Multi-criteria route optimization for dangerous goods transport using fuzzy risk assessment and agent-based traffic simulation

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Optimisation multicritère des itinéraires pour transport des marchandises dangereuses en employant une évaluation en logique floue du risque et la simulation du trafic à base d'agents.

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T H È S E

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Preface

The transportation of dangerous goods is considered as the most critical and complex activity in the transport industry. Yet, it is one of the most relevant factor in the economy of every country.

Everyday thousands of trucks transporting hundreds of thousands of tons of dangerous goods through specific infrastructures both within and across nations. The infrastructures depend on various mode of transport namely, road, railway, sea, inland waterway, air and pipeline. The shares of these modalities is linked to the economic strategy of each country. However, the term "dangerous" indicates an intrinsic adversity that characterize these products, which can manifest in an accident leading to release of a hazardous substance. In this situation, the consequences can be lethal to human beings and damage the environment and public/private properties. These dangerous goods include materials that are radioactive, flammable, explosive, corrosive, oxidizing, asphyxiating, bio-hazardous, toxic, pathogenic, or allergenic.

The importance of dangerous goods boils down to the significant economic benefits that generates. In fact, one cannot deny the contribution of the transport of all fossil fuel derived product, which represents more than 60% of dangerous goods transported in Europe. Eni, the Italian leading petrochemical company, every day operates a fleet of about 1,500 trucks, which performs numerous trips from loading terminals to filling stations. Distribution of petroleum products is a risky activity, and an accident during the transportation may lead to serious consequences.

Aware of what is at stake, the division Eni R&M historically active in Genoa headquarters is collaborating since 2002 with the Department of Computer Science, Biomedical Engineering, Robotics and Systems Engineering (DIBRIS) at University of Genoa, with the purpose of studying possible improvements regarding safety in transport of dangerous goods, particularly petroleum products. Over years, this collaboration, which has been enriched by the contribution of the Crisis and Risk research Centre (CRC) at Mines ParisTech, has led to the development of different technologies and mainly to an information and decision support system. The major component of this system is a platform for monitoring Eni fleet, at the national level, to deliver the products to the distribution points, called the Transport Integrated Platform. These vehicles are equipped with a device capable of transmitting data stream in real-time using a GPRS modem. The data transmitted can be of different nature and contain information about the state of the vehicle and occurred events during the trip. These data are intended to be received by centralized servers then get processed and stored, in order to support various applications within the Transport Integrated Platform.

With this in mind, the studies undertook throughout the thesis are directed towards the development of a proposal to further minimize the risks. In other words, a trade-off based model for route selection taking into consideration economic and safety factors. The goal is prompted by the need to support existing regulations and safety standards, which does not assure a full warranty against accidents involving dangerous goods.

The goal is carried out by considering the existing system as basis for developing an Intelligent Transportation System aggregating multiple software platforms. These platforms should allow planners and decision makers to monitor in real-time their fleet, to assess risk and evaluate all possible routes, to simulate and create different scenarios, and to assist at finding solutions to particular problems.

Throughout this dissertation, I highlight the motivation for such research work, the related problem statements, and the challenges in dangerous goods transport. I introduce the Transport Integrated Platform as the core for the proposed Intelligent Transportation System architecture. For simulation purposes, virtual vehicles are injected into the system. The management of the data collection is improved for more reliability, efficiency and scalability in real-time monitoring of dangerous goods shipment. Finally, I present a systematic explanation of the methodologies for route optimization considering both economic and risk criterions. The risk is assessed based on various factors mainly the frequency of accident leading to hazardous substance release and its consequences. Uncertainty quantification in risk assessment is modelled using fuzzy sets theory.

Acknowledgements

One of the joys of thesis completion is to look over the journey past and remember all the friends and family who have helped and supported me along this long but fulfilling road.

Foremost, I would like to express my heartfelt respect and gratitude to my thesis supervisors Pr. Roberto Sacile and Dr. Emmanuel Garbolino. Their patient, continual support and constructive criticism in numerous research work have always inspired me in my research skills and personal development. They are not only mentors but also dear friends, who offered their help and assistance during my stay in Italy and France. A special thanks to Pr. Valerie Godfrin for assistance and administration.

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My personal sincere thank goes to Rafiullah, Waqar and Nicola together with all my colleagues and friends of the doctoral schools, both at the University of Genoa and Mines ParisTech. I am also fortunate by being part of the DELAB, for the pleasing work environment which I really enjoyed. My thanks goes as well to my swimming coach of Piscine di Albaro.

I would not have contemplated this road if not for my mother, Horria, who instilled within me a love of creative pursuits of knowledge and science, all of which finds a place in this thesis. I am, as ever, especially indebted to her for the love, prays and ubiquitous support throughout my studies. To my parents, grandmother, siblings and nephews, thank you for your continual support.

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I have no special talent. I am only passionately curious.

Albert Einstein

Chapter 1. Introduction

This chapter starts by giving the motivation for undertaking research on this critical industrial activity that is the transport of dangerous goods. Then highlights the most important problem statements judged worth to discuss and of interest to any stakeholders. The chapter also addresses the thesis context and objectives to be achieved. Finally, the structure of the dissertation is introduced.

I. Research motivation

I.1. Overview on Dangerous Goods Transport (DGT)

Nowadays, dangerous goods are used in a wide range of industrial and economic activities. Products such as the Liquefied Petroleum Gas (LPG) for example, are used wherever power, heat or light are required by end-users and society. As all products derived from fossil fuel sources, it generates important economic benefits at all levels: energy, transportation, heating and refrigeration. However, the term "dangerous" goods is a label indicating the intrinsic adverse characteristics of these products, which can manifest in certain conditions such accident events. If this happens, the consequences can be lethal to human beings and damage the environment. In this dissertation, dangerous goods are a pack of hazardous materials considered as goods within a supply chain. These materials includes radioactive, flammable, explosive, corrosive, oxidizing, asphyxiating, bio-hazardous, toxic, pathogenic, or allergenic materials (Tomasoni, 2010). All liquids, gasses and solids goods that might harm humans, other living organisms, environment and public/private properties.

From this point onwards, I use the common acronyms "DG" for Dangerous Goods and "HazMat" for Hazardous Materials. "DGT" is also a common term referring to Dangerous Goods Transport. "Catastrophic accident" is a term that implies every accident involving HazMat or leading to HazMat release.

Regarding the commercial road traffic of DGT, increasingly over years, continues to rise throughout the world whatsoever at national or international level particularly in Europe. Despite the decline along 2008 and 2009 attributed to the financial crisis, in which DGT experienced a regression of 4% in total, where flammable liquids dropped by 12%. Then, as portrayed on the Fig. 1-1, a significant regrowth affected goods shipment and DGT by 2010. In addition, the dangerous nature, the implemented security measures and confidentiality regarding DGs management, make DGT one of the most complex and sensitive activity that requires special attention from stakeholders, decision makers and researchers within governmental and non-governmental safety organization. This activity may have catastrophic consequences when certain events take place in specific conditions, such explosions in a high populated area or toxic chemicals release into groundwater, leading to casualties directly or indirectly through environmental degradation.

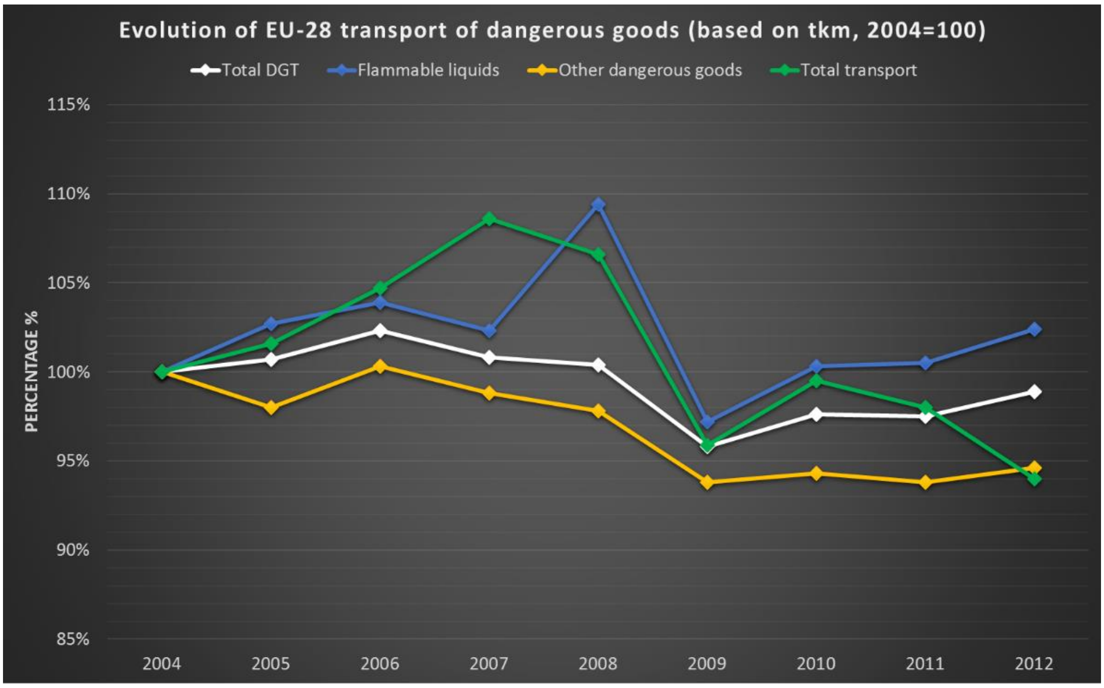


Fig. 1-1 Evolution of EU-27 transport of dangerous goods (based on tkm, 2004=100)

In this work, we will focus mainly on transport of DG by road. Since it seems to be the major source of catastrophic accidents among all transportation mode, as shown on Fig. 1-2. Indeed, 64.9% of catastrophic accidents are caused by road traffic, whereas railway traffic represents only

26.8%, according to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration. However, the work can be easily extended to other modalities.

When a catastrophic accident involving dangerous goods, the consequences cannot be often contained and lowered (Tomasoni, 2010). For this reason, stakeholders have no choice but to seek risk management strategies for DGT as preventive measures to mitigate either the probability of occurrence or magnitude of the consequences, while minimizing the costs.

I.2. Who are the potential DGT stakeholders?

The DGT stakeholders are the individuals or groups that are likely to affect or be affected by the transport of dangerous goods. The question then arises as to who are the potential stakeholders in DGT. In literature, works such (Glickman, 1992) confirm that some of the stakeholders are more interested by the economic factors; whilst others are more concerned by safety and well-being of the population and environment. Among all the possible stakeholders, four potential stakeholders can be identified: the transport companies, the industrial companies, the national/local authorities, and non-profit organization acting on behalf of the population.

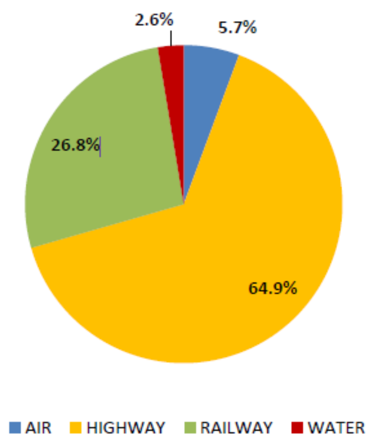


Fig. 1-2 Weighted High-Impact Causalities by Transportation Mode as Percent of Total, 2005-2009. PHMSA's Hazmat Intelligence Portal (HIP) in Sept 2010 with modifications in Feb 2011.

The transport companies (private or public) in charge of DGT are mostly interested in maximizing their profits. One of the steps that help achieve this objective is mitigating operational costs. Each unit of length travelled by a vehicles is estimated by a cost, price, fuel consumption or rather travel time. For instance, if the travel time can be minimized then, consequently, the operational cost can be minimized, therefore maximizing profit.

The industrial companies (private or public) that have HazMat production plants, HazMat storage facilities, manage distribution or use these hazardous materials. In other words, every company whose activity requires HazMat. These companies influence the whole DG supply chain, and mainly the transport companies who are concerned by the transport process.

Depending on the case study area, the term Local or National Authority (LNA) refers to either local or central government. Two main issues dealt with by the LNA. First, the proper functioning of the transport network at all time. Second, maintaining a safe urban/rural environment. In case of an accident occurs involving DG, the transport network system can be significantly disrupted and the surrounding environment can suffer from heavy damages. The negative effects on the environment in case a catastrophic event extend to transport network itself, buildings, hospitals, parks, schools, etc. The damage cost can be expressed in economic terms, as well as in human lives.

Non-profit organization concerned by population in general and especially the ones living in or nearby the area where the DG are being transported. This becomes even more relevant when the transport of DG takes place in urban areas where there is high population density. People are always interested in their safety, and will not agree about being exposed to a hazard in their work place or residential area. In risk management, the population is the main element at risk to be considered, and often risk is expressed in term of human lives. Non-profit organization are also concerned by the impact of DGT on the environment.

II. Problem statements

In DGT, dangerous goods have to be transported from an origin to one or more destinations. Generally, the origin are facilities producing, storing, or distributing DG. After production, goods are transported to other facilities where they are required. Due to the dangerous nature of these goods, safety measures have to be considered along the entire supply chains, from production to distribution. Therefore, regulations and safety standards are implemented to mitigate risk of any incident related to DG, and to ensure the smooth running of all operations. The main goals of these standards is to minimize the risk of managing dangerous goods. However, the implementation of such regulations does not assure a full warranty against accidents involving DG, since these regulations cannot take into consideration all possible scenarios and every environments. A time-dependent management is then required to improve the desired safety measures along the DG supply chains. What I mean by time-dependent management, is the continuous monitoring where decisions are taken locally within a time horizon of few seconds, minutes or hours. This means, a decision maker needs to be aware of the state of the dangerous goods at all times and in all places where are located. They also need to be assisted at making decision, and in addition, test solution and models of problem they encounter in the management of DGT.

I highlight hereinafter the most important needs I judged worth to discuss and of interest to any stakeholder or decision-maker.

II.1. Need for ubiquitous real-time monitoring system

Only two decades ago, it was not possible to have such ubiquitous technologies, since the GPS[1] was not fully operational until 1995. Today, GPS network has around 30 active satellites and used for multiple GIS[2] applications, such route navigation systems as the global leader product *TomTom*. Yet for mapping, the study of earthquakes, floods, climate, population behaviour during catastrophic accidents, epidemics or disease outbreaks. There are even GPS-based games, such *Geocaching*, an outdoor game for treasure hunting.

[1] Global Positioning System (GPS) is a network of satellite navigation system that provides in any condition the time and location

[2]Geographical Information System (GIS) is a software for capturing, storing, analysing, manipulating, and presenting all kind of geographical data.

Having said that, the emerging information and communication technologies including the GPS and computer network, allowed researchers and engineer to design and develop ubiquitous systems offering a platform for real-time monitoring. It is a software and hardware challenges that is easier to take up than to achieve it. That will not stop the urge of stakeholders to be aware of the whereabouts and status of the vehicles. Many sophisticated devices can be used such speed and engine activity sensors, besides to the GPS modem. Thus stakeholders can control in real-time their interests, which is, in our context, the smooth flow of the DG supply chain.

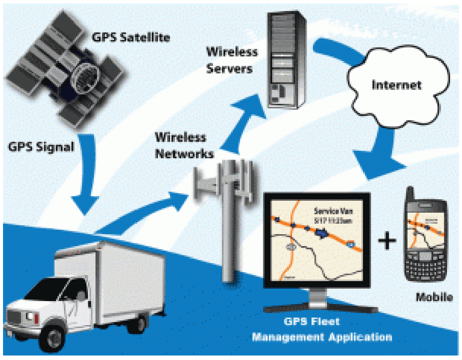


Fig. 1-3 GPS fleet tracking system

II.2. Need for a powerful data collection system

One of the challenges in real-time monitoring is the system in charge of data transmission, reception, processing and storage called the data collection system. It is a highly technical issue where the objective is to design a system capable of managing a large amount of data transmitted simultaneously and continuously. In other words, the system should be:

- Reliable: Ability to ensure transmission and reception of uncorrupted data, with error checking and acknowledgement system. Very low probability of corrupted data;
- Efficient: Ability to handle fast enough the received data. Very low probability of lost/late data;
- Scalable: Ability to handle a growing amount of data received. Very low probability of system crash when overloaded.

II.3. Need for a route optimization algorithm

II.3.1. Multicriteria optimization

Over time, real-time monitoring produces a tremendous quantity of valuable data that can be analysed and studied to understand specific phenomenon or scenarios. It can be also used for planning and scheduling of fleet of vehicles that are supposed to deliver goods from a source "loading terminal" to one or multiple destinations "distribution points". Decision makers can then figure out the best path for routing the vehicles carrying DG. The commonly used model is one that is concerned by saving millions of gallons of fuel each year, where routing is based on the economic factors. However, it is not enough when dealing with dangerous goods. Better path selection models will be those where safety factors are considered as well. That is to say, what factors matters in Decision Support Systems, depends on the stakeholders interests involved in the DGT.

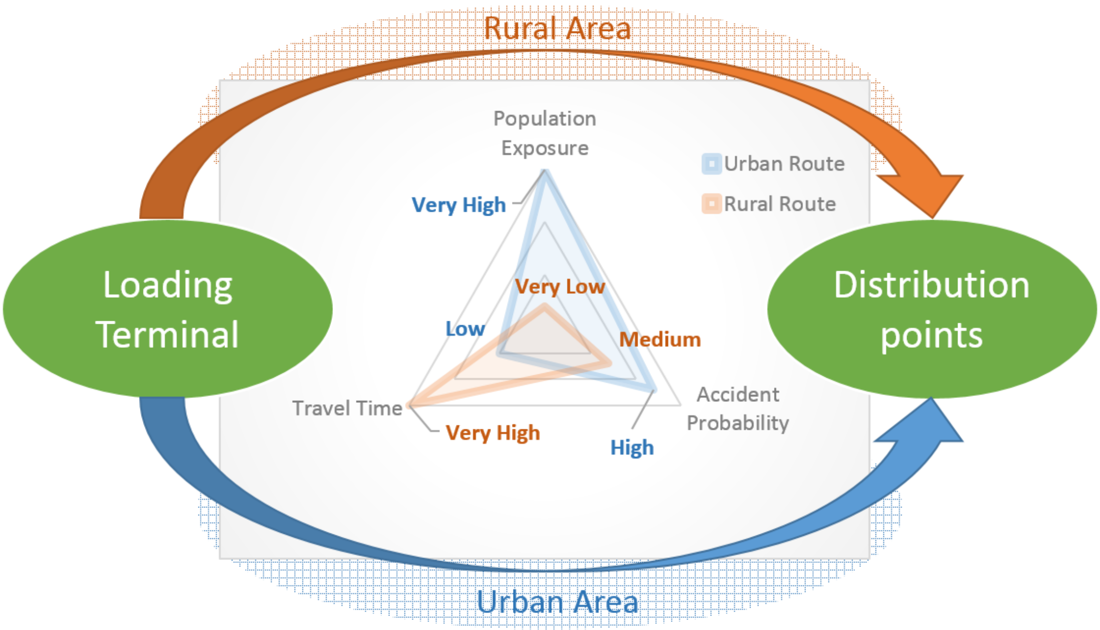


Fig. 1-4 Vulgarization of conflict between economic and safety factors while selecting a route from a loading terminal to the various distribution points.

Generally, safety interests oppose the economic ones, which complicate the decision-making process, as well portrayed by Fig. 1-4. Consider for instance the differences in risk perception and economic interest that may exist in different countries. There will be a greater awareness of the dangers of DG in some countries as compared to others. This is reflected on, for instance, who is concerned by natural disasters and DGT management. Countries lacking of interest and awareness, will consider natural disaster affect more the private and public sector organization than those dealing with dangerous goods (Glickman, 1992). DGT management are usually left for stakeholders involved directly in the dangerous goods management. Consequently, the same stakeholders will often select the routes based only on economic factors, which is saving fuel and logistics. The challenge is to design an optimization model that come out with solutions, which consider safety factors, while keeping their attractiveness from economic point of view.

II.3.2. Time-dependent optimization

Usually, in route planning only static information are taken into consideration, such historical data on population density, road infrastructure. Though a factor such the "travel time" of a road segment depends on the time instant at which the vehicle enter the road segment. This is obviously due to the dynamic nature of the road network environment, which is impacted by e.g. the traffic density or weather condition. Similarly, most risk factors depends on the time and the lieu. This dependence requires a full knowledge on real-time traffic density, population density, nearby HazMat, transported HazMat, weather condition (Tomasoni et al., 2010). The algorithm for path selection has to be applied on a time-dependent network, where each road segment is linked with a time-dependent cost and risk functions.

II.4. Need for defining factors of each criterion

II.4.1. The economic criterion

The problem that arises when transporting DG is how to select a route where economic and risk issues are considered. On one hand, the DGT has to be economically feasible for the stakeholders directly involved in this activity. On the other hand, the DGT must pursue the safe transport by minimizing the risk throughout the whole transportation process. Defining the economical factor is a straightforward task. However, defining what determines risk is a far more complex reality. The economic feasibility of a transport activity can be seen in terms of the operational costs. The more the operational costs involved in the transport process are kept under ascertain threshold, the more economically feasible the process will be. For simplicity reasons, the operational costs of DG shipment are usually considered to be proportional to transport duration, which results at focusing only on being fast at delivering goods. In other words, the economic factors is usually simplified to be equivalent to travel time. For decision makers, the logic is simple, by reducing the travel duration costs will inevitably be reduced.

II.4.2. The risk criterion

Regarding risk factors, the term "risk" is often defined as the probability of a damaging event to occur multiplied by its consequences (Fabiano, 2005). Risk is the interaction of hazards and vulnerability factors of one or more elements at risk. The interaction of these factors can be determined and/or influenced by other external factors e.g. environment, society, politics, etc. There is a considerable amount of research on route modelling for the transport of DG where factors such as accident probability, explosion probability, and population vulnerability are considered when it comes to risk assessment. Some of these research studies are the ones carried by (Karkazis and Boffey, 1995), (Bonvicini et al., 1998), (Frank et al., 2000), (Leonelli et al., 2000), and (Zografos and Androutsopoulos, 2004) just to name a few (a discussion related to this references is presented in the chapter 2). However, the influence of other natural or socio-natural hazards, affecting elements at risk other than population, has not been considered, or at least I have not come across research studies which have considered these issues.

II.4.3. Uncertainty quantification of risk factors

Another issue concerns risk analysis that is the methodology for uncertainty quantification. It is generally acknowledged that there are substantial uncertainties present in any analysis of risk. Many techniques used for uncertainty analyses exist, but most of them are inappropriate for practical use in the complete risk assessment process. Such the traditional probabilistic approach using a Monte Carlo simulation due to its non-statistical nature (Quelch and Cameron, 1994). The concept of fuzzy sets as a means for quantifying uncertainty is introduced in this dissertation. In fact, Quelch proves that the amount of computation required by the latter is substantially reduced compared to the traditional probabilistic approach.

Using fuzzy set theories for uncertainty quantification of risk related to DGT represents an important and original scientific contribution. Risk factors should be defined then undertake a Fuzzification methodology to capture the best quantification possible of the uncertainty surrounding each factors. This is usual done by considering experts' opinion or statistical/historical data.

II.5. Need for traffic simulation system

Models and algorithms for scheduling, route optimization and supply chain management cannot be proven to be reliable and efficient till they are tested in different case scenarios. Often it is hard to test them in real world due to the complexity, costs, confidentiality, dangerous nature of the transported products, and sometimes the unavailability of the data regarding specific scenarios in spite of the data collected from the real-time monitoring system. That is why visual traffic simulation is needed to mimic the real world with a full power of customization. Applications on serious games, financial market, and engineering are evidence of success of the visual simulation system.

The challenge consists on how to design a system that represents real-world traffic systems with an appropriate degree of complexity and dynamics. Several researchers have already suggested solutions since the 50s. These solutions have been classified in three levels: microscopic, mesoscopic and macroscopic simulation. The microscopic approach using an agent-based model is the most appropriate to simulate individual vehicles and by the way mimic the real ones. Agents are autonomous, goal-driven and interacting entities. By injecting those agents into the real-time monitoring system, we will have a larger group of vehicles behaving identically, yet some of them are virtual and fully customizable.

II.6. Need for Intelligent Transportation System

To be able to select economic and safe routes for the transport of DG it is necessary to use software platforms that allow planners and decision maker: to monitor in real-time their fleet, to assess risk and evaluate all possible routes, to simulate and create different scenarios, and to assist in finding a solution to a particular problem. The aggregation of these software platforms make up what is called by the Intelligent Transportation System (ITS[3]). Stakeholders and decision-makers are, no doubt, very interested by having at hand a platform aggregating all information and tools for decision support. The ITS was initially motivated in US by the increasing interest on homeland security for roadways monitoring. In highly populated cities with complex transport network, ITS was an excellent solution for managing multimodal systems from walking to private and public transport. The ITS also helps countries and cities experiencing a fast growing urbanisation to manage congestion and improve the traffic network. An ITS application for transport of dangerous goods is then became substantial and necessary.

III. Thesis context

The thesis falls under Ph.D. co-tutorship between University of Genoa, Italy, and Mines ParisTech, France, as shown on Fig. 1-5. Enrolled respectively into the course of *monitoring of systems and environmental risks management*, and the course of *sciences and engineering of hazardous activities*. From both courses, one can easily notice three keywords: Monitoring, Risk, Hazard. Besides, an R&D collaboration is undertook with the Faculty of Science and Technology of Mohammedia.

In this section, I describe the context from which it emerges this thesis research. Since works have been done, others are ongoing, and an operational system exist. Then I define the objectives to meet, for my mission

[3] The Intelligent Transportation System (ITS) is a recent concept emerged with latest technological development as it is thoroughly discussed in (Hernndez et al., 2002; Crainicet al., 2009; Taniguchi and Shimamoto, 2004).

as a Ph.D. candidate, by projecting them on the motivations, context and the problem statements.

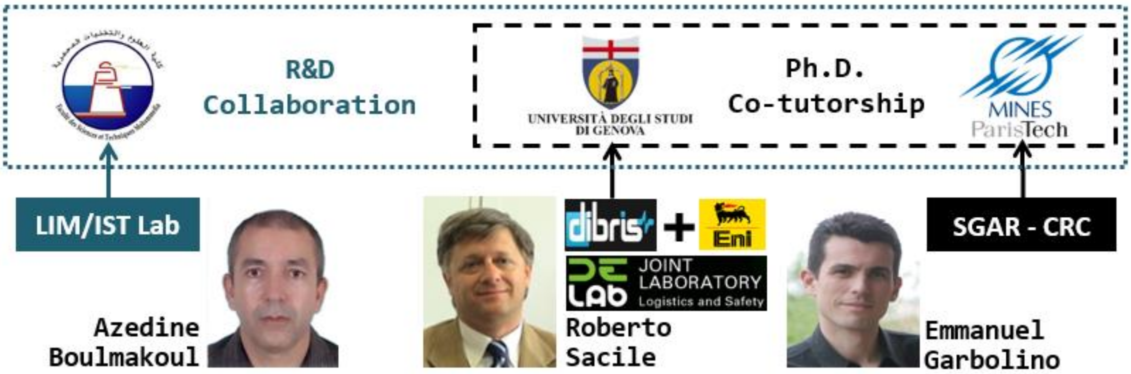


Fig. 1-5 The institution contributing in the PhD Thesis along with the respective tutors

III.1. Previous works: the existing system

This thesis is part of series of works that started some years ago and continues to evolve with the emergence of new advanced technologies. Since 2001, the Italian leading petrochemical company *Eni*[4] *R&M - Logistics Secondary division*, collaborates with the DIBRIS[5] department of University of Genoa in Italy, under the name of *DELAB - DIBRIS & Eni Joint Laboratory* (see Fig. 1-5). The objective is to study possible improvements regarding transport safety of DG, petroleum products in particular. This collaboration has exploited various technologies and architectures of decision-making and information. The basis of this information system is the *Transport Integrated Platform (TIP)*, a basic ITS application on road transportation of DG (Benza et al., 2012). This application has as main purpose the monitoring the fleet of vehicles that distribute petroleum products in Europe. Such vehicles are equipped with a GPRS device allowing the transmission of real-time data stream. The data are formatted following an internal syntax convention, and it describes the truck's state, GPS coordinates, and special/critical events. Then data are conveyed to a centralized server to provide support for the

[4] Eni S.p.A. (http://www.eni.com/) is an Italian multinational oil and gas company based in Rome. It operates in 79 countries, and represents Italy's largest industrial company.

[5] Department of Computer science, Bioengineering, Robotics and Systems engineering

various other logistical tools; such fleet management and scheduling, data mining, customer orders management, drivers training program, truck technical management and more (Benza et al., 2012). All these tools are available through a dashboard the one shown on Fig. 1-6.

Eni fleet consists (in the time of thesis writing) of more than 4600 vehicles, 1600 of them are dedicated to petrol product supplying through service stations for the automotive market. Currently more than 600 vehicles are monitored and transmit data regularly. These vehicles make two or three trips with an average distance of 170 km for each trip. The TIP platform for real-time monitoring consists of four main components: the On-board Unit, Transmission System (or Data Collector), Transmission Database Server and the GIS web application. The On-board unit is a sets of software and hardware devices installed in the vehicle. It collects events and telemetry data such temperature, speed, geographical coordinates, and GPRS transmitter/receiver for transmission over IP network. Whereas the GIS web application is a visual human-machine interface that translates the collected data to visual information easier to understand and analyse by the decision-maker, as depicted by Fig. 1-6.

Fig. 1-6 The graphical user interface of the Tranport Integrated Platform: the dashboard on the left, web mapping on the rigth showing a monitored truck over italian territories.

The TIP, addresses mostly the needs stated along the section. However, it still has to be enhanced to keep track of the growing number of monitored vehicles. Since, in the short terms, it will cover a larger number of vehicles and countries. In fact, the actual data collection system is costly in terms of

GPRS connection transmission and, consequently, convey data at a frequency of 5 minutes. That is why we need a better ubiquitous real-time monitoring system with a frequency of transmission of few seconds, and scalable, which is dealing with larger number of transmitted data. These issues will be thoroughly discussed in the Chapter 4.

III.2. Thesis objectives

The objectives I had to carry out during my Ph.D. emanate from the need to addresses all problems highlighted so far, from the need of improvement of the existing system, and from the state of art and works carried out by my tutors. The whole is to be seen in the context of the development of an **Intelligent Transportation System** as pictured by Fig. 1-7, where we can see the real-time monitoring, the data collection system, real and virtual vehicles, and route optimization algorithm. This research aims at contributing to the ITS platform that can be used in the planning and management of DGT. However, the research problem is much more oriented towards the development of a route optimization model considering economic and safety factors of DGT. By doing so, we are contributing to the management of the DGT system. Here below the four objectives of my thesis.

First, the development of a reliable and scalable **data collection middleware**, which represents an important component of the real-time monitoring system for data transmission, processing and storage. This represents a very important technical improvement for the TIP and a significant scientific contribution in data management. Secondly, the design of an architecture allowing the integration of **agent-based traffic simulation** in the real-time monitoring system of the TIP. The reason for traffic simulation stems from the need of a broader freedom and customization, scenarios creation and refinement of tests, models and instruments whose reliability are yet to be determined. This does not challenge the field-testing, which it is supposed to be executed at later stages. Thirdly, the conception and development of an algorithm for **time-dependent route optimization**. The algorithm should select the best path for shipment of a vehicle carrying dangerous goods from the loading terminal (such production site) to the distribution point. In this work, the best path means the fastest and safest one, where economic (time) and risk factors are taking into consideration for decision support. These factors are time-dependent; they continuously evolve and change since a dynamic environment affects them. Finally, the **fuzzy risk modelling** as uncertainty representation approach. Since risk is a fuzzy notion, and can be neither exactly determined nor being null. The perception of hazard and risk is hard to quantify, and can be better-expressed using fuzzy logic. Initially, the various risk factors that can influence somehow the DGT should be defined.

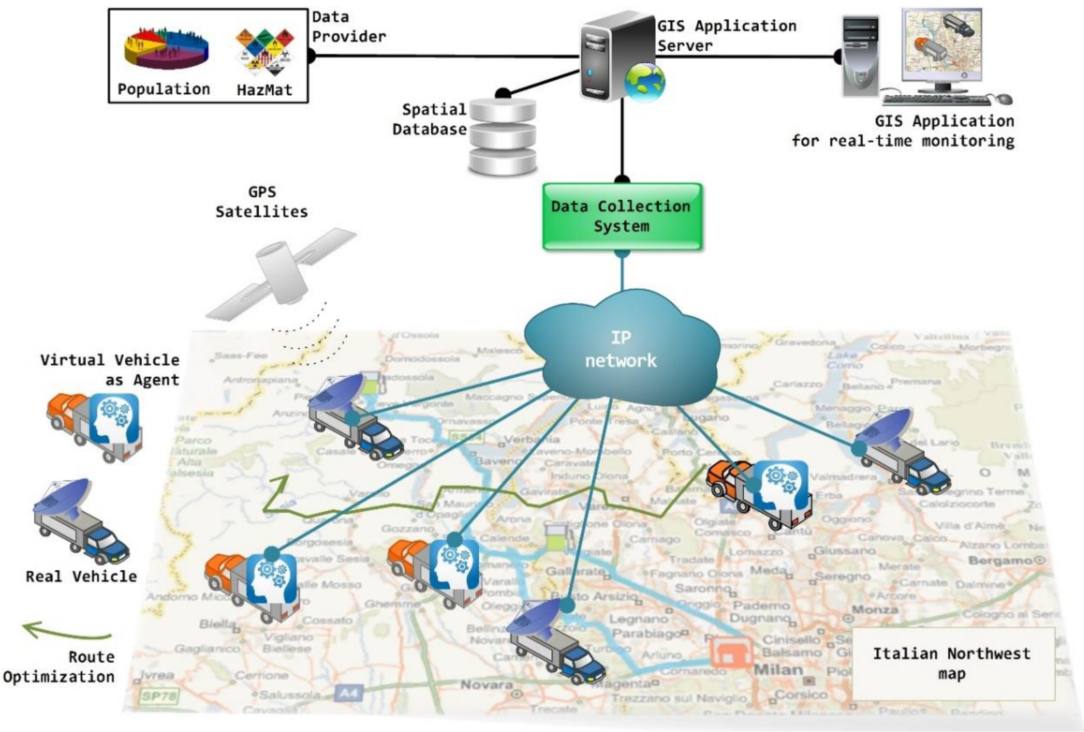


Fig. 1-7 an overview of an Intelligent Transportation System for Real-time monitoring, simulation, route optimization taking into consideration travel time, population, transported HazMat

IV. Thesis outline

Up to now, I have introduced facts proving the importance of dangerous goods, and the growing quantity shipped over the last decade. I also highlighted the hazard of transporting DG and its serious impact on population and environment if any catastrophic accident occurs, which are mostly caused by DGT road traffic. To understand the challenges of DGT, I identified the potential DGT stakeholders and their roles. Then, I listed the reasons for undertaken a research on optimizing the road transport system of DG. The second section concerned the main problem statements encountering DGT. Finally, I detailed the thesis context and the objectives I should achieve as a Ph.D. candidate. Let me introduce the outline of this thesis dissertation. It is divided into six chapters:

Chapter 2. Dangerous Goods Transport. It comes after the current one. This chapter is a literature review of the risk management in Dangerous Goods Transport. First, it starts by highlighting facts about the important of DGT and the modality of transportation. Then focus on the road traffic accident and its impact on DGT. Finally, risk management strategies in DGT are discussed.

Chapter 3. An Intelligent Transportation System. This chapter details the general goal of the thesis. First, it starts by detailing the existing system that is the Transport Integrated platform. Then, it addresses the agent-based traffic simulation for injection of virtual vehicles in the TIP.

Chapter 4. Data Collection Middleware. I dedicate this chapter to problem of achieving a reliable, efficient and scalable data collection system. As mentioned before, this technical and scientific contribution addresses the most important component of the real-time monitoring system.

Chapter 5. Fuzzy Risk & Fuzzy Ranking. The methodology for risk uncertainty quantification using fuzzy sets theories is the theme of this chapter. In addition, I also address the ranking problem within fuzzy sets, thus an original approach is introduced for this matter.

Chapter 6. Multicriteria Route Optimization. In this chapter, I tackle step by step the methodology for optimizing route selection. The algorithm is based on A-star bidirectional search using Voronoi diagrams for graph subdivision. The algorithm is extended to manage the trade-off between the economic and safety criteria, respectively travel time and risk by using a multi-objective function. An example portraying the algorithm steps is presented toward the end of the chapter.

Chapter 2. Dangerous Goods Transport

The purpose of this chapter is to provide facts that support the goal of this research work. First, by underlining the criticality of road transport of dangerous goods. Then, by discussing risk assessment in DGT. Finally, by considering the uncertainty factors and their representation using fuzzy set theory.

I. Chapter introduction

In Europe and all over the world, goods are transported by various modalities: air, sea, inland waterways, roads, railways, and pipelines. The economic and geo strategies, besides to the infrastructure, resources and transportation cost of each country, influence greatly the modal split of goods transport. Yet, the road has the most important modal shares. In certain region, sea transport exceed significantly road transport for international freight traffic. In the following, I will discuss in detail the modal split to understand better the importance of road traffic in Europe and especially in Italy and France. Thus, it seemed appropriate, as well as interesting, to start by describing the statistical data regarding the volume of freight traffic.

