk in the area. As point out in Section 5.3, there is no uniformity of approach in the definition of risk acceptability criteria, but there are eligibility criteria commonly adopted as “International Standards”.

The best known is the “ALARP (As Low As Reasonably Practicable) [126] showed in Figure [?].

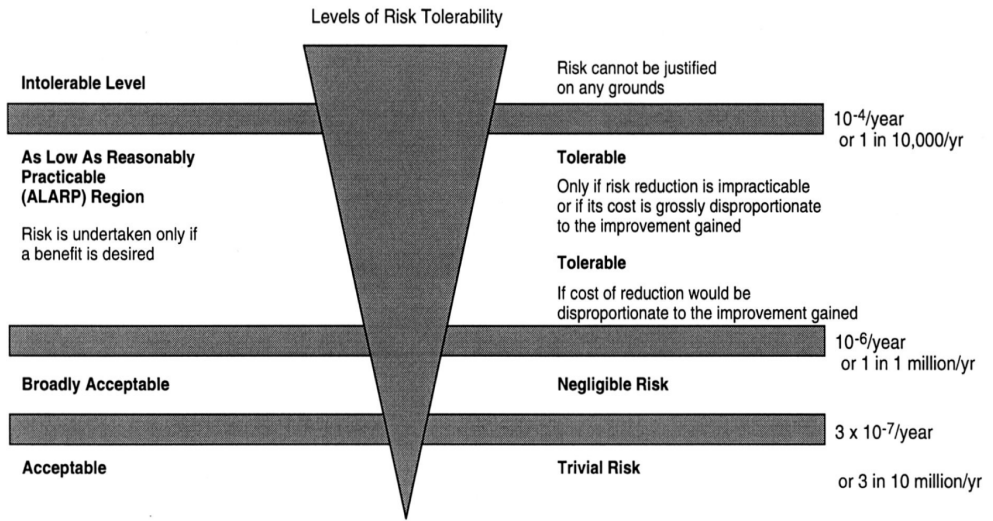


Figure 6.1: Levels of Risk Tolerability in G.B.

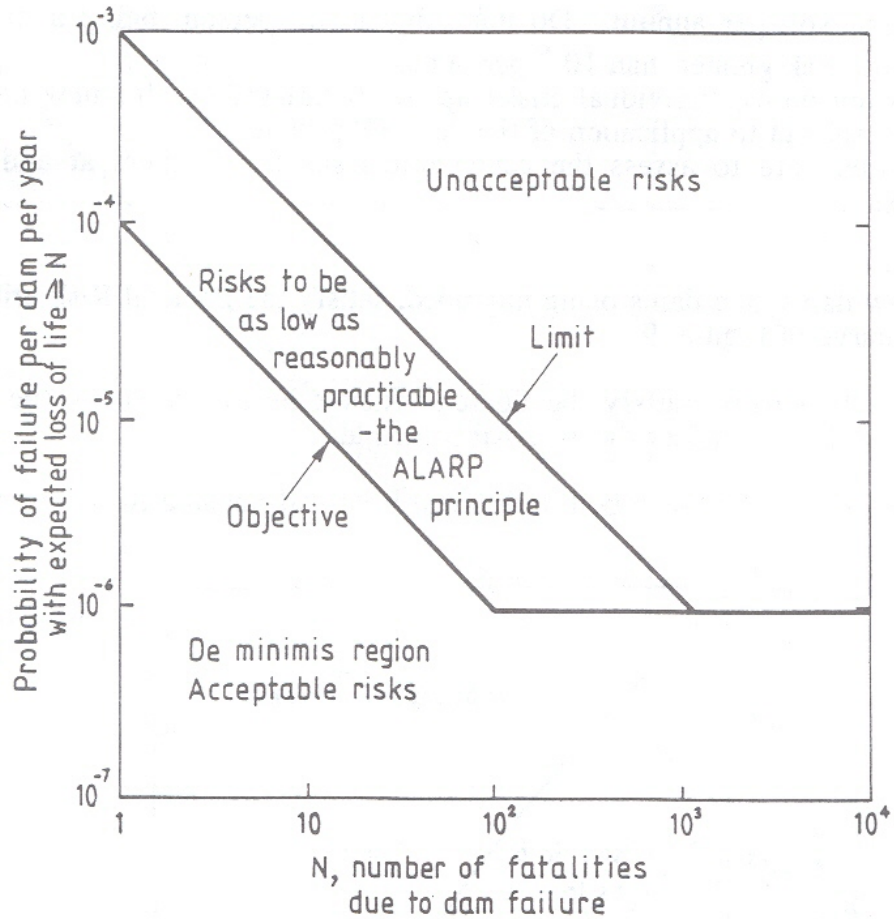


Figure 6.2: The curves $F(N)$ and ALARP thresholds

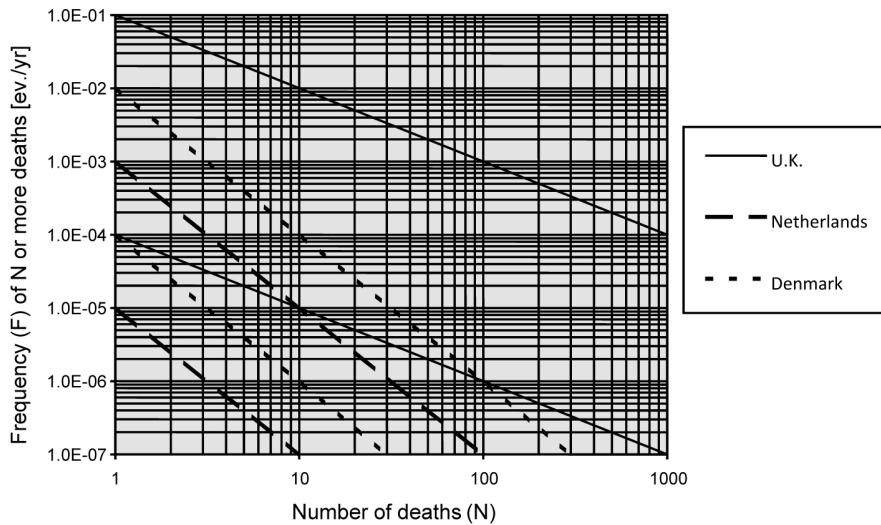


Figure 6.3: The curves $F(N)$ threshold for a range in the United Kingdom, Netherlands, Denmark

This criterion is related to the individual or societal risk, and correlates the levels and thresholds of tolerability of risk at the best reasonably available technology [169]. It can also be expressed as “the degree of risk where further reduction in risk would cost too much more than the benefit obtained by reducing the same”. These two definitions are complementary and represent two possible (opposite) objectives of assessing the acceptability of risk. In Figure 6.3, the curves $F(N)$ threshold for a range of countries, particularly the United Kingdom, Netherlands, Denmark.

In Figure 6.4 are presented data for curves $F(N)$ for different Countries.

The HSC recommends taking what level of risk to “acceptable” the value $10^{-6}/year$ and the values $10^{-4}/year$ and $10^{-3}/year$ what level of risk to “not acceptable”, respectively for operators of the test and for the population [92]. Figure [?] shows these HSC levels of acceptability.

6.3 System Architecture

The DSS shall be a part of an automated system that aims at reducing the overall risk of HAZMATs transportation through European motorways.

Several subsystems (telematic modules, on-board units, sensors, real-time data providing modules, etc.) cooperate toward the goal of maximizing the safety of such transportation, while also taking into account business demands, network efficiency and conflicts resolution.