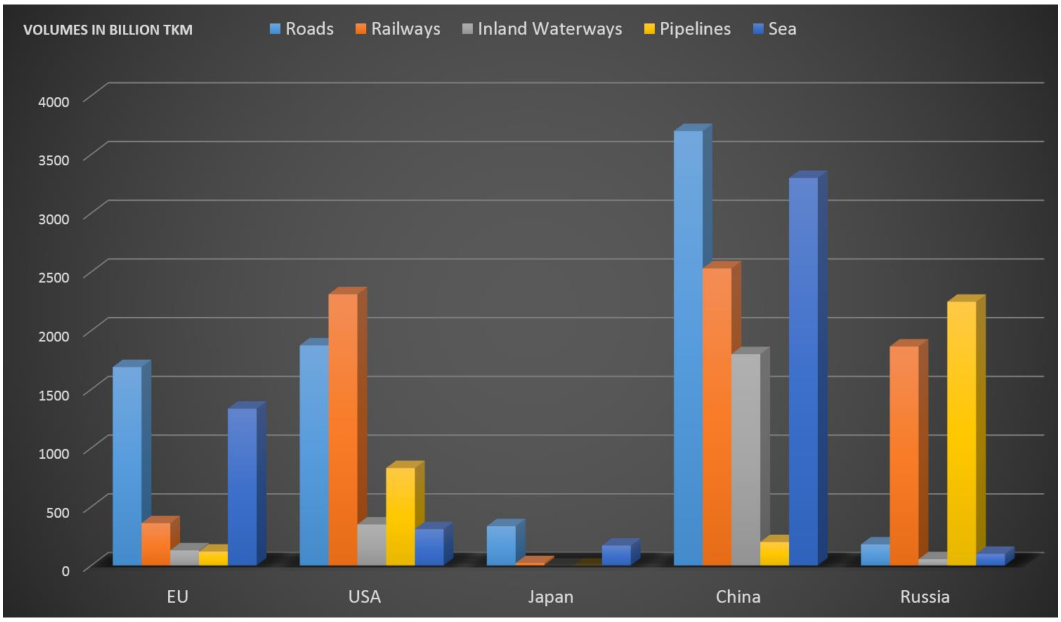


Fig. 2-1 Quantity (in Billion tkm) of internal freight traffic in 2009 by mode of transport, in the world, Eurostat, ITF

The Fig. 2-1 compares the annual quantity of internal freight traffic (in billion tkm) between UE, USA, Japan, China and Russia and for each modes of transport: Roads, Railways, Inland waterways, Pipelines. From these data it is clear that, in addition to the geographic and economic factors, in all the areas considered (except for Russia) the quantities of goods transported by road is particularly high. Whereas the railways modality is extensively used in countries with a large surface area such the United States, China and Russia. Inland waterways (by river or lake) have less importance except for China. Pipelines play a fundamental role in Russia, given its great asset of oil and natural gas. These data affects, obviously, the development of road infrastructure and the motorways, under which it is expected to boost the road freight traffic in developing countries, as well as, in developed ones.

The observations on Fig. 2-1 become more apparent when we compare rather the modal shares of the internal freight traffic as shown on Fig. 2-2. This figure highlights the contribution of each modality in the total of internal freight traffic. We also observe the importance of sea traffic in freight transportation.

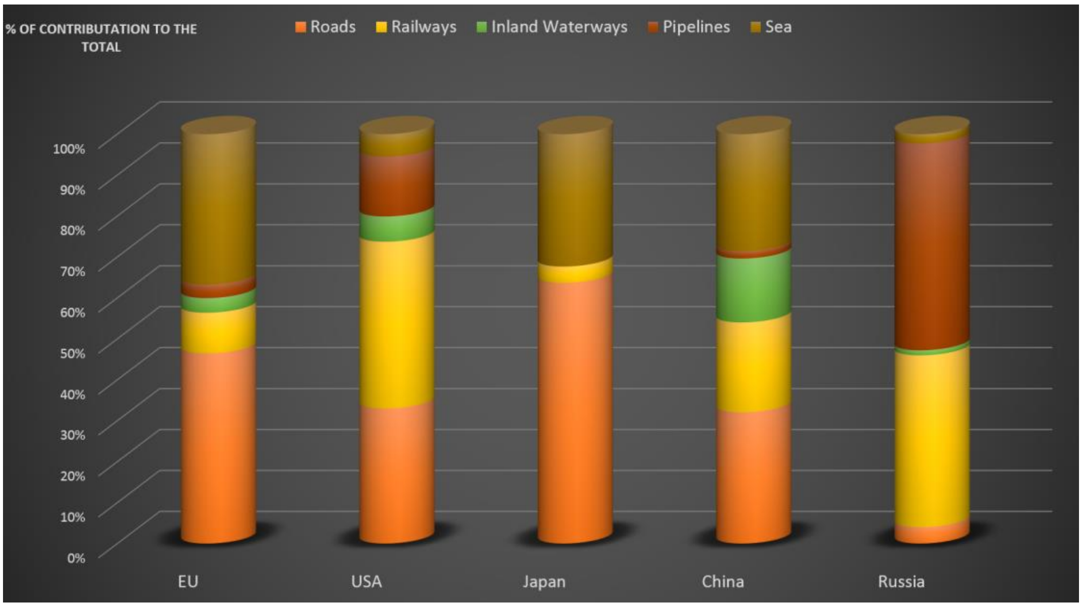


Fig. 2-2. Modal split of the internal freight traffic throughout the world, Eurostat, ITF

Up to now, we have analysed the extent and the relative importance of the major mode of transport for the internal freight traffic. It is also interesting to analyse what are the common modalities used in foreign trade. The only statistics available are those related to the European Union and provided by Eurostat. One of the interesting points that emerge when analysing foreign trade is, what are the most used transport modalities in import-export?

The following chart in Fig. 2-3 (measured in terms of value and weight of the goods transported by different modes) shows the role of maritime transport. This mode is used for transporting roughly 76.9% of quantity of goods over which it has almost no competition. Consequently, maritime transport manages 47.4% of the worth of total goods transported, in which the aviation is the biggest competitor by 26.8%. Although the road is less used in foreign trade, it still has a significant portion in the transport of goods with high value by 20.6%, and leaves an important part to railways for transportation of heavy goods.

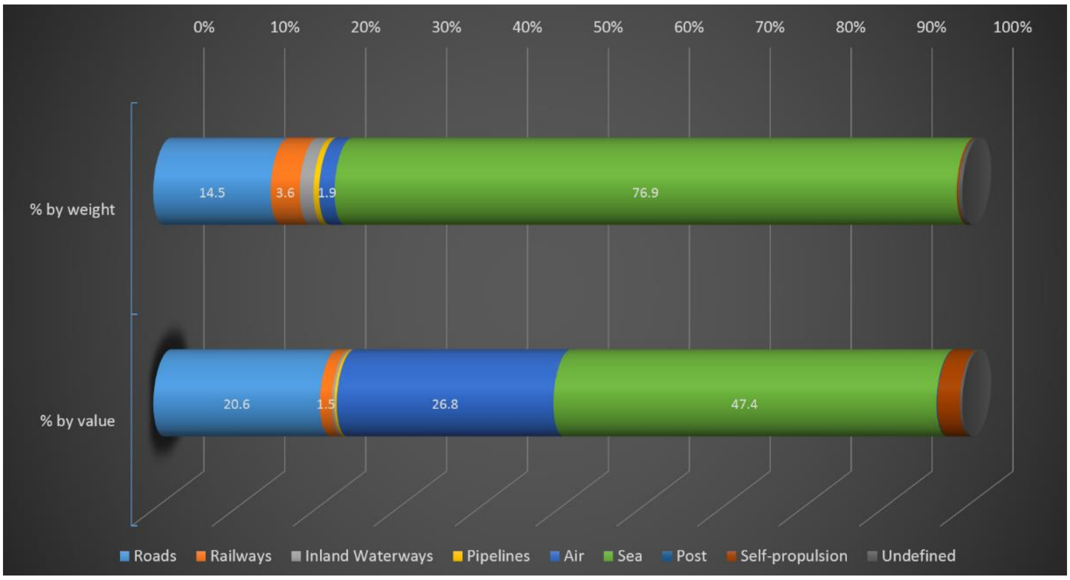


Fig. 2-3. Modal split in foreign trade expressed in terms of value and weight, in EU27, Eurostat

Let us now compare the modal shares of roads, railways, inland waterways, and pipelines in freight traffic among the Western European countries (Fig. 2-4). Roads modality is predominant in Italy, France, Spain and UK, whereas less predominant in Germany to the benefit of railways. Germany also maintains high shares of inland navigation, practically absent in most of the countries of the EU. Germany represents the first EU country with the higher volume of goods transported by road (313.1 billion tkm), followed by Poland

and Spain (over 210 billion tkm). Poland is the country that has experienced the greatest growth, by almost 40%, in the period 2007-2010, contributing along with Bulgaria, Slovenia and the Czech Republic to shifting eastward the centroid of the European freight traffic. An important exception is Romania, which in the same period, has seen a reduction in freight traffic by more than 55%. In major European countries, the transport of goods by road is mostly national and generally represents at least 70% of total freight traffic.

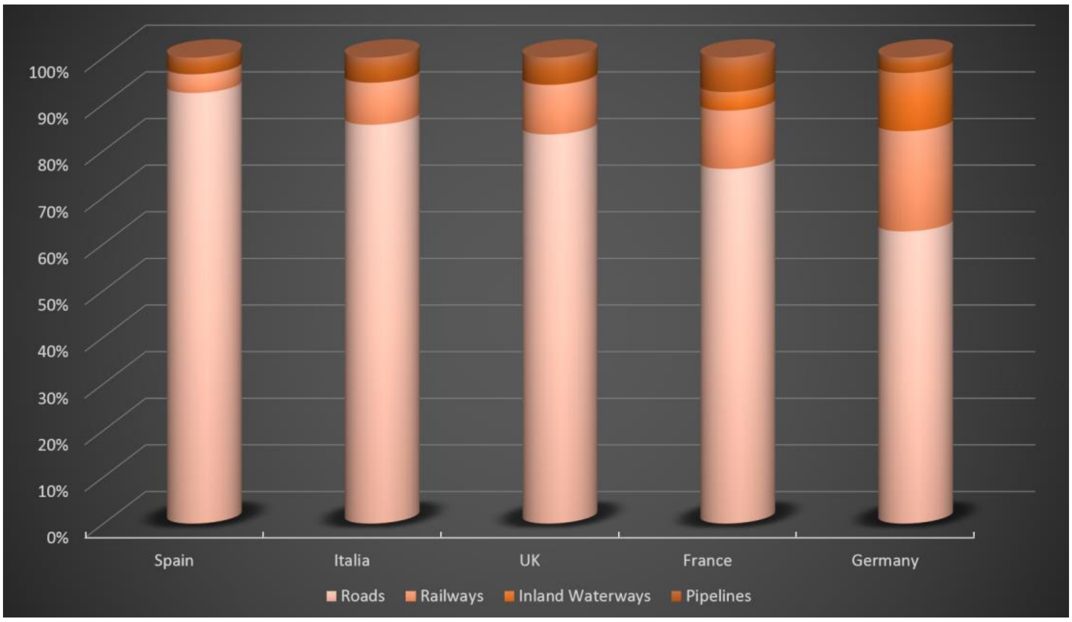


Fig. 2-4. Modal split of Domestic and international freight traffic in Western Europe, Eurostat 2012

As regards to the ratio of population to the volume of freight traffic, is more consistent in Luxembourg (171.5 million tkm per ten thousand inhabitants), as well as in Slovenia, Lithuania, Poland, Finland and Slovakia, all with values greater than 50 million tkm per ten thousand inhabitants. In Italy, by 2010 the ratio of population to the volume of traffic of goods by road is amounted to 29 million tkm per ten thousand inhabitants, slightly higher to what was recorded in same year in France (28.1 million tkm per ten thousand inhabitants). Much lower than ratio of Spain (45.6) and Germany (38.3), and higher than in United Kingdom (22.6). The greatest increases of the ratio in the period 2007-2010, are found amongst same countries with the greatest growth of freight traffic (Poland, Bulgaria, Slovenia and the Czech Republic).

Finally, the Fig. 2-5 summarizes the last 20 years evolution of the modal split of freight traffic in the European Union. It is clear that roads were and still predominant mode of transportation, and continue to gain in traffic share. Despite the European desire to give more importance to railways traffic.

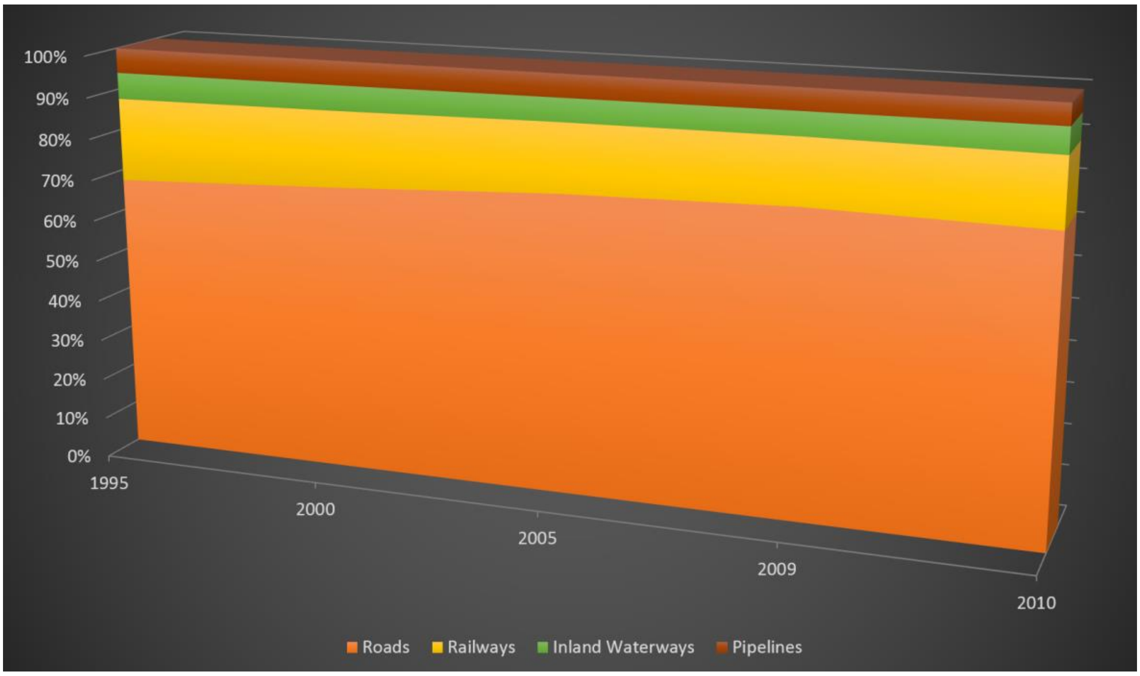


Fig. 2-5. Evolution of the modal split of freight traffic along 1995-2010 in UE27, Eurostat 2012

II. Road transport of dangerous goods

II.1. Dangerous Goods (DG), what are they?

Dangerous goods, DG, (or hazardous materials, HazMat, as often called in USA), may be mixtures of substances, pure chemicals, articles or manufactured products that can threaten safety of people, any living organisms, the environment or surrounding properties if handled awkwardly while in manufacturing, storage, transport or usage.

II.2. DG in transport

In transport, dangerous goods are materials and substances that present apparent risks during the transportation, as risk of explosion or toxic chemicals release into groundwater.

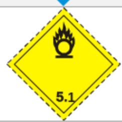
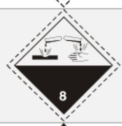
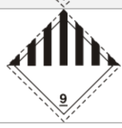
The DGT is regulated to prevent as possible catastrophic accidents involving human, damage the environment, the vehicle of transport, goods transported, property. Each transport modality (road, railway, sea, air, inland waterway, and pipeline) has its own regulations. The UN regulations for the DGT, published for the first time in 1957 and periodically updated, are the point of reference for all the laws specific to the different modes of transport at international, local and national level. For each modality a set of international regulations are in place, as the following:

- ADR: the transport of dangerous goods by road;
- RID: the international transport of dangerous goods by railway;
- AND: the international transport of dangerous goods on internal rivers/canals;
- ICAO and IATA: transport by aeroplane;
- IMDG Code: maritime transport.

The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) is the main regulation on DG transport on road. ADR has been written at Geneva on 30 September 1957 under the auspices of the United Nations Economic Commission for Europe, and it came into force on 29 January 1968. The Agreement itself was modified by the Protocol amending article 14 approved at New York on 21 August 1975, which entered into force on 19 April 1985 (ADR, 2013). The ADR was approved by law in Italy on 12th August 1962 n. 1839, in France with act n. 60 – 794 on 22nd June 1960, and approved by the Moroccan parliament then came into effect in June 2003.

The ADR regulations use a classification system in which each dangerous substance or article is assigned to a “Class”, depending on the nature of the danger it presents. There are nine Classes, some of which are sub-divided, as shown on Table 2-1. These hazardous materials can be radioactive, flammable, explosive, corrosive, oxidizing, asphyxiating, bio-hazardous, toxic, pathogenic, or allergenic materials (Berman et al., 2007), and in any state, liquid, solid or gas.

Table 2-1 the classes of dangerous goods according to ADR applicable as from 1 January 2013. (Copyright© United Nations, 2012. All right reserved)

Class 1		**Explosive substances and articles**	
Class 2	2.1	Flammable gases	
	2.2	Non-toxic and non-flammable gases	
	2.3	Poison gases	
Class 3		Flammable liquids	
Class 4	4.1	Flammables solids, self-reactive substances and solid desensitized explosives	
	4.2	Substances liable to spontaneous combustion	
	4.3	Substances which, in contact with water, emit flammable gases	
Class 5.	5.1	Oxidizing substances	
	5.2	Organic peroxides	
Class 6.	5.1	Toxic substances	
	5.2	Infectious substances	
Class 7		Radioactive material	
Class 8		Corrosive substances	
Class 9		Miscellaneous dangerous substances and articles	

The ADR regulations topic goes from method of identification of dangerous goods, passing by the technical suitability checking of the vehicles, to the training of the vehicle drivers. In addition to monitoring of the vehicles that must be equipped with devices transmitting data such geographical position coordinates.

II.3. DG transportation shares

To determine the percentage of the contribution of DGT in the total freight traffic in Italy, I rely on the data collected by the National Institute for Statistics ISTAT[6], as reported on Fig. 2-6. Statistics show that in the last twenty years, the DGT shares has been oscillating around 10% with peaks reached in the early 90s of the last century both in terms of tons and tkm.

More detailed analyses show that, overall, in Italy the majority ($\sim 80\%$) of dangerous goods transported by roads are petroleum products. Regarding the ADR classification, in terms of tonnes:

- 77.7% are flammable liquids (class 3, includes Gasoline, Methanol, Fuel, Crude oil, Mineral oil);
- 12.6% are compressed gas, liquefied or dissolved under pressure (mainly Propane and Ammonia);
- 7.0% consisting of corrosive (class 8, includes acids and other corrosive substances such as Oleum, Sulphuric Acid, Nitric acid and Hydrochloric acid, Sodium and Potassium Hydroxide, and Hypochlorite solutions);

These three categories accounted for 97.3% of the quantity of dangerous goods transported by road in Italy.

[6] The National Institute for Statistics (ISTAT) is the main supplier of official statistical information in Italy.

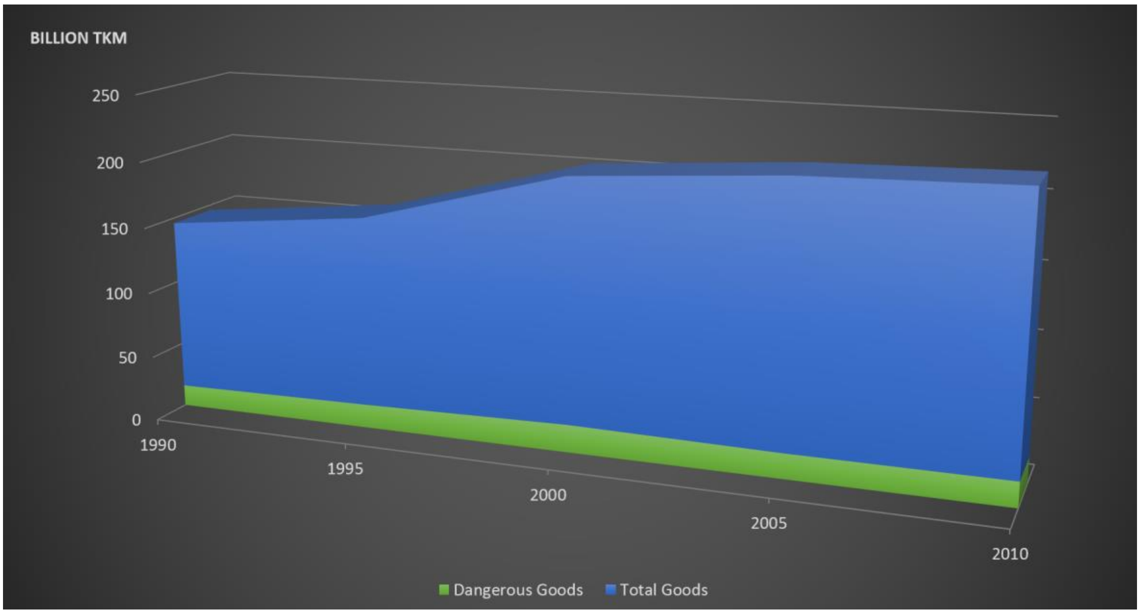


Fig. 2-6 Evolution of the total traffic of goods and dangerous goods (Billion tkm) in Italy 1990-2010

As regards the transport of radioactive material (Class 7), in Italy it is very rare (due to the elimination, not yet completed, of old waste). In other European countries, where there are fully operational nuclear power plants, the transportation of these HazMat products is closely monitored and much of their weight account for the protective packaging weight. Regarding other radioactive materials used for medical purposes are transported by air.

II.4. DG transportation and road traffic accidents

One cannot predict easily the occurrence of road accidents due to the great many degrees of freedom. Since the main variables (day, time, location, traffic intensity, type of vehicle) does not always appear to be determinately connected. What cause directly an accident is much more likely to be the psychophysical state of the driver, whom level of concentration affect inversely the level of unpredictability.

In the last few years, accident statistics follow a fluctuating trend with a recent slight decline. A first view of the ISTAT data indicates the overall trend in the number of accidents on Italian roads, and highlights a sharp decline in the mortality rate (Fig. 2-7). By considering the type of road, in 2010 most accidents occurred on urban roads (75.7%), which caused 72.1% of total injuries and 43% of total deaths. Much lower, 5.7% of accident occurred on the motorway with a ratio of injuries and deaths 6.8% and 9.2% of the total, respectively. On other roads, state, provincial, suburban municipalities and regional roads, there were 18.6% of accidents, 21% of injuries and 47.8% of death.

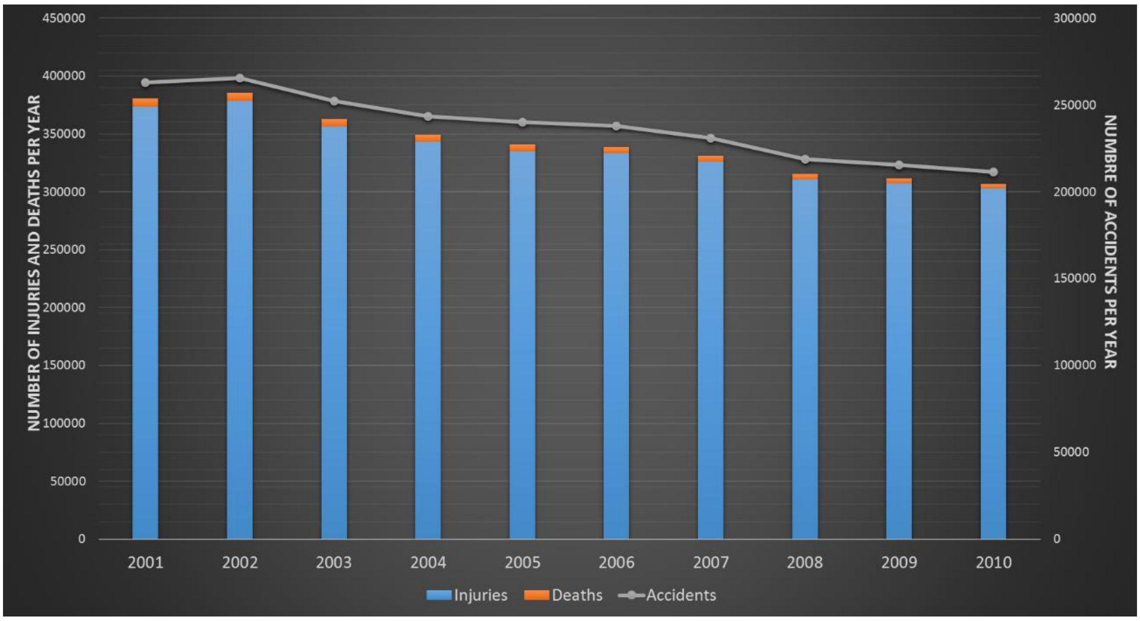


Fig. 2-7 Deaths and injuries in accidents in Italy, Trend 2001-2011, ISTAT-ACI

More importantly, accidents involving HazMat have consequences that go beyond the loss of vehicles and death or injury of the driver and passengers. In fact, if a tanker spills HazMat, it can lead to a serious damage to the environment and lethal to nearby people. For instance, if the load is some kind of oil products, which is a flammable, it may cause fire and affect the area in the immediate vicinity of the accident (primary damage), it can evolve and extend to the remaining parts of the roadway or drainage system (secondary damage) amplifying thus the consequences of the accident. It is also important to consider that a flammable substance can have toxic properties and/or corrosive, which might go beyond the secondary damage.

Although the percentage of accidents involving trucks (or heavy vehicles in general) is reduced, 14% of serious accidents are caused by heavy vehicles. One out of three of these accidents are caused by tiredness and bad driving behaviours, which represent the main causes for accidents and constitute an aggravating factors. That is why researches link HazMat release with road traffic accidents, and precisely with driving behaviour and distribution planning.

It is worth to mention, that a HazMat tank leak also occur in the absence of accidents and without injuries and/or deaths. In this sense, the DGT is a complex activity that can cause serious damages even outside the eventuality of an accident.

II.5. DG transportation and safety

All the data presented so far clearly indicates the importance of the safety in DGT. Indeed, managing the transport of dangerous goods is extremely complex and fraught with uncertainty. Administrators, planners, and engineers coordinate a multitude of organizational and technical resources to manage DG transportation network performance. The performance is also measured by how much organizations are risk aware in order to achieve their objectives. Risk management is a very substantial, not only for the sake of population safety and environment protection, but also an essence of business growth and survival.

For this reason, many organizations worldwide are pushing stakeholders in an effort to drastically reduce road accidents. The EU has set strategic objectives for safe mobility, including the halving of road accident victims by 2020. This is will be done by, on one hand, using latest information and communication technologies, such real-time monitoring, advanced braking systems, automated assistance for drivers, better communications between vehicle and infrastructure, control systems, study of driver behaviour, and more. On the other hand, the strict application of rules and road safety education.

In the following, I will give a brief literature review on risk management related to transportation of DG.

III. Risk management in DGT

III.1. DGT management

Every matter has a priority and management decisions too. Some decisions are more important than others are, which depends on the immediate or long-term impacts. One of the crucial point in decision-making is how much time a decision requires, and applied on what is it is scope. Naturally, a decisional process can be seen as a set of decisions class characterised by a proportional relationship of time and scope. Larger the scope of a decision, more time it needs to be implemented. The Fig. 2-8 portrays four management decision levels that are ordered following the time horizon and the size of the scope of application (larger the scale is, fewer details are considered).

In the **strategic management**, decisions are taken on a national scale with a time horizon of some years. Generally, at this scale decisions concern the transport network infrastructure as well as the types of DG that can be transported in the considered infrastructure. These decisions depends on the estimation of DGT demand trends and future contracts. The strategic management requires a long time and enormous resources and it is undertook generally by the public administration, with possible collaboration of external and private experts for either decision support or the running of the DGT activities and services.

The **tactical management** requires a time horizon few months to one or two years, and the scope of decisions are made on a multi-regional scale. The management decisions made in this level concern the definition of the DGT supply chain: the contracts, the distribution points and their whereabouts, the type of DG. Both the public administration and private companies intervene at this level.

Fig. 2-8 the DGT management classification by time horizon and level of details

The **operative management** considers a time horizon of a few days and the decisions undertook concern the DGT scheduling and route planning at a regional or multi-regional scale. Often algorithms are used for route selection with risk factors taken into account to minimize the risk deriving from the DGT. Local administrations and companies' managers, usually, intervene at the operative management.

The **real-time management** is aimed at the continuous monitoring of the DGT activities, through suitable vehicle on-board system and a software platform. These decisions are taken at local scale and in few minutes or hours. The reason is to be able to keep a reactive attitude towards the uncertainties of transport network, such the temporary unavailability, high traffic intensity, and accidents. Transport companies are at the heart of the real-time management to ensure the smooth running of the supply chain.

III.2. What is risk?

The International Organization for standardization ISO 31000 defines **Risk** as "*the effects of uncertainty on objectives*". In other words, risk represents anything inherent uncertainties that might prevent from achieving predefined objectives. More precisely for DGT and from mathematical point of view, **Risk**, according to (Royal Society, 1992), is "*The combination of the probability, or frequency, of occurrence of a defined hazard and the* *magnitude of the consequences of the occurrence*". Whilst **Hazard** is defined by (Royal Society, 1992) as "*the potential to cause harm*". It is related to the intrinsic characteristic of a material, good, condition or activity, which have significant probability to cause harm to people, environment or property (EEA, 1998).

III.3. What is Risk Management?

In DGT, Risk Management is the process of identifying, assessing and prioritizing risk to monitor, control, and minimize either probability/frequency of catastrophic events or the impact/magnitude of the hazard. Several Risk Management standards and models have been developed, as on Fig. 2-9, and they are designed and implemented to support stakeholders in their decisional process. In fact, accident prevention and crisis management in the DGT interest all kind of stakeholders, which are affected by or affect this complex activity.

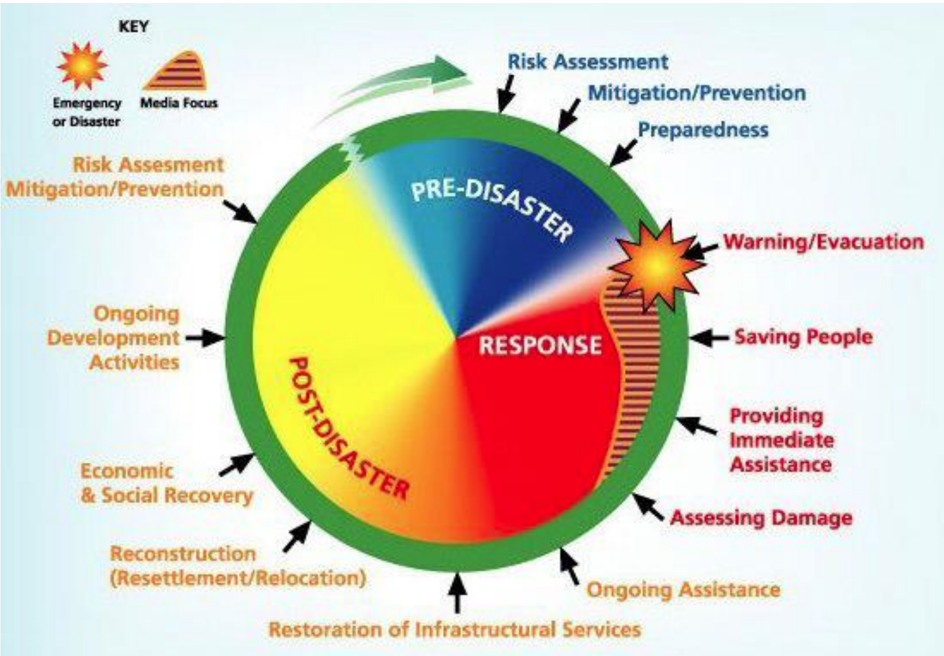


Fig. 2-9 risk management plan for emergency response to disasters (Bernardinis, 2007)

According to (Tomasoni, 2010), the DGT risk management in case of accident events can be classified into the following three levels (with respect to Fig. 2-10):

- Strategic management: a **Pre-accident** phase where the decision-makers have to define a plan of intervention and contingency in case of catastrophic accident. As well as to standards and regulations to minimize consequences and probability of accidents.
- Tactical/Operative management: the **Post-accident** phase after the accident consequences have been estimated. The plan pre-defined (in the strategic management phase) has to be applied: Medical treatment, evacuation, assurance compensations, and expropriations. Furthermore, people have to be sensitized to react to these kind of dangerous events. The experience has to be feedback to actors involved in the DGT activities, such manager and drivers.
- Real-time/Operative management: Either the **Response** phase or immediate reaction towards an accident occurrence, where all the decision-makers involved have to act on the bases of standards, protocols, and regulations for the emergency conditions;

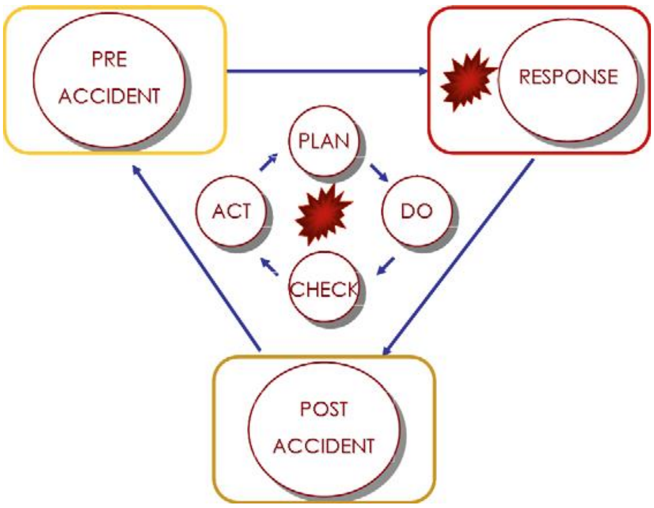


Fig. 2-10 process of the DGT accident risk management (Tomasoni, 2010)

The main aspect of this study that I want to highlight is the important of a decision support system for DGT risk management to support not only policies and regulations but also decision of public and private stakeholders. (Chevallier and Caron, 2002) introduce an interesting approach that fills the gap between science and policies. Indeed, the use of a spatial decision support system as a technology for structuring data related to organizational aspects, human aspects, science aspects, and software aspects is a very practical solution for sharing, visualizing data and managing it from a local or territorial point of view.

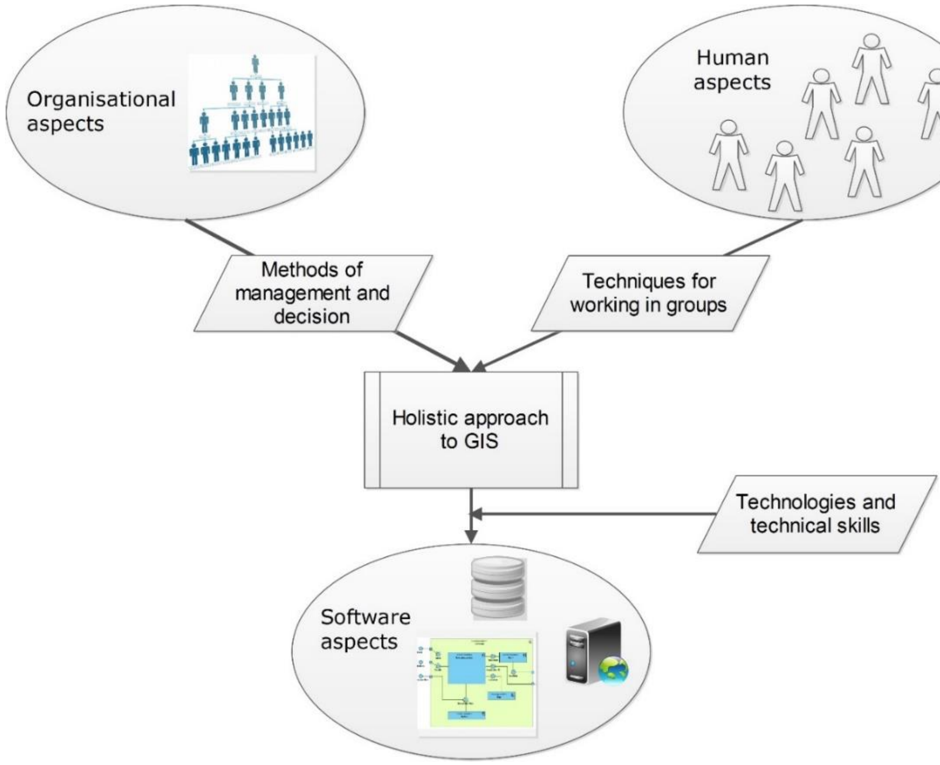


Fig. 2-11 (Chevallier and Caron, 2002) approach that uses GIS to fill the gap between science and regulations

The spatial decision support can be at different level of management, but what we are interested in this thesis is the "Real-time/Operative management". More precisely, the real-time monitoring and real-time route selection considering risk factors related to DG transportation.

III.4. Risk Assessment

The assessment of DGT risks has always been a matter of controversy in the literature. Multiple methods exist for the purpose of analysing and evaluating major risks that threaten the DGT activities. The main methods used by industrial and transport companies are:

- Hazard and Operability studies (HAZOP)
- Quantitative Risk Assessment (QRA)
- Probabilistic risk Assessment (PRA)
- Environmental Risk Assessment (ERA)

The risk of transportation of DG is derived from human settlements, technologies, biological and chemical activities, and socio-political behaviours, where the relation cause-effect is mostly dependent to human factor. (Rinatech, 2010) consider technological risk as all risk derived from human activities.

When a dangerous event happens, caused by human error, and involving DG, the consequences cannot always be reduced or contained. For this reason, it is substantial to undertake preventive measures to mitigate the probability of occurrence, and/or magnitude of consequences (Tomasoni, 2010).

In this thesis, I am mostly concerned by risk related to catastrophic accident, which is leading to HazMat release: explosions, thermal accidents, fires, water pollution, and toxic clouds. In the following, I will start by introducing some methodologies for risk assessment and risk perception.

III.4.1. Methodologies for risk assessment

HAZOP. Hazard and operability studies is a technique that must be performed by a group of experts, who know in detail the system that they intend to analyse. This is a very expensive process, both in terms of hours worked and number of skills involved. This technique requires a deep knowledge of the activity since the experts have to examine any possible failure or rupture, using a variety of keywords that drive this analysis. This methodology is considered as a *qualitative risk assessment* where every aspect of risk is deeply analysed, as for the following methodologies: "What-if/Checklist", "Failure Modes and Effects Analysis", "Job Safety Analysis", "Cause-Consequence Analysis", and more.