An advanced and well documented risk assessments for the transportation of HAZMAT on motorway must take into account:

- statistics-based loss of road tankers frequencies;
- specification of potential consequences for a given release situations (for example, using event tree methodology as an organizational tool;

Country	Population density/km ²	f-values			Slope (b)
		N=1	N=10	N=100	
Japan	336	1	0.8	0.07	-0.53
China	136	1	1	0.06	-0.61
Italy	193	0.9	0.008	5x10 ⁻⁵	-1.99
Hong Kong	6437	0.6	0.01	-	-0.79
Canada	3	0.4	0.07	-	-0.92
Colombia	37	0.04	0.001	-	-1.63
Nepal	173	0.08	0.004	-	-1.31
Norway	14	0.006	0.001	-	-0.72

Figure 6.4: Values for $F(N)$ curves in different Countries

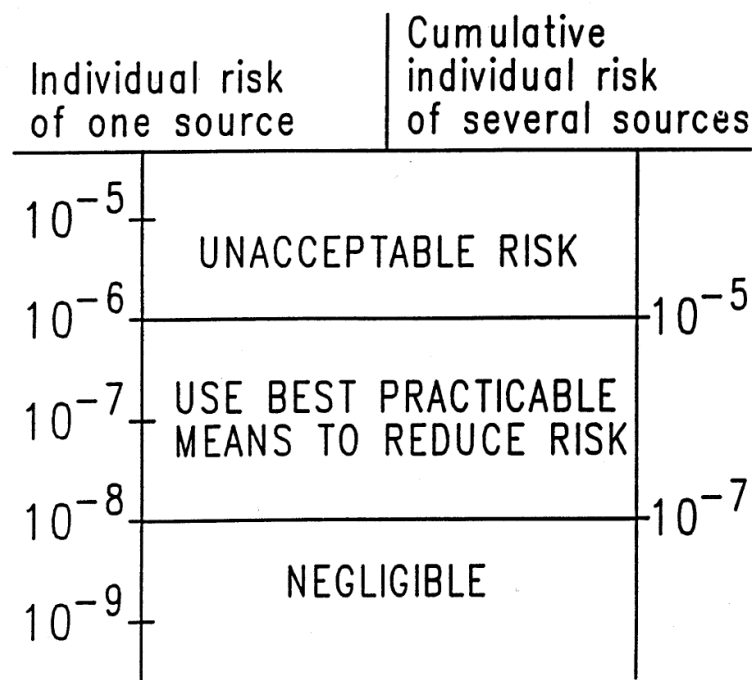


Figure 6.5: Thresholds of acceptability of individual risk (HSC)

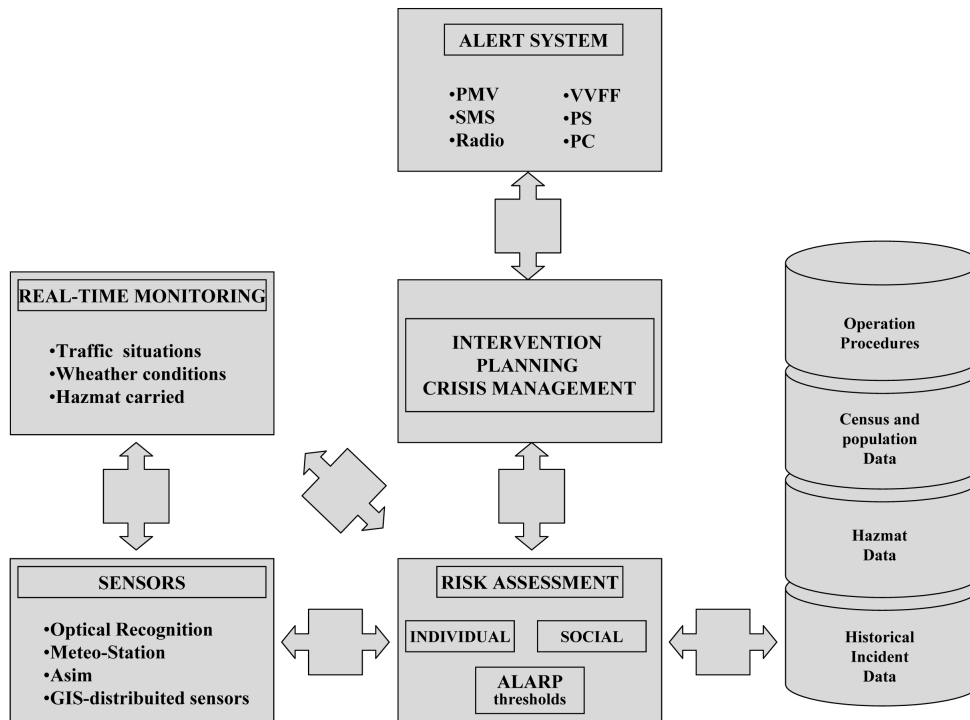


Figure 6.6: The proposed System Architecture

- consequence calculation models to determine individual and societal risk

Such procedures for the risk assessment (including for example decision-making on preventive measures) may offer only a limited insight into the causes and sequences leading to an accident and do not allow for any kind of predictive analysis. Literature review in Section 4.3 about risk analysis relative to industrial systems and HAZMAT transportation is wide and its know like Quantitative Risk Analysis (QRA).

This approach is applied in many projects to analyze risk relative to fixed systems (ARIPAR, SIMAGE, Canvey Island, Rijmond, ARTIS, ARIPAL, GRIPAL).

The evolution of the QRA for transport activity is known like Transportation Risk Analysis (TRA). Literature about TRA is recent and relative models are in evolution. Risk analysis relative to HAZMAT is applied to realize Decision Support System (DSS) to plan and to manage system (FLAG, OPTIPATH, TRAMP e RELAMP). Risk relative to dangerous goods transport is estimated generally in an aggregate way. In other cases systems of models to estimate single components of the risk (probability, vulnerability and exposure) are proposed.

In this thesis, a model for estimating road accident probability involving HAZMAT and to access individual and societal risks have been proposed in Section 6.2

The System Architecture to implement the DSS is proposed in Figure 6.6

The architecture take in account the proposed model and is based on a structure representing a set of macro-events that characterize the incident:

- a vehicle is involved in a road accident with or without dangerous goods;
- a vehicle with dangerous goods or its components is failed;
- a dangerous good generates a consequence on surrounding environment.

In the approach proposed, single event can be represented by different components and for a road accident the conditioned probability components are following.

- an heavy vehicle is involved;
- a vehicle carrying dangerous goods is involved (alone or with other vehicles);
- a release of dangerous goods is verified.

Singles probabilities relative to these components are estimated with descriptive model calibrated based on the official data [123] relative to the years 2000-2001. Models to estimate these probabilities depends on human factors and environmental characteristics. For a failure of vehicle, the probability components are the follows:

- an element of container of dangerous good is failed;
- a a release of dangerous goods is verified.

A software module that must be situated in the Control Centre of the infrastructure. It communicates with the other modules of the system through web services. It considers individually every HAZMAT transport traveling on the motorway.

For every HAZMAT transport, software module calculates either the minimum risk, the minimum cost, or the minimum combined-cost route. It takes into account the individual and societal risk cost, in addition to the economic cost, and calculates the optimum route by eliminating the combination of them.

The inputs to the system include the road network, population distribution data, sensitive “hot spots” (e.g. hospitals, schools) real-time as well as statistical traffic and weather data, statistical accident data, road characteristics, real-time vehicle and cargo status.

Those data are, whenever possible, time-dependent, with the day being divided into a certain number of time intervals, each of which corresponds to a different value of the time-dependent data.

Singles probabilities relative to these components are estimated with descriptive model available in literature (CCPS, 1995); models to estimate these probabilities depends on vehicle characteristics; - for an effect generates from a dangerous good (for example dispersion, fire or explosion), the probability is estimated with a model calibrated based on the official data relative to the incidents involving dangerous goods in Italy relative to the years 1995-2005 (APAT, 2006).

The architecture introduces an enhanced solution, and a related software platform, which attempts to integrate loss of containment causes and consequences with system’s infrastructure and its environment.