QRA. Quantitative Risk Assessment is a strictly mathematical technique that numerically determines the absolute frequency of "accidents". This technique is used not only in the petro-chemical, but also in the nuclear and aerospace industries. With this technique, it is possible to quantify the risks to an activity, or system. Examples of QRA methodologies are: "Fault Tree

Analysis", "Probit Statistical Analysis", "Event probabilities" and "Risk/Cost trade-off".

PRA. Probabilistic risk Assessment is a technique obtained by linking the probability of individual events, such as failures or disruption of a plant components and poorly functioning security system. The PRA is indeed a complex and systematic methodology for assessing the risk associated with complex technological devices, such as aircraft or power plants (Kumamoto and Henley, 1996). The PRA is a well established technology, where PRA analysts aim to estimate parameters used to determine the frequencies and probabilities of different events. According to (Muhlbauer, 1996), the probabilistic risk assessment usually answers three questions: What can go wrong? How likely is it? What are the adverse consequences? The two methods normally used to answer these questions are the "Event Tree Analysis" and the "Fault Tree Analysis". (Muhlbauer, 1996) suggests also a way to facilitate the understanding of the PRA by combining each hazard with a Likelihood-Consequence matrix, as shown on Fig. 2-12.

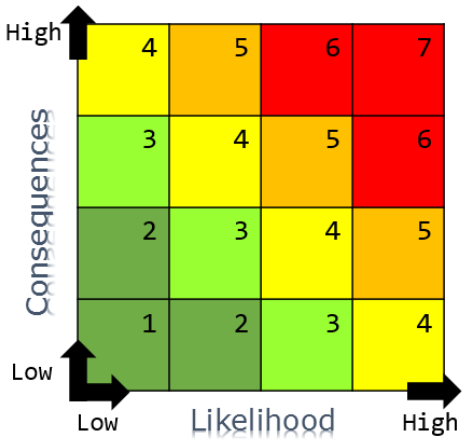


Fig. 2-12 Likelihood-Consequence risk matrix (Muhlbauer, 1996)

ERA. Environmental Risk Assessment is the examination of risks resulting from technology that threaten ecosystems, animals and people. It includes the risk assessment of human health, ecology or eco-toxicology, and specific industrial applications. Identify, evaluate, and assess environmental risk is a complex task, due to its complexity from system architecture point of view, levels of decision, both public and private actors are involved. In addition, indirect economic costs, associated to either risk evaluation or impact on environment, have to be taken into account, which is another level of complexity. ERA depends, at least, on four components (see Fig. 2-13):

- Ecological risk assessment;
- Health risk assessment;
- Industrial risk assessment leading to facilities at strategic and planning level;
- Industrial risk assessment leading to supply chain and system utilities, such as transportation, at strategic, planning, operational or real time level.

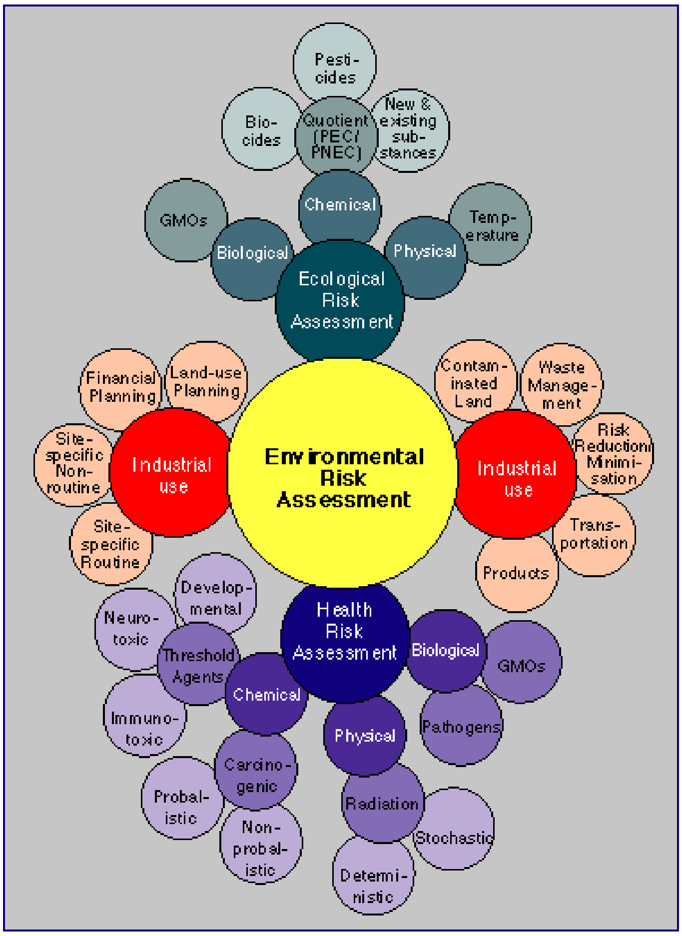


Fig. 2-13 A Typology of Risk Assessment (Fairman and Mead, 1996)

To conduct an ERA the socio-political, economical, territorial, industrial, and health systems have to share decisions and objectives, which is the minimisation of the occurrence and severity of consequences on all components of the environment. This is a **risk management** issue, in which a smooth communication between all stakeholders is substantial, as well as the sharing of knowledge, standards, regulations and technologies.

Finally, risk assessment is carried out to enable a risk management decision to be made. It has been argued that the scientific risk assessment process should be separated from the policy risk management process but it is now widely recognised that this is not possible. The two are intimately linked. (EEA, 1998).

III.4.2. Risk perception

In the risk assessment, **a zero risk does not exist**. In any high-risk industrial activity, and especially DGT activities, there is always a level of risk acceptability, even if the perception of hazard and fuzziness of risk are not easy to quantify.

The risk assessment may include an evaluation of what the risks mean in practice to those affected. This will depend heavily on how the risk is perceived. Risk perception involves people's beliefs, attitudes, judgements and feelings, as well as the wider social or cultural values that people adopt towards hazards and their benefits. The way in which people perceive risk is vital in the process of assessing and managing risk. Risk perception will be a major determinant in whether a risk is deemed to be "acceptable" and whether the risk management measures imposed are seen to resolve the problem (EEA, 1998).

The notion of acceptability is one of the most important concept the risk assessment, although it is hard to define due to dependence on various dynamic factors. The most obvious example is that the concept of acceptability completely change from one European country to another.

Risks are acceptable only if reasonable practical measures have been taken to reduce risks (IAEA 1992). In the literature, the level of acceptability is quantified using three different concepts:

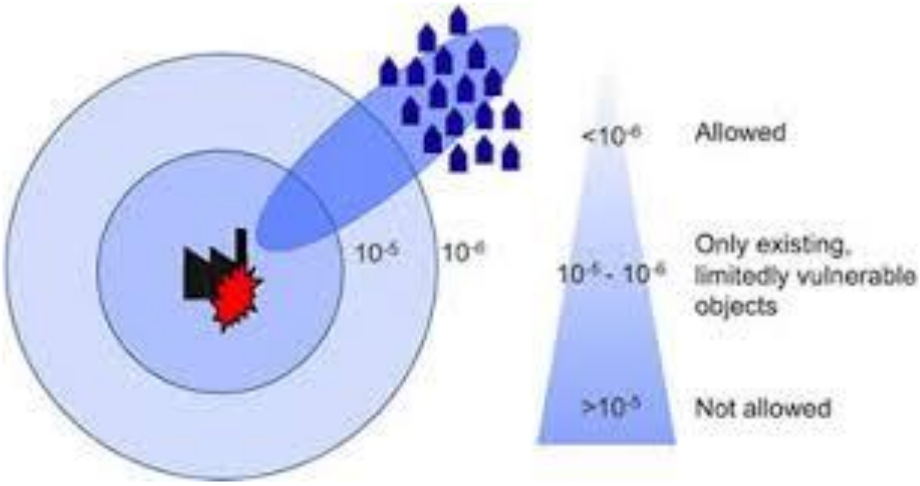


Fig. 2-14 Individual risk contours

IR. Individual Risk is defined as the probability that an unprotected person, who permanently is located at a specific position in the vicinity of a risk source, is affected by the undesired consequences of an event, and he/she will be killed. IR is expressed as a period of year. As shown on Fig. 2-14, it can be pictured on a map by connecting points of equal IR (Ale, 2002).

SR. Societal Risk is defined as the relationship between the number of people killed in a single accident (N) and the chance (F) that this number will be exceeded. It is the probability that in an incident more than a certain number of people are killed. Societal risk usually is represented as a graph in which the probability or frequency F is given as a function of N, the number of people killed. This graph is called the FN curve.

PLL. Potential Loss of Life is the expectation value of the number of people killed per year. It is the sum of all individual risks and it is the area under the FN curve.

In Italy, four levels of risk are taken into account, as shown on Table 2-2: "Acceptable", "Region of tolerability: type A", "Region of tolerability: type B" and "unacceptable" (Fabiano et al., 2002).

Italian analysts processed ISTAT data for 20 years of accidents, showing that the rate of IR is between 10^{-3} and 10^{-4}. Regarding the IR for DGT accidents is about 5×10^{-4}, while the SR is modelled with an approach that uses the FN curve of accident deaths (Fabiano et al., 2002).

Table 2-2 risk acceptability criteria. P is the cumulative frequency in one year, and N is the number of deaths. Analysis performed by Dutch studies. (Hoj and Kroger, 2002).

Risk Evaluation	Criteria	Description
Acceptable risk	$P < \frac{10^{-5}}{N^2}$	Verify that risk remains at this level, no need for detailed study.
Region of tolerability: type A	$\frac{10^{-5}}{N^2} < P < \frac{10^{-4}}{N}$	Tolerable risk. If cost of reduction would exceed the improvements achieved.
Region of tolerability: type B	$\frac{10^{-4}}{N} < P < \frac{10^{-3}}{N^2}$	Tolerable only if risk reduction is impracticable or the cost is disproportionate in relation to the improvements obtained.
Unacceptable risk	$P > \frac{10^{-3}}{N^2}$	Risk intolerable: risk cannot be justified even in extraordinary circumstances.

Finally, risk perception is a subjective judgment constructed by people to express the characteristics and severity of a hazard. This judgement is influenced by the cultural heritage and socio-political conditions. Whatever the estimation is, risk has always an intrinsic uncertainty component in its structure, since it deals with the future and with a very dynamic environment like the DGT.

III.5. Uncertainties in risk assessment

III.5.1. Uncertainty vs Risk

For (knight, 2012), **uncertainty** is the lack of complete certainty, that is, the existence of more than one possibility. The true outcome/state/value is not known. **Uncertainty** is measured with a set of probabilities assigned to as set of possibilities. Whilst **risk** is a state of uncertainty where some of the possibilities involve loss, catastrophe, or other undesirable outcome. Its measurement is done through a set of possibilities each with quantified probabilities and quantified losses.

Following these definition by Knight, one may have uncertainty without risk, but cannot have risk without uncertainty. That is why; modelling uncertainty in risk assessment is a substantial component for effective decision-making. However, most of risk assessment methodologies lack of uncertainty analysis.

III.5.2. Uncertainty factors

The risk involved in DGT is related to various factors such as network infrastructure, HazMat properties, likelihood of catastrophic accident, propagation, location, population density, and effects on human and environment. (Ernesto, 2004) in his research work considered a basic conceptual model, as shown on Fig. 2-15, where the small circles represent the factors that affect directly or indirectly the dangerous goods transport.

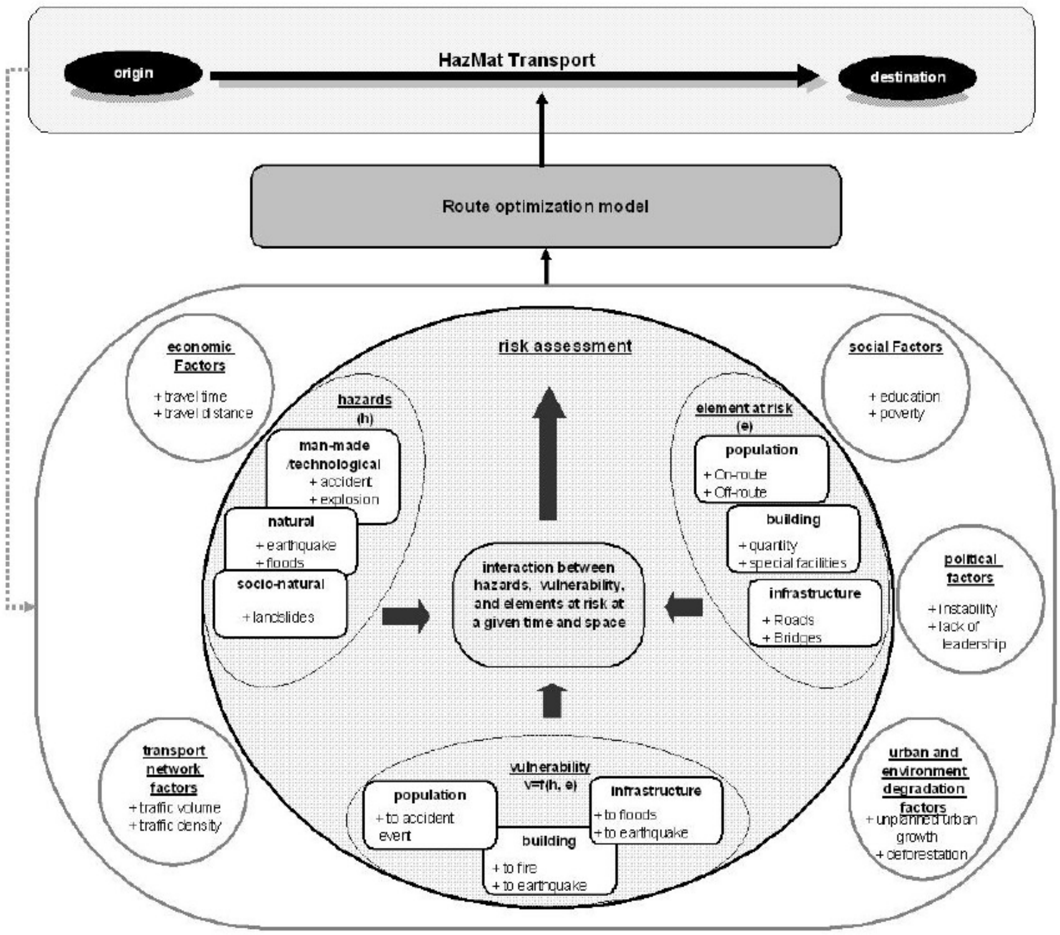


Fig. 2-15 factors in risk assessment for route optimization by (Ernesto, 2004)

Some factors can be clearly defined and evaluated such road infrastructure. However, most of these factors are sparse and imprecise information. In these situations, uncertainty evaluation cannot be neglected. Besides, risk in decision-making is more efficient when the risk capture realistically and accurately the uncertainty. Generally, the uncertainty cannot be reducible from models and data. Rather, it arises from input data, inappropriate structure and erroneous calibration of the model (Lowell and Benke, 2006). Consequently, negligible risk source, vague risk analysis approach, and ambiguous results lead to unacceptable safety levels (Arunraj et al., 2013).

(Backlund and Hannu, 2002) discussed the factors that affects the quality of risk assessment. (Pasman et al., 2009) identified the issue of the quantitative risk assessment (QRA), which boils down to a large variability in output results is observed after various risk assessment methodologies have been applied to some particular hazardous events. The same work provides information about origins of variability, such human judgment and the mathematical approach used to model complex systems of the real world. The authors also highlight the importance of the domino effect, and according to them, it should be taken into consideration while conducting any QRA.

The hazard identification, initial consequence analysis, risk estimation, and results analysis are very important steps in risk assessment for efficient decision-making process (Khanzode et al., 2011, 2012). In the literature, the uncertainty analysis in risk assessment was undertook in different applications:

- Injury risk (McCauley and Badiru, 1992; Vadeby, 2004);
- Ecological risk (Ferson and Kuhn, 1992; (Hobday et al., 2011a,b);
- Chemical risk (Quelch and Cameron, 1994);
- Software development risk (Lees, 1996);
- Transportation risk (Bonvicini et al., 1998; Koornneef et al., 2010);
- Human health risk (Kentel and Aral, 2004; Kumar and Xagoraraki, 2010);

- And more (Chauhan and Bowles, 2003, Davidson et al., 2006, Wang and Elhag, 2007; Zavadskas et al., 2010; Van der Pas et al., 2012, Badri et al., 2012 ; Pinto et al., 2012).

III.5.3. Uncertainty quantification

The quantification of uncertainty in risk assessment can be done by quantifying each parameters considered as factor of risk. This technique is called sometimes Parameter Uncertainty Analysis (IAEA, 1989). The DGT risk is often expressed as the spectrum of consequences C_i and the associated probabilities P_i, that is $(C1, P1), (C2, P2), \ldots, (Cn, Pn)$.

The uncertainty arises from two different phenomenon: stochasticity and subjectivity (Oberkampf et al., 2004). The first phenomenon, which is the stochastic uncertainty, emerge from a randomness. For instance, the frequency of accidents is a factor with a stochastic uncertainty, since it may not be same at every road segment and at any time slot. In this case, the distribution of the frequency allows to reflect the difference between road-segment/time-slot and to classify them into homogeneous groups.

The subjective uncertainty, which is the second phenomenon, is mainly due to the lack of knowledge, measurement error, vagueness, ambiguity, under-specificity, indeterminacy, and subjective judgment (Van der Pas et al., 2012). The stochastic uncertainty is irreducible, as it is inherent nature of the system under study, such weather condition, human factor. In this case, fuzzy set theory is used for representation of this type of uncertainty.

As shown on Fig. 2-16, the total uncertainty is divided into two subsets, variability and uncertainty. (Vose, 2000) proposed the term of verity for total uncertainty.

In risk assessment, the representation of uncertainties has been addressed by many researchers using either arithmetic intervals, probability density functions, or fuzzy sets. For instance, (Button and Reilly, 2000) expressed the uncertainties quantification in terms of sensitivity, confidence intervals, and probability distribution. (Chang et al., 1985) used probability density functions to model the uncertainty. (Quelch and Cameron, 1994; Boncivini et al., 1998; Davidson et al. , 2006) suggested the fuzzy set theory as practical model for uncertainty quantification.

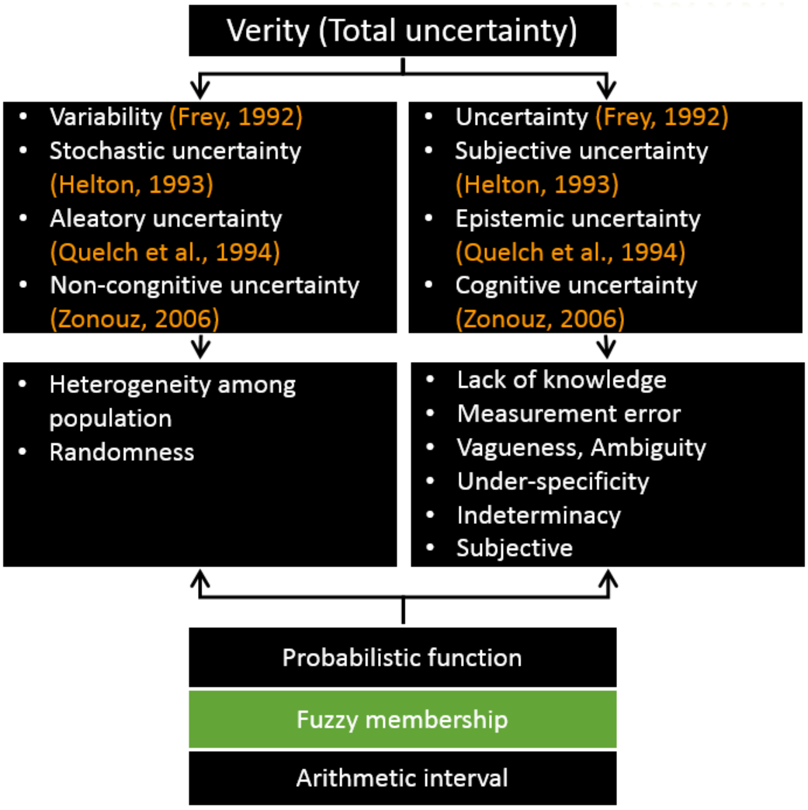


Fig. 2-16 Classification of Verity or total uncertainty (Arunraj et al., 2013).

Alternative methodologies of uncertainties quantification in risk assessment exist. Such the ANP for analytic network process (Kumar and Maiti, 2012). The Bayesian Network analysis as probabilistic directed acyclic graphical model which is mainly used to represent a set of random variables formed by nodes of the graph, and their conditional dependencies are represented as arcs of a directed acyclic graph. Bayesian methodologies are preferred in literature in cases where subjective information such as expert opinion or personal judgments of analyst is to be considered for quantification of risk (Arunraj et al., 2013). However, (Dubois and Prade, 1992) criticized its use in uncertainty analysis since it considers a unique distribution when detailed information are not available to support it.

The theory of fuzzy sets has the potential to overcome these inadequacies (Quelch and Cameron, 1994). The same authors prove that this theory is much more practical and efficient than the traditional probabilistic approach to uncertainty using a Monte Carlo simulation. This theory is applied to a simple case study as application of fuzzy set theory to risk assessment.

III.5.4. Uncertainty representation using Fuzzy sets

Lotfi Zadeh first introduced fuzzy sets in 1965. In order to describe imprecisely defined classes or sets that play an important role in human thought processes and communication. In essence, the theory of fuzzy sets is aimed at the development of a body of concepts and techniques for dealing with sources of uncertainty or imprecision that are non-statistical in naturel. Fuzzy sets allow vague concepts to be defined in a mathematical sense. In classical set theory, an object either belongs to a set or does not belong to a set, whereas fuzzy set theory allows an object to have partial membership of a set (Quelch and Cameron, 1994).

Using fuzzy sets, it is possible to represent a set A by a membership function $A(x)$ that maps the members of the set into the entire unit interval $[0,1]$. The value of $A(x)$ is called the grade of membership of x in A. Compared to crisp sets, fuzzy sets correspond to continuous logic: all shades of grey between black and white and all values between 0 and 1 are possible. The membership function of an object describes the degree to which this object satisfies the properties of the set. For example, if the fuzzy set N is described by the property "about 7", then the closer a member x is to 7, the closer $N(x)$ is to 1. The concept of a continuous grade of membership, instead of a binary one, allows us to describe vague concepts in a more complete manner. For example, statements such as "about $15", "numbers much greater than 500" or "somewhere between 34 and 50 and most likely to be 42" can be described by fuzzy sets without omitting any of the information given in the vague statement.

A fuzzy set can also be viewed as a possibility distribution, as opposed to a probability distribution. While a probability distribution is subject to the laws of statistics, the shape or structure of a fuzzy set is subject to few mathematical constraints. For example, the laws of statistics require that the sum of the probabilities associated with a random variable must equal 1. However, the sum of the grades of membership of a fuzzy set is not required to equal 1 and it is therefore possible for more than one member to have a grade of membership equal to 1. It is this flexibility of fuzzy sets that makes them ideal for representing vague concepts in risk assessment where the information available is often insufficient for use of probability theory (Quelch and Cameron, 1994).

IV. Chapter summary

In this chapter, I started by highlighting the importance of road shipment of goods. The modal split of internal freight transport gives enough credit to road transport to be considered as one of the main modality for goods transportation. Then Dangerous Goods have been introduced and the safety in their transportation has been discussed. We have seen that the greatest share of catastrophic accidents involving HazMat have been related to road transport. The third section addresses one of the main aspects of this thesis, which is risk in DGT. There is no consensus on risk definition, so I considered one of the most common risk definition in DG management. Then, a brief literature review on risk management. One of its substantial steps is the risk assessment, which is the main concern in this research work. In this respect, various risk assessment methodologies from the literature were introduced.

In risk analysis, two issues arises. First, researchers noticed that risk estimation of acceptability depends strongly to how it is perceived within the cultural and socio-political environment. In the literature, the level of acceptability is estimated mainly using two different concepts, the individual risk and the societal risk. The second issue is related to the intrinsic characteristic of risk: the uncertainty. It is not always obvious to quantify the uncertainty, which is why I addressed his issue. We have decided to use fuzzy sets concept for the modelling of vagueness a form of uncertainty we often encounter in risk analysis. The choice was supported by feedbacks from the literature, which consider fuzzy membership is the most practical and efficient way for dealing with uncertainty.

Chapter 3. An Intelligent Transportation System

This chapter introduces the Intelligent Transportation System considered for management of dangerous goods transport. Two main components of the system are addressed. The first is the existent Transport Integrated Platform, for real-time monitoring of vehicles transporting petroleum products. The second component is driving simulator for studying human factor and traffic simulation for injecting virtual vehicles into the real-time monitoring system.

I. Chapter introduction

This chapter is divided into two main parts. The first, introduces the existing system developed for real-time monitoring of a fleet of dangerous goods carriers. The second part concerns the agent-based traffic simulation. Before addressing them, let me start first by defining an ITS and introducing the global architecture.

I.1. Overview: ITS

Intelligent Transportation System (ITS) are a set of technological advanced applications that make available services for traffic management, and for various transport modalities. The system also inform users in general, and decision-makers in special so to be able to use smartly the transport network.

Stakeholders and decision-makers are very interested by having at hand a platform aggregating all information and tools for decision support. The ITS was initially motivated in US by the increasing interest on homeland security for roadways monitoring. In highly populated cities with complex transport network, ITS was an excellent solution for managing multimodal systems from walking to private and public transport. The ITS also helps countries and cities experiencing a fast growing urbanisation to manage congestion and improve the traffic network. An ITS application for the transport of dangerous goods is then became substantial and necessary.

Although ITS concern all transport modalities, the EU Directive 2010/40/EU, of 7 July 2010, considers ITS as an application of information and communication technologies to the "road transport sector". According to the same directive, the interfacing of ITS with other modes of transport will make a significant contribution to improve safety and security of "road transport of dangerous goods".

To be able to select economic and safe routes for the transport of DG. It is necessary to use software platforms that allow planners and decision makers: to monitor in real-time their fleet, to assess risk and evaluate all possible routes, to simulate and create different scenarios, and to assist in finding a solution to a particular problem. The aggregation of these software platforms is shown on Fig. 3-1 and make up what is called by the Intelligent Transportation System.

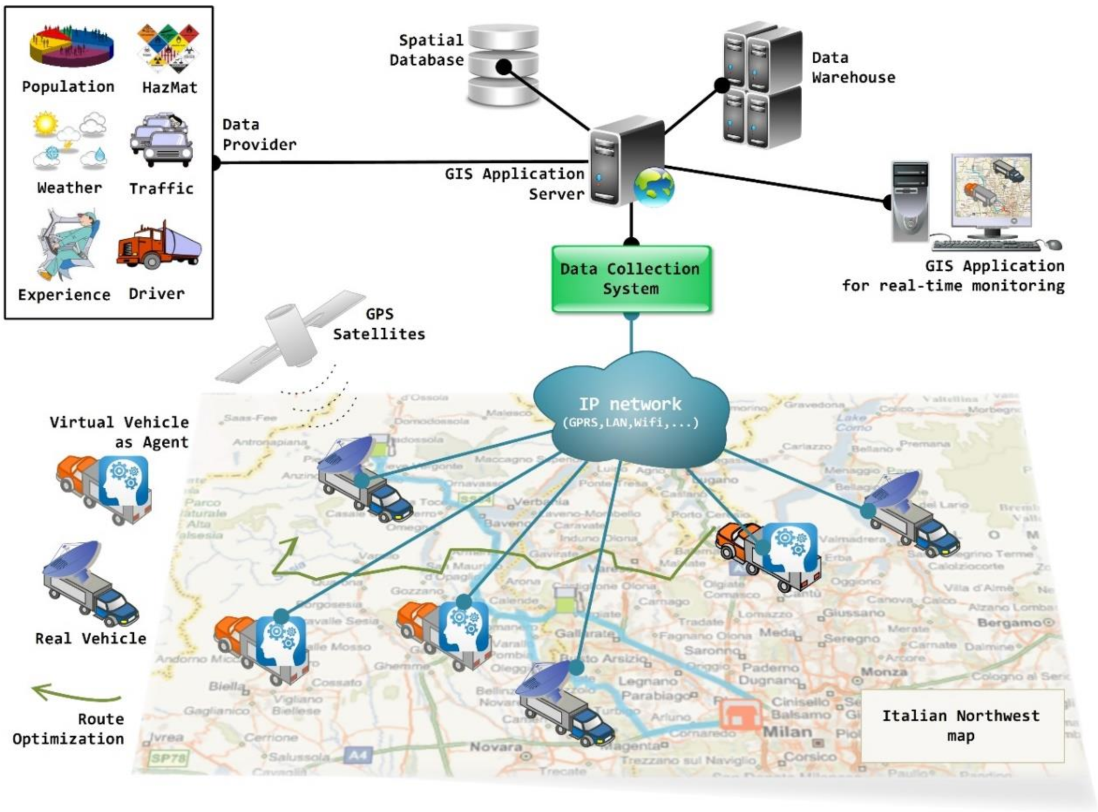


Fig. 3-1 the designed Intelligent Transportation System where all main component are drawn

I.2. Overview: Existing system

This thesis is part of series of works that started some years ago and continues to evolve with the emergence of new advanced technologies. The objective is to study possible improvements regarding transport safety of DG. Various technologies and architectures of decision-making and information have been exploited. The basis of this information system is the *Transport Integrated Platform (TIP)*, a basic ITS application on road transportation of DG (Benza et al., 2012). This application has as main purpose the monitoring the fleet of vehicles that distribute petroleum products in Europe. In this chapter I will introduce this platform as existing system on which is based the overall architecture.

I.3. Overview: Traffic simulation

In recent decades, risk management of DGT has been the subject of several research studies. It has been usually approached from operational research and logistic control perspective: the routing and scheduling analysis, supply chain and inventory management. Multiple approaches exist addressing this need such as the risk averse routing approach (Bell, 2007). The minimum cost flow network (Kazantzi et al., 2011). The meta-heuristic algorithm (Zografos, 2010). The bi-criterion path-finding problem (Androutsopoulos and Zografos, 2010). The risk definition, assessment and uncertainty quantification are subject of multiple interpretations. In this respect, multiple methodologies exist as have been discussed in Chapter 2.

These approaches and models need to be proven efficient and reliable, in spite of their originality from theoretical point of view. Going for field-testing is not always a good idea, since it requires lot of resources. Simulation is a better alternative since it offers a wider area of freedom and customization, and many measures are still on testing phase and their acquisition use instruments whose reliability are yet to be determined. It is even more intricate when DGT activity is considered, due to the caution that surrounds it from dangerous nature, confidentiality and security. A decision has been made to design a virtual system that will simulate real world behaviour. This system has to provide the user with entries for testing their algorithms and produce results similar to those of real experiments. This does not challenge the field-testing, which it is supposed to take place at later stages of experimentation, but only refines the tests and approximates the results we expect.

Two classes of simulation techniques are usually used in modelling traffic flows. Microscopic approaches consider discrete entities with complex set of rules governing their behaviour. Macroscopic or Continuum methods allow the modelling of aggregated behaviour of many vehicles. While the latter provide tools for large-scale traffic flows using fluid dynamics equations, the micro approach captures highly detailed information about each vehicles considering their intrinsic properties, in addition to the interaction with either other vehicles or the environment.

II. The existing system

This thesis is part of a larger project that in recent years has led to the implementation of an information technology platform to support logistics and transport of dangerous goods by ENI R&M, in addition to accident prevention.

Interestingly, the introduction of features such as monitoring, training and the strengthening of technical control have led to a significant drop in accidents occurrence trend. For this reason, but especially for the fact that this platform constitutes the starting point of the proposed architecture, we will illustrate in this section the main components of the platform, which are:

- On-board System
- Transmission System
- Data Collection System
- The Transport Integrated Platform

In the following, we will briefly explain each component to have a more complete introduction to the platform, and especially to understand the real purpose and future developments to which it could lead.

II.1. On-board System

On board of every truck installed a set of devices (see Fig. 3-2) whose purpose is to collect specific data and convey it to the centralised server. These data represent detailed information on the state of the transported product and the vehicle, in addition to the whole activities concerning the procedures of shipment and delivery of dangerous goods from the loading terminals to the various distribution points.

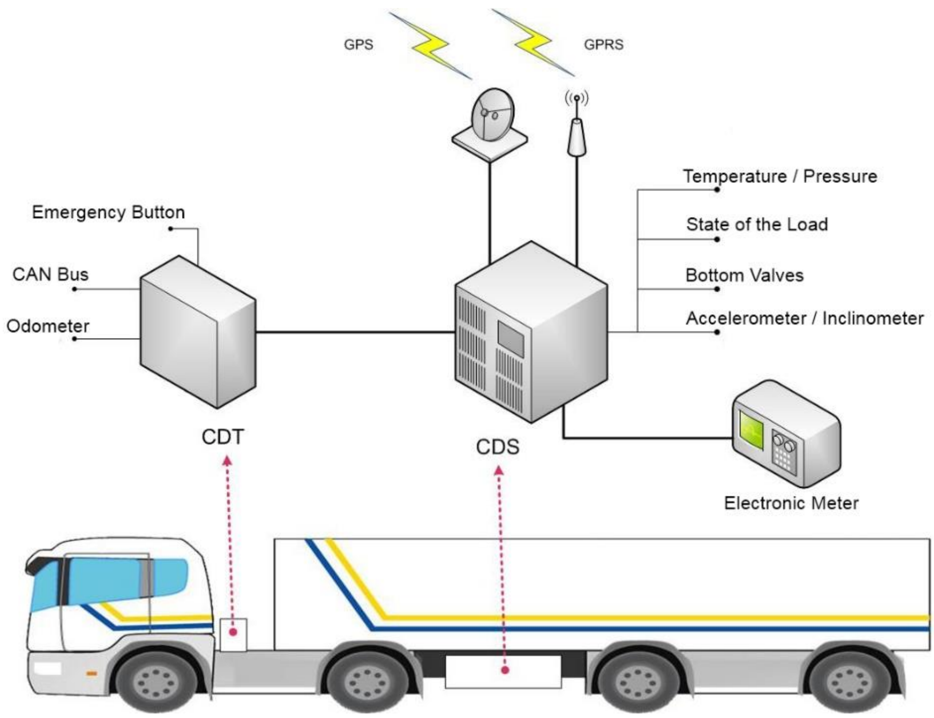


Fig. 3-2 The On-board Unit installed in heavy goods vehicles (trucks), for telemetry/events data collection

The collection, processing and transmission of these data are the tasks of one of the main component of the on-board system, called the concentrator. This component is a device, a cutting edge technology, that is characterized by a large processing capacity and designed to interface with both analogue and digital peripherals. The concentrator is able, as well, to communicate with the central servers, and it is connected with other components such:

Global Positioning System (GPS): this module provides the means to geo-reference the data, with a latitude, longitude, and speed.

General Packet Radio Service (GPRS): this module provides mobile connectivity for data transmission on the IP network.

Electronic head: is a flow meter endowed with intelligence, which make it able to process and transmit data related to events of products loading and unloading for statistical and safety reasons.

Sensors: a set of probes and control devices to monitor specific status changes of particular elements of the truck (inclinometers, accelerometers, pressure analogue sensors, odometer, on/off dashboard, emergency buttons) or tank (products temperature and pressure sensors, opening/closing of doors and hatches, opening/closing of foot valves, Insertion of closed loop).

CANBUS: a communication standard that allows the interaction between electronic devices embedded on the vehicle. In particular, it receives information from the vehicle control units, elements of bodywork, cabins or the vehicle communication systems. The CANBUS is therefore able to provide real-time information of the truck state, such as power on/off, fuel level, pressure and temperature inside the motor, ambient temperatures and cabin, use of the handbrake, use of exchange/accelerator/brake, axle load, speed, and more.

The above hardware equipment are housed inside two junction boxes. One is placed on the tractor and the other on the semitrailer, linked together by a multipolar connector. All devices listed, including concentrators, are ATEX[7] certified or housed in containers that ensure compliance.

The TIP, also, boasts an experimental setup located at the DELAB within the DIBRIS department. The Fig. 3-3 shows a faithful replica of the main device installed on board the vehicles. It preserves the separation between tractor and semitrailer present on board of the real vehicles.

[7] ATEX certification (ATmosphères EXplosibles) concerns the installation of devices in potentially explosive atmospheres. Under this name are known the European Directives 94/9/CE.

Fig. 3-3. Synoptic panel, a replica of the on-board unit installed in the trucks

In the front part is housed the tractor, which collects state information on the ignition system and the emergency button. We can also find in the front, a CANBUS simulator driven by a computer through a serial port. It can properly emulate CANBUS packages and transmit them to the concentrator. Regarding the rear part, we find the semitrailer within which is located the concentrator that in turn is connected to various sensors such product temperature and pressure sensors, foot valves, pneumatic logic, doors opening sensors and more.

This setup in its almost totality is identical to the ones mounted on real vehicles and, as well, indistinguishable to the TIP, since it is considered by the system as any other real truck.

II.2. The Transport Integrated Platform (TIP)

The TIP is a software platform designed and built by the DELAB[8] in order to ensure, under the context of DGT, a service of high quality, in compliance with the standard rules for the protection of environment, workers and population. Given the high degree of outsourcing of the transportation services, it was necessary to develop tools for monitoring processes and performance, and to ensure an adequate level of control at each point of the supply chain.

[8] ENI R&M in collaboration with DIBRIS

As portrayed by the Fig. 3-4, the platform consists in an aggregated set of applications with a structured web portal environment. Through this interface, Eni R&M processes and shares data over Internet with both internal users (Eni employees) and external ones such suppliers or transporters, with respective access credentials. Besides, TIP allows a continuous monitoring of all activities related to the products shipment.

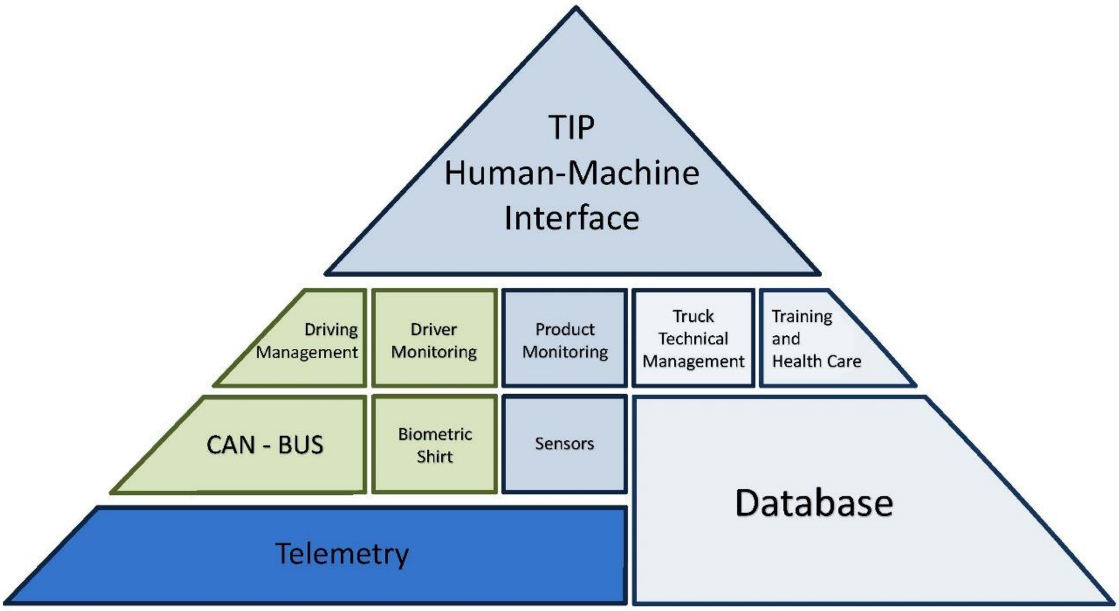


Fig. 3-4. Architecture component of the Transport Integrated Platform (TIP)

The information are made easier to understand thanks to the tabular reports and the web mapping interface for real-time monitoring of Eni fleet of trucks deployed along the European territories. Finally, the set of management applications complete the full functionalities of the platform.

Listed below are the environments currently operational on the TIP:

- Control Room
- Remote
- Planning Travel
- Emergency Room
- Key Performance
- Reporting Accidents
- Management Wagons
- Training
- Document Management
- Quality
- Compliance / Audit
- Technical Management Means
- Loading Unloading Points

- Operational Checks

The strategy of the design of the platform is based on four fundamental pillars:

- Monitoring
- Truck Technical Management
- Training
- Health Care

The real-time monitoring consists at mapping data originating from the vehicles with those existing in the database where it contains all the details regarding vehicles, travel, goods, and drivers. By processing data, we get all information about the status of the vehicle, the product and the trips, and allows the detection of possible abnormalities or unexpected and potentially dangerous events. Yet for risk mitigation purpose, the TIP provides the management and control of all data related to the state of the technical efficiency of the vehicles.

The TIP also includes a special environment developed to ensure to Eni own drivers and those of third-party carriers a high quality training service. This component allows the management of the overall program of staff training through classroom courses, self-training and self-assessment. This is done by providing tools for courses management and bringing up the appropriate material to the topic covered. Then, to complete the training process, the TIP allows one to test, periodically, his knowledge concerning the DGT regulations and procedures.

The database generated by this environment allows the continuous control over the training, tools, content for training, costs mitigation and at the same time monitoring the shortcomings level of the staff. In addition, drivers' health is monitored, as well, since it contributes at risk prevention of road traffic accidents.

Finally, Eni can handle its entire logistics information system with TIP Human-Machine Interface, through powerful tools grafted on a web application, and directed towards safety transportation of the products.

II.3. Driving Simulation

In addition to real-time monitoring of DGT, drivers' health condition, their mental states and their shortcoming, the DELAB have another ace in its pocket, which is a 3D Driving Simulator. The first involved the collection of data directly from the fleet already being monitored. The second for studying driver behaviour through driving sessions on the simulator. Since it offers a wider area of freedom and customization, and many measures are still on testing phase and their acquisition use instruments whose reliability are yet to be determined.

II.3.1. General Overview

Driving is the most ordinary and universal task that people used to go through every day despite its complexity and lethal risk: thousands are killed in car crash accidents every day. It requires a greater use of senses, perceptions, motor and cognitive functions, each of which can be affected by many factors such as tiredness, stress and driving skills. It is interesting to note that the driving simulation emerged very early, initially for vehicle technologies research and then on the study of driver behaviours.

Over the last two decades, the technological progress – particularly in information technologies such the tremendous growth in computing power – led to the development of simulators increasingly sophisticated, complex and essential for research and development. Since, it allows to undertake driving measurements, the study of driving impact on the environment and more challenging, the driving behaviours for driving style improvement. The experimental studies in virtual scenarios do not exclude the field-testing, although simulation is safer and often cheaper. Not to mention a key aspect in scientific research, which is the indefinite repeatability and reproducibility of experiments.

In the literature, there are an extensive bibliography on the use of the simulator and its reliability. Much has been said about the validity of the measures, the quality of the experience and the drive training compared to real vehicles (Fisher et al, 2011). The Fig. 3-5 depicts all main components of a driving simulator environment for a quasi-real experiment in a laboratory. The components are classified in four categories:

- Simulation Computer Processing: Represents the core of the simulation system where data are stored, computer processing are undertook, and vehicle equations of motion are defined;
- Sensory Feedback Generation: Generates the corresponding feedback, which try to mimic as closer as possible the real-world environment, to be interpreted by the external peripherals (or Human-Machine Interface);
- Sensory Display Devices: The Human-Machine Interface in the form of 3D visualisation, auditory, driving peripherals, and motion reproduction;
- Human Operator + Cabin.

Finally, the driver decision and reaction recorded by the external peripherals are fed back to the core of the system for performance measurement and sensory feedback generation.

II.3.2. Driving simulation experiment

The DELAB has its own driving simulator environment as shown on Fig. 3-6. It consists in all required component for quasi-real driving experiment described on Fig. 3-5, except the motion feedback simulator.

The software used for driving simulation is SCANeR Studio 1.2 by Oktal, a French company that operates in interactive simulations. This software is used extensively in research environment by both universities and companies. In fact, SCANeR has a long list of users, in which we find important universities and research institutes on transportation engineering, as well as major car manufacturers such as Audi, Ford, Fiat, Renault, Nissan, Hyundai and Volvo.

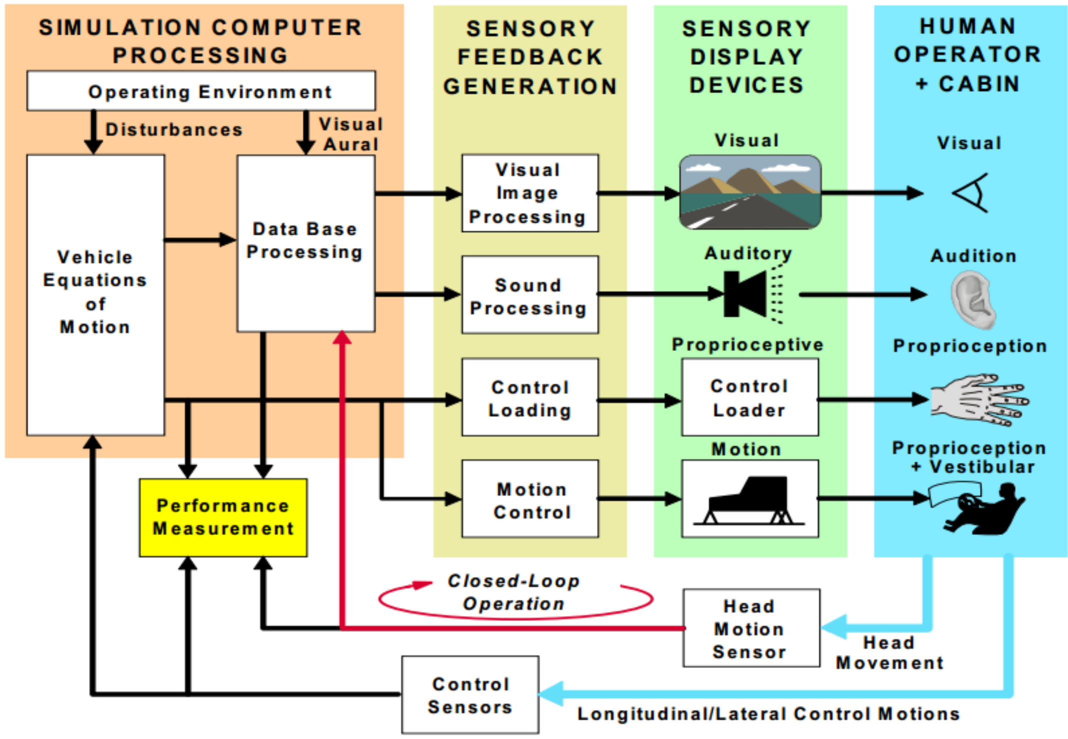


Fig. 3-5. The architecture of a driving simulator environment for full driving experiment

SCANeR Studio is a software package used for the analysis of vehicle ergonomics and advanced engineering studies related to the mechanics and aerodynamics of vehicles and traffic. It is also used for research on the human factors and driver training. It allows you to drive any type of vehicle and test it in diverse weather and traffic conditions.

The interesting aspect of that software is the ability to interface with diverse devices, yet with very different architecture: from a simple device costing few hundred euros to those that provide the most advanced technologies with costs considerably higher (around million euros).

Furthermore, SCANeR meets the particular needs in which the DELAB is interested in to undertake the intended studies. Indeed, the software can simulate the driving of heavy vehicles since we are dealing with trucks, and that represents a crucial aspect. Other needs can be summed up to software customization by building custom scenario, configuration and meticulous programmatically controllable events. Interfacing with specific devices and the possibility to choose whether we can get certain measures by simulation.

The last fulfilled requirement is the ability to undertake long free driving sessions, without being tied to individual exercises and repetitive tasks.

Fig. 3-6. The overall of the 3D driving simulator setup: SCANeR, Simulator server, Controllers, Screen

Regarding the hardware or devices that interface with SCANeR, It was therefore decided by the DELAB to carry out directly the driver's seat with following devices:

- 55″ LCD Screen for visualisation;
- Screen as side mirror;
- Logitech G27 Controls for driving;
- 15″ LCD screen for simulation of the on-board tools (dashboard, lights, etc);
- Dell OptiPlex 990 Computer for controlling, recording and analysing data.

III. Agent-based traffic simulation

Transportation engineering, and especially of Dangerous Goods (DG), is one of the areas in which technological development is crucial. Logistic control systems, routing and scheduling algorithms, supply chain management have been applied in this aspect to improve the cost-effectiveness ratio and to reduce risks. Unfortunately, some of these works remain theoretical since tests on real case scenario sometimes proves difficult to achieve especially when dealing with Dangerous Goods Transport. Thus, the objective is the achievement of a traffic simulation system for DGT. It has to provide entries for testing algorithms and to produce results close to real experiments. Applications on serious games, financial market, and engineering are evidence of success of the visual simulation system. From a methodological viewpoint, a special concern on the process of designing a system representing real-world systems with appropriate degree of complexity and dynamics. Several researchers have already suggested solutions since the 50s. These solutions have been classified in three levels: microscopic, mesoscopic and macroscopic simulation. It has been decided to use a microscopic approach using an agent-based model. It allows the representation of systems at different levels of complexity, such a System of Systems (SoS), through the use of autonomous, goal-driven and interacting entities.

III.1. Multi-Agent Systems (MAS)

III.1.1. Definition

“Multiagent systems are systems composed of multiple interacting computing elements, known as agents” (Wooldridge, 2009). They are a kind of System of Systems (SoS), whose subsystems are agents endowed with autonomy and social abilities (interaction, cooperation, coordination, negotiation etc.). MAS are a recent sub-field of computer science - they have only been studied since 1980 and gained widespread recognition since the mid-1990s (Wooldridge, 2009). The international interest in the field has expanded mostly to its intrinsic distributed computing property, which reduces the complexity and task processing time.

An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives (Wooldridge, 1995). This is a Wooldridge and Jennings (1995) definition of the term agent; unfortunately, there is no common accepted definition of it. While there is consensus on the centrality of the autonomy notion of agency, there is some controversy regarding other aspects—for instance the auto-learning aspect, which remains undesirable in some cases.

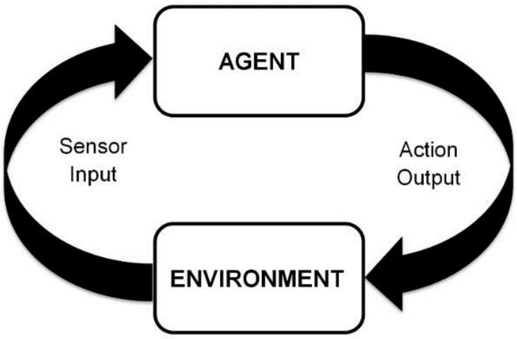


Fig. 3-7. An agent perceives the environment state and alter it through decided actions

The Fig. 3-7 shows the agent that takes sensory input from the environment, and produces as output actions that affect it. The interaction is usually an on-going, non-terminating one (Wooldridge, 2009). An agent is a physical entity that:

- is able to perceive its environment, then it is capable to act in an environment based on their perceptions;
- can communicate directly with other agents;
- is driven by a set of patterns;
- has its own resources;
- whose behaviour tends to meet its objectives, taking into account resources and expertise at its disposal, and communicate.

III.1.2. Type of agent

Different type of agents exist:

- Deliberative agents: This type of agent has its purpose and plan for achieving its purpose. It can store the state of the real world by the symbolic model, and can analyse to decide to act.
- Reagents: This type of agent is not environment symbolic model in which exists, it cannot make decision based on prediction. But detect current environment state then feed back its reply to the changes in real time thanks to its sensors and response rules.
- Personal Agents: This type of agent cooperates with users to performing a task. Its main role is to observe the interaction between the user and application.
- Mobile agents: agent can migrate from one machine to another machine.
- Informational Agents: manages the explosive growth of information and provides data to the users.
- Virus: autonomous agent that can migrate from one computer to another computer and reproduce itself.
- Heterogeneous agents: mixing at least two different types of agents.

III.1.3. Agent's Communication

To cooperate, coordinate, negotiate, one need communication between agents, this concept is one of the most important aspects of multi-agents. Communication is either synchronous or asynchronous. Agents communicate via the exchange of messages or shared variables. There are different communication protocols, the best known are KQML, FIPA's ACL, KIF. The following illustrates the relationship between them (Fig. 3-8).

In (Chopra, 2009) the authors introduce a commitment-based abstraction, which is simple and clear way of designing a Multi-Agent System. It focus mainly on agents' interaction, which yield a business-level notion of compliance. The Fig. 3-9 highlights this interaction; the agents communicate through a middleware preserving two level of abstractions: business and implementation level.

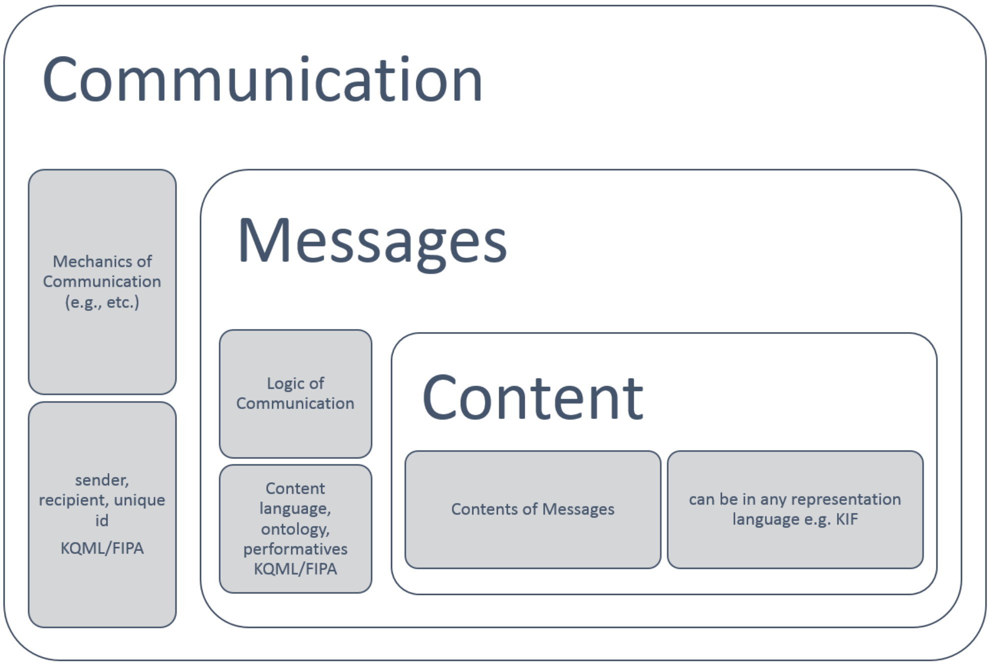


Fig. 3-8. Layers in an agent's message in communication protocols (Chopra, 2009)

To avoid going into details (Chopra, 2009), the most interesting fact in this architecture is the role of the middleware in simplifying and standardizing the inter-agents communication, in addition to managing conflict. This will help in balancing agent reactivity and pro-activeness.

III.1.4. Agent’s Knowledge

Generally, the agent do not have complete control on the environment, it only influences it. Indeed, (Russel, 1995) have suggested a classification of the environment properties. It concerns the following aspects: Accessibility, Determinism, Dynamism and Continuity. Thus, the agent can have a complete, partially or no access to the environment's state. The environment could have deterministic or foreseeable behaviour; static or dynamic state; discrete or continuous actions and perceptions. As it is difficult to deal with an unpredictable environment, the agent must be endowed with mental state (Wooldridge, 2009) and intelligence - a kind of reasoning engine and *reactive system* (Pnueli, 1986) - and abilities, which allows it to adapt to it and reach the goals.

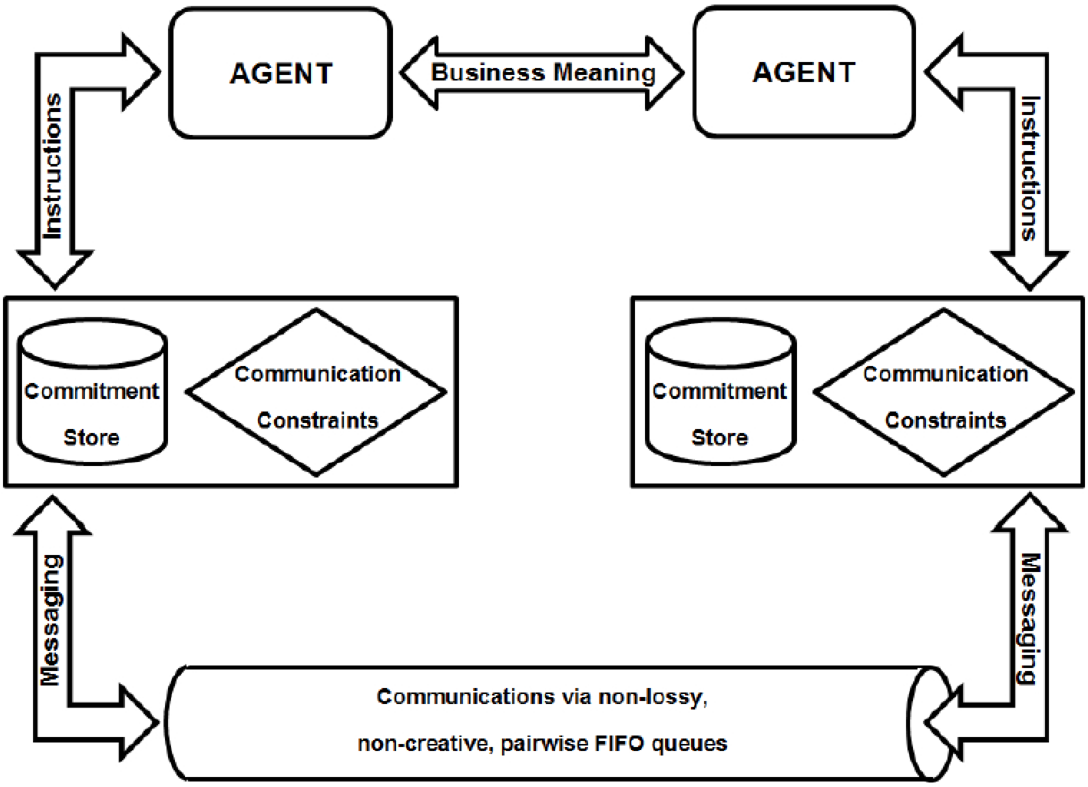


Fig. 3-9. Multi-Agent System Commitment-Based Architecture (Chopra, 2009)

Once an agent have access some information, they have symbols, numbers, characters, beliefs for information representation into the mental state. Each symbol represents an object or an idea; it is called the representation of knowledge. There are several methods for knowledge representation: Predicate calculus, Semantic networks, Frames, Production systems, Bayesian networks, Fuzzy systems.

III.1.5. Agent's Architecture

When it comes to designing a MAS architecture, there is therefore many way of doing it. The Procedural Reasoning System (PRS) concept portrayed by Fig. 3-10 (Georgeff, 1986), was developed by the Artificial Intelligence Centre at Stanford Research Institute and applied as fault detection system for the reaction control system of the NASA Space Shuttle Discovery. It summarizes very clearly, what has been said so far. The agent has a sensor allowing him to monitor the environment; it has actuators for performing actions and therefore influence environment state. A reasoning engine process the agent perception of the outside information, taking into consideration its mental state (Desires and Plans). Then it transduces decisions to a set of actions.

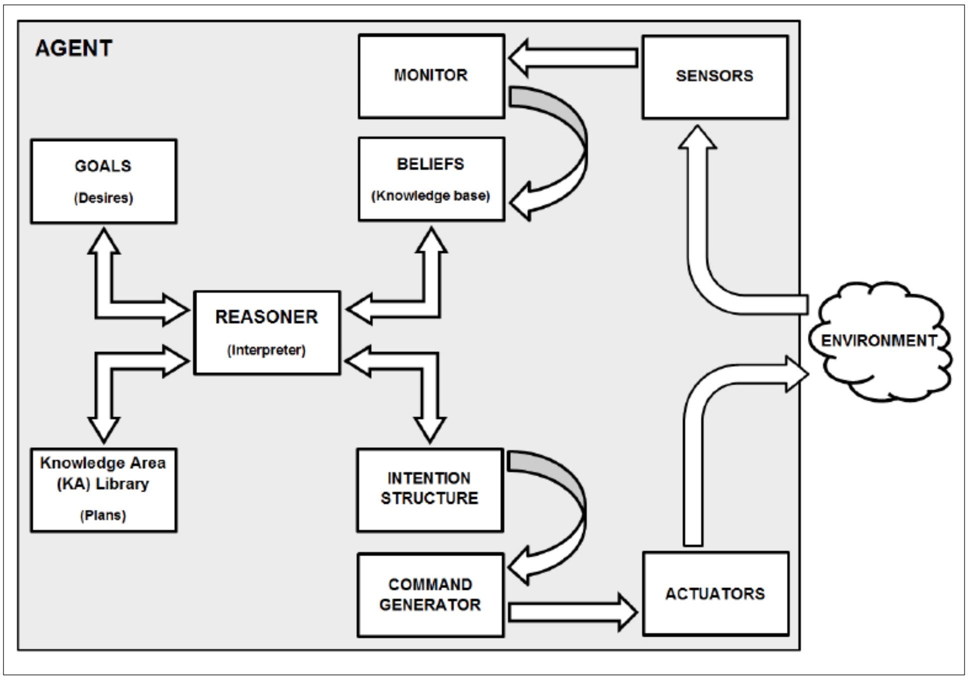


Fig. 3-10. Procedural Reasoning System "PRS" (Georgeff, 1986)

III.2. Traffic Simulation

III.2.1. Various models of traffic simulation

Two classes of simulation techniques are usually used in modelling traffic flows as shown on Fig. 3-11. Microscopic approaches consider discrete entities with complex set of rules governing their behaviour. Macroscopic or Continuum methods allow the modelling of aggregated behaviour of many vehicles. While the latter provide tools for large-scale traffic flows using fluid dynamics equations, the micro approach captures highly detailed information about each vehicles considering their intrinsic properties, in addition to the interaction with either other vehicles or the environment. Thus, it has been decided to use micro-simulation for DGT since we are interested by a detailed analysis. It generates discrete and pseudo-real data that allows accurate assessment and particular case studies. Various models have emerged approaching the microscopic traffic simulation:

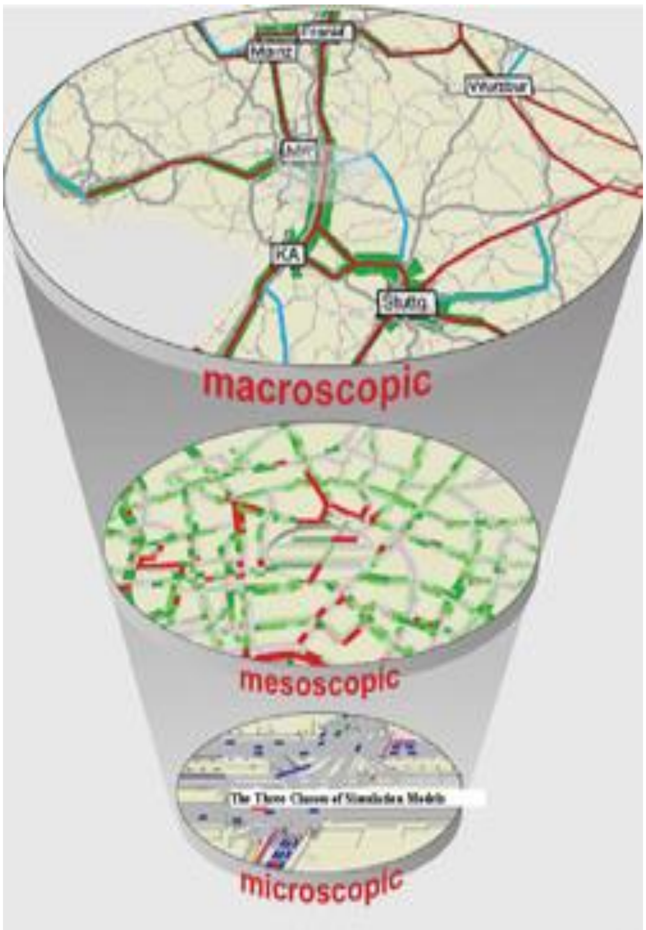


Fig. 3-11 the three levels of traffic simulation approaches

DynaMIT couples a detailed network representation with models of traveller behaviour.

TRANSIMS tracks each individual traveller agent through its day, and its design is contrary to an agent-based model, since it keeps person information decentralized in different files.

MATSim is a fully agent-based model that bypass Origin-Destination (OD) matrices completely and feeds the complete information from activity-based generation into the assignment process. MATSim supports large scenarios and can simulates millions of agents and highly detailed networks. MATSim is perfectly suitable for the study of mass urban traffic trends. It allows the simulation of samples, and this is done by reducing road capacity assuming thereby a whole traffic simulation. MATSim consists in improving all agent plan by assigning a score to each plan, and hoping for individual score as well as for the global score to improve in future iterations; till the simulation reach a kind of equilibrium state. The output of the simulation is an event file detailing all event occurring during the simulation, such starting an activity. It represents also the mean of communication between different agents of the system: an event-driven simulation.

SUMO is an open source, highly portable, microscopic and space-continuous/ time-discrete road traffic simulation package designed to handle large road networks. It allows to simulate how a given traffic demand which consists of single vehicles moves through a given road network. The simulation allows to address a large set of traffic management topics. It is purely microscopic: each vehicle is modelled explicitly, has an own route, and moves individually through the network.

Significant interest on agent-based traffic and crowd simulation has evolved since the boids model proposed by Reynolds in 1987 (Reynolds, 1987). The studies performed on this aspect covered motion and activities planning, routing, behavioural modelling and collision avoidance (Pettre, 2008), (Pelechano, 2008). In contrast, few studies approached the visual traffic simulation. Gerlough's Car-following model (Gerlough, 1955). (Newell, 1961) and (Helbing, 2001) enhanced the solution by adding new features. (Nagel and Schreckenberg, 1992) proposed a new approach based on Cellular Automata. (Mallikarjuna, 2007) and (Pal and Mallikarjuna, 2012) pointed out the possibility of overcoming the gap maintaining behaviour issue, due to the heterogeneous nature of the traffic (Vehicles of different width and length).

III.2.2. The agent model

In an agent-based traffic simulation system, agents are vehicles with their drivers endowed with pro-activeness and autonomy. The Fig. 3-12 introduces the structure of an agent. Agents communicate by messages exchanged. Each agent has a sensor, which gives the agent the information from the environment and to itself (speed). Sensor information is sent to the communication module of the agent to decode the messages and then sends the results to the memory of the agent. The short-term planner predicts the position of all agents in the environment, and uses the rules of behaviour to propose actions with priorities. The Arbiter selects the best action and sends it to the communication module. In the end, the agent can act.

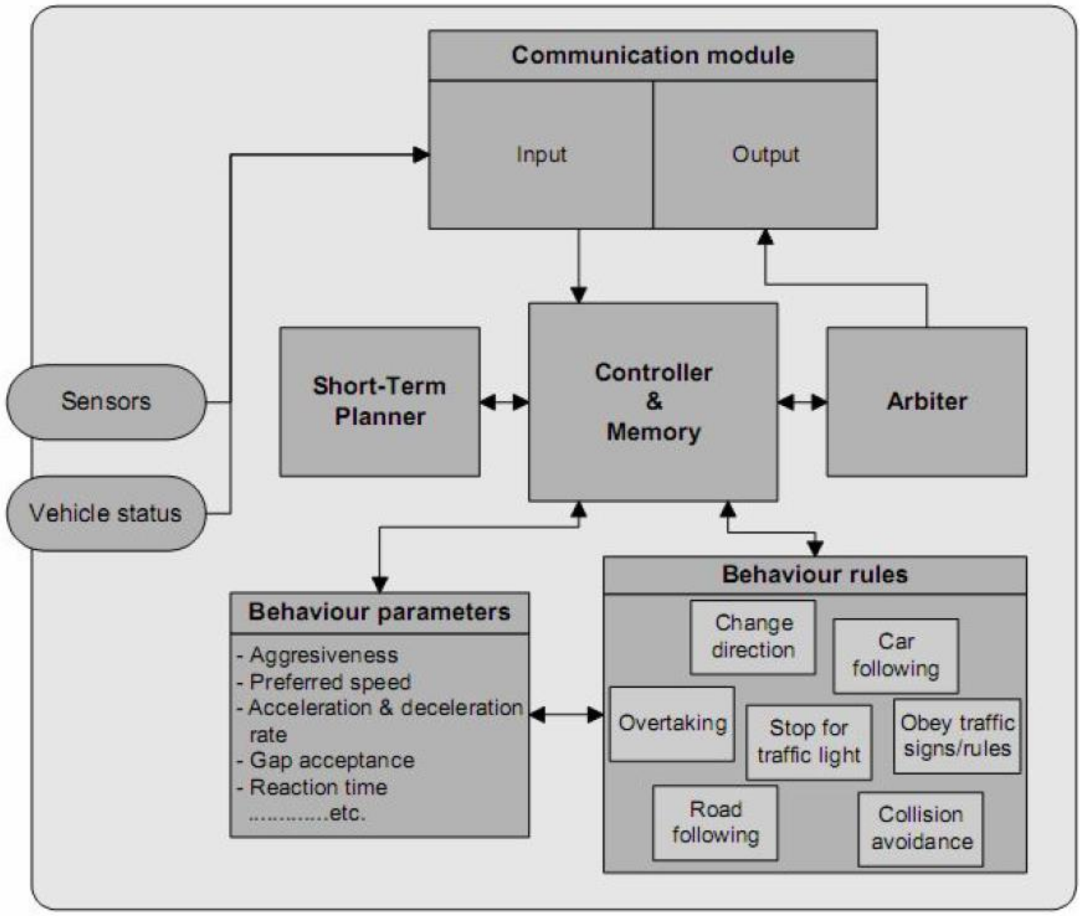


Fig. 3-12. A vehicle/driver agent architecture

III.3. DGT modelling with MATSim

III.3.1. Why MATSim?

MATSim provides a framework to implement large-scale agent-based transport simulations. The framework consists of several modules, which can be combined or used stand-alone. Modules can be replaced by own implementations to test single aspects. Currently, MATSim offers a framework for demand-modelling, agent-based mobility-simulation (traffic flow simulation), re-planning, a controller to iteratively run simulations as well as methods to analyse the output generated by the modules.

MATSim has several key features. A fast dynamic and Agent-based traffic simulation, which simulate whole days within minutes. Private and public traffic, whereas both private cars and transit traffic can be simulated. Supports large scenarios, up to millions of agents or huge, detailed networks. Versatile analyses and simulation output. Modular approach, which is easily customizable. Interactive Visualizer (see Fig. 3-13). Open Source and active development.

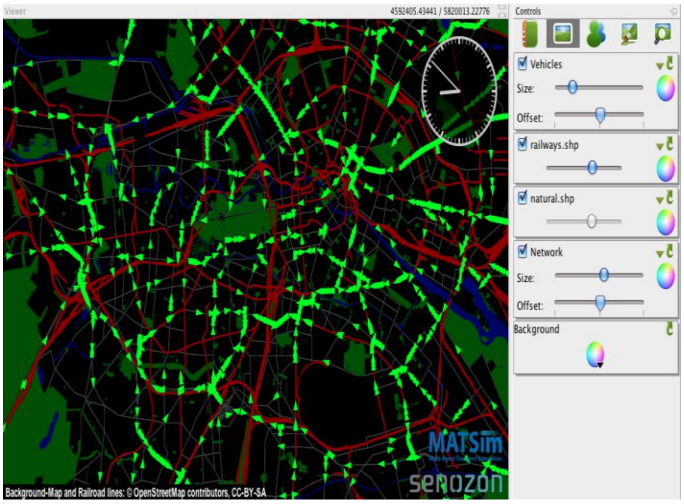


Fig. 3-13 Interface of simulation of MATSim by Senozon

III.3.2. How MATSim works?

MATSim approach in traffic simulation is based mostly on the separation of two dimensions (see Fig. 3-14), which the first one, the strategic world represents all set of methods, algorithms and plans, which is applied to the second dimension, the physical world. This dimension represents the mobility simulation, where the plans and strategies are carried out, then feedback the first dimension with the outcomes and state of environment.

Injecting virtual vehicles into the Transport Integrated Platform is the main objective for implementing agents in traffic simulation. The queue model (Gawron, 1998) fulfils this requirement. Indeed, MATSim models every road segment as a queue in which vehicles have to wait for at least the free speed travel time on that road segment. In addition, both the flow and the storage capacity of each link is limited.

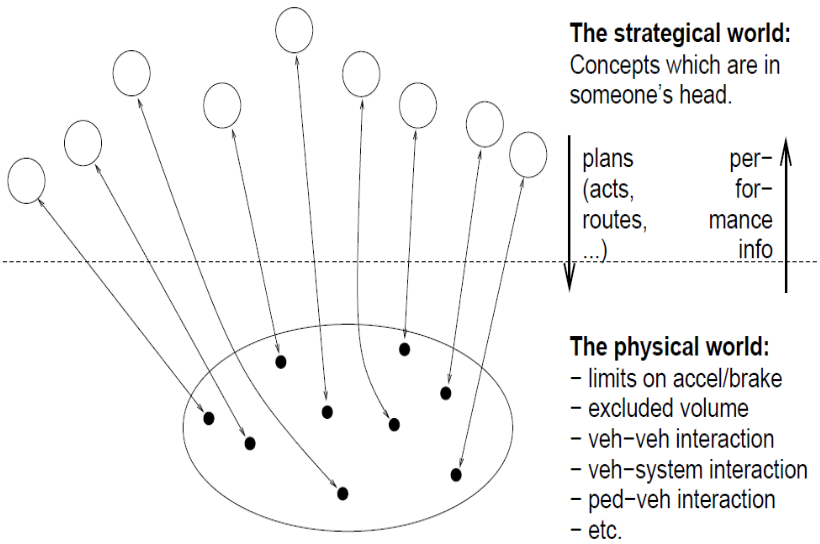


Fig. 3-14 the two dimensions of simulation in MATSim

MATSim traffic flow simulations produce information about where each agent is at a specific time of the day and what it is doing at that time. Each agent generates for each of its actions (begin/end of an activity, entering or leaving a link, etc.) a temporal and spatial localized event. We call this an event driven simulation portrayed on Fig. 3-15. The simulation consists in executing a discrete set of steps or events fulfilling an agent plan. Each event executed will update the agent mental state and the environment.

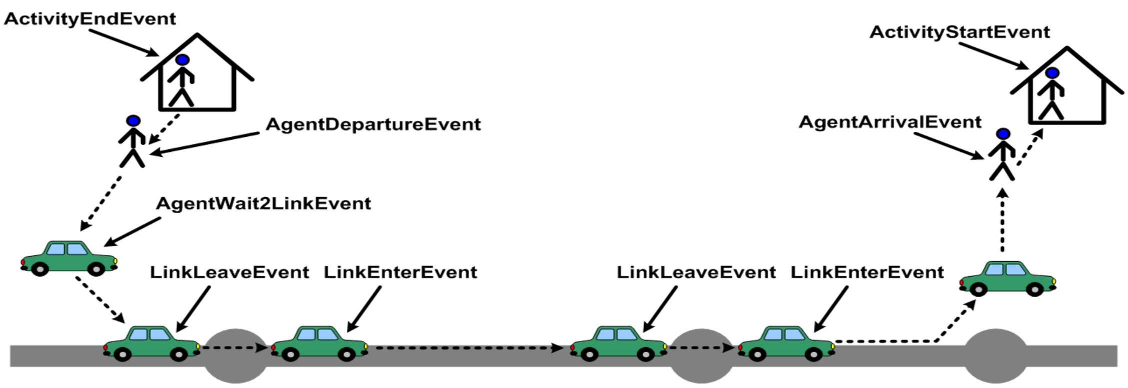


Fig. 3-15 the event driven simulation in MATSim

III.3.3. MATSim Agent interfacing

In MATSim, an agent is a person characterized by an id, age, income etc. This person has the capability to have plans, which are a set of activities with main attributes are the latitude and longitude of the whereabouts of the activity, such work place. Each activity are linked to each other with a "Leg", which is the mode of transportation used to move from an activity to another one (see Fig. 3-16).