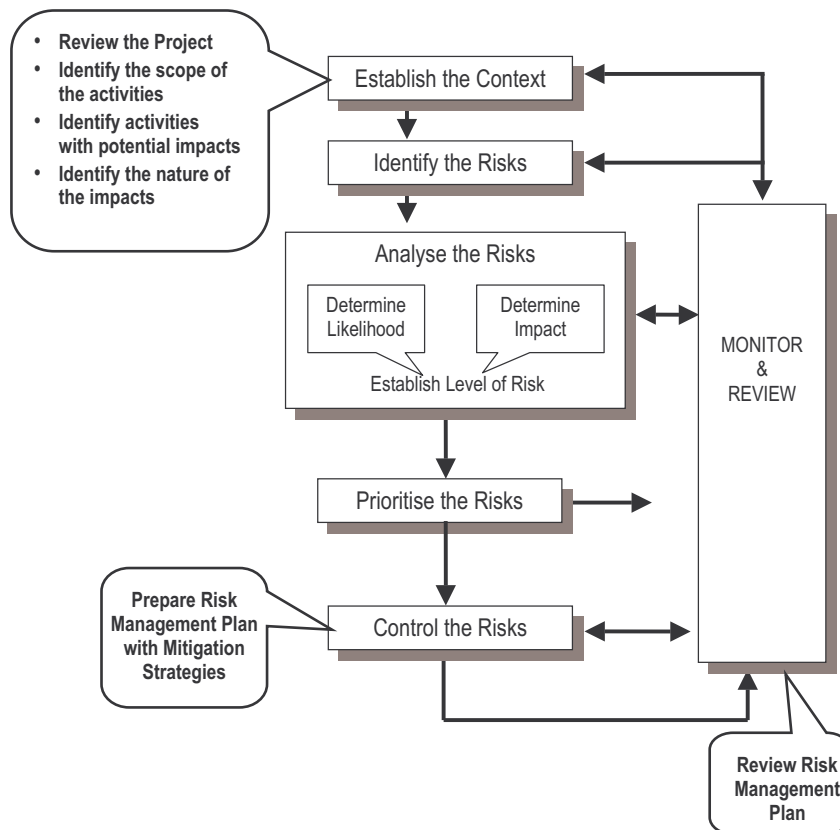


Figure 6.7: HAZMAT Transport Comparative Risk Assessment

In Figure 6.7 and in Figure 6.8 are shown two block diagrams relative to risk assessment and risk management in motorway environment used as logic reference for implement the architecture.

The solution features:

- the use of a detailed Master Logical Diagram, including fault/event tree analysis to determine a loss of containment frequency based on different initiating events, scenarios and specific basic data;
- the characterization of a resulting source term following a release situation, and
- the calculation of various potential impacts on the neighboring site. Results are wrapped into a CCDF format for each selected traffic segment.

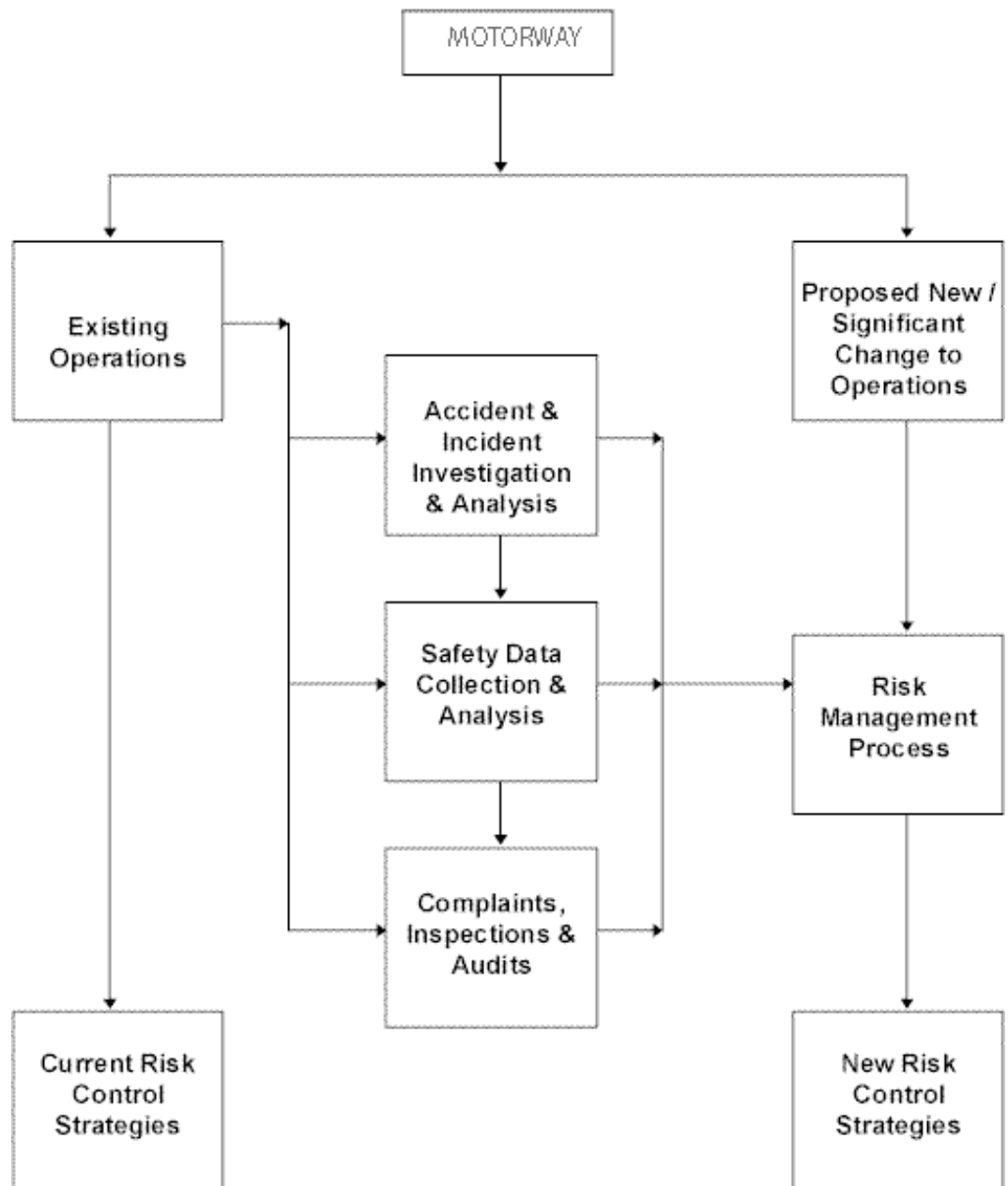


Figure 6.8: Model of Risk Management Motorway

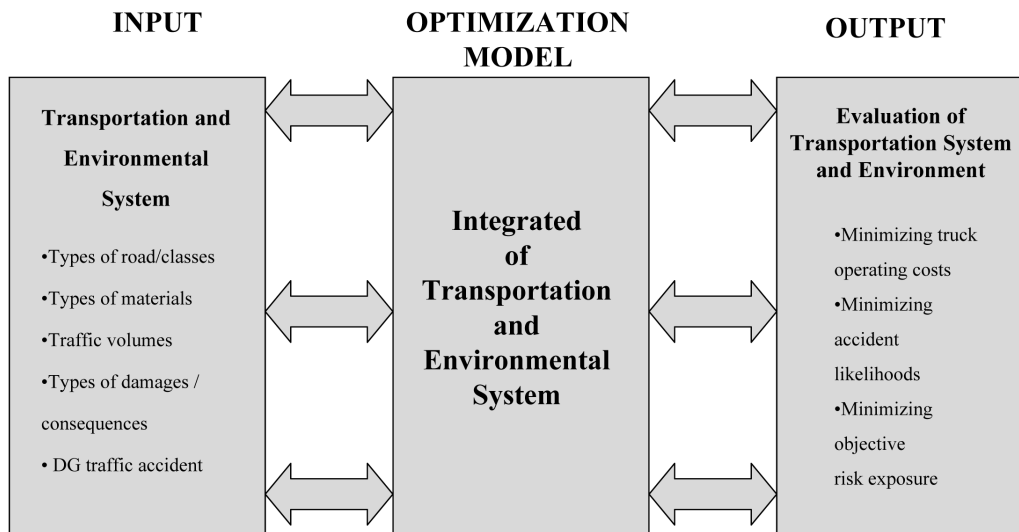


Figure 6.9: Model of Integrated transportation and Environmental System

The risk-related results are integrated on a software platform, structured as a decision support system using intelligent maps and a variety of GIS (Geographical Information System) data processing procedures.