Fig. 3-16 Agent & Plan definition in MATSim

In our case, we consider a DGT Agent that consists of a driver (person), a vehicle of heavy type (truck), and the dangerous products transported, as well described by Fig. 3-17. The main attributes of this DGT agent can be extended to have the plate number, size, weight, speed, besides to attributes related to the state of the product such the temperature, pressure etc. This DGT Agent also transmit data generated such GPS coordinate and events which is collected by Data Collection Middleware, which will be discussed the following chapter.

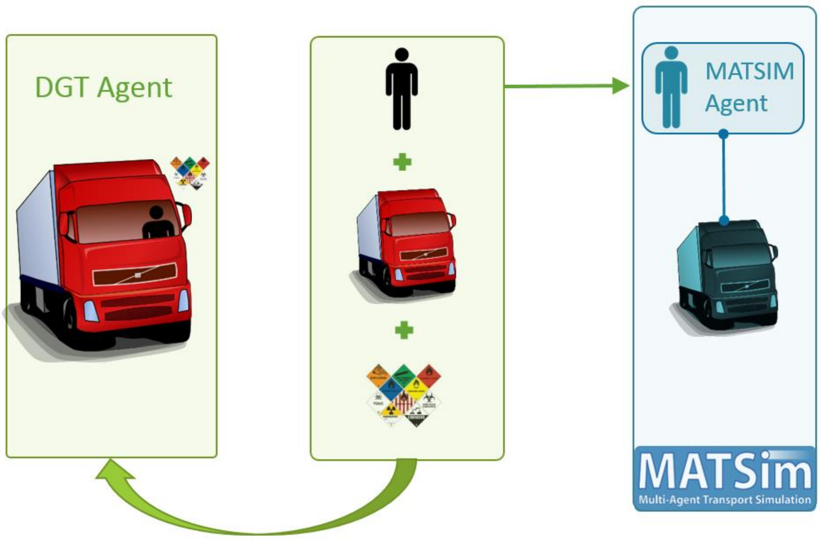


Fig. 3-17 The DGT Agent modelling based on MATSim person agent where (Person) Agent is mapped with (Driver, Truck, HazMat) agent

III.3.4. Interfacing implementation

The extension of MATSim is done in a way that avoids tight couplings with the core and all components of MATSim. Since it has a modular and extensible architecture, allowing the grafting of new modules. The new external modules interface with MATSim through a thin layer that link the DGT Agent with individuals as driver agents using the corresponding modality of transportation. For instance, we define the following XML file structure used in MATSim and shown in Fig. 3-18, which represents a DGT Agent's plan file structure to be interpreted by MATSim. This agent, "id 489", using a truck as modality of transportation with a plate number "PK07LVD", loads 21000 litre of LPG at 8am, then leaves home (loading terminal) and travel to the client's facility for 90 minutes. The agent unload all the content then leaves the facility and return back to loading terminal. The agent finishes the day schedule at 12am. x and y are the geographic coordinates of both home and client facilities.

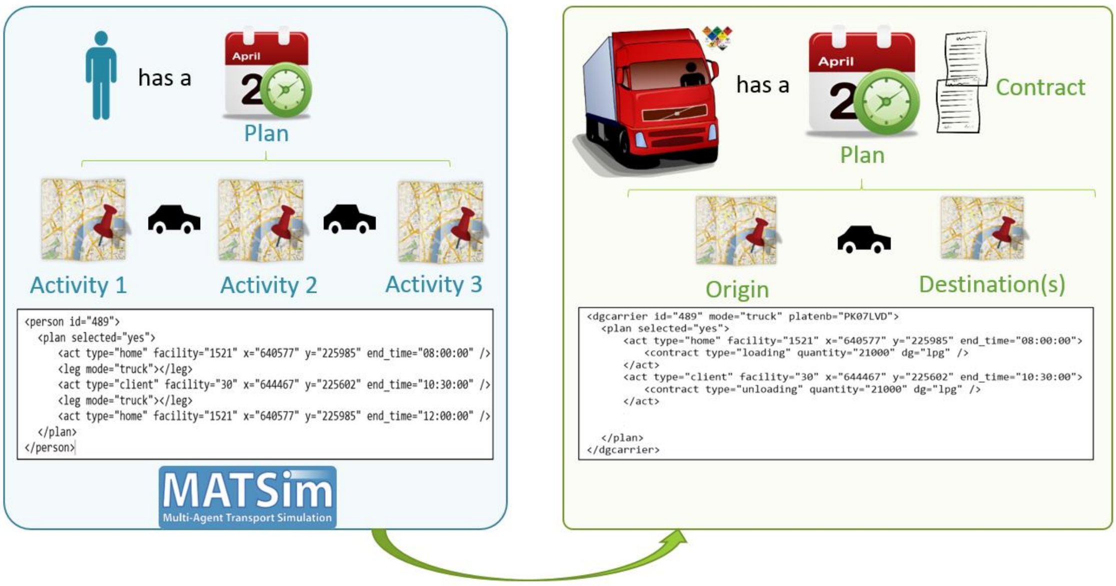


Fig. 3-18 A typical plan files as used in MATSim. First file is an original MATSim plan file, however the second one is a new structure designed for interfacing with MATSim.

The interaction between the components is based mainly on the stream of events delivered by the mobility simulation. It allows the external modules to monitor and track in real-time all agents and environment data coming out from the simulation. MATSim has a within-day planning horizons, but longhaul DGT traffic takes many days, so we extend the time frame to a longer period. However, this might cause congestion delays for several days and thereby we need to reset the traffic flow.

The Fig. 3-19 shows the software components diagram of the DGT Module interfacing with MATSim. The DGT Agent uses the MATSIM-POP to inject individual agents into the system. MATSIM-STRATEGY and MATSIM-SCORES uses the custom re-planning algorithms and scoring function, respectively. However, this can be customized to take into account the developed algorithm for managing the trade-off Travel Time/Risk in route optimization. Finally, the environment is extended by considering new data such population density, weather condition and HazMat information that will be used by the mental module.

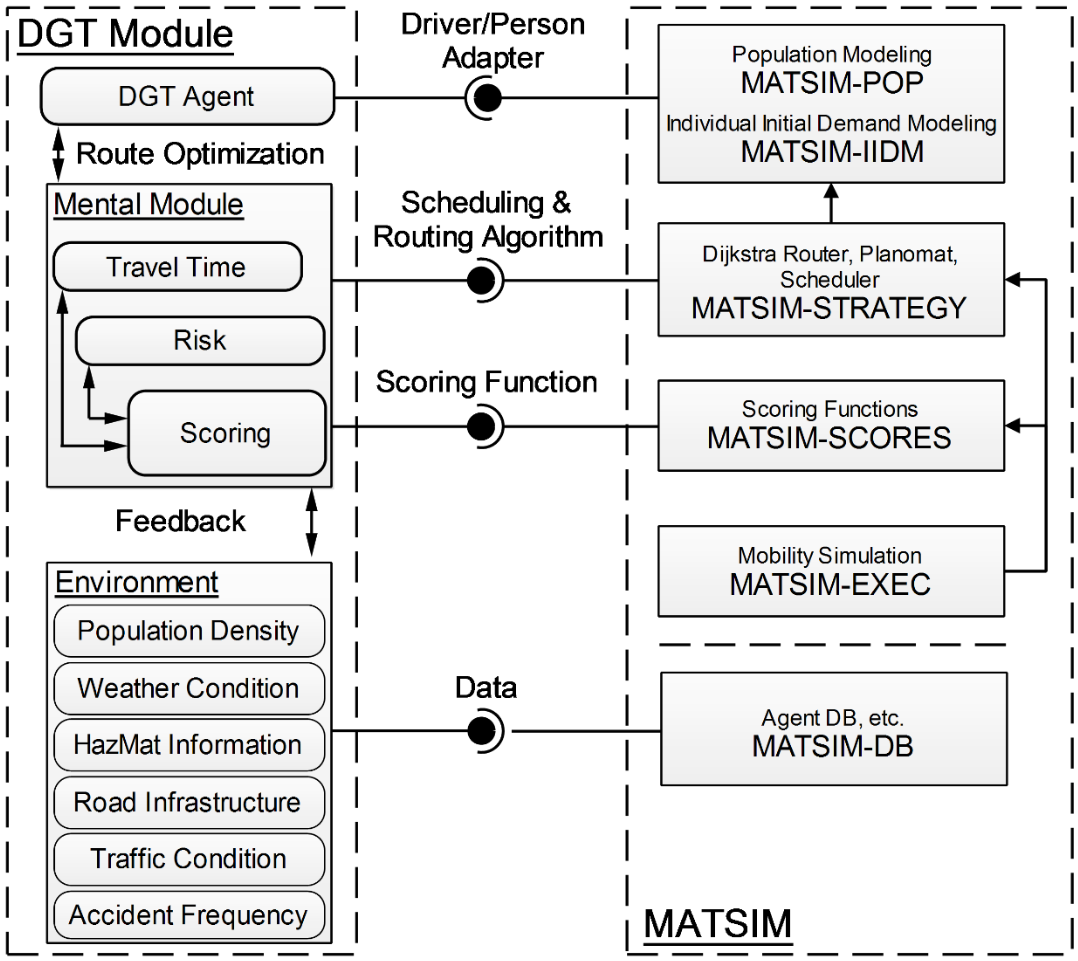


Fig. 3-19 the modular architecture of the system, which highlights the main components and their interaction

IV. Chapter summary

In this chapter, we have addressed two main components of an Intelligent Transportation System. First component is the real-time monitoring system that has been developed in the laboratory in partnership with Eni, DIBRIS and CRC, and appointed as the Transport Integrated Platform. The purpose of such system is to monitor Eni fleet transporting petroleum products to meet the need of the demands. This platform offers further services besides to the real-time monitoring, such the truck technical management and driver training.

The second component regards the driving and traffic simulation. The driving simulation using 3D simulation software is undertaking so to be able to study the driver behaviour (or human factor) while carrying out his mission. The traffic simulation is rather for the purpose of supporting the real-time monitoring system by injecting virtual vehicles into the TIP with possibility of full customization and scenario creation.

Chapter 4. Data Collection Middleware

This chapter addresses the technical challenge of data collection for real-time monitoring of dangerous goods transport. The reason stems from the need to reduce the cost of GPRS data transmission related to the existing data collection system. In the chapter, I introduce the existent system and its drawbacks. Then I prove how changing data transmission, processing and storing affect drastically the performance.

I. Chapter introduction

Recently, real-time monitoring of Dangerous Goods Transport has drawn a lot of attention, thanks to its capability to provide a better visibility on dynamically moving vehicles, particularly through a Web Mapping application. Yet, one of the challenges to be faced designing such a system is an effective architecture for real-time collection of telemetry and event data conveyed by the vehicle on-board system, such the Global Positioning System coordinates.

The GPRS-based data transmission is a widely and commonly used system in real-time monitoring of behaviours and states of remote and scattered entities for security, data collection, service quality enhancement and/or decision-making whether at strategic, tactical or operational level. For instance, the work described in (Xu and Fang, 2008; Ji et al., 2011), respectively monitoring out-of-hospital cardiac patients and water quality, are two different applications of the real-time GPRS-based monitoring. Last but not least, this system like has the capacity to generate large quantities of data (Aydin et al., 2007). Thus, it requires efficient management strategies for data collection, processing and storage within a short period: the Southern California Integrated GPS Network or GPS Earth Observation Network System in Japan, collect data once per second with a latency of less than a second.

In this chapter, we have focused on optimizing the process for managing a large quantity of data transmitted via network sockets that use the Transmission Control Protocol. Then we prove the process efficiency through performance and scalability tests. The middleware is being implemented as a part of the TIP project that aims to monitor the Italian petrochemical company Eni's oil trucks shipment along Europe and USA territories. In addition, virtual trucks will be injected into the monitoring system for simulation of DGT, risk analysis and performance measurement as has been discussed in (Laarabi et al., 2013b; Boulmakoul et al., 2014). This will lead to a significant surge of vehicles, which transmits continuously data to the server. Therefore, the objective is to design an efficient and scalable system for data collection even at high data transmission rate and number of vehicles. It represents a substantial contribution in transport engineering and particularly in DGTs management.

II. Transmission system of the TIP

As detailed beforehand, the TIP is an Intelligent Transportation System dedicated to road transport of DG (petrol products), and it consists of four main components: the On-board Unit, Transmission System, Transmission Database Server (T-DB) and the GIS application.

II.1. The on-board unit

Sets of hardware devices and software are embedded into a vehicle at different places. It collects events and telemetry data such temperature, speed, GPS coordinates. As previously shown, the concentrator, positioned in the trailer, equipped with a GPS antenna and a GPRS transmitter/receiver for real-time data transmission.

II.2. The transmission database server (T-DB)

The T-DB receives all raw messages, without exception, coming from the Transmission System and stores them for diagnostic purposes. However, messages parsing are not directly executed on this database due to tables locking issues. The application server moves unpacked data from the T-DB to the Main Database Server (M-DB) at regular intervals. The M-DB backups all data on the Backups Database Server (B-DB). It can quickly substitute the M-DB in event of failure with minimum data loss and periodically oldest backup data are purged.

II.3. The GIS application

The web application is about providing tools for fleet management and scheduling and real-time monitoring. It integrates hardware, software, and data for capturing, managing, analysing, and displaying all forms of geographically referenced information. Fig. 4-1 (left) displays graphical information about a monitored Eni truck, and in real-time. By pointing the truck, a pop-up window appears with the vehicle's ID "SR010294", time of the last received event, type and quantity of an on-board product and more. Fig. 4-1 (right) shows the daily DG flow along the Italian northeast territories.

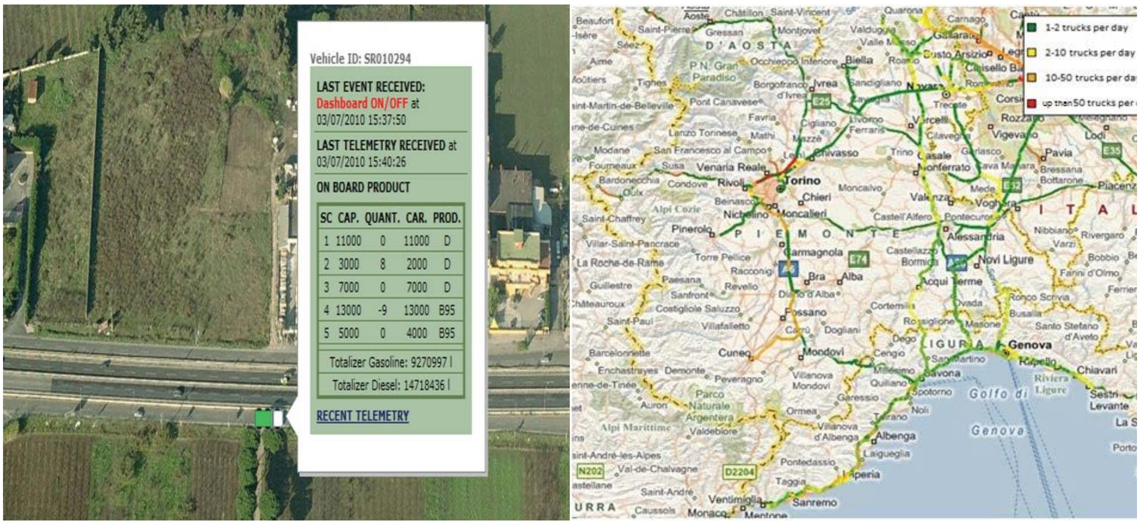


Fig. 4-1 (left) the graphical interface of the GIS application (one of TIP component) displaying information about a monitored Eni truck in real-time, (right) the evaluation of dangerous goods flow in Northwest Italy on the TIP.

II.4. Data collection using a web service

The data collected by the concentrator, which represents the client in a client/server architecture, are sent through GPRS network to the server that deals with data reception and processing. The information is organized into messages, which according to the different level of priority, are sent to different output queues. The composition of such messages is dictated by a precise predetermined communication standard decided by Eni to ensure the trucks-TIP communication. However, the protocol stays completely independent from the supplier of the electronics mounted on-board.

II.4.1. The web service architecture

The TIP uses the web service technology for data transmission as shown on Fig. 4-2, which is based on the IP protocol (Benza et al., 2012). The web services are housed in a Microsoft web server called the Internet Information Services (IIS) (Snedaker, 2004). It allows the outsourcing of complicated tasks as concurrency and memory management.

According to the definition of the W3C, the Web Services can be described as *a software system designed to support interoperability between different computers on the same network*.

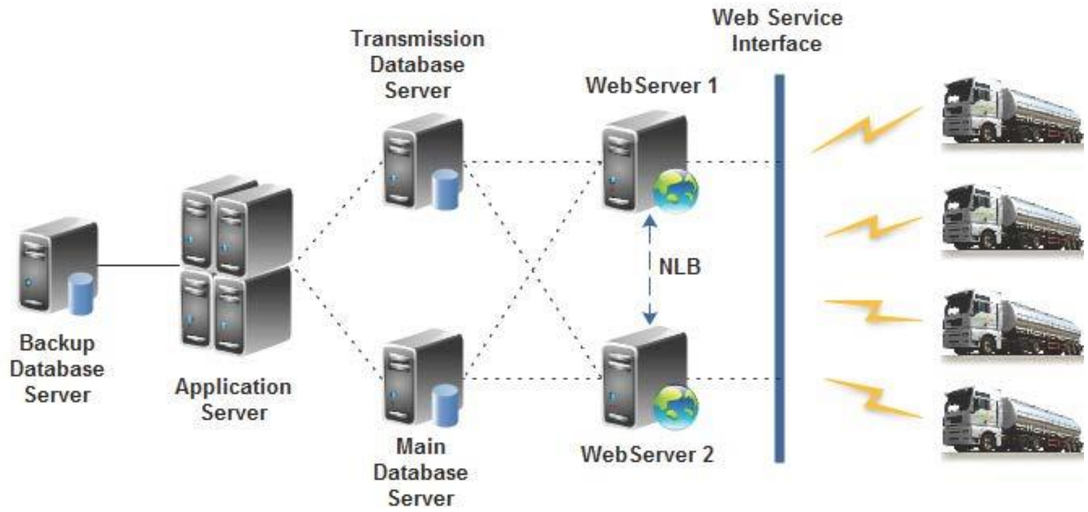


Fig. 4-2 A Web Service Interface operating between the centralized servers cluster for receiving and processing the data, and the on-board units that transmit

A fundamental characteristic of a web service is to provide a software interface, described in a format which can be processed automatically. Other systems can interact with the same web service only by activating the operations described in the interface. The interaction takes place via special messages that are included in an envelope (the most famous is SOAP[9]). These messages are transported using the HTTP protocol and formatted according to the XML standard.

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[9] The Simple Object Access Protocol (SOAP) is a protocol for exchanging structured data used by web services in computer networks. It relies on various application layer protocols, such eXtensible Markup Language (XML) for message formatting, and HyperText Transfer Protocol (HTTP) for message transmission (Gudgin et al., 2007).

The web services protocol stack is a set of network protocols used to define, locate, implement and interact with each other. In brief, the web service concept can be summed up to:

- Transport service: responsible for transporting messages between applications on the network, including protocols such as HTTP, SMTP, FTP, XMPP and the recent BEEP.
- XML Messaging: all data are formatted using XML tags in order to ensure the interoperability at both ends (client/server). The message can be encoded in accordance with the SOAP standard, or with JAX-RPC, XML-RPC or REST.
- Services description: the public interface of a web service is described by the Web Services Description Language (WSDL), which is an XML-based formal language used to create documents describing the procedures for interfacing and using the web services.
- Services enumeration: the centralization of the description and location of the web services in a common registry allows a quick search and retrieval of web services available on the network.

The WSDL is then used in combination with SOAP and XML Schema to make available web services on local networks or the Internet. A client program may read the WSDL document related to a web service in order to determine what are the functions available on the server and then use the SOAP protocol to activate one or more of the listed procedure. A WSDL document contains, relative to the web service described, information on:

- Functionality provided by the service;
- Communication protocol to use to access the service, the format of messages allowed in input and in output returned by the service and the related data or constraints of the service;
- How to access the service or the so-called service endpoint, which usually corresponds to the address that provides the web service.

Thanks to the use of XML-based standards, through an architecture based on web service, software applications written in different programming languages and deployed on different hardware platforms can then communicate.

II.4.2. The messages

The messages are encapsulated in a SOAP envelop and sent thanks to the embedded GPRS module. The message itself encapsulate the telemetry and events data, and it is structured following a predefined format, according to the established communication standard. The structure is composed of fields holding geographical position and events collected by the truck and tank sensors. These fields are concatenated in such way that a semicolon separates two subsequent fields. The format of the transmitted message string look exactly as:

[source id; transmission date; reception date; creation; driver id; truck id; trailer id; CIM; last MTC; latitude; longitude; data id; value]

II.4.3. Data collection workflow

The data stream sent by the media to the server is organized into messages that are received, processed and stored. To complete the process, a response is sent to the vehicle from which the message was originally sent. As indicated in the Fig. 4-3 data collection follows a succession of well-defined steps.

The first step is the one concerning the real-time transmission. Once a message is transmitted, a cluster of servers received it. These servers, which host the deployed Web Services, deal alternately with the transmitted messages by adopting the Network Load Balancing concept (MicrosoftTechNet, 2012), which consists at redirecting a network packet to the less overloaded web server. Then the message is processed and parsed in order to check the validity of the format according to the established communication standard. Afterwards, the program check for existing duplicate to the received message. In case of reception of a valid and unique message, it is flagged as valid message then stored in the Transmission Database (T-DB), otherwise it is flagged invalid and even in this case, the message is stored in the T-DB for later troubleshooting. At this point the Web Service acknowledge to the truck on-board system the “OK” message at a success or "KO" otherwise.

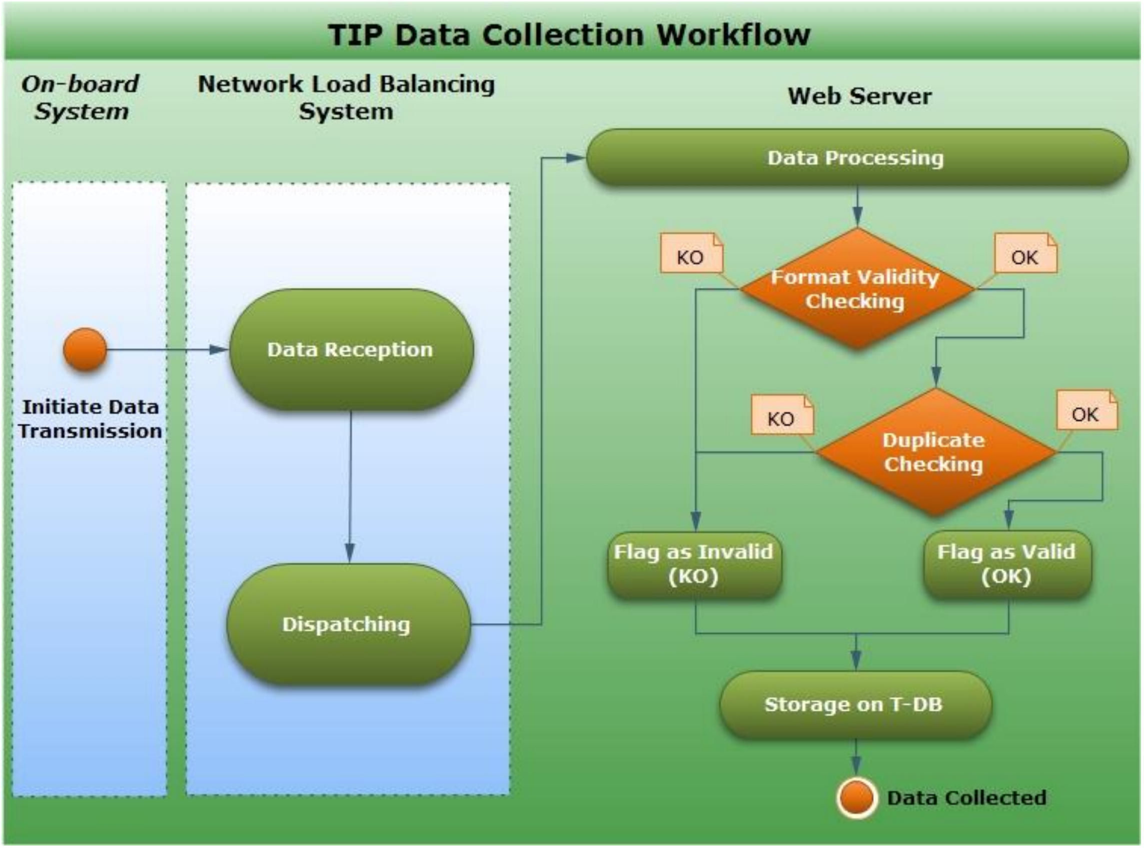

Fig. 4-3 The workflow of the TIP data collection process for real-time monitoring of the fleet, where data are received, dispatched, processed, then checked and finally stored.

II.4.4. Web service drawbacks

To summarize, the web-service data transmission consists in encapsulating messages inside SOAP envelope, which is formatted with XML and transmitted along with HTTP. Consequently, the SOAP makes messages bigger or heavier, which increases significantly the costs for transmission over GPRS. Not to mention the impact of the performance and transmission time due to XML Parsing and Memory Management.

In practical terms, this system has been designed and deployed to track more than 600 Eni oil trucks in Europe, given the fact that each truck provides its GPS data every 5 minutes. This updating period is set up taking into consideration the GPRS data transmission cost. In the case, we multiply the number of tracked vehicles and we shorten the transmission period, it will inevitably impact drastically the performance and transmission cost. For this reason, looking for an alternative solution seems paramount for the reliability of the TIP. We will discuss in detail the proposed solution in the following sections.

III. Data collection middleware architecture

The implementation of a new data collection middleware has for main objective, the reduction of cost by dropping out the web service based approach. As it has been brief explained, the SOAP envelope that wraps the messages, increase significantly the size of the transmitted packets. Currently the rate of data transmission is around 5 minutes for each vehicle, knowing that 600 vehicles are currently monitored. Therefore, at least 161280 messages are daily transmitted. The SOAP envelope extends the size of the packet by at least 50% in best circumstances. It means to send 241920 instead of 161280.

Consequently, if Eni decides to increase the rate of data transmission to few seconds and/or expand the monitored fleet, the cost of GPRS transmission will exponentially expand. Our objective is to propose an alternative solution for data collection, such that on one hand, the halving of the 50% SOAP header to converge to 0%, on the other hand, to ensure a scalable system able to handle surges in transmission rate. Indeed, we have to design a system capable of handling the 4600 vehicles of Eni in addition to virtual vehicles for DGT simulation purposes, with a transmission rate of not more than few seconds.

The Fig. 4-4 shows the source of transmitted messages: real vehicles through GPRS network and virtual vehicles through local network, since the simulator and the TIP are both present within the DELAB local network. Then, the collected data are stored in the M-DB, which will be translated then graphically interpreted within the GIS application for visual monitoring.

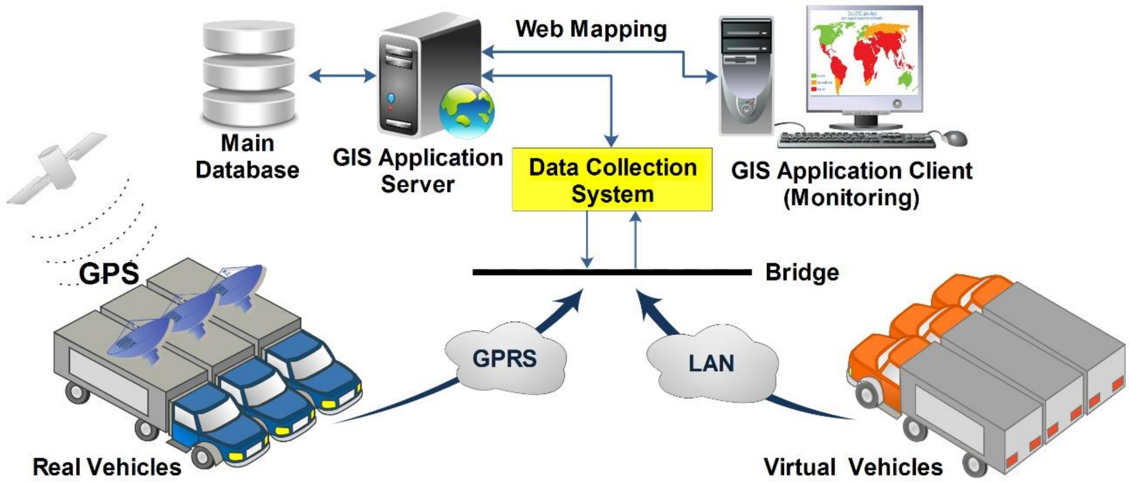

Fig. 4-4 An Overview on the Monitoring System Architecture that highlights the critical role of the Data Collection System in the heart of the monitoring

Throughout the next sections, we will introduce the alternative data collection middleware and prove its efficiency and scalability. Indeed, the transmission rate has been cut down to around 5 seconds for 5000 vehicles, with a stable system that does not collapse due to the overload. This is achieved by conveying raw data, without SOAP envelop, through TCP[10] sockets using the C++ programming language. The proposed solution concerns two different scopes. Whilst the first scope is linked to the protocol of communication between the server and vehicles, the other is rather focusing on server side data processing.

Fig. 4-5 presents the Sequence Diagram of the overall process of Monitoring System, which is a commonly used UML[11] Diagrams that shows how entities interact in a given situation. After every n seconds a message is sent to the data collector server. The message is pushed back into the buffer. Then it is removed from the buffer and labelled valid or invalid by a controller, then stored into the T-DB. After $x\,seconds$, valid data (package of valid messages) are parsed and re-structured, then stored into the M-DB by the GIS application server. Finally, the GIS application client updates the visual monitoring by the data freshly placed in the M-DB.

[10] The Transmission Control Protocol (TCP) is a reliable and ordered data transmission protocol, with error-checking system.
[11] The Unified Modelling Language (UML) is a modelling language designed to standardize a system architecture conception in software engineering

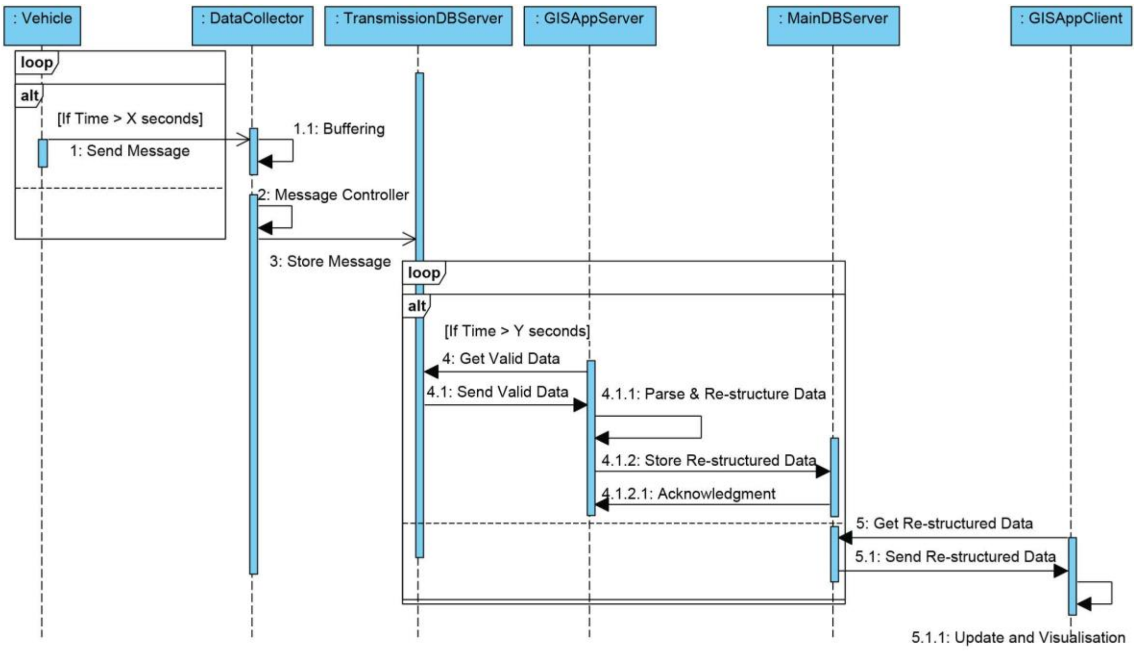

Fig. 4-5 The UML Sequence diagram summarizing the whole process of the real-time data collection activity.

III.1. TCP Socket-based architecture

Data are transmitted directly according to a TCP protocol using GPRS connection as shown in the Fig. 4-6. Once the server receives a quantity of messages, it proceeds to verification, storage and validity acknowledgement. In the case of reception of invalid messages, the server asks the clients, which are sources of invalidity, to stop transmission. Since it requires human operator intervention. On the server side, two options are available to deal with incoming clients requests. The first one is the synchronous communication, which enables one connection at a time and thus multiple threads (thread pool) to be created then associates a socket for each thread. As a result, the server can process all incoming requests in a pseudo-parallel mode. Therefore, concurrency, processes performance and memory leak have to be managed. Regarding the second option that is asynchronous communication, a handle is associated with each socket. These handles are run in an event-processing loop, where they are instantiated; and block the calling function while there are on-going asynchronous operations. This solution was adopted, since there is no need for either concurrency and critical resources management nor memory leak handling at level of processes management (see Fig. 4-6).

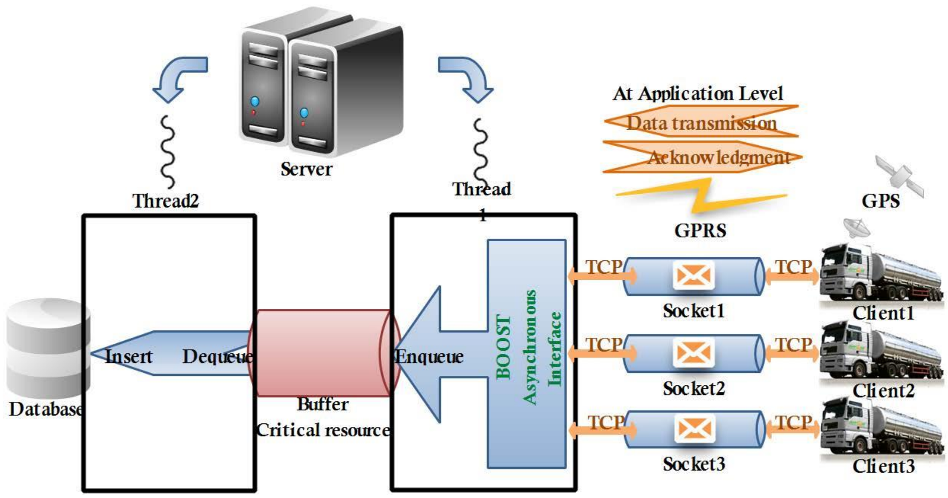

Fig. 4-6 TCP-Socket based data transmission operating between the server and the on-board units, using BOOST for data processing and storage.

Since the event-processing loop is a blocking function, we associate it with a thread. Once the server receives a message, the thread reads it from the socket buffer then puts it down in a shared buffer that represents the critical resource. Another thread accesses this buffer, then checks the validity of the message and stores it in the database. In a server environment with multi-core processor, the program will generate as many thread as available cores for checking and storing data. Regarding technologies used for building solution, the C++ Boost Libraries provides powerful and reliable tools to overcome some intricate tasks (see Fig. 4-7). Thus, the use of the smart pointer library will ensure the releasing of allocated memory. The threads and timer, random number generator and handler binder represent also an important asset for the system and laboratory tests. Finally, ASynchronous Input/Output library (Socket, Input/Output tools, asynchronous interface) was the main component that allowed us to deal with data transmission efficiently. On the other hand, the Input/Output Completion Ports (Library, 2012) is less simple to use.

Fig. 4-7 depicts the relation between the different entities of the system. When the "`tcp_server`" receives a client connection request, a "`tcp_connection`" is created and associated to a "`tcp_session`". The "`tcp_session`" will manage the communication session with the client. The pattern observer is an implementation of the Observer pattern in charge of the triggering of the storage process whenever data is received. The "db_connection" entity provides interfaces for database storage.

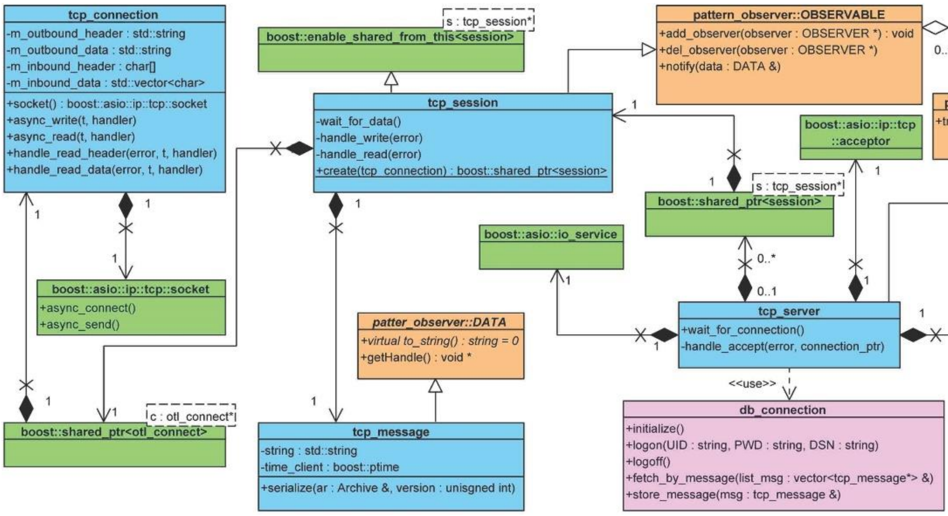

Fig. 4-7 The UML Class diagram detailing the architecture of the TCP-Socket based data collection.