In order to take in account of the sustainability problems another subsystem is proposed and shown in Figure 6.9.

6.4 Case study

This section will be offered an example of application of real-time model proposed in Section 6.1.3 for the calculation of the Individual and Societal Risks.

6.4.1 The transport network

With regard to the transport network, was considered the motorway network of S.p.A. Autovie Venete, including the A4 (Venice - Trieste), A28 (Portogruaro - Godega SU) and A23 (Palmanova - Udine Sud).

The network under consideration has been modeled as a arcs and nodes network in which nodes represent exits / junctions of the motorway and (link) the stretches (sections) of motorway between two exits / junctions.

For each (link) thus identified were obtained the following data:

1. length [Km] ;
2. average population density [inhabitants / Km], around *link*.

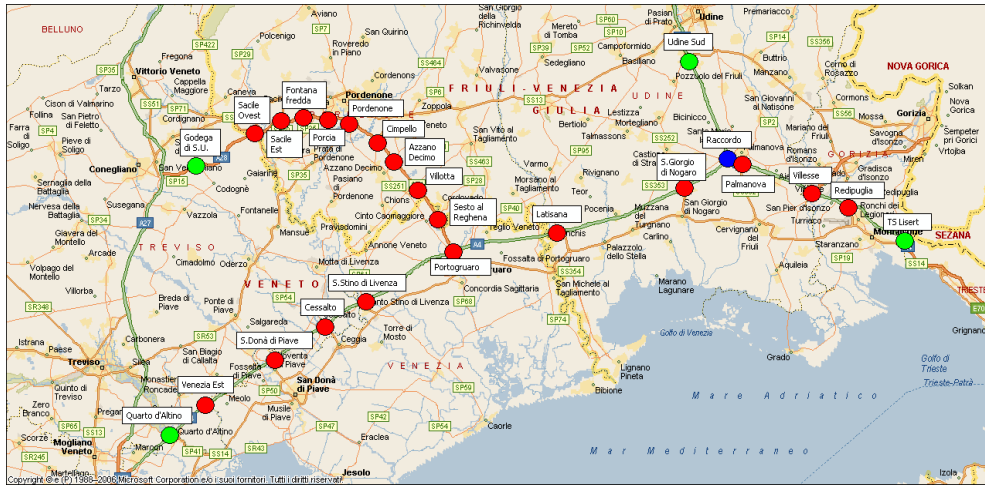


Figure 6.10: Motorway network of the case study

As for the average population density, it was calculated as follows.

1. the geographical map of the municipalities has been overlapped on the motorway network of S.p.A. Autovie Venete through Google Earth software in order to identify common cross each textit (link).
2. for each (link) we have identified the municipalities involved and measured the kilometers of infrastructure that pass through each town in order to identify the weights for calculating the average density on the (link) in question. These weights are derived by dividing the kilometers of infrastructure that affect each municipality with the total length of the (link).
3. Note the density of population in each Italian municipality, using data on the census in 2001 [?], we shall calculate the weighted average with weights determined in step 2.

Link	Municipalities	Population Density (inhab/Km ²)	Municipalities-Weight	Length- (Km)	Average-Population-Density- (inhab/Km ²)
A4					
Quarto d'Altino – Venezia Est	Roncade(TV)	192	0,9	5,5	198,5
	Quarto d'Altino (VE)	257	0,1		
Venezia Est - S.Don di Piave	Meolo (VE)	228	0,2	11,4	197,22
	Roncade (TV)	192	0,26		
	Annone Veneto (VE)	136	0,2		
	Fossalta di Piave (VE)	185	0,26		
	Noventa di Piave (VE)	330	0,08		
S.Don di Piave - Cessalto	Cessalto (TV)	111	0,4	7,7	266,6
	Noventa di Piave (VE)	330	0,4		
	S.Don di Piave (VE)	451	0,2		
Cessalto - S.Stino di Livenza	Cessalto (TV)	111	0,7	6,6	129,6
	S.Stino di Livenza (VE)	173	0,3		
S.Stino di Livenza - Portogruaro	S.Stino di Livenza (VE)	173	0,15	12,8	214,35
	Annone Veneto (VE)	136	0,15		
	Portogruaro (VE)	240	0,7		
Portogruaro - Latisana	Portogruaro (VE)	240	0,18	13,5	166,05
	Fossalta di Portogruaro (VE)	185	0,47		
	S.Michele al Tagliamento (VE)	102	0,3		
	Ronchis (UD)	106	0,05		
Latisana - S.Giorgio di Nogaro	Ronchis (UD)	106	0,09	17,6	112,66
	Palazzolo dello Stella (UD)	88	0,17		
	Teor (UD)	118	0,12		
	Pocenia (UD)	108	0,06		
	Muzzana del Turgnano (UD)	109	0,14		
	Castions di Strada (UD)	113	0,22		
	Porpetto (UD)	137	0,2		
S.Giorgio di Nogaro – Raccordo Palmanova	Porpetto (UD)	137	0,67	6,9	168,68
	Gonars (UD)	233	0,33		
Raccordo Palmanova - Palmanova	Gonars (UD)	233	0,3	1,6	350,6
	Palmanova (UD)	401	0,7		
Palmanova - Villesse	Palmanova (UD)	401	0,05	10,2	164,55
	Bagnaria Arsa (UD)	180	0,15		
	Aiello del Friuli (UD)	167	0,45		
	Campolongo al Torre (UD)	122	0,2		
	Tapogliano (UD)	91	0,05		

	Villesse (GO)	134	0,1		
Villesse - Redipuglia	Villesse (GO)	134	0,45	4,9	219,4
	S.Pier D'Isonzo (GO)	208	0,45		
	Ronchi dei Legionari (GO)	655	0,1		
Redipuglia - Trieste Liser- ert	Ronchi dei Legionari (GO)	655	0,5	8,8	970,5
	Monfalcone (GO)	1286	0,5		
A23					
Raccordo Palmanova - Udine Sud	Palmanova (UD)	401	0,1	13	175,7
	Santa Maria la Longa (UD)	118	0,36		
	Pavia di Udine (UD)	158	0,24		
	Pozzuolo del Friuli (UD)	184	0,3		
A28					
Portogruaro - Sesto al Reghena	Potogruaro (VE)	240	0,3	3	174,95
	Gruaro (VE)	156	0,45		
	Sesto al Reghena (PN)	131	0,25		
Sesto al Reghena - Vil- lotta	Sesto al Reghena (PN)	131	0,15	4	142,85
	Cinto Caomaggiore (VE)	148	0,65		
	Chions (PN)	135	0,2		
Villotta - Azzano Decimo	Chions (PN)	135	0,35	5	215,65
	Azzano Decimo (PN)	251	0,5		
	Fiume Veneto (PN)	286	0,15		
Azzano Decimo - Cim- pello	Azzano Decimo (PN)	251	0,9	3	254,5
	Fiume Veneto (PN)	286	0,1		
Cimpello - Pordenone	Fiume Veneto (PN)	286	0,4	5	885,4
	Pordenone (PN)	1285	0,6		
Pordenone - Porcia	Pordenone (PN)	1285	0,5	2	873,5
	Porcia (PN)	462	0,5		
Porcia - Fontanafredda	Porcia (PN)	462	1	4	462
Fontanafredda - Sacile Est	Porcia (PN)	462	0,6	3	366,4
	FontanaFredda (PN)	205	0,3		
	Brugnera (PN)	277	0,1		
Sacile Est - Sacile Ovest	FontanaFredda (PN)	205	0,2	4	487,4
	Sacile (PN)	558	0,8		
Sacile Ovest - Godega	Sacile (PN)	558	0,3	9	361,8
	Cordignano (TV)	244	0,1		
	Orsago (TV)	337	0,25		
	Godega di S.Urbano (TV)	245	0,35		

Table 6.1: Average population density and link length under test

Table 6.1 illustrates the *link* in discussion with the relevant data.