III.2. Buffering strategy

The main issue encountered during the development of the data collection middleware is the synchronization between reception and storage. How to manage and share resources among threads? How to ensure the critical resources integrity? In addition to memory and process, database connection is a critical resource. Instead of re-establishment and breaking of connections, which has adverse effects on performance, the connection pooling remains an efficient solution. It is a concept for managing a set of pre-created connections made available for the concurrent process. Thus, a connection will be allocated and released as required. Moreover, the connection pooling can be expressed in another way by using the thread pooling, which is a collection of threads to call upon them to process tasks, and each thread can maintain a database connection throughout its life cycle. It avoids the concurrency on a connection pool and, thereby, improves the performance. By adopting this method, the reception and storage process will communicate through a Buffer or a Task List (TL) as shown in Fig. 4-6, instead of proceeding in a sequential manner. Its role is to hold temporarily received message to be stored later. In (Delis and Roussopoulos, 1992), the TL is called Jobs Queue and it operates in the same way by holding waiting tasks;

knowing that, in the quoted paper, the tasks are actions in the form of SQL12 queries.

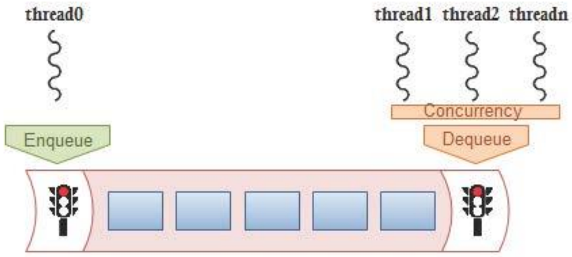

Fig. 4-8 Multithread/ task list.

The TL concept can be implemented in different ways. The first schema of Fig. 4-8 depicts the use of one TL for multiple readers (threads). While the writer (or reception thread) pushes messages at the back of the queue (or TL), multiple concurrent readers try to read from the front of the queue. However, this leads to a high concurrent access to the TL, which is very costly in terms of performance. This is due to the frequent Context Switching (CS) by using semaphore techniques to preserve data integrity. In order to reduce the CS frequency, a TL for each reader is proposed in the second schema of the Fig. 4-9. Then the concurrency for one critical resource is eliminated and the semaphores will only be used during the queue filling by the writer:

$$\frac{(n_{th} \times (n_{th} - 1))}{2} \xrightarrow{become} (n_{th} - 1)$$

where n_{th} is the number of times when the resource is locked by a thread while another one is looking to access to it.

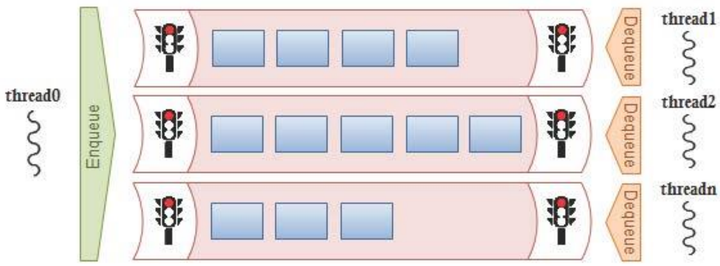

Fig. 4-9 Multithread/ Multi task list.

[12] The Structured Query Language (SQL) is a programming language designed for data management in relational databases.

Yet despite the achieved improvement, the results are not quite satisfactory. Still significant data loss and increasing transmission delay when a high number of clients are launched. As the program is not yet scalable, another approach is proposed that relies less on concurrency. Up to now, the relationship between loss of data and the delay reception is proportional, and microseconds delays in data processing may cause the overloading of the socket buffer and induce data overwriting. To overcome the issue, the writer process has to be more or less independent from storage process to avoid CS during data reception. The idea is to create a multiple intermediate buffers (or TL) to keep the reader and the writer using (or locking) two different buffers avoiding, thereby, the CS induced by the allocation and release of critical resources (see Fig. 4-10).

It is necessary to point the fact that the number of buffers and their sizes are settled beforehand. A similar approach has been implemented in (Delis and Roussopoulos, 1992). The authors used multiple kinds of buffers with different functions. The `ReadyQueue` has the same role as the buffer in this solution: to hold temporarily received jobs requested by the clients. They use also Concurrency Control Queue and Blocked Queue, which are not needed in this work.

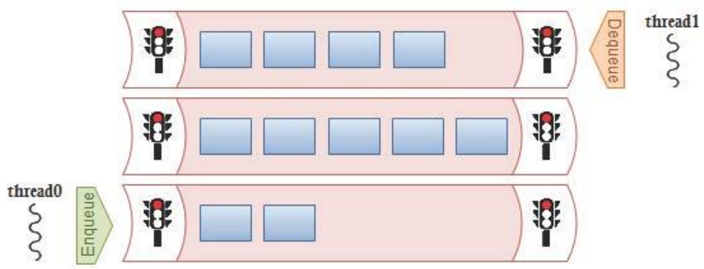

Fig. 4-10 Multi buffering.

This solution has achieved good results but not for long. In fact, the writer and reader speed are not similar. When the writer fills all available buffer, it keeps waiting for reader to release the on-going one. Therefore, at the end, the writer might depend on the reader, consequently the performances decrease. The second schema of the Fig. 4-11 describes an extensible buffer, which are not limited by the number of buffers: if there is no available queue, the writer creates one and fills it; at the same time, the reader keeps reading, and then destroys the queue when it is empty. Therefore, the writer is completely independent of the reader, which has to be fast enough to avoid memory leak by the expanding gap between the two workers. A better storage strategy has to be designed.

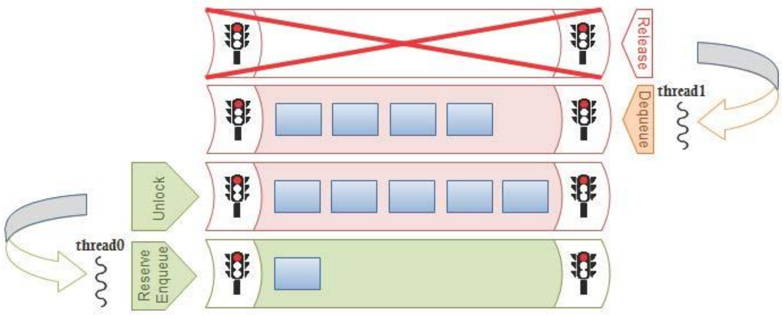

Fig. 4-11 Extensible buffering.

III.3. Database storage strategy

Regarding persistence, SQL Server 2008 Database is used for storing data received from clients. In order to access the database with C++, the program needs an Application Programming Interface, which acts as an interface. The choice fell on Oracle Template Library (OTL) for its performance, simplicity and available documentation (Kuchin, 2012). In fact, OTL provides object oriented C++ interfaces and use a generic implementation of the concept of streams (based on C++ Input/Output Stream): buffered stream that hold outgoing requests and incoming results. It is also highly portable, self-sufficient and compact enough, only one header file and no Dynamic-Link Library (DLL) or Driver needed. Finally, it is reliable in multiprocessor environments and adopts C++ Standard.

The transmission of an INSERT query once the server receives a message is definitely not the right strategy for a real-time data storing. Even a bulk insert will not make a great difference. Fortunately, SQL Server provides a much better mechanism that is the stored procedure. It is a compiled subroutine ready to use at the disposal of the caller. By using a stored procedure, and according to (MSDNLibrary, 2012), the program in one hand will no longer send SQL queries but only the light packet RPC[13] with data to store as parameters. On the other hand, the SQL Server does not need to parse queries strings, checking validation or compiling them; it will execute directly the already compiled stored procedure. Additionally, the stored procedure is implemented in a way to insert at once multiple rows (Bulk Insert): one RPC call instead of multiple ones.

IV. Test and results analysis

In order to build a reliable and scalable system, a test plan has to be defined covering multiple levels: Application, database, operation system and network (Liu, 2009). The tests will highlight at application level, strategic and conceptual issues dealing with synchronization or critical resources management, handling of multi-threads, performance and speed of data processing. Regarding the second level, it is a matter of database access and query enhancement. Nevertheless, at operation system and network level it concerns multi-threading support, memory management, multi-connection and transmission rate. In fact, these tests are intended to the server side as well to the client side. The latter will simulate virtual clients sending data to the server, and it has to be robust enough to run without crashing (see Fig. 4-14 & Fig. 4-15). Once the both sides were fairly steady from the synchronization, memory management and database storage point of view as described in the previous sections, the server was ready for stress testing to reach the bottleneck.

Then we break the system by overwhelming its resources or by taking resources away from it to measure its recoverability (Hung Q. Nguyen, 2003). For instance, in face if the system notices unusual growth of the buffer size leading to memory leak, it will react by halting temporarily data reception but keeps trying to store the buffer content in the database. If the latter is unreachable, the memory will be released and the server sleeps for a random amount of time. In the same way, the server will reduce its activity by halting

[13] The Remote Procedure Call (RPC) is a remote procedure invocation used by computer programs for inter-process communication. At computer networks level, it is considered as a light packet, since it contains only the name of the procedure to execute and its parameters, which, by the way, significantly reduces the bandwidth consumption.

threads since no client has transmitted data for a long time. Before presenting the tests results of the new architecture, hereinafter, on Fig. 4-12, some outcomes chart of the WS-based architecture. The latency is 13 seconds for 50 messages transmitted per second using one server with a transmission delay of 4 seconds. Regarding database performance, we note that the storage delay is almost constant (about 80 milliseconds) up to 50 connections per second, then a sudden increase reached 180ms delay by 100 connections per second.

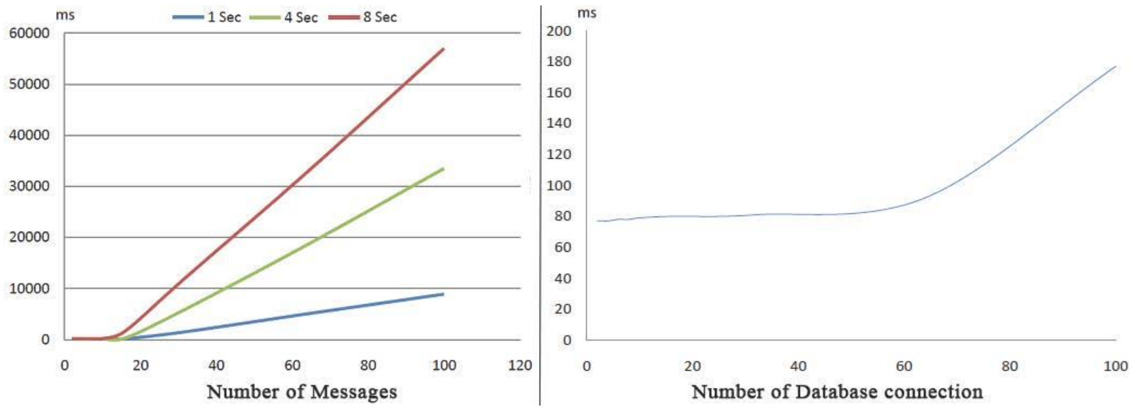

Fig. 4-12 Web service and database performance tests.

Regarding the TCP socket-based architecture, a chart of a scalable test is presented in the Fig. 4-14. During this test, 5000 clients were launched with a transmission delay belonging to the interval:

$$[\mathrm{min_D}, min_D + Random \times min_D] \qquad with \quad Random \in [0,1] \quad and \quad min_D = 5\, sec$$

The server was running on a Microsoft SQL Server 2003 Operation System with 2 GB physical Memory and configured with two single-core Intel R Xeon TM processors at 3 GHz with hyper threading support (1 Core, 2 Threads) for approximately 4 days. The server side and the client side are running in a 100 Mbps local network. The purpose of this test is to monitor the behaviour of the server, especially to see whether they have memory leaks over time, running in a limited environment with mediocre performance and undergoing a fairly high load of clients. In addition, the clients may loss connection from time to time; thereby the number of clients must follow a stochastic approach to keep it variable in an interval of 10%.

Hence, Fig. 4-14 presents the relationship between the server transmission, the database storage delay and the quantity of messages processed. The point here is the obvious dependence of the storage process on the reception process. The first one is faster than the latter one, thereby; the thread responsible for database storage keeps waiting for the buffer to be released to proceed to verification and storage. In addition, the number of messages received influences the other measures. However, in terms of performance, on one hand the speed of data reception per message was around 0:950 second and about 1:5 second to store it using buffer of 500 messages. To convey and to store 50000 messages, it roughly takes70 seconds (taking into consideration the 5 seconds time delay). In terms of scalability, the resources consumptions were fairly moderate and steady namely either in process level or in memory level (see Fig. 4-13).

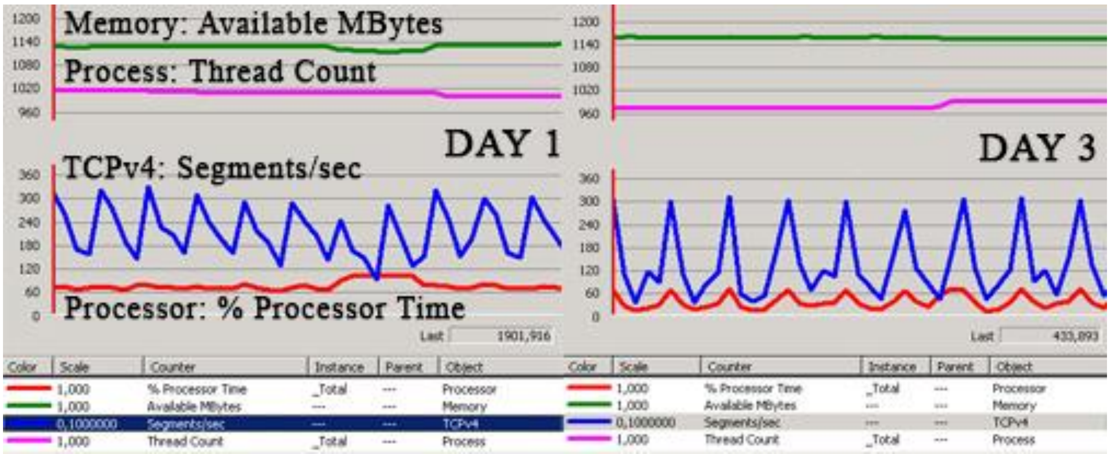

Fig. 4-13 Process and memory status by windows performance monitor.

Throughout the test, more than 250 million messages have been sent and processed by the server in 4 days. The "TCPv4: Segments/sec" in the Fig. 4-13 represents the number of TCP segments per second processed. The "Processor: %Processor Time" describes the Central Processing Unit (CPU) activity. Whilst the "Memory: Available MBytes" and "Process: Thread Count" refer respectively to the MBytes of physical memory available and to the number of threads. The figure clearly exhibits the stability of the Data Collection Middle-ware: absence of memory leak and processing surge through the test. All these indicators are proof of stability.

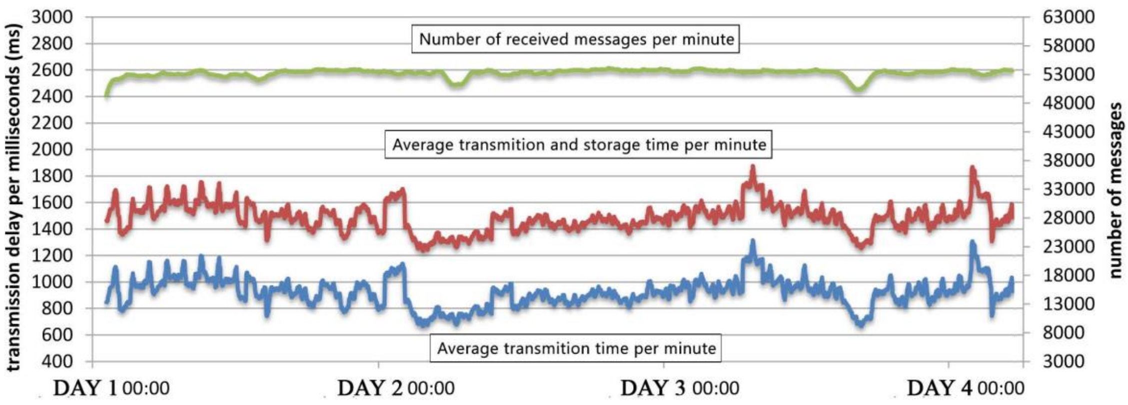

Fig. 4-14 Scalability test.

Another test has been done (see Fig. 4-15) but this time only 50 virtual clients sending messages through a GPRS-like network with 56 kbps bandwidth. Thus, the figure describes, especially, the storage performance which tends to less than 150 milliseconds (_transmission delay). This is due to reduction of the buffer size to 5 messages, since the frequency of messages received is about 6 messages per second. The transmission is relatively high due to the share of GPRS connection among virtual clients, which burden on the bandwidth. The table 4-1 summarizes the results reached with the proposed solution by comparing it with the WS based architecture.

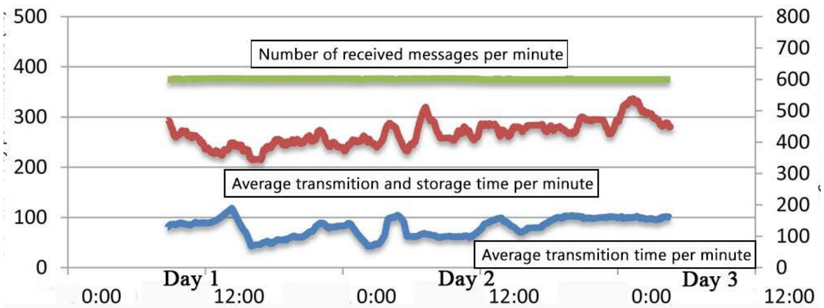

Fig. 4-15 Performance test with GPRS connection.

V. Chapter summary

In this paper, an alternative solution for a real-time GPRS-based monitoring has been described. It consists at using a direct TCP socket communication channel instead of a WS architecture. The system, therefore, can monitor a larger number of vehicles transmitting data within an interval of a length of a few seconds, instead of 5 minutes. The most important result achieved is the roughly 1:5 second as real-time latency difference. The Data

Collection Middleware can be enhanced for better performance, reliability and modularity. It is possible to extend and add new features as the User Datagram Protocol (UDP) support. As mentioned, the reason behind the implementation of this middleware is a result of our needs of monitoring dynamically evolving fleet of vehicles, real and virtual ones injected by the simulation system. Further issues raise. Indeed, data storage, parsing and interpretation are one of the major computer scientists' concern, in addition to data quality such GPS accuracy as highlighted by (Hong et al., 2013). Therefore, our future works will have to deal thoroughly with these issues. Finally, the objectives of the present work have been fully achieved. On one hand, the wrap of the message presents almost 1% of the message size. On the other hand, the system is efficient and scalable enough to manage real-time data collection. The scientific contribution of the middleware in transport engineering is undoubtedly clear: flexible and adaptable for any real-time data collection system, in particular for transportation industry whether for freight shipment or all kind of traffic and mode of transportation.

Table 4-1 Comparison of the two approaches.

	Web Service Based Architecture	Direct TCP transmission
Technology	C# / IIS / SQLServer	C++ / Boost / OTL / SQLServer
Encapsulation	High	Low
Server	Heavier + High Level + Good Performance + High CPU/Memory usage	Lightweight + Low Level + Better performance + Low CPU/Memory usage
Performance	High	Low
Interoperability	Costly (HTTP + XML + Message)	Cheaper (only Message)
Cost	≈13 sec real-time delay (50 simultaneous messages + 4 sec delay in transmission)	≈1.5 sec real-time delay (5000 simultaneous messages + ≈5 sec delay in transmission)

Chapter 5. Fuzzy Risk Assessment & Fuzzy Ranking

Risk assessment and uncertainty quantification are the main concern of this chapter. The solution proposed is based on Fuzzy sets theory subject of considerable literature. It was proven to be very practical at modelling uncertainty and vagueness in risk factors. Decision making for selection among fuzzy solutions is also addressed thoroughly hereinafter.

I. Chapter introduction

Dangerous goods logistics is a complex industrial activity of which the shipment is a substantial component, flawed with uncertainty and risks covering multiple dimensions: Safety, Planning and scheduling, Policies and regulations, Operation and freight mobility, Network infrastructure and Environment. The thesis statement consider solely risk related to safety shipment of dangerous goods.

When a critical event happens, caused directly or indirectly by human error, and implying hazardous material, the consequences often cannot be contained and lowered (Tomasoni, 2012). For this reason, it is important to settle preventive measure to mitigate either the probability of occurrence or magnitude of the consequences. These preventive measures are decided upon safety risk analysis, which involves defining, quantitatively or qualitatively, the consequence and likelihood of a risk hazardous material release or explosion. Such a framework should accurately represents the risk, and catch its dynamic aspect.

When tackling risk analysis related to transport of dangerous goods, it has been often approached from operational research perspective, and less from probability and statistics-based modelling perspective (Clark et al., 2009; Raemdonck et al., 2013). In fact, studying and assessing potential occurrences of incidents, then minimizing risk was mainly the way literature dealt with this issue. Whereas, historical data can be valuable in the computation of a global risk map.

The solution proposed in this thesis work, as discussed through Chapter 6, which uses a two stages multiobjective A-star search. The pre-computation stage computes the minimal travel time all over the network, without overestimating the travel time at any moment. At this stage, a probabilistic risk assessment is necessary to deduce the risk based on historical data estimation. The latter will allow us to determine frequencies and probabilities of events all over the studied network. Thus, we will end up with a preliminary risk map that in a way never overestimate risk.

Then on the real-time stage, search for the optimal path uses a heuristic function (computed on the basis of the pre-computed travel time) that direct search towards the goal. The algorithm should captures the trade-off between the time-dependent risk and travel time, among the optimal found solutions.

The first challenge is the re-assessment of the pre-computed risk at every unit of time, by taking into consideration changing factors. To achieve that, we should first define the dynamic factors, then quantifying uncertainty of each factor, and finally propose a suitable formula for risk estimation.

As the uncertainty modelling is based on Zadeh's fuzzy sets theory, which will levy the complexity and fuzziness of real world systems. The second challenge is, on one hand, to propose an appropriate fuzzy model for risk assessment. On the other hand, is decision making when dealing with selection between possible fuzzy solutions.

In this chapter, I will address all these challenges, which represent a significant scientific contribution in the area of risk assessment.

II. Risk Assessment

II.1. Risk definition

Risk is defined as a measure of frequency and severity of harm due to a hazard. The hazard in our context is the presence of dangerous goods having toxic, explosive, and/or flammable characteristics with the potential to cause harm to humans (and property or the environment if a broader context is considered). In the context of public safety, risk is commonly characterized by fatalities (and injury) to members of the public.

However, multiple factors make of DG risk assessment a complex task to achieve, such:

- The diversity of hazards: the substances transported are multiple and can be flammable, toxic, explosive, corrosive or radioactive materials;
- Diversity of accident sites: highways, county roads, local roads, in or out of town (75% of road accidents take place in open country), facilities, pipelines, etc.
- Diversity of causes: failure mode of transport, containment, human error, etc.

Several methods exists for risk assessment (as discussed through Chapter 2) and each one of them has a cost, effectiveness and a degree of appropriateness for the system under study. They tackle the issue from different perspectives, and frequently adopting quantitative approaches. Thus, multiple vehicles carrying dangerous goods can be seen as a risk source composed of moving point of risks, taking into consideration a variable population density along a network segment.

Authors in (Leonelli et al., 1999) indicate that risk assessment is typically structured as a process resulting from the interaction among (a) the transportation network, (b) the vehicles or travelling risk source and (c) the impact area. In (Zhang et al., 2000), authors define the risk as the product of the probability of an undesirable consequence and the population affected. The author structure the evaluation procedure into three stages: (a) determining the probability of an undesirable event, (b) estimating the level of potential exposure, given the nature of the event, and (c) estimating the magnitude of consequences (fatalities, injuries and property damages) given the level of exposure.

Authors in (Frank et al., 2000) discuss several strategies for DGT risk mitigation. Authors states that, first of all, a careful choice of itineraries can reduce the probability of an accident. Well, choosing a route passing through less populated areas, means fewer people exposed to hazard. Then, vehicle and container design, and driver training could be enhanced for safer shipment of dangerous goods.

Author in (Serafini, 2006) highlights that the travelling of DG has raised the problem of determining vehicle routes minimizing not only the length (related to cost and/or time), but also the risk of dangerous goods accidents. Indeed, two quantities are typically involved in the assessment of the risk associated to a certain route. First, the probability of accident occurrence on a certain route link, and, second, the cost incurred in case of accident on that link. Following (Akgun et al., 2007) highlight the weather conditions as a dynamic factor that affect the accident probabilities, as well as the costs/travel time involved.

In this proposed method for the estimation of DGT-related risk, we consider, on one hand, the classification of hazardous substances into four types based on the following scenarios:

- Puddle fire for flammable liquids;
- Evaporating puddle for toxic liquids;
- Toxic cloud for toxic gasses;
- BLEVE (‘boiling liquid expanding vapor explosion’) for flammable (liquefied) gasses.

On the other hand, the risk map of accidents involving hazmat can be segregated to two disjoint level, the static and dynamic one:

The static risk map is estimated during the pre-computation stage and it represents the general probability calculation based on national/international accident data of transport of hazardous substances

While over the real-time stage, the dynamic risk map represents the time-dependent probability of hazmat accident that is calculated by taking into account, for instance, the population density, transported HazMat and the vehicle speed.

These two components are connected through the following relationship:

$$P(t) = P_s \times P_d(t)$$

With:

$P(t)$: Estimated probability of occurrence of a catastrophic accident at instant t.

P_s: Static probability;

$P_d(t)$: Dynamic probability.

The dynamic parameter ($P_d(t)$) is a coefficient which reflects the location specific circumstances at a specific time instant that may lead to an accident with any freight. The very first step of the proposed approach is to divide the trajectory into different segments with a fixed length. Next, a static risk map is set up, based on the general probability of occurrence of a catastrophic accident as shown above, and the consequences of such an accident. If the local infrastructure parameters of the segments are known, a local risk map can be developed in more detail. This methodology can be applied analogously for the different transport modes, always with the assumption that risk equals 'probability times consequence'. The result of these calculations can then be visualized on a geographical map.

II.2. Risk factors

Several factors exist and can be considered in risk assessment. Each of these factors had specific significant and role to play in risk estimation. Some of them are attributes of risk amplification and mitigation; others are hazard attributes, while vulnerabilities attributes represent the ones that affect directly the population.

The Table 5-1 lists all the considered factors for risk assessment. Many of these factors are time-dependent(t), such population. It can be estimated based on the geographic positions of SIM cards that are determined by the location of the mobile phone tower through which each SIM card connects. The authors in (Bengtsson et al., 2011) used position data of SIM cards from the largest mobile phone company in Haiti (Digicel) to estimate the magnitude and trends of population movements following the Haiti 2010 earthquake and cholera outbreak. They used 3.2 persons per included SIM card as ratio to extrapolate from the number of moving SIM cards to the number of moving persons.

Most of these factors have some uncertainty and vagueness (~), such time-dependent population density estimation, weather condition, driver experience and impact radius of each HazMat that is an exact information.

Table 5-1 Considered factors in risk assessment for safe shipment of dangerous goods, (t) for time-dependent, (~) for uncertainty.

Type	Factors	Details
Amplification and Mitigation	Road Curve (~)	Straight Road (radius ∞)
		Curved Road (radius > 200 m);
		Tightly Curved Road (radius < 200 m)
	Road Slope (~)	Plane Road (gradient 0%);
		Slope Road (gradient < 5%);
		Steep Slope Road (gradient > 5%);
		Downhill Road (gradient < 5%);
		Steep Downhill Road (gradient < 5%);
	Road Lanes (t)	Two lanes for each carriageway
		Two lanes and emergency lane for each carriageway
		Three lanes and emergency lane for each carriageway
	Road Type	Normal
		Tunnel
		Bridge
	Weather Condition	Fine
		Rain/Fog

	(t,~)	Snow/Ice
	Traffic Condition (t,~)	Low intensity (< 500 vehicles/h)
		Medium intensity + heavy vehicles (<1250 vehicles/h + < 125 Lorries/d)
		High intensity (> 1250 vehicles/h)
		High intensity + heavy vehicles (> 1250 vehicles/h + > 250 Lorries/d)
	Speed (t,~)	Low (Avg-10km/h)
		Medium (Avg)
		High (Avg+10km/h)
		Very high (Avg+15km/h)
	Driver Experience (~)	Experienced
		Good
		Novice
	Truck Configuration	Passenger
		Single Unit
		Single Trailer
		Double Trailer
Hazard	Basic Accident Frequency (~)	Can be obtained from historical data on traffic accident for each road segment.
	HazMat Quantity (t)	The quantity of Hazardous Material being transported. Greater the quantity is, higher the risk will be.
	Impact Radius (~)	The bigger the impact radius is, the greater the damage magnitude will be. This factor depends on the type and condition of the transported HazMat.

Vulnerabilities	Distance	Represents the distance between the position of the HazMat carrier and the studied target.
	Population density (t,~)	The nearby population density at distance of the studied target.

II.3. Risk formulation

According to (Carotenuto et al, 2007), the unit-length segment risk σ_x of traveling on a unit-length segment x for the population of the regional area is

$$\sigma_x = P_x \sum_{y \in S} pop_y \cdot e^{-\alpha[d(x,y)]^2}$$

Which is the sum for all risk on each target segment (Fig. 5-1). With P_x is the probability of an accident on the unit-length segment x. The definition of the *link risk* r_h on link h

$$r_h = \sum_{s=1}^{q_h} \sigma_{h_s}$$

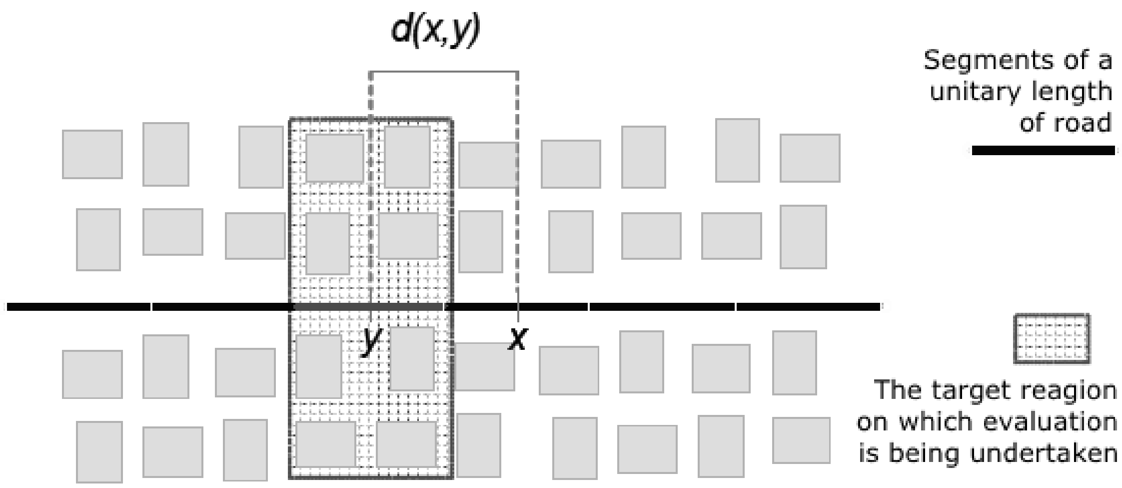

Fig. 5-1 Area targeted and its distance with HazMat carrier position

According to (Fabiano et al, 2005), the frequency of an accident on the i_{th} road stretch can be expressed by the following

$$f_i = \gamma_i L_i n_i$$

Where γ_i is the expected frequency on i_{th} road stretch (accident km^{-1} per vehicle)

$$\gamma_i = \gamma_0 \sum_{j=1}^{k} h_j$$

L_i the road length (km), n_i is the vehicle number (vehicle), γ_0 the basic frequency (accident km^{-1} per vehicle) and h_j is the local amplification/mitigating parameters. Authors in (Fabiano et al, 2005) suggest these amplification/mitigation parameters:

- h_1& h_2: Geometric characteristics of the road;
- h_3: Roadway type;
- h_4: Weather condition;
- h_5: Type and intensity of the traffic;
- h_6: Presence of bridge or tunnel;

(Tomasoni, 2010) introduced a diagram that combines the (Fabiano et al, 2005)'s definition of frequency of accidents, with risk definition of the population involved proposed by (Carotenuto et al, 2007), so to obtain a complete definition of road segment risk, as shown on Fig. 5-2.

As stated earlier, (Fabiano et al, 2005) suggest an original approach to estimate accident frequency on the i-esimo stretch f_i. The definition can be improved by considering further local amplification/mitigation attributes such: speed and driver experience, etc.

(Erkut & Ingolfsson, 2005) propose a definition for risk assessment regarding impact on local population. Thus, the risk value on the i-esimo stretch r_i is equal to the probability of a hazmat release accident on the i-esimo strech p_i times the measure of the consequence on local population of a release accident c_i.

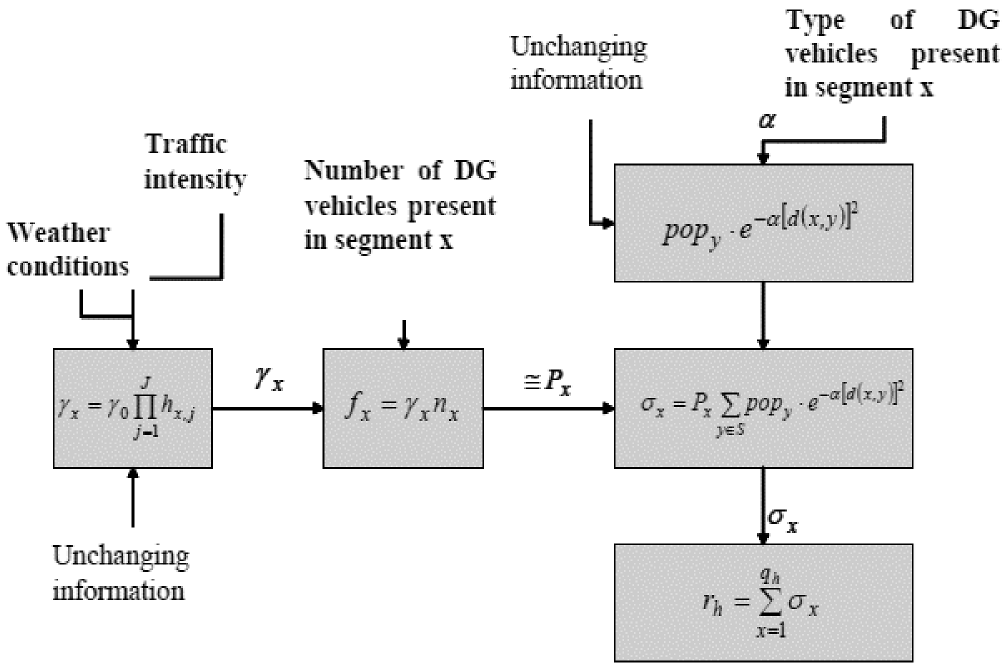

Fig. 5-2 (Tomasoni, 2010)'s summary diagram of the definition of risk in the transport of dangerous goods.

(Tomasoni, 2010) consider the (Fabiano et al, 2005)'s frequency of accident equivalent to probability of catastrophic accident in (Carotenuto et al, 2007). However, this not fully accurate, since (Raemdonck et al., 2013) propose definition of the general probability of the occurrence of a catastrophic accident with hazmat transport p_i, as the multiplication of the number of tonnes of one type of hazardous substance being transported on a given route q_i, with the frequency of hazmat accident per tkm f_i.

An issue arise, how to define the risk R_v that represents a link v ? Shall we consider the worst-case scenario among the set of unit-length segment risk $\{r_1, r_2 \cdots, r_3\}$, the mean of the set, the mode or other.

The authors in (Carotenuto et al, 2007) suggest the aggregation of all unit-length segment risk. This is done simply by summation.

Indeed, to compute the risk R_v we should multiply the probability p_i of incident in a segment i with the probability of no incident in the previous segments of that link. Since incident probabilities are very small (on the order of one-in-a-million-miles), (Carotenuto et al, 2007) and (Erkut & Ingolfsson,

2005) assume that the probability of no incident is very close to 1, and hence approximate R_v as the sum of the unit-length segment risks of the segments of link v. The following figure (Fig. 5-3) summarize the suggested mathematical formulation for estimation of risk related to dangerous goods transport.

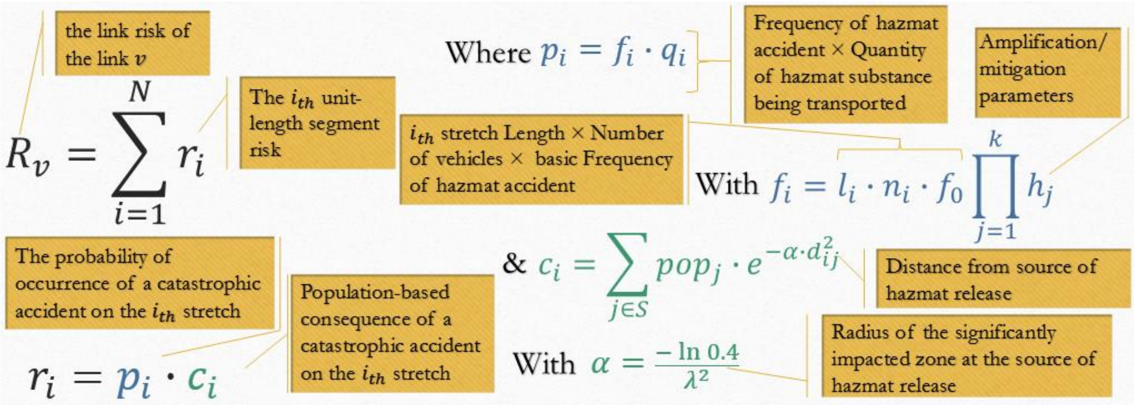

Fig. 5-3 Mathematical formulation of the risk assessment

III. Fuzzy theory for the management of uncertainty

III.1. Fuzzy modelling

Several risk factors are fraught with uncertainty such population density and weather condition (see Table 5-1). Using Zadeh's fuzzy set theory as a mean for uncertainty modelling has been proven very practical and efficient, especially when dealing with real-time risk computation. We introduce in Fig. 5-4 the process for Fuzzification of uncertainty factors. Once the input attributes are modelled as fuzzy quantities (in this work as Triangular Fuzzy Numbers), fuzzy arithmetic operators are used for computation. Indeed, one of the most useful principles, in fuzzy set theory is the extension principle, which provides a general method for extending non-fuzzy mathematical concepts to a fuzzy domain, and then, for instance, two fuzzy numbers can be summed or multiplied (Quelch and Cameron, 1994). This will be addressed in detail thought the last section. Last but not least, all the computed unitary fuzzy risk is aggregated then classified using the ranking decision-making process (discussed in the last section), or Deffuzified.