6.4.2 The accident probability

We use (4.1) and the Truck Accident Rate of Harwood [114, 115] in order to calculate the accident probability (λ_{incl}) in terms of $events/(vehicle * km)$, supposed be uniform throughout the (link).

We can also calculate in (6.12) the rate of accidents on a single stretch of length unit road by using the number of accidents in a time period of ten years and the total distance traveled by heavy vehicles during the same period, data provided by AISCAT (Associazione Italiana Societ Concessionarie Autostrade e Trafori) [7].

$$TAR_a = \frac{A_a}{VKT_a} \quad (6.12)$$

where TAR_a = average accident rate for trucks $events/(vehicle * km)$ on the Italian motorway network; A_a = number of accidents involving trucks in a year on the Italian motorway network; VKT_a = total distance traveled (vehicle-kilometers) by trucks on the network under consideration.

Table (6.2) shows the number of accidents involving heavy vehicles, the total distance traveled and the *Truck accident rate* year by year from 1997 to 2007 and the summary data for the years under consideration.

		ROUTES	ACCIDENTS	TAR
YEAR	ESTENSION	(veh. - km * 10 ⁶)		
	KM	<i>Heavy</i>	<i>Heavy</i>	<i>Heavy</i>
1997	5.371	14.428	7.825	5,42E-07
1998	5.380	15.161	8.854	5,84E-07
1999	5.380	15.974	10.024	6,28E-07
2000	5.380	16.790	9.681	5,77E-07
2001	5.388	17.254	9.647	5,59E-07
2002	5.388	17.836	9.691	5,43E-07
2003	5.388	18.359	9.198	5,01E-07
2004	5.391	19.059	8.841	4,64E-07
2005	5.432	19.184	9.005	4,69E-07
2006	5.441	19.764	9.000	4,55E-07
2007	5.446	20.229	8.613	4,26E-07
		194.038	100.379	5,17E-07

Table 6.2: Accidents, TAR and the total distance traveled by heavy vehicles year by year from 1997 to 2007

6.4.3 The HAZMAT

In the next step, obtained the information discussed above, we select the HAZMATs that are to be considered in calculating the risk. In particular, we have been selected substances that are more frequent or more significant on the network under consideration.

For each of these goods were obtained the following data.

- The probability of releases due to the accident ($P(R|A)$) depending in general on the characteristics of the vehicle transporting the HAZMAT (mechanical strength, possible internal partitioning, presence of double walls and insulation) and on the type of accident where the vehicle is involved. This probability was derived from the study published by Brown and Dunn [33].
- The types of possible releases classified in relation to the size of the leakage hole and consequently the rate of release or the amount of material spilled ($N_{reltype}(\nu)$).
- The consequences types of *incident* caused by different types of releas of HAZMAT since *accident* for a given type of substance ($N_{out}(\nu, r)$).
- The likelihood of occurrence a final result given the *incident* ($p_{out}(i)$). This probability was derived for each triplet [substance - means of escape - type of final outcome] from the information relating to incidents involving HAZMAT from 1997 to 2008 contained in the HMIS database [184]. This database contains detailed information on accidents involving dangerous substances in the U.S., such as the type of event or the final result that has occurred (explosion, toxic cloud, fire, etc.).
- The lethal area radius of each pair [type of release - final outcome] calculated using the free software RMPComp distributed by U.S. EPA (Environmental Protection Agency).
- The frequency on the occurrence of a given scenario:
 $f_{\nu,t}^{scen}(i, r) = \lambda_{inc} \cdot p_{rel}(\nu) \cdot p_{reltype}(r) \cdot p_{out}(i)$ whereas:
 λ_{inc} is the accident probability (TAR in Section 6.4.2),
 $p_{rel}(\nu)$ is the probability of having a release of the substance ν since the accident ($P(Release/Accident)$),
 $p_{reltype}(r)$ is the probability of having a release type r given a release and a accident ($P(ReleaseType/Relase, Accident)$),
 $p_{out}(i)$ is the probability that there is a particular incident given the type of release, the release and the accident ($P(Incident/ReleaseType, Release, Accident)$).

The logic diagrams (Event Tree) on the release types and the consequences final outcome with their probabilities are shown below for each substance examined. These data are then summarized in tabular form.

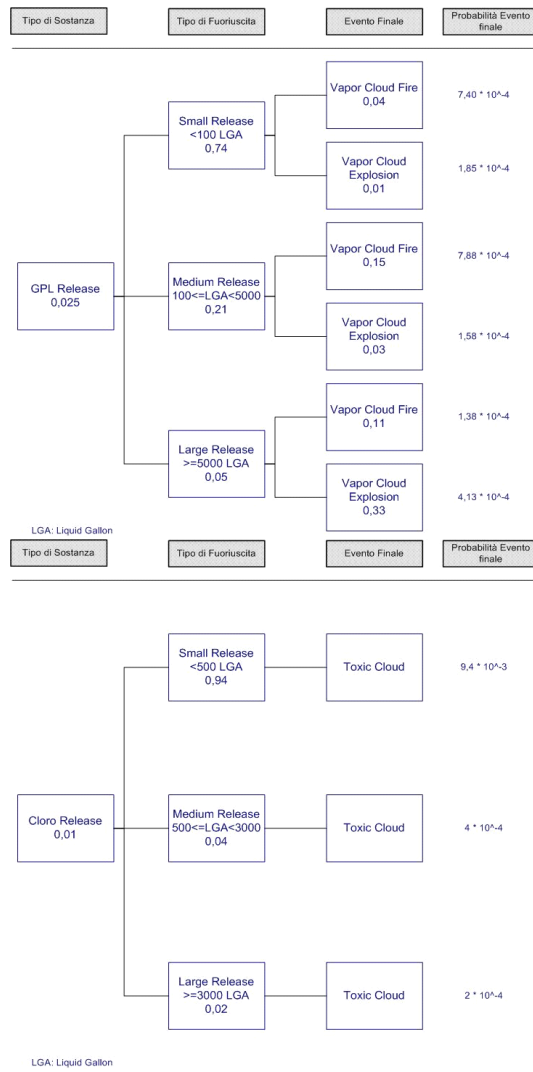


Figure 6.11: Event Tree Diagrams - GPL, Chlorine

HAZMAT	p_{rel}	Release Type	p_{relt}	Incident Type	p_{out}	Incident Prob.	Scenario Frequency	Lethal area radius (Km)
GPL	0,025	Small Spillage	0,74	Vapor Cloud Fire	0,04	7,40E-04	3,83E-10	0,16
	0,025		0,74	Vapor Explosion	0,01	1,85E-04	9,57E-11	0,05
	0,025	Medium Spillage	0,21	Vapor Cloud Fire	0,15	7,88E-04	4,07E-10	0,16

	0,025		0,21	Vapor Explo- sion	0,03	1,58E-04	8,15E-11	0,2
	0,025	Large Spillage	0,05	Vapor Cloud Fire	0,11	1,38E-04	7,11E-11	0,16
	0,025		0,05	Vapor Explo- sion	0,33	4,13E-04	2,13E-10	0,5
Cloro	0,01	Small Spillage	0,94	Toxic Cloud	1	9,40E-03	4,86E-09	1
	0,01	Medium Spillage	0,04	Toxic Cloud	1	4,00E-04	2,07E-10	2,8
	0,01	Large Spillage	0,02	Toxic Cloud	1	2,00E-04	1,03E-10	5,6
Ammoniaca	0,025	Small Spillage	0,93	Toxic Cloud	1	2,31E-02	1,20E-08	0,2
	0,025	Medium Spillage	0,05	Toxic Cloud	1	1,33E-03	6,88E-10	1
	0,025	Large Spillage	0,02	Toxic Cloud	1	5,32E-04	2,75E-10	2,1
Acido Nitrico	0,015	Small Spillage	0,93	Toxic Cloud	1	1,39E-02	7,19E-09	0,3
	0,015	Medium Spillage	0,06	Toxic Cloud	1	8,82E-04	4,56E-10	0,5
	0,015	Large Spillage	0,01	Toxic Cloud	1	2,21E-04	1,14E-10	1,9
Acido Cloridrico	0,015	Small Spillage	0,92	Toxic Cloud	1	1,38E-02	7,13E-09	0,3
	0,015	Medium Spillage	0,05	Toxic Cloud	1	7,37E-04	3,81E-10	0,8
	0,015	Large Spillage	0,03	Toxic Cloud	1	4,81E-04	2,49E-10	2,6

Table 6.3: Frequency scenarios

Table 6.4 shows the situation of the network under consideration (for each (link) it shows the dangerous and the number of vehicles in transit).