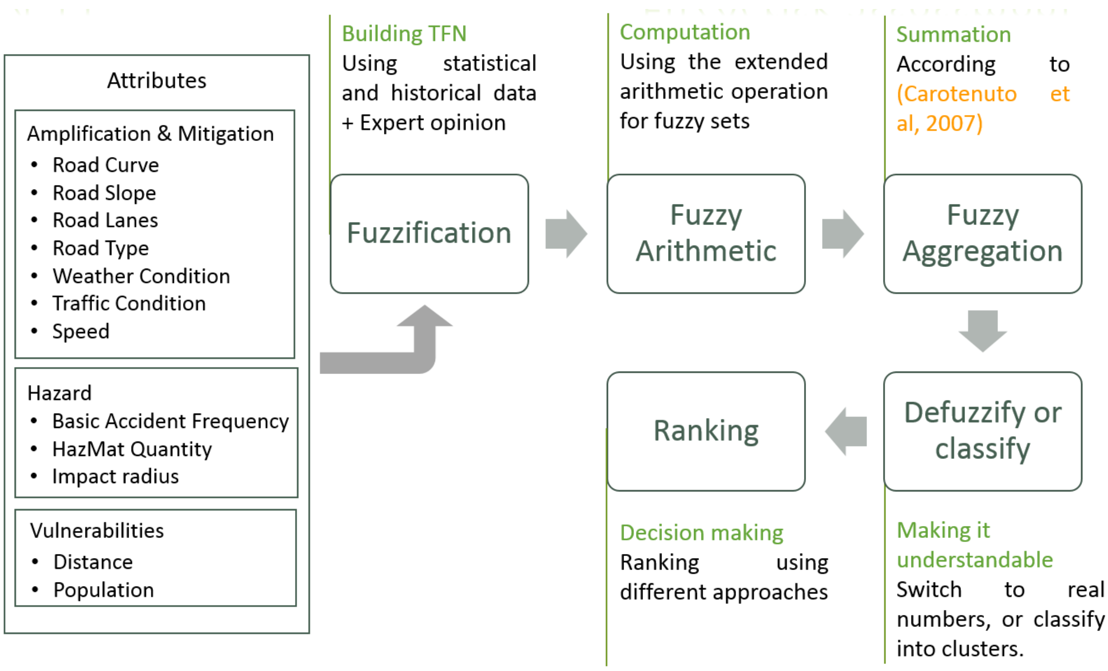

Fig. 5-4 Layout of the fuzzy risk analysis process

The Fig. 5-5 describes the interaction between all elements of the fuzzy risk computation process. The amplification/mitigation input attributes contribute to estimation of the frequency of HazMat accident. When the latter is multiplied by the HazMat quantity, we get the probability of accident leading to HazMat release. On the other side, the damage magnitude is obtained by considering the impact radius and the distance from the source. Once multiplied by the population density we obtain the estimated consequence on the local population. We get the unit-length segment risk with the probability times the consequences.

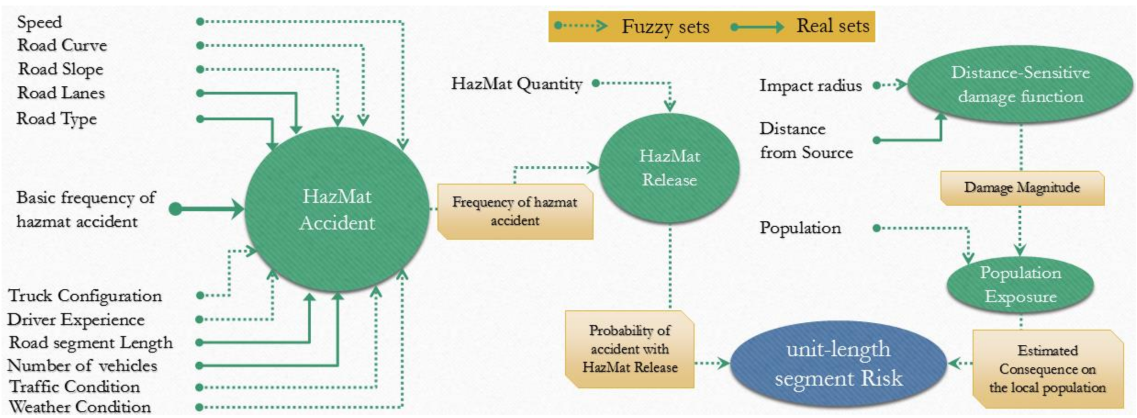

Fig. 5-5 Overview of the summary diagram of the proposed fuzzy risk computation

III.2. Fuzzification

One of the main issues in fuzzy theory is the Fuzzification process. In the literature, the Fuzzification is based on either expert opinions or historical data. Then fuzzy sets are used to portray this information the more realistically possible. In this work we used triangular and trapezoidal fuzzy numbers as straightforward and practical fuzzy sets.

Triangular Fuzzy Numbers (TFN) are represented as $\langle k, \alpha, \beta \rangle$. Its mathematical definition is:

Definition 6-1. *A TFN denoted by Λ =⟨ k,α,β ⟩ or (Λ^-,Λ^0,Λ^+) , has the membership function*

$$\Lambda(\mathrm{x}) = \begin{cases} 0 & for \quad x \leq \Lambda^{-} \\ 1 - \frac{k-x}{\alpha} & for \quad \Lambda^{-} < \mathrm{x} < \Lambda^{0} \\ 1 & for \quad \mathrm{x} = \Lambda^{0} \\ 1 - \frac{x-k}{\beta} & for \quad \Lambda^{0} < \mathrm{x} < \Lambda^{+} \\ 0 & for \quad \mathrm{x} \geq \Lambda^{+} \end{cases} \tag{1}$$

with $\Lambda^0 = k$, $\Lambda^- = k - \alpha$ and $\Lambda^+ = k + \beta$. k is the kernel value of the TFN with a membership value equal to 1. α, β are, respectively, the left and right hand spreads of TFN Λ. The support is the crisp set that contains all the elements of X that have non-zero membership grades in Λ, such that $supp(\Lambda) = \{x \mid \Lambda(x) > 0\}$.

Fig. 5-6 shows a TFN according to the membership function in (1). In addition to different shapes of fuzzy sets, (Puri, 1986) introduced the Fuzzy Random Variables, which covers random experiments whose outcomes are neither numbers or vectors in $\mathbb{R}$. As for fuzzy numbers, the statistical aspect of Fuzzy Random Variables lacks the arithmetic linearity.

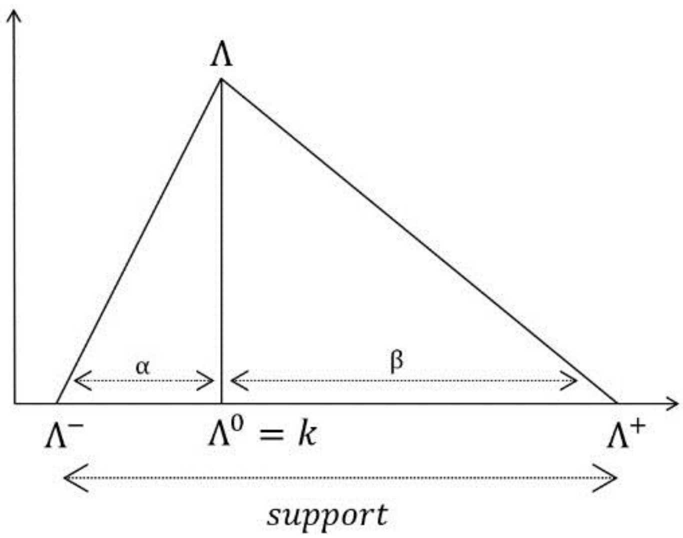

Fig. 5-6 TFN representation according to the membership function in

In the following, we fuzzify the attributes with uncertainty characteristics.

III.2.1. Speed

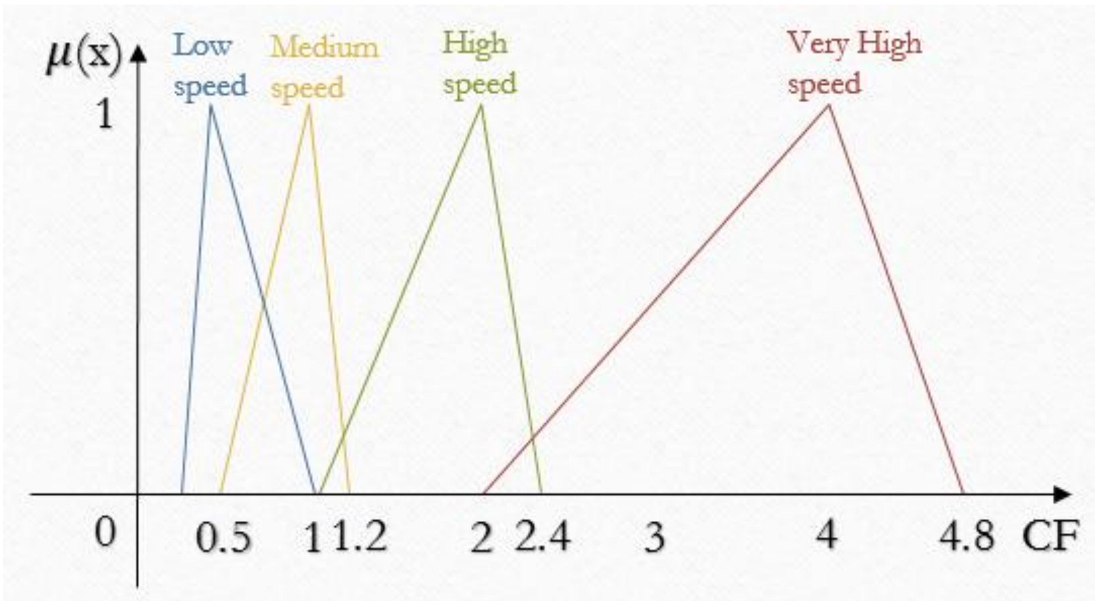

Fig. 5-7 Fuzzy correlated factor of the vehicle speed

The shape of the membership functions are based on the correlation analysis of speed/accident risk at the (European Road Safety Observatory), where Avg is the average speed on a specific road segment. The result of the correlation shows that the accident risk almost double when speed increase to $Avg + 10km/h$, and $Avg + 15km/h$, then grow exponentially for a higher speed.

III.2.2. Driver experience

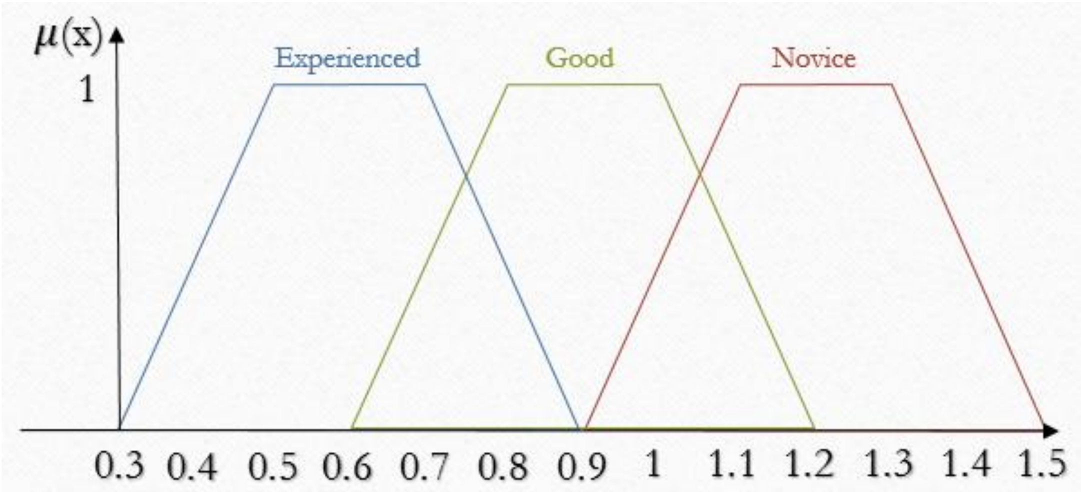

Fig. 5-8 Fuzzy correlated factor of the driver experience

Authors in (Qiao et al., 2009) suggest a fuzzy set description of driver experience, which captures the essence of the gradations between experience ranges. Three fuzzy sets represent the different experience groups, Novice, Good, and Experienced. Each membership function in the figure is represented by a TFN that indicates the assignment of a degree of membership in a fuzzy set to each variable representing degrees of impact of driver experience on accident frequency.

III.2.3. Road curve

The Fuzzification is based on (Fabiano et al., 2005) work, where correlated factor are suggested to be equal respectively to, 1.0, 1.3 and 2.2. A curved road can have a radius, for instance, of 400m or 250m, which will have a slight impact on the accident rate estimation. A trapezoidal fuzzy number catch perfectly this fuzziness.

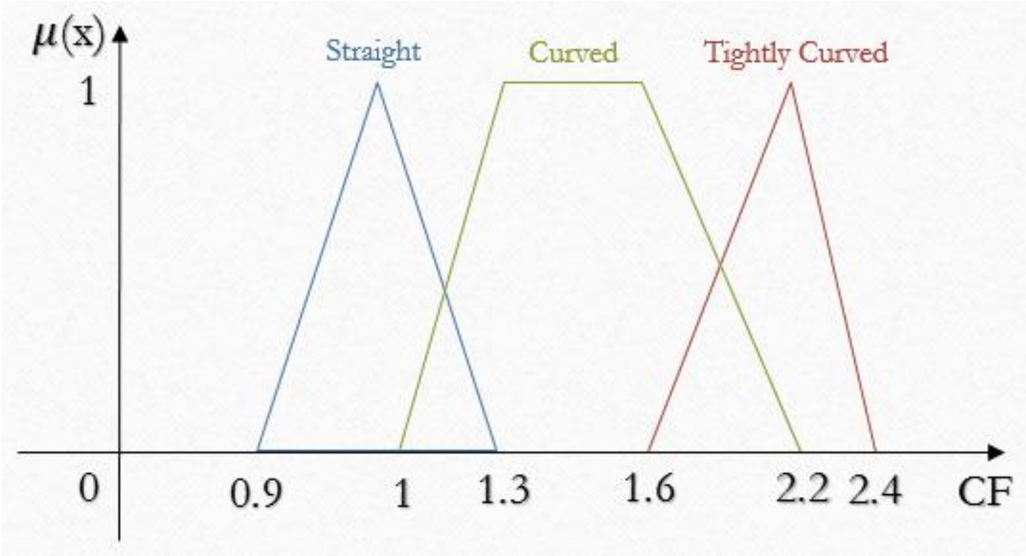

Fig. 5-9 Fuzzy values of the correlated factor of the road curve

III.2.4. Road slope

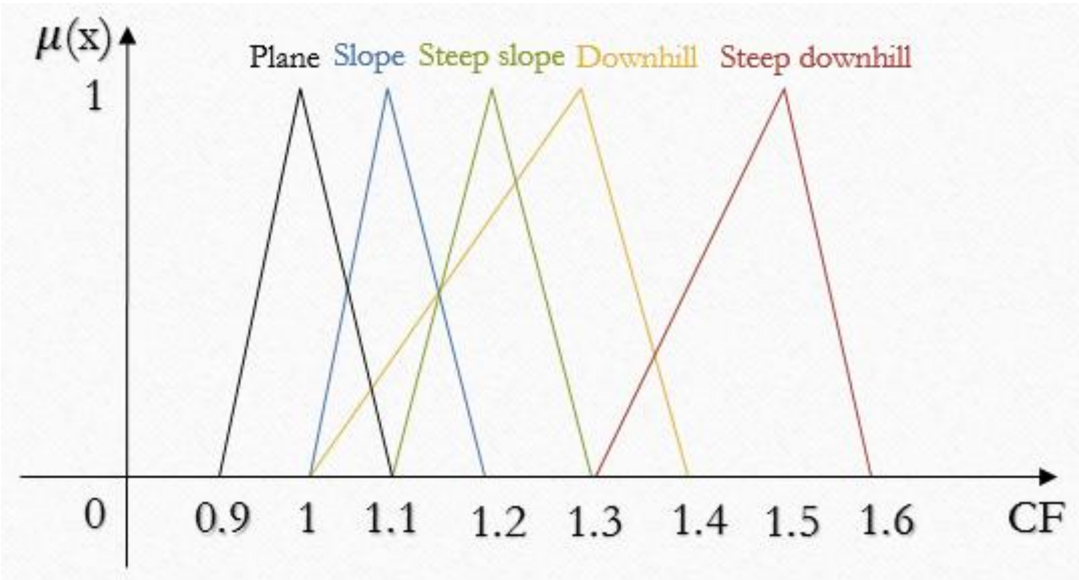

Fig. 5-10 Fuzzy correlated factor of the road slope

The Fuzzification is based on (Fabiano et al., 2005) work, where correlated factor are suggested to be equal respectively to, 1.0, 1.1, 1.2, 1.3 and 1.5. A downhill road of 1% gradient can be also considered as a plane road, and share with a slope road it correlated factor.

III.2.5. Traffic condition

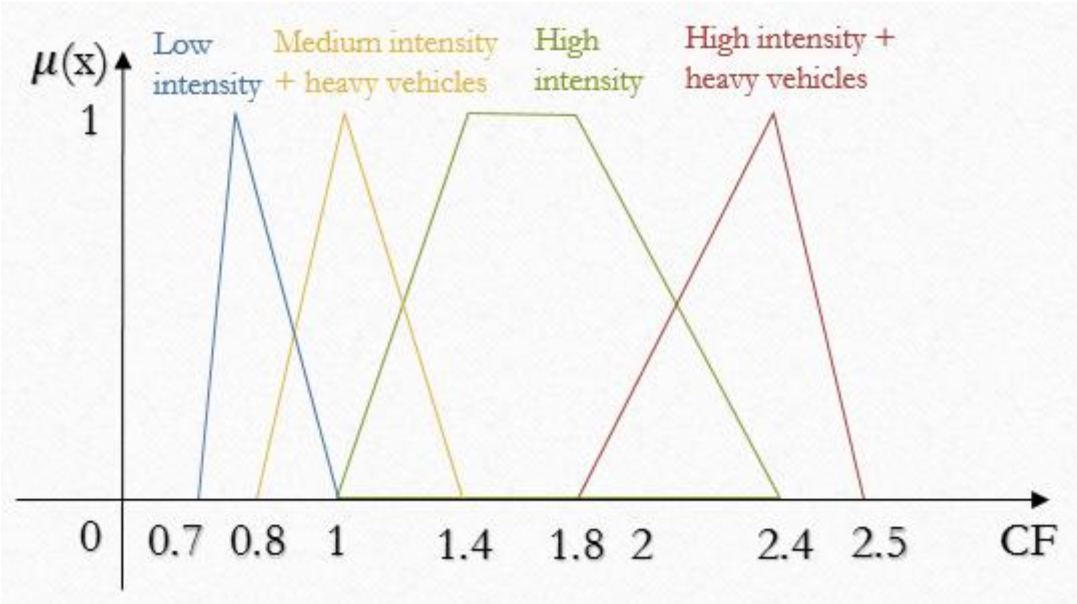

Fig. 5-11 Fuzzy correlated factor of the traffic condition

The Fuzzification is based on (Fabiano et al., 2005) work, where correlated factor are suggested to be equal respectively to, 0.8, 1.0, 1.4 and 2.4. For instance, High intensity with 240 Lorries per day can have the same impact factor as high intensity with heavy traffic.

III.2.6. Weather condition

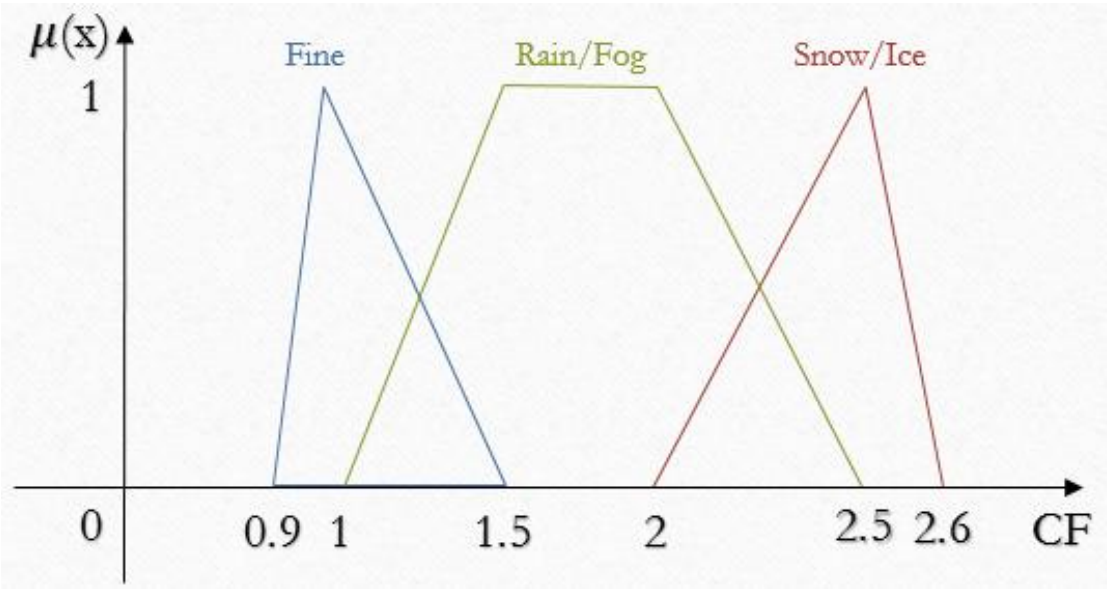

Fig. 5-12 Fuzzy correlated factor of the weather condition

The Fuzzification is based on (Fabiano et al., 2005) work, where correlated factor are suggested to be equal respectively to, 1, 1.5 and 2.5. An extremely rainy and foggy day can be as dangerous as a snowy day.

III.2.7. Truck configuration

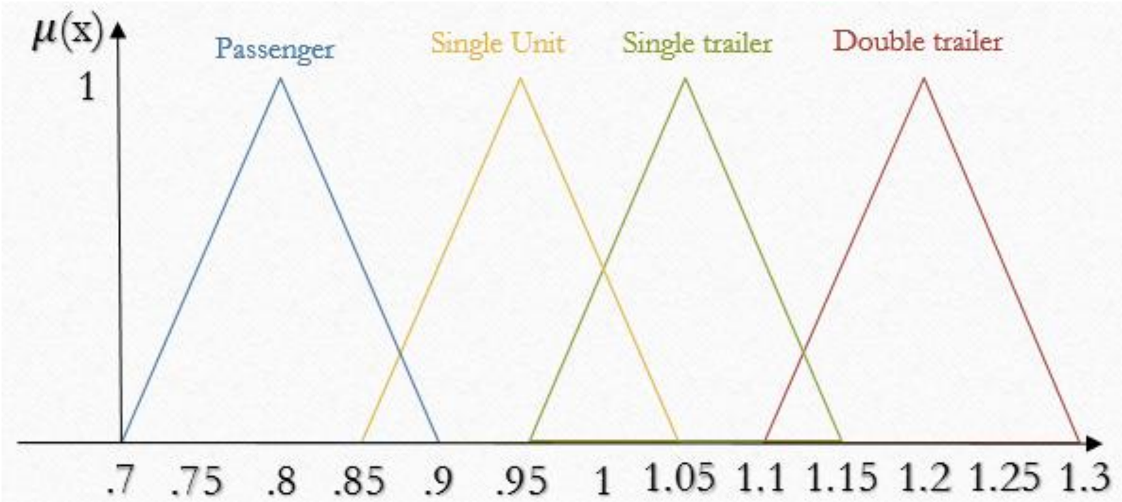

Fig. 5-13 Fuzzy correlated factor of the truck configuration

(Harwood & Russell, 1990) studied the effects of truck configuration on accident frequency. Their study shows that accident frequency can increase by almost 50% if the truck configuration is changed significantly. Therefore, (Qiao et al., 2009) define the correlated factor by a range from 0.8 to 1.2, which results in a median of 1 and a maximum of a 50% increase (from 0.8 to 1.2).

III.2.8. Population density

In the context of this work, we fuzzify the estimated population number, by defining the corresponding triangular fuzzy number. The TFN highlights the uncertainty around the estimated number of population by considering two values η and θ defining respectively, the minimum and maximum possible of the population number within the i-esimo stretch.

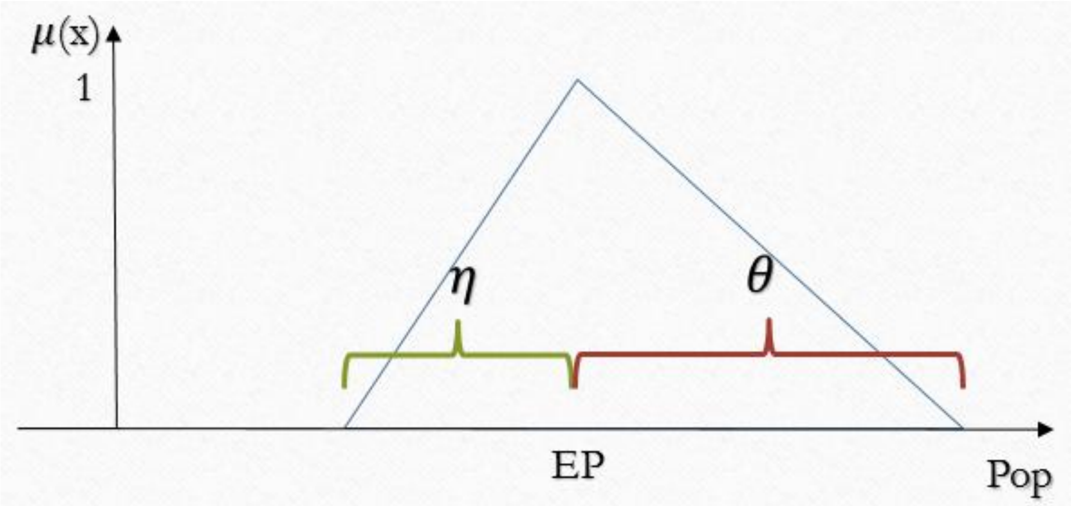

Fig. 5-14 Fuzzification of the estimated population (EP)

III.2.9. Damage magnitude

No one can disagree on the uncertainty around the impact distance, since too many variables are affecting the result. Having said that, let us consider the estimated, minimum and maximum impact distance of specific hazardous substance: λ, λ_{min}, λ_{max}. Knowing that $\alpha = \frac{-\ln 0.4}{\lambda^2}$, the bigger the impact distance the greater the damage magnitude.

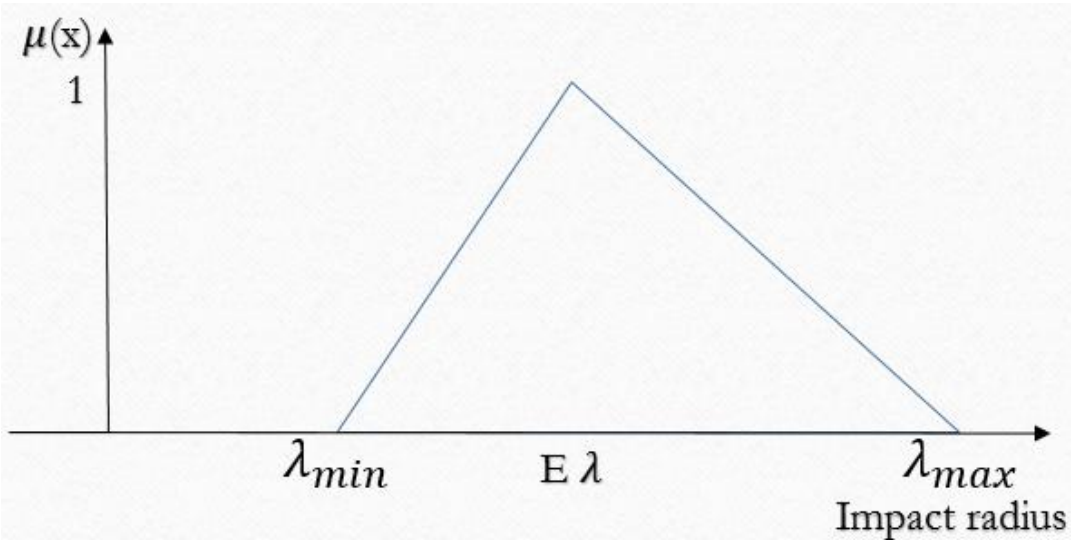

Fig. 5-15 Fuzzification of the estimated impact radius λ

IV. Ranking of fuzzy quantities

"In many applications of the fuzzy set theory to decision making, we are faced with the problem of selecting one from a collection of possible solutions, and in general we want to know which is the best one" (Detynieck, 2000). The process of selection may require ordering, and it is still a controversial issue. Indeed, it is not as simple as ordering crisp sets (e.g. $\mathbb{R}$), due to the linearity of the sets. Thus $<$, $\leq$ and $=$ cannot be directly extended to fuzzy sets, (Zadeh, 1965). Therefore, several propositions emerged whilst addressing this issue. (Yao, 2000) proposed a signed distance-based ranking, which allowed the distance evaluation between two fuzzy numbers. (Yager, 1981) used a fuzzy number weighted mean value for comparison. (Wang, 2006) suggested a centroid-based distance method. (Lee, 1999) introduced the user viewpoint-based evaluation of fuzzy sets as a pre-step to ordering using a satisfaction function. Further studies have addressed this issue as in (Chou, 2011); (Ezzati, 2012); Chen (1985); (Abbasbandy, 2009); (Chu, 2002); (Wang, 2008); (Cheng, 1998); (Choobineh, 1993); (Baldwin, 1979).

The reason stems from our need to achieve a fast and reliable algorithm when processing large amounts of fuzzy data in the context of real-time decision-making on dangerous goods transport (Boulmakoul, 2006, 2004, 2002); (Laarabi, 2013); (Roncoli, 2012). We propose a ranking method that classifies the various topological relationship of the membership functions of two fuzzy sets, into a group of categories identified by a pattern. Once classified, we can pre-compute the ranking outcomes to each category. Then deduce the results by only looking at the respective pattern. To cut a long story short, we will apply it only on Triangular Fuzzy Numbers (TFN), i.e. the fuzzy set with triangular shape, allowing a straightforward application of the approach.

Let us introduce first the mainstay works, the basis of the proposed ranking approach: The one that provides the mathematical foundations of operations on fuzzy numbers is (Dubois, 1978)'s work, which extends the usual real-numbers algebraic operations to fuzzy sets by the use of the Fuzzification principles. (Chiu, 2002) suggests an easy and intuitive technique for computing the fuzzy lattice operators MIN and MAX; by combining it with (Bordogna, 1996) and (Beg, 2011) works on the concept of fuzzy inclusion, we can deduce easily the degree of inclusion then the ranking outcomes. Finally yet importantly, (Boukezzoula, 2007) classifies the Triangular Fuzzy

Numbers by their mutual topological relationship, allowing us to suggest a pattern-based ranking.

IV.1. Methodology

IV.1.1. Background

a. Fuzzy arithmetic

Definition 6-2. Fuzzy Addition, Let $A = \langle k_A, \alpha_A, \beta_B \rangle$ and $B = \langle k_B, \alpha_B, \beta_B \rangle$ be two TFNs. (Dubois, 1978) introduces a simplified addition for triangular fuzzy number as follows:

$$A + B = \langle k_A + k_B, \alpha_A + \alpha_B, \beta_A + \beta_B \rangle$$

And generally, for all kind of fuzzy numbers, (Zadeh, 1965) defined the addition operator based on real number lattice min:

$$(A + B)(z) = \sup_{z=x+y} min[A(x), B(y)], \qquad \forall z \in \mathbb{R}$$

Definition 6-3. *Fuzzy Multiplication,* Let $A = \langle k_A, \alpha_A, \beta_B \rangle$ be a TFN, and λ be a scalar:

$$\begin{cases} \lambda . A = \langle \lambda . k_A, \lambda . \alpha_A, \lambda . \beta_A \rangle & for\ \lambda \geq 0 \\ \lambda . A = \langle \lambda . k_A, -\lambda . \beta_A, -\lambda . \alpha_A \rangle & for\ \lambda < 0 \end{cases}$$

In particular, $-A = \langle -k_A, \beta_A, \alpha_A \rangle$

b. MIN and MAX, the fuzzy lattices

As well known, the real numbers set is linearly ordered, but it does not extend to fuzzy numbers. (klir, 1995) shows that fuzzy numbers can be partially ordered in a natural way, by extending the real numbers lattice operations min and max to corresponding MIN and MAX fuzzy operations. The lattice operators definition is based on any two TFNs A and B such that

$$\begin{cases} MIN(A, B)(z) = \sup\limits_{z=\min(x,y)} min[A(x), B(y)] \\ MAX(A, B)(z) = \sup\limits_{z=\max(x,y)} min[A(x), B(y)] \end{cases} \qquad \forall x, y, z \in \mathbb{R} \qquad (2)$$

In addition to the fact that these fuzzy lattice operators are proven to be also fuzzy numbers, we are considering them as an important pillar of the proposed approach. We will detail later the role of the MIN operator at simplifying substantially the measurement of the inclusion index in most situations. Following the previous definition, (Chiu, 2002) introduced a Theorem pointing out the simplicity of the computation of MIN and MAX as follows,

Definition 6-4. For any two TFNs A and B, defined on the universal set $\mathbb{R}$, with continuous membership function and $(A \cap B) \neq \emptyset$, let $x_m (\in \mathbb{R})$ be the point such that $(A \cap B)(x_m) \geq (A \cap B)(x)\ \forall x \in R\ and\ A(x_m) = B(x_m)$, moreover, x_m is between two mean values of A and B (if the number of x_m is not unique, any one point of those x_m is suitable). Then the operation MIN can be implemented as

$$\mathrm{MIN(A,B)(z)} = \begin{cases} (A \cup B)(z), & as \quad z < x_m \\ (A \cap B)(z), & as \quad \mathrm{z \geq x_m} \end{cases} \tag{3}$$

where $z \in Z = R$*, and* $\cup$ *and* $\cap$ *denote the standard fuzzy intersection and union, respectively.*

The theorem given above provides a simple procedure for the implementation of MIN operator. As previously emphasized, the MIN operator is the key element for guessing and sometimes measuring the index of inclusion that in turn helps on the classification of TFNs topological layout.

IV.1.2. Inclusion Index

a. Reminding the absolute and relative cardinality

For a discrete (resp. continuous) and finite set $A, A \subseteq X$ the absolute cardinality can be formulated as

$$Card(A) = |A| = \sum_{x \in X} \mu_A(x)$$
$$(resp. \ = \int_{x \in X} \mu_A(x)dx) \tag{4}$$

The relative cardinality $Card_X(A)$ of the set A with respect to a finite universal set X is defined as

$$Card_X(A) = \frac{Card(A)}{Card(X)} = \frac{\sum_{x\in X}\mu_A(x)}{\sum_{x\in X}1} \\ (resp. \;\; = \frac{\int_{x\in X}\mu_A(x)dx}{\int_{x\in X}dx}) \tag{5}$$

b. Defining the index of inclusion

It is a quantitative indicator expressing the Degree of Inclusion, whose definition consists in considering that $E \subseteq F \Leftrightarrow (Card(E \cap F) = Card(E))$ with E and F are fuzzy sets, as introduced by (Dubois, 1978) and (Bordogna, 1996). Then the degree $\partial(E \subseteq F)$ that is $Card_E(E \subseteq F)$ according to (4), is given by:

$$\partial(E \subseteq F) = \frac{\sum|E \cap F|}{\sum|E|} = \frac{\sum_{x\in X} T(\mu_E(x).\mu_F(x))}{\sum_{x\in X}\mu_E(x)} \\ = \frac{\int|E \cap F|}{\int|E|} = \frac{\int_X T(\mu_E(x).\mu_F(x))}{\int_X \mu_E(x)} \tag{6}$$

where T is a triangular norm and $|\cdot|$ denote the standard fuzzy cardinal operator $Card$; μ_E and μ_F are respectively the membership function of E and F. Two cases may be distinguished depending on the role assumed by the degrees in F. If the degrees $\mu_F(x)$ act as thresholds on the values $\mu_E(x)$, the choice of the norm T in (6) is the minimum. Alternatively, if $\mu_F(x)$ is an importance assigned to the element x, the norm T is the product, and (6) becomes a weighted average.

(Klir, 1995) distinguishes between comparable and non-comparable. A comparable fuzzy sets satisfy the condition $MIN(A,B) \in \{A,B\}$. Hence it is not necessary any more to measure the degree of inclusion since $MIN(A,B) \in \{A,B\}$. Yet when $MIN(A,B) \notin \{A,B\}$ the corresponding fuzzy sets are considered as non-comparable.

Intuitively, if the minimum of fuzzy sets A and B is neither A nor B, then the minimum will be one of the sets A and B where the fuzzy set $MIN(A,B)$ is more strongly included. Thus the Inclusion Index will be used for this purpose.