Link	Substance type	Num. of Vehicles
A4		
Quarto d'Altino - Venezia Est	Ammonia	1
	Chlorine	1
Venezia Est - S.Don di Piave	Nitric Acid	2
	Hydrochloric Acid	1
S.Don di Piave - Cessalto	GPL	1
	Chlorine	2
Cessalto - S.Stino di Livenza	GPL	2
	Hydrochloric Acid	2
S.Stino di Livenza - Portogruaro	Chlorine	2

Portogruaro - Latisana	Ammonia	2
Latisana - S.Giorgio di Nogaro	Hydrochloric Acid	2
	Nitric Acid	2
S.Giorgio di Nogaro - Raccordo Palmanova	GPL	1
Raccordo Palmanova - Palmanova	Chlorine	1
	Nitric Acid	2
Palmanova - Villesse	GPL	1
Villesse - Redipuglia	Chlorine	2
Redipuglia - Trieste Lisert	Ammonia	1
	Nitric Acid	2
A23		
Raccordo Palmanova - Udine Sud	Chlorine	2
	Ammonia	2
A28		
Portogruaro - Sesto al Reghena	GPL	2
Sesto al Reghena - Villotta	Nitric Acid	1
Villotta - Azzano Decimo	Ammonia	1
	Chlorine	2
Azzano Decimo - Cimpello	Hydrochloric Acid	2
Cimpello - Pordenone	Nitric Acid	2
Pordenone - Porcia	GPL	2
Porcia - Fontanafredda	Chlorine	1
	Ammonia	2
Fontanafredda - Sacile Est	Ammonia	1
	Nitric Acid	2
Sacile Est - Sacile Ovest	GPL	1
	Chlorine	2
Sacile Ovest - Godega	Hydrochloric Acid	1
	Nitric Acid	2

Table 6.4: Vehicles and substances on tested *link*

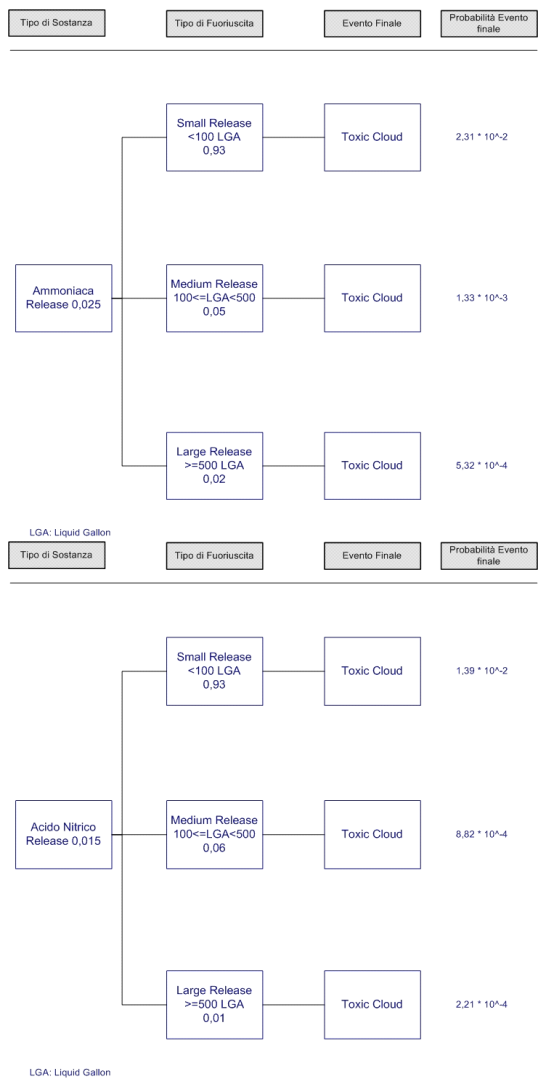


Figure 6.12: Event Tree Diagrams - Ammonia, Nitric Acid

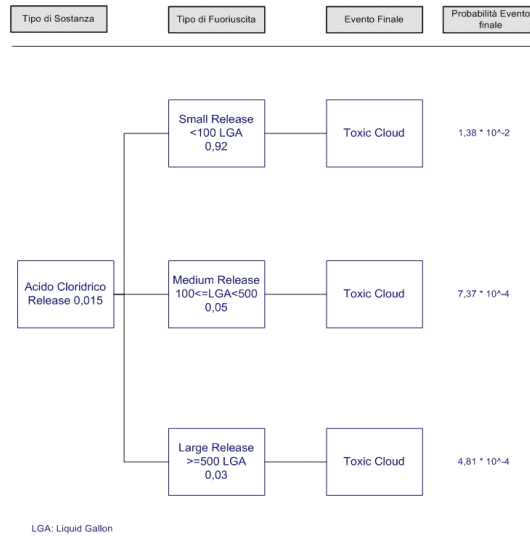


Figure 6.13: Event Tree Diagrams - Hydrochloric Acid

6.4.4 Assumptions

In the simulation carried out have been taken the following assumptions.

1. $\lambda_{inc}(l)$ uniform throughout the *link* and constant for all *links* taken into consideration: λ_{inc} ;
2. exposure area of type *danger circle* centered at the point of the incident with a radius depending of nature of the substance, the type of release and the type of final outcome;
3. any person within the exposure area is suffering from the same injury (death) in the same way regardless of the choice position, while the people who are outside that area are not affected by incident;
4. the seasons (j) are not taken into account and the weather conditions on *link* $C_{met}^t(l)$ and wind direction $\vartheta^t(l)$;
5. the simulation is performed on a single moment in time;
6. use the model to the risk neutral ($\alpha = 1$).

6.4.5 Individual Risk Calculation

The simulation were carried out on three adjacent (*links*) between ones of network under consideration.

As Individual Risk is the annual probability of an individual placed in a designated point of interest is affected by some degree of damage as a result of a specific incident [126], four points were chosen as “hot spots” at which to calculate the individual risk.

Tables 6.5 and 6.6 show respectively the *links* with the relevant substances circulating and the geographical coordinates of the points chosen for the calculation of individual risk.

Link	Substance type	Number of Vehicles
A4		
S.Stino di Livenza - Portogruaro	Chlorine	2
Portogruaro - Latisana	Ammonia	2
Latisana - S.Giorgio di Nogaro	Hydrochloric Acid	2
	Nitric Acid	2

Table 6.5: HAZMAT and Number of Vehicles carry them on *links* under test

Point Location	Latitude	Longitude
Portogruaro Centro	45,78	12,83
Area di Servizio Fratta Nord	45,8	12,88
Latisana Ospedale	45,77	13
Muzzana del Turgnano Centro	45,82	13,13

Table 6.6: Geographical coordinates of the points chosen for Individual Risk calculation



Figure 6.14: Representation of points and the network portion under consideration

According to 6.2.1, for the calculations have been used (6.5) suitably modified to highlight the different types of release.

Consequently, we made explicit that each event i belongs to the $N_{(out)}(\nu)$ of the general model may consist of a pair type of release - final outcome (*incident*) as in this case.

$$IRP^t = \sum_{i=1}^{N_{links}} \sum_{v=1}^{N_{veh}^t(l)} \sum_{r=1}^{N_{reltype}(v)} N_{type}^t(l, v) \cdot f_{rel}(v, r) \cdot \int_{Ll} \sum_{i=1}^{N_{out}(v, r)} p_{out}(i) \cdot V_{Q(x)v \rightarrow S}(i) \quad (6.13)$$

$$f_{rel}(v, r) = \lambda_{inc} \cdot p_{rel}(v) \cdot p_{reltype}(r) \quad (6.14)$$

where $V_{Q(x)v \rightarrow S}(i)$ is equal to:

1 if the point S is inside the *danger circle* centered at the point of possible accident Q related the triplet substance - release type - final outcome;

0 if the point S is external the same *danger circle*.

Line integral was calculated using the method of Cavalieri-Simpson, dividing each of the three *link* in 10 intervals of equal length.

Table 6.7 shows the results of the simulation.

Point	Individual Risk
Portogruaro Centro	2,28E-09
Area di Servizio Fratta Nord	5,78E-09
Latisana Ospedale	0
Muzzana del Turgnano Centro	1,75E-09

Table 6.7: Simulation results - Individual Risk

From the evidence we can establish that the Individual Risk in the four issues examined is acceptable according to the British ALARP threshold as the value of that risk is much lower than the limit value of 10^{-6} 6.2.4.

6.4.6 Societal Risk Calculation

In order to calculate the Societal Risk for each (link) knowing the vehicles that are going through, we use the the curves $F(N)$ representation.

According to [?], the values of F cumulative frequency (per year) are given with the curves $F(N)$ as a result of all possible accidents.

The values of F refer to the damage of a reference not less than N (and thus, as has been described as the damage of reference, a number of deaths greater than or equal to N units) cite () Spadoni1999.

In correspondence to the values of F is considered a damage in the area of reference not less than N (and thus, as has been described as the damage of reference, a number of deaths greater than or equal to N units).

To construct such a curve is necessary to derive, for each scenario defined by:

- *link*;

- HAZMAT on *link*;
- release type;
- final outcome (*incident*);

the scenario total frequency and the number of possible deaths.

The scenario total frequency is derived by multiplying the frequency of the scenario discussed in the Table 6.3 by the number of vehicles on the same *link* carrying the test substance.

In order to calculate the number of possible deaths we need to obtain the area of exposure on all the *link fixed bandwidth* and then to the scenario under consideration.

We obtained this translating the *danger circle*, whose radius depends on the triplet substance type, release type, final outcome, along the *ink*.

$$Area_{\nu,r,i,l} = raggio_{\nu,r,i}^2 \cdot \pi + raggio_{\nu,r,i} \cdot L_{link} \quad (6.15)$$

where:

- ν is the substance type;
- r is the release type;
- i is the type of event caused by the outcome (*incident*);
- L_{link} is the length of *link* under consideration.

Finally, in order to calculate the number of deaths related to each scenario we multiply the area value obtained in (6.15) by average population density of the *link*.

In Figure 6.15 is drawn the curve $F(N)$ relative to the simulation with different thresholds of acceptability as presented in Section 6.2.4.

The graph can be seen that the societal risk at moment of the simulation is ALARP zone, according to the British acceptability thresholds, of while it is not acceptable according to Dutch and Danish thresholds.

6.5 Conclusions

The main objective of this part of the thesis has been the development of a practical and efficient method of Quantitative Risk Assessment for the HAZMAT transportation, with particular reference to transport by motorway.

Using this approach it is possible to scientifically and quantitatively assess the risk derived by the transport of such goods in transit on the infrastructure and in addition to implement a Decision Support System in Management System of HAZMAT transportation on a motorway sustainable oriented motorway environment.

After a brief digression about the dangerous goods, the international classifications and the ADR legislation, the methodology of Quantitative Risk Assessment has been illustrated and developed.

This technique is characterized by a series of *sequential* steps to obtain a quantitative assessment and scientific risk.

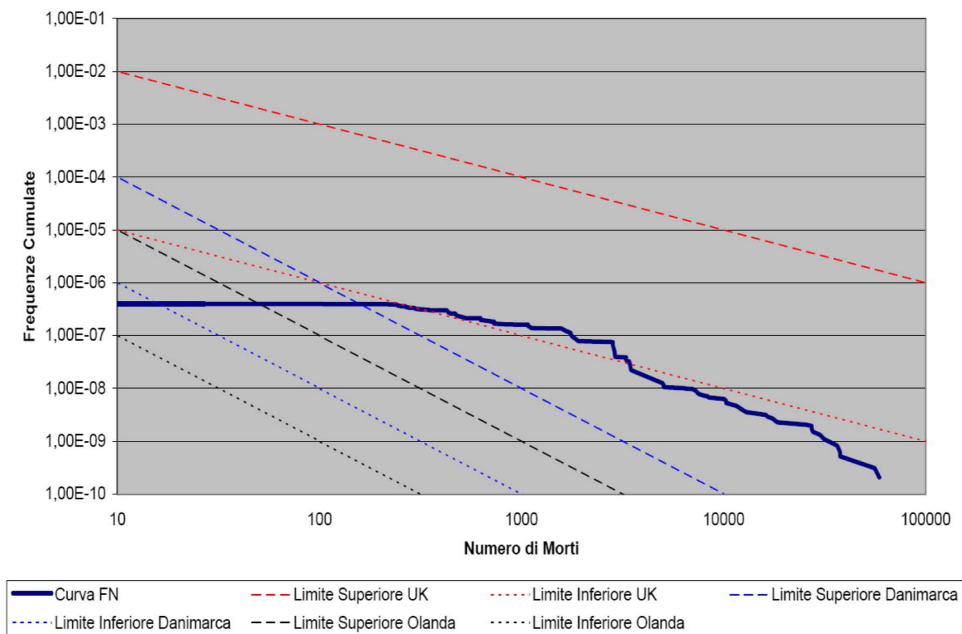


Figure 6.15: Simulation results - Individual Risk

By following this procedure, the main techniques for assessing the probability of an accident (*accident, incident, release*) and shape areas of impact or exposure have been studied.

These elements are the input model to calculate the risk that considers the interaction among the transport network, the vehicle or mobile source of risk and the area of impact.

In addition, as people or rather the *decision makers* are not usually neutral to risk facing the possibility of accidents involving dangerous goods, we have analyzed numerical models to measure the individual and societal risk taking into account the perception of risk.

Finally, in order to assess the acceptability of risk, the last step of the procedure makes it possible identifying situations of risk not acceptable and, therefore, highlight the need for remedial and mitigation of risk.

ALARP thresholds have been introduced to developed the last step of the procedure.

It is important to stress that this methodology is very general, can be applied in the assessment of risk in the transport of dangerous goods on other modes of transport.

Calculation and assessment of risk make a distinction among the different procedures, because each mode of transport has its distinctive characteristics that must be taken into account in the calculation model of individual and societal risk.

However, it was found that the developed procedures, and in general all the techniques of Quantitative Risk Assessment, suffer from some problems. Essentially they are based on analysis of data contained in the various public and private database of accidents which are not always available.

As a consequence, only an abundant availability of data allows to improve the accuracy and practicality of the methodology.

However, in recent years especially since September the 11th 2001, many institutions, agencies or private organizations have also made public their accident databases allowing researchers to access a wider source of information and therefore easier to develop research on theme.

The developed risk assessment methodology has been integrated into a Decision Support System to calculate in real time the individual and societal risk related to the transit of dangerous substances on a motorway network.

The aims is to assess whether these risks are acceptable and possibly, if they were not, notify the situation through alert messages in order to take appropriate action.

The need to integrate the proposed methodology, and in particular the model for calculating the risk, with the modern GIS is one of the emerged elements in this work.

In order to achieve an accurate QRA, the knowledge of information relating to the territory, or rather which analysis must be developed, are of enormous importance.

In particular, it is necessary to know the distribution of the population, the rates of accidents and the weather conditions.

By using this software, it is possible to integrate these information in a more simple way and to do the calculations rapidly. Consequently, shorter response times facilitate the implementation of real-time applications, such as the proposed DSS. A developable graphical interface *user friendly* will allow a easier use of the system.

With regard to possible developments, a next step will be the practice implementation of the DSS using the proposed methodology at the operational level.

A further development could be to extend the procedure of QRA methodology, regarding in particular the model for calculating the individual and societal risk, to other situations which transport of HAZMAT by road outside a motorway or other modes of transport.

Chapter 7

Synthesis, Conclusions and Possible Further Developments

7.1 Synthesis and Conclusions

In this section we provide a synthesis of the topics presented in the thesis. For a more detailed summary we suggest to refer to Section 2.7 and Section 6.5.

7.1.1 Synthesis

During the last few decades there has been a shift in transport planning objectives from economic efficiency toward strategic policy goals, such as cohesion or environmental issues, intimately linked with the “sustainable transport” paradigm.

However, the treatment of these strategic aspects is uneven and scarce among sustainable assessment methodologies. As a consequence, the development of harmonized methodologies for the strategic assessment of large scale transport infrastructure investments, in a sustainable vision, is a current challenge for the research community.

In spite of these perspectives, business has a responsibility, beyond its basic responsibility to its shareholders, to a broader constituency that includes its key stakeholders: customers, employees, government and the people of the communities in which it operates.

Organizational ethics, values and Corporate Social Responsibility initiatives are becoming increasingly important value drivers in companies and have implications right across the organization in the sector of transport.

As ethics are not a substitute for a fundamentally sound business strategy, it is important to provide value-added tools for companies to help them manage all aspects of sustainable and socially responsible business practices most of all in the road and motorway environment.

As a consequence, the sector of transport needs methodologies capable of addressing strategic effects of transport infrastructure plans, which are not usually covered by traditional assessment methodologies.

This doctoral thesis was just aimed to develop methodologies with an original approach in making an attempt to encompass both professional experience and theoretical knowledge with application oriented studies from disparate areas related to the commercial transport of hazardous materials on motorway.

In order to address this challenge, we present two methodologies to perform:

1. the objective of a Sustainable Value Added in a Strategic Plan for Corporate Social Responsibility in the sector of Build-Operate-Transfer, road operators and motorway concessionaires;
2. the individual and societal risk assessment related to HAZMAT transport in a sustainable oriented motorway environment.

We suggest to refer to Section 2.7 and Section 6.5 for more detailed conclusions.

The first proposed methodology constitutes a strategic approach, based on an original idea to use the Balanced Scorecard model in the specific sector of motorway concessionaires to estimate its corporate efficiency and to evaluate environmental and social performance.

We analyzed the key features and principles of sustainable development by examining emerging needs, available capitals, and productivity capacities of motorway environment.

We have developed a performance measurement program based on outcome measures related the activities a concessionaire undertakes to its strategic goals.

The proposed performance measurement system includes the common performance measurements in a number of measures limited to those that are really important to a motorway company as the followings: system condition and preservation, safety, accessibility and traffic conditions-mobility.

In addition, a user satisfaction index is reported which may be estimated from customer surveys.

As protection of environment and sustainability are important goals for most transportation agencies, public or private, around the world, there is a common desire to be able to measure performance in this regard. The Balanced Scorecard proposed model can really to be useful to estimate corporate efficiency and to evaluate environmental and social performance in a motorway company.

Finally, we proposed a model for sustainable development for a motorway concessionaire completed with the four perspectives of the Balanced Scorecard, the vision and the mission customized for S.p.A. Autovie Venete.

The second proposed methodology constitutes a practical and efficient method of Quantitative Risk Assessment for the HAZMAT transportation, with particular reference to motorway environment.

HAZMAT transportation problems which consider all involved parties (government and the carriers) are a relatively young research topic.

In general, the studies in the HAZMAT transport literature do not have an exploratory modeling focus. Nevertheless various analytical equations for risk are used in route optimization or quantitative risk assessment research.

In this research we take a novel approach to analyze hazardous materials transportation risk.

Previous studies analyzed this risk from an operations research (OR) or quantitative risk assessment (QRA) perspective by minimizing or calculating risk along a transport route.

Further, even though the majority of incidents occur when containers are unloaded, the research has not focused on transportation-related activities, including container loading and unloading.

The proposed methodology constitutes a strategic approach, based on the utilization of spatial impact analysis tools supported by a Geographical Information System (GIS). The assessment criteria, based on the “sustainable transport” paradigm, are structured into efficiency, cohesion and environmental criteria.

Using this approach it is possible to scientifically and quantitatively assess the individual and societal risks derived by the transport of dangerous goods in transit on the infrastructure. In addition, it is possible to implement a Decision Support System in Management System of HAZMAT transportation on a sustainable oriented motorway environment.

The aims is to assess whether these risks are acceptable and possibly, if they were not, notify the situation through alert messages in order to take appropriate actions.

Two new numerical procedures have been presented: these procedures allow the calculation of individual and societal risk values in the case of hazardous material transportation on motorway environment with the same accuracy used when examining fixed plants.

These procedures take into account the different transport methods and hazardous materials, different equivalence holes for each vehicle, different meteorological conditions and seasonal situations, a non uniform wind rose distribution and a very precise description of the outdoor and indoor population, both on-route and off-route.

When performing transportation risk assessments, some simplifying hypothesis are introduced, which are mainly due to the necessity of bypassing computational difficulties.

Finally, we offered an example of application of the proposed real-time model for the calculation of the Individual and Societal Risks. The case study involves a stretch of A4 motorway managed by S.p.A. Autovie Venete.

In spite of a limited number of trucks transporting HAZMAT on the motorway, the results of the application point out the concrete possibility to exceed the thresholds of the ALARP limits for the societal risk.

7.1.2 Conclusions and Possible Further Developments

Road traffic injuries and deaths are a major public health issue worldwide. Unless appropriate action is taken urgently, the problem will worsen globally. This will particularly be the case in those developing countries where rapid motorization is likely to occur over the next two decades. A sizable portion of the burden of injury will continue to be borne by vulnerable road users.

The transportation of dangerous goods on congested motorways is becoming an area of increasing concern for public safety and environmental awareness. The risk to population and damage to environment is a major concern to the general public and government policy makers.

There is hope, though, that the devastating loss of life and health entailed in such a worsening scenario can be avoided.

Over the last forty years the science of traffic safety has developed to a point where the effective strategies for preventing or reducing crashes and injuries are

well known. As a scientific systemic approach to the problem of road safety is essential, this aspect is not yet fully accepted in many places. Several studies on the transportation of hazardous materials have been reported in the literature. They relate aspects such as database development, selecting criteria for designating HAZMAT motorway routes.

Researchers need to have access to high quality accident probability data and empirical or theoretical researches that lead to improvements in the quality of such data. Applying national data uniformly on all road segments of similar type is quite problematic since “hot spots” such as road intersections, highway ramps, and bridges are frequently ignored. There is no agreement on general truck accident probabilities and conflicting numbers are reported by different researchers.

Given the limitation of QRA, and the fact that public opposition is a function of perceived risks, perhaps more attention should be paid to quantifying and modeling of perceived risks. We believe more work is needed to improve our understanding of how perceived risks change as a function of the hazardous substance, the distance to a hazardous activity, and the volume of the activity.

Geographic information systems make it possible to use more precise population information. However, using census-based population data for daytime HAZMAT movements makes little sense since census data is residence-based and most residents are not at home during the day.

Researchers need to take the next step and incorporate day versus night population distributions, as well as high-density population installations such as schools and hospitals. While this is done relatively easily for QRA of a single route, it is more complicated to generate the necessary data for an entire transportation network.

In addition, the formidable challenge of reducing the level of human loss on the roads and to favor a sustainable development requires the following to be developed: increased capacity for policy-making, research and interventions, in both the public and private sectors, national strategic plans, incorporating targets where data allow, good data systems for identifying problems and evaluating responses, collaboration across a range of sectors, including the health sector, partnerships between public and private sectors.

Finally, we believe that there are still many important OR problems in HAZMAT transportation for instance: intermodal HAZMAT transportation, HAZMAT transportation via air or pipeline, HAZMAT transportation network design problem which considers all involved parties (government and the carriers), and HAZMAT logistics management involving decisions based on multiple criteria (e.g., cost, risk, equity).

However, we think the focus will shift from a priori optimization toward real-time adaptive decision making for several reasons, such as the availability of the necessary technology and data, as well as security concerns.

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