In fact, (Koczy, 1993) introduced the concept of similarity between two fuzzy terms, in order to reduce the number of rules in a fuzzy knowledge base. The similarity was measured with the index "degree of overlapping"; and from their distance, their closeness is derived.

The following subsection includes our proposal for a new ranking operator of Triangular Fuzzy Numbers.

IV.2. The proposed approach for TFN ranking

IV.2.1. Proposed operators

We introduce hereinafter the definition of the proposed ranking operators $\prec$, $\succ$ and $\simeq$:

Definition 6-5. For every fuzzy sets A and B, the ranking operators are defined by the following implications:

$$\begin{cases} \mathrm{A} \prec \mathrm{B} & \Leftrightarrow & \partial(\mathrm{MIN} \subseteq \mathrm{A}) > \partial(\mathrm{MIN} \subseteq \mathrm{B}) \\ \mathrm{A} \succ \mathrm{B} & \Leftrightarrow & \partial(\mathrm{MIN} \subseteq \mathrm{A}) < \partial(\mathrm{MIN} \subseteq \mathrm{B}) \\ \mathrm{A} \approx \mathrm{B} & \Leftrightarrow & \partial(\mathrm{MIN} \subseteq \mathrm{A}) = \partial(\mathrm{MIN} \subseteq \mathrm{B}) \end{cases} \tag{7}$$

and as special case we have

$$\begin{cases} \mathrm{A} \prec \mathrm{B} & \Leftrightarrow & \mathrm{MIN} \approx \mathrm{A} \\ \mathrm{A} \succ \mathrm{B} & \Leftrightarrow & \mathrm{MIN} \approx \mathrm{B} \\ \mathrm{A} \approx \mathrm{B} & \Leftrightarrow & \mathrm{MIN} \approx \mathrm{A} \text{ and } \mathrm{MIN} \approx \mathrm{B} \end{cases} \tag{8}$$

The question then arises: How to measure or estimate the value of these Inclusion Index $\partial(MIN(A,B) \subseteq A)$ and $(MIN(A,B) \subseteq B)$? The following theorem (Theorem D.2) simplified the problem statement.

Definition 6-6. For any two TFNs A and B, defined on the universal set $\mathbb{R}$, with $(A \cap B) \neq \emptyset$, and $x_m \in \mathbb{R}$ is the point that satisfy the 0 of (Chiu, 2002). Then the ranking operator $\preccurlyeq$ can be implemented as

$$\boldsymbol{A} \preccurlyeq \boldsymbol{B} \iff \sum_{x<x_m} \boldsymbol{A}(\boldsymbol{x}) \geq \sum_{x<x_m} \boldsymbol{B}(\boldsymbol{x}), \qquad \forall \boldsymbol{x} \in \mathbb{R}$$

Proof 6-5. Let $\boldsymbol{u}$ and $\boldsymbol{v}$ be two TFNs. According to (6) we have

$$\boldsymbol{u \preccurlyeq v \Leftrightarrow \partial(MIN(u,v) \subseteq u) \geq \partial(MIN(u,v) \subseteq v)}$$

Otherwise, according to *(4)*

$$u \preccurlyeq v \ \Leftrightarrow |MIN(u,v) \cap u| \geq |MIN(u,v) \cap v|$$

We also have according to Theorem D.1

$$MIN(u,v)(x) = \begin{cases} (u \cup \ v), & x < \ x_m \\ (u \cap \ v), & x \geq \ x_m \end{cases} = \begin{cases} max(u(x), v(x)) & x < x_m \\ min(u(x), v(x)) & x \geq x_m \end{cases}$$

So

$$\begin{aligned} &\boldsymbol{|MIN(u,v) \cap u|} \\ &\quad = \sum_{x<x_m} \boldsymbol{min\left(max\big(u(x), v(x)\big), u(x)\right)} \\ &\quad + \sum_{x\geq x_m} \boldsymbol{min\left(min\big(u(x), v(x)\big), u(x)\right)} \\ &\quad = \sum_{x<x_m} \boldsymbol{u(x)} + \sum_{x\geq x_m} \boldsymbol{min\big(u(x), v(x)\big)} \end{aligned}$$

Since

$$\boldsymbol{min\left(max\big(u(x), v(x)\big), u(x)\right) = u(x)}$$

$$\boldsymbol{min\left(min\big(u(x), v(x)\big), u(x)\right) = min\big(u(x), v(x)\big)}$$

Then

$$\boldsymbol{|MIN(u,v) \cap u| = \sum_{x<x_m} u(x) + \sum_{x\geq x_m} min\big(u(x), v(x)\big)}$$

$$\boldsymbol{|MIN(u,v) \cap v| = \sum_{x<x_m} v(x) + \sum_{x\geq x_m} min\big(u(x), v(x)\big)}$$

Consequently

$$\boldsymbol{|MIN(u,v) \cap u| \geq |\ MIN(u,v) \cap v| \Leftrightarrow \sum_{x<x_m} u(x) \geq \sum_{x<x_m} v(x)}$$

Hence the theorem

We will see in the following how the measurement of the Inclusion Index can be simplified to the point where we can deduce it by just looking at the pattern previously constructed according to the topological relationship.

IV.2.2. Topological relationship

A majority of relative layout exists between two TFNs, where a causal deduction of the Inclusion Index can be applied. Fig. 5-16 introduces the different situations that encompass all possible layout according to (Boukezzoula, 2007). A pattern is constructed based on the topological relationship between two fuzzy numbers. It consists in matching both TFN identification triplet $(\Lambda^{-}, \Lambda^{0}, \Lambda^{+})$ with the topological layout. For instance, the topological layout of the Fuzzy Weak-Overlapping situation is matched with one possible pattern, which is $[A^{-}, A^{0}, B^{-}, A^{+}, B^{0}, B^{+}]$.

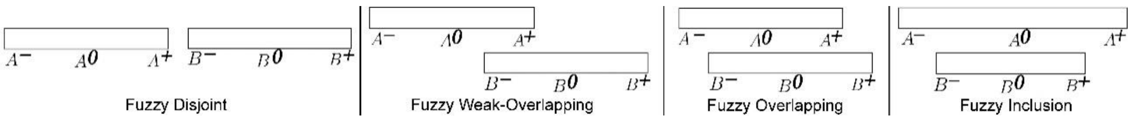

Fig. 5-16. All possible topological situations for two TFNs

IV.3. Analysis and properties of the proposed ranking

IV.3.1. Classification

The classification of the different topological relationship are obtained by swapping the sextuplet. The sextuplet is nothing by the combination of bother triplet defining, respectively, each TFN. However, due to a topological constraint, which is $\Lambda^{-} \leq \Lambda^{0} \leq \Lambda^{+}$, we cannot undertake all possible swapping. This reduced considerably the number of combination, and led to merely 20 possible cases. Half of these combinations are symmetrical, which leave us, fortunately, with just 10 cases. Mathematically, it is a combinatorial problem formulated as $\frac{1}{2}C_3^6 = \frac{6!}{2\times 3!\times(6-3)!} = 10$. It is a combination since we have to ignore the order to obey the topological constraint. We halve to eliminate the 10 remaining possibilities that are symmetrical to those presented hereinafter.

a. Fuzzy Disjoint

The Fig. 5-17-C1 shows the Fuzzy Disjoint case and we can deduce obviously that $A \prec B$ since $\forall\, x, A(x) < B(x)$.

b. Fuzzy Weak Overlapping

The Fig. 5-17-C2 portrays how it looks like the topological relationship in the case of the Fuzzy Weak Overlapping. The outcome of the ranking method is $A \prec B$, since $MIN(A, B) = A$ and according to the 0 and (8).

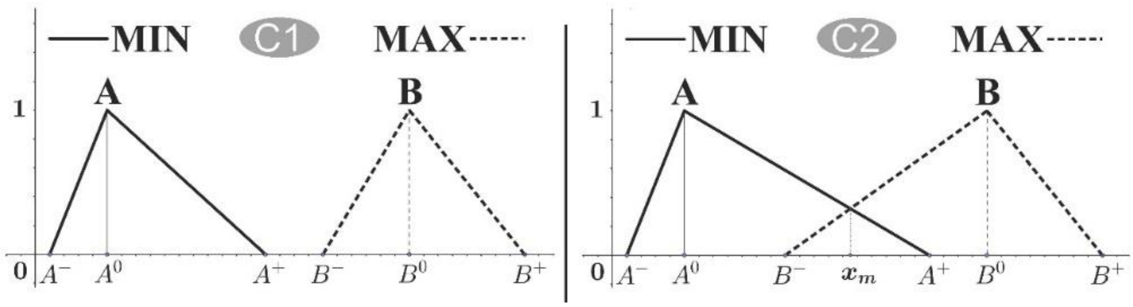

Fig. 5-17. Topological Representation of the Situation 1 & 2: Disjoint & Weak cases

c. Fuzzy Overlapping

In this situation, four possible cases have been defined. The first three: C3, C4 and C5, as shown on Fig. 5-18, indicate that $A \prec B$ according to 0 and (8). The fourth, C6, cannot be deduced directly from the topological relationship using Inclusion Index, since

$$\left| \begin{array}{l} MIN(A,B) \notin \{A,B\} \\ \{\forall\, x \in \mathbb{R} \mid MIN(A,B)(x) > 0\} \nsubseteq \{\forall\, x \in \mathbb{R} \mid A(x) > 0\} \\ \{\forall\, x \in \mathbb{R} \mid MIN(A,B)(x) > 0\} \nsubseteq \{\forall\, x \in \mathbb{R} \mid B(x) > 0\} \end{array} \right.$$

We propose, hereafter, a method for measuring the degree of inclusion to decide the ranking results.

$$\left| \begin{array}{l} A_{inc} \subseteq MIN(A,B) \\ B_{inc} \subseteq MIN(A,B) \end{array} \right. but \left| \begin{array}{l} A_{inc} \nsubseteq A \cap B \\ B_{inc} \nsubseteq A \cap B \end{array} \right.$$

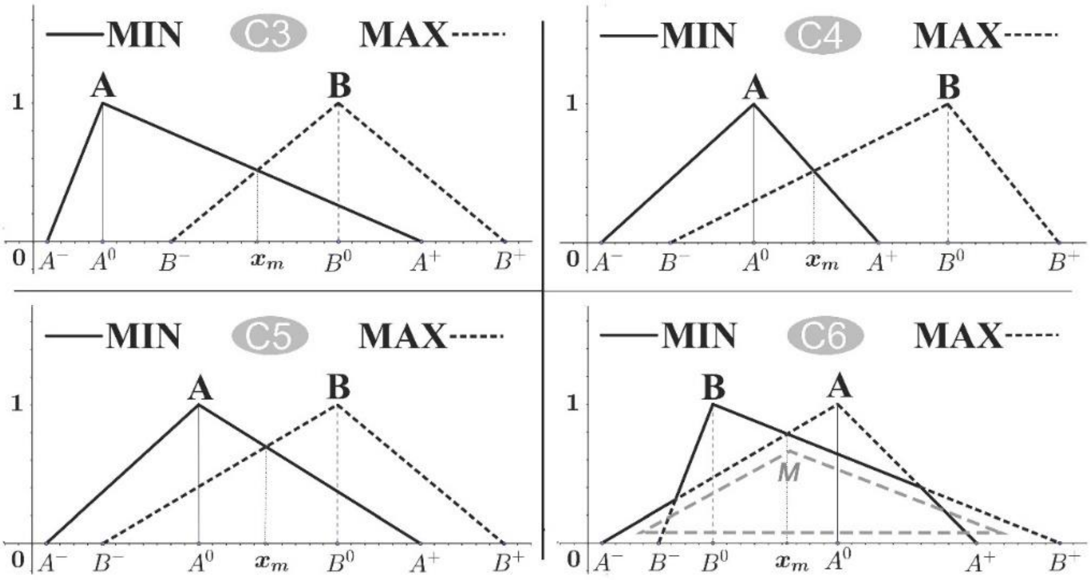

Fig. 5-18. Topological Representation of the Situation 3: overlapping cases

d. Fuzzy Inclusion

Finally, the Fig. 5-19 introduces the last four cases related to the Inclusion situation. For the first two, C7 and C8, we have

$$MIN(A\,,B) \notin \{A, B\}$$

$$and$$

$$\begin{cases} \{\forall\, x \in \mathbb{R} \mid MIN(A,B)(x) > 0\} \subseteq \{\forall\, x \in \mathbb{R} \mid A(x) > 0\} \\ \{\forall\, x \in \mathbb{R} \mid MIN(A,B)(x) > 0\} \nsubseteq \{\forall\, x \in \mathbb{R} \mid B(x) > 0\} \end{cases}$$

therefore the degree of inclusion of A in $MIN(A,B)$ is greater than B. It is, then, obvious that $A \prec B$ according to the degree of inclusion concept (7). As previously with the overlapping case, the ranking of C9 and CX are irregular situations, hereinafter we deal with them.

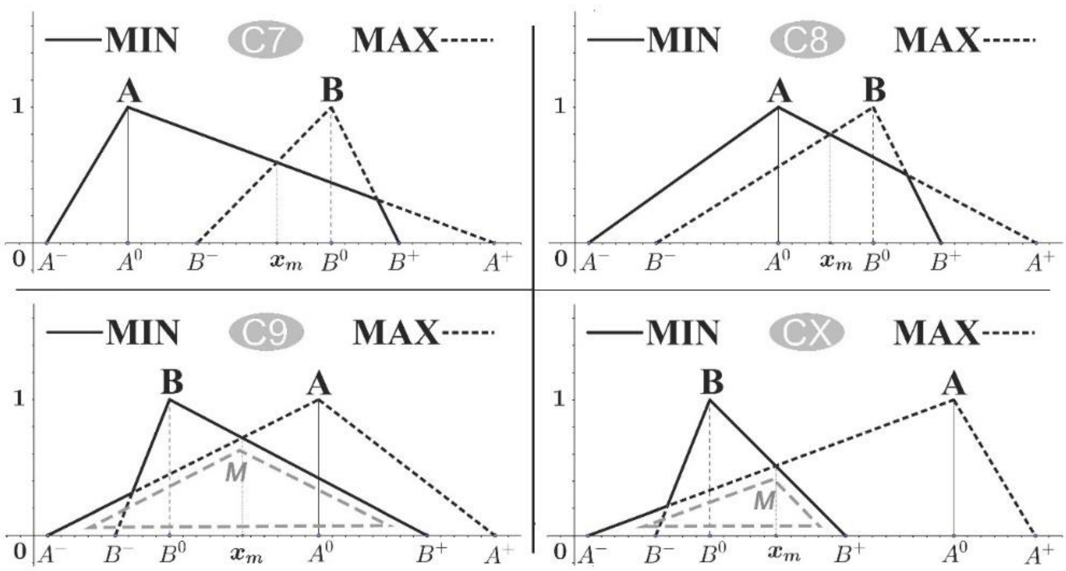

Fig. 5-19. Topological Representation of the Situation 4: inclusion cases

e. The irregular cases

Among the ten possibilities, three of them are irregular: Fig. 5-18-C6, Fig. 5-19-C9 and Fig. 5-19-CX. In these cases, it is not possible to guess the comparison of the Inclusion Index. We have then to measure the degree of inclusion.

Let us consider the triangle B and triangle M as on the Fig. 5-20. The comparison of the area of the TFN B, with the area of the triangle M indicated on the figure, respectively S_B and S_M, allows the deduction of the results (see Definition 6-4). In fact according to Fig. 5-20, the surface measurement of the two triangles A_{inc} and B_{inc} is adequate to deduce the Inclusion Index; since

$$A_{inc} \subseteq MIN(A,B) \;\; and \;\; B_{inc} \subseteq MIN(A,B)$$

$$A_{inc} \nsubseteq A \cap B \;\; and \;\; B_{inc} \nsubseteq A \cap B$$

By comparing S_B and S_M, which is similar to the comparison of $S_{A_{inc}}$ and $S_{B_{inc}}$, the ranking is carried out. In order to calculate the S_M surface, M coordinates need to be found, thus, we need to resolve the following system:

$$\begin{cases} l_{A(x_M)} = y_M = 1 - \dfrac{k_A - x_M}{\alpha_A} \\ r_{B(x_M)} = y_M = 1 - \dfrac{x_M - k_B}{\beta_B} \end{cases} \quad (9)$$

The intersection point of the two straight lines $l_A(x)$ and $r_B(x)$ as defined in Definition 6-1.

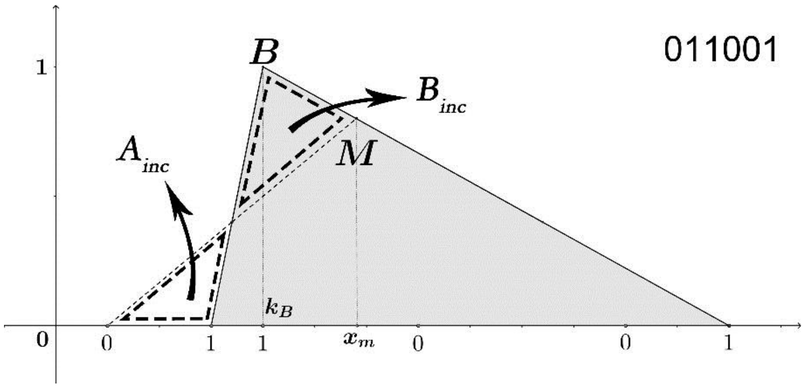

Fig. 5-20. The degree of inclusion in $\boldsymbol{MIN}(\boldsymbol{A}, \boldsymbol{B})$

IV.4. Properties of the TFN ranking operators

IV.4.1. Proof of Reasonableness

The authors in (Wang and Kerre, 2001) propose a reasonable axioms for ranking fuzzy numbers. We have successfully proven the reasonableness of our ranking method by studying it under the following Wang & Kerre's axiomatic system.

Let $\mathcal{M}$ be an ordering method, $\mathcal{S}$ the set of fuzzy numbers for which the method $\mathcal{M}$ can be applied and $\mathcal{A}$ a finite subset of $\mathcal{S}$. The statement two elements A and B in $\mathcal{A}$ satisfy that A has a higher ranking than B when $\mathcal{R}$ is applied to the fuzzy numbers in $\mathcal{A}$ will be written as $A \succ B$ by $\mathcal{R}$ on $\mathcal{A}$. $A \simeq B$ by $\mathcal{R}$ on $\mathcal{A}$, and $A \succcurlyeq B$ by $\mathcal{R}$ on $\mathcal{A}$ are similarly interpreted. In addition, the following is assumed:

- The fuzzy quantities satisfy the conditions for the application of the ranking method when a method is investigated.
- When a ranking method is applied on the set $\mathcal{S}$ of fuzzy quantities one of the following is true for every $(A, B) \in \mathcal{S}^2$: $A \succ B$, $A \prec B$ and $A \simeq B$

The following proposition shows the reasonable properties (Wang and Kerre, 2001) of the ordering approach $\mathcal{M}$.

$\mathbb{A}_1$ For an arbitrary finite subset $\mathcal{A}$ of $\mathcal{S}$ and $A \in A$, $A \succcurlyeq A$ by $\mathcal{M}$ on $\mathcal{A}$.

$\mathbb{A}_2$ For an arbitrary finite subset $\mathcal{A}$ of $\mathcal{S}$ and $(A, B) \in \mathcal{A}^2$, $A \succcurlyeq B$ and $B \succcurlyeq A$ by $\mathcal{M}$ on $\mathcal{A}$, we should have $A \simeq B$ by $\mathcal{M}$ on $\mathcal{A}$.

$\mathbb{A}_3$ For an arbitrary finite subset $\mathcal{A}$ of $\mathcal{S}$ and $(A, B, C) \in A^3$, $A \succcurlyeq B$ and $B \succcurlyeq C$ by $\mathcal{M}$ on $\mathcal{A}$, we should have $A \succcurlyeq C$ by $\mathcal{M}$ on $\mathcal{A}$.

$\mathbb{A}_4$ For an arbitrary finite subset $\mathcal{A}$ of $\mathcal{S}$ and $(A, B) \in \mathcal{A}^2$, $inf[supp(A)] > sup[supp(B)]$, we should have $A \succcurlyeq B$ by $\mathcal{M}$ on $\mathcal{A}$.

$\mathbb{A}_4$ means that if two fuzzy numbers have separate supports then the fuzzy number with the support on the right is at least as good as the one with the support on the left. One stronger version of this axiom is as follows:

$\mathbb{A}_4'$ For an arbitrary finite subset $\mathcal{A}$ of $\mathcal{S}$ and $(A, B) \in \mathcal{A}^2$, $inf[supp(B)] > sup[supp(A)]$, we should have $A \prec B$ by $\mathcal{M}$ on $\mathcal{A}$.

$\mathbb{A}_5$ Let $\mathcal{S}$ and $\mathcal{S}'$ be two arbitrary finite sets of fuzzy numbers in which $\mathcal{M}$ can be applied and A and B are in $\mathcal{S} \cap \mathcal{S}'$. We obtain the ranking order $A \succ B$ by $\mathcal{M}$ on $\mathcal{S}'$ iff $A \succ B$ by $\mathcal{M}$ on $\mathcal{S}$

$\mathbb{A}_6$ Let A, B, $A + C$ and $B + C$ be elements of $\mathcal{S}$. If $A \succcurlyeq B$ by $\mathcal{M}$ on $\{A, B\}$, then $A + C \succcurlyeq B + C$ by $\mathcal{M}$ on $\{A + C, B + C\}$.

The axiom $\mathbb{A}_6$ indicates that $+$ is compatible with $\succcurlyeq$ defined by the ordering approach $\mathcal{M}$. Concerning $\succ$, a similar axiom is as follows:

$\mathbb{A}_6'$ If $A \succ B$ by $\mathcal{M}$ on $\{A, B\}$, then $A + C \succ B + C$ by $\mathcal{M}$ on $\{A + C, B + C\}$ when $C \neq \emptyset$.

$\mathbb{A}_7$ Let A, B, AC and BC be elements of $\mathcal{S}$ and $C \geq 0$. $A \succcurlyeq B$ by $\mathcal{M}$ on $\{A, B\}$ implies $AC \succcurlyeq BC$ by $\mathcal{M}$ on $\{AC, BC\}$.

IV.4.2. Comparison with other ranking methods

Thorough comparison have been undertaken with various major approaches. Notably the comparison with the maximizing and minimizing set method proposed by (Chen, 1985), which is a commonly used approach, highly cited and has wide applications according to (Chou, 2011). Hereinafter, we present some of the examples on which our studies took as a comparing means.

a. Example 1

(Asady, 2007) consider the three TFNs shown in Fig. 5-21-a.

$$\begin{vmatrix} A = (5, 6, 7; 1) \\ B = (5.9, 6, 7; 1) \\ C = (6, 6, 7;\ 1) \end{vmatrix}$$

The application of most methods such Chen's approach (Chen, 1985), and the proposed method infer the following outcome: $A \prec B \prec C$. Whereas, with the Cheng method (Cheng, 1998) infer $C \prec B \prec A$.

b. Example 2

The ranking of TFNs in the Fig. 5-21-b, results in $C \prec B \prec A$.

$$\begin{vmatrix} C = (-0.70, -0.40, -0.25;\ 1) \\ B = (-0.58, -0.32, -0.17;\ 1) \\ A = (-0.50, -0.30, -0.20;\ 1) \end{vmatrix}$$

The same result is obtained by Choobineh (Choobineh, 1993) and Chu (Chu, 2002) methods, however the Cheng (Cheng, 1998) and (Chen, 1985) methods results in $A \prec B \prec C$.

c. Example 3

Consider the two TFNs shown in Fig. 5-21-c, as in (Ezzati et al., 2012)

$$\begin{vmatrix} \mathrm{A}\ =\ (3, 6, 9;\ 1) \\ \mathrm{B}\ =\ (5, 6, 7;\ 1) \end{vmatrix}$$

It is a common problem, and yet a very controversial one. Indeed, A and B have the same symmetrical spread (Wang, 2009) and most existing methods fail to rank them properly (Wang, 2009). By using the approaches in (Abbasbandy, 2009), (Wang, 2008), (Yao, 2000), (Chu, 2002), we obtain $A \simeq B$; and with (Ezzati, 2012) the ranking order resulted is $A \succ B$. Different ranking results are obtained when different indices of optimism are considered among the approaches (Abbasbandy, 2006). (Ezzati et al., 2012) consider that the decision makers prefer the result $A \succ B$ and adds, it is intuitive. However, by applying our approach $A \prec B$ since A has a greater degree of inclusion in $MIN(A, B)$ than$B$. Therefore A has a greater tendency to be lower than B.

d. Example 4

Consider the followings set of Fig. 5-21-d, as in (Ezzati et al., 2012) and (Yao, 2000):

$$\left|\begin{array}{l} \mathrm{A} = (0.4, 0.5, 1; 1) \\ \mathrm{B} = (0.4, 0.7, 1; 1) \\ \mathrm{C} = (0.4, 0.9, 1; 1) \end{array}\right.$$

With the proposed method we get $A \prec B \prec C$, as well as with most of approaches (Ezzati et al., 2012); (Aabbasbandy, 2009), (Abbasbandy, 2006); (Asady, 2007); (Choobineh, 1993); (Chen, 1985); (Chu, 2002); (Cheng, 1998). But Cheng obtains $A \prec C \prec B$ (Cheng, 1999).

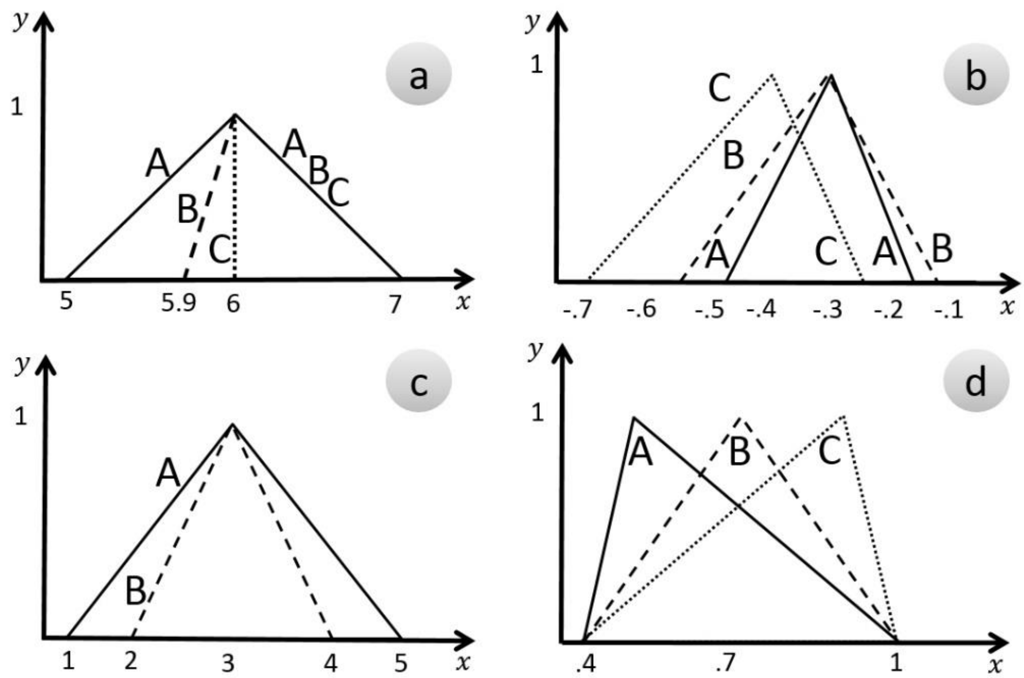

Fig. 5-21. 4 controversial examples: (a) shows 3 positives TFNs; (b) shows 3 negatives TFNs; (d) shows same symmetrical spread TFNs; (d) shows same support TFNs

V. Chapter summary

In this chapter, on one hand a fuzzy based modelling for risk assessment have been proposed. After defining the risk and its factors considered in this work, the Fuzzification process was presented. It is based either on historical data or on expert opinion.

On the other hand, a new method for ranking TFNs is introduced. It consists in deducing intuitively and easily the ranking results of a set of TFNs using the Inclusion Index concept; then with the we classify them into a group of categories identified by a pattern. Following the comparative results of different case studies that have been presented, our approach enables to deduce directly in 70% of cases the comparison outcome of two TFNs, just by looking at the pattern. We observed the similarity of results obtained with either other suggested approaches outcomes and human intuition, which proves its efficiency. Furthermore, the proposed method can also be extrapolated to Trapezoidal Fuzzy Numbers and to others shapes. Some issues to explore the limits of our approach need to be asked: Can we use other Inclusion Index defined on fuzzy sets? How to revise Inclusion Index axioms' with partial orders defined on fuzzy numbers? Is the proposed approach generalizable to all shapes of fuzzy numbers? Future developments of this work will address these issues in depth. Deployment of this approach for computing the fuzzy optimal path in DGT is addressed in the following chapter

Chapter 6. Multicriteria Route Optimization

Managing the trade-off between safety and economic factors in route optimization is the purpose of this chapter. For route selection, a bidirectional A-star search algorithm is used. The algorithm is based on a time-dependent network, Voronoi diagram, multiobjective function and fuzzy weighted graph.

I. Chapter introduction

Decision makers in the transport industry can easily obtain computed paths with the easy-to-use route planning web applications, by only defining the Origin/Destination points, and optionally other criteria such travel time, total path length and estimated travel cost. Typically, the optimal path for goods delivering to multiple destinations is a very critical issue related to shipment cost mitigation. Usually only static information, gathered from past feedback studies, are taken into account when computing such algorithms. Whereas travel time over a network link depends on the traffic condition during a specific time slot. To assess the traffic condition we should have information on, for instance, real-time traffic intensity, weather condition, network infrastructure etc. Fortunately, latest mobile and wireless communication technologies allow real-time data transmission by sensors located at strategic places on road networks, vehicles and weather stations, such as for the Transport Integrated Platform introduced in the third chapter (Benza et al., 2012). These data are, then, collected through wireless and mobile communication technologies such GPRS (Laarabi et al., 2012), or through a traffic simulation system (Laarabi et al., 2013) and stored in large databases. Yet automated decision support systems (Garbolino et al., 2007) can analyse these data, produce statistical reports, and use sophisticated mathematical models for the prediction, to a certain degree of accuracy, of the traffic density evolution.

In a real-time situation, minimizing the travel time from point A to a point B, requires the consideration of a time-dependent transport network. Since the time distance between two adjacent points depends substantially on the exact moment when a vehicle is crossing the link. Furthermore, it is widely recognized that DGT risk may be drastically reduced by planning routes that minimise the accident probability and/or the expected consequences of an accident. Significant research has been focused on developing mathematical models and algorithms for determining safe and economical routes. The major part of the relevant research has been focused on routing decisions for transporting DG from an origin to a single destination minimising cost and/or risk related criteria.

Recently, authors in (Androutsopoulos et al., 2010) suggested a bi-criterion solution for routing and scheduling problem for hazardous materials distribution. Under the assumption that the cost and risk attributes of each arc of the underlying transportation network are time-dependent, the proposed routing and scheduling problem determines the k-shortest time-dependent path. The solution captures the trade-off between risk and travel time in the neighbourhood of the travel time optimal solution.

Earlier, (Stewart and White, 1991) introduced the multiobjective extension of A-star (MOA-star) with proofs on admissibility, node expansion and comparison heuristics. (Mandow and De la Cruz, 2005) reconsidered the MOA-star to preserves path selection and expansion as the basic operations. The Mandow is new algorithm shows interesting properties analogous to those of A-star but not shared by Stewart’s MOA-star, such substantial memory consumption mitigation.

Under reasonable assumptions, Single-Source algorithm (as Dijkstra's) already solved in polynomial time the optimal path-finding problem on a time-dependent graph. However, running these kind of algorithms on large and detailed network, will consume considerably the CPU time, and therefore, inconvenient for a real-time processing system. Fortunately, another kind of algorithms based on the Point-to-Point approach and use speed-up techniques, allow search restriction that leads to ignore all less significant network links. As a result, we avoid scanning nodes that are not part of the potential node sets of the optimal path. One of these techniques is the Bidirectional A-star search, as introduced by (Demiryurek et al., 2005), which applies restrictions on the nodes scope of the forward search, by bounding them to those will be explored by the backward search.

According to (Demiryurek et al., 2005), executing a pre-computation tasks before going online, is proven as a very efficient step to enhance the accuracy of the heuristic function that are supposed to direct the search towards the goal and eliminates unnecessary scanning. In this thesis, the pre-computation stage consist in breaking-down the network to non-overlapping sub-networks with Network Voronoi Diagrams (Okabe and Sugihara, 2012). Then a lower bound graph is computed for each criteria (objective) by considering, respectively, the minimum travel time and the minimum risk, which never overestimate their values. This lower bound graph represents a reliable information on which heuristic function can use to direct the search toward the goal.

Finally, in real world networks either travel time or risk cannot be an exact value, since they depend on many factors fraught with uncertainty and vagueness. This uncertainty can be modelled with the Fuzzy Logic (Zadeh, 1965) that catch properly the vagueness of travel time and some risk factors as discussed in Chapter 5. We suggest in here a *Fuzzy Weighted Graph*, which should deal with a goal-driven fuzzy modelling and fuzzy ranking as decision-making tools to find for the optimal path.

II. Fuzzy time-dependent travel time

For the sake of simplicity, I start in this section by introducing the route optimization approach considering solely one criterion, which is the travel time. Then, in the following section I extend it to the multi-criteria route optimization.

II.1. Time-dependent network

A graph structure can be extended by considering a time-variable edge weight, i.e. the weight of each edge is a function of the departure time at the starting vertex, as shown on Fig. 6-1. Such network with variable edge weight is called a time-dependent (TD) network. The fastest path problem in a time-dependent network is called the time-dependent fastest path problem

(TDFP). The traditional fastest path problem (FP) is a special case of TDFP with invariable edge length. In the real world, TDFP problems arise frequently in transport industry, for instance by considering travel time (or time distance) as road segment weight that vary over time slots due to traffic situation.

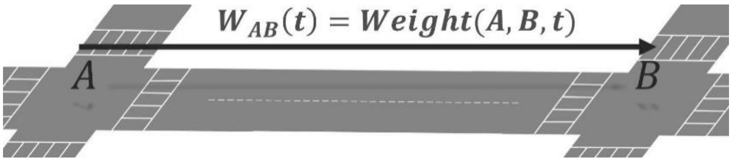

Fig. 6-1. Road segment weight as a function of the departure time at the starting vertex A to destination B

The used model is a piecewise linear functions representing the travel time on a time-dependent travel time weighted graph. Hereinafter, we introduce the definition of the time-dependent weight and travel time function along a path from a source to a destination as in (Demiryurek et al., 2011):

Definition 5-7. *A Time-Dependent Graph is represented by* $G(V, E, T)$ *where* $V = \{v_i\}$ *is a set of nodes and* $E \subseteq V \times V$ *is a set of edges that connect nodes and considered as network road segment. For all* $e(v_i, v_j) = e_{i,j} \subseteq E$*, and* $v_i \neq v_j$*, we associate a cost function* $w_{i,j}(t)$*, where t is the time variable in time domain* T*. This cost function* $w_{i,j}(t)$ *represents the travel duration (or travel time) from node* v_i *to node* v_j *starting at time* t *(see Fig. 6-1).*

Definition 5-8. *Let* $\{s = v_1, v_2, \ldots, v_k = d\}$ *be a path with a sequence of nodes such that* $e_{i,i+1} \subseteq E$ *and* $i = 1, \ldots, k-1$*. Given a* $G(V, E, T)$*, a* $(s, d) - path$ *from* s *to* d *as shown on Fig. 6-2, and a departure time at the source* t_s*, the time-dependent travel time, denoted as* $TT(s, d, t_s)$*, is the time duration to travel over the* (s, d)*-path. Since the travel time of an edge varies depending on the arrival time to that edge, then the travel time is computed as follows:*

$$TT(s, d, t_s) = \sum_{i=1}^{k-1} w_{i,i+1}(t_i) \qquad (10)$$

where $t_1 = t_s,\ t_{i+1} = t_i + w_{i,i+1}(t_i)$ *with* $i \in \{1, \dots, k\}$

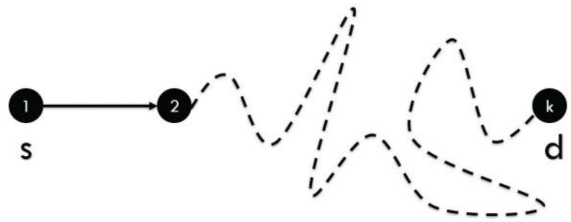

Fig. 6-2 an $(\boldsymbol{s}, \boldsymbol{d}) - \boldsymbol{path}$ *from source* $\boldsymbol{s}$ *to destination* $\boldsymbol{d}$

II.2. Fuzzy Weighted Graph

II.2.1. Fuzzy Logic

We have come by Fuzzy set theory through Chapter 5. Fuzzy logic is a different kind of logic that deals with approximate reasoning (i.e. continuum degree of truth) rather than crisp and fixed logic (i.e. true/false) (Zadeh, 1965). The similarity with real world logic is the main advantage of the fuzzy concept. In this context, the travel time weight over road networks cannot be considered as an exact value, since vehicles, driving behaviours and traffic intensity, for instance, impact slightly the travel time on the same time window. Even crossing intersection cannot be considered as exact offsets (as modelled in certain traffic simulation system). Thereafter, crisp logic will not picture the real-world complexity as far as the fuzzy logic will do. Besides travel time, risk related to goods transportation or accident in general can also be modelled using fuzzy concept as in (Boulmakoul, 2006), (Qiao et al., 2009). The corresponding algorithm of the fuzzy time-dependent fastest path is represented by F-TDFP.

The substitution of a Real Numbers by Fuzzy Numbers, which represents travel time, will eventually rise the issue of Ranking Fuzzy quantities, which is less evident and more complex matter than crisp sets ranking, such Real Numbers. In addition to the different existing works on Fuzzy Ranking since its introduction by (Zadeh, 1965), we have proposed in our turn (Boulmakoul et al., 2013) an original way for ranking Triangular Fuzzy Numbers (TFN). The proposed approach addressed in Chapter 5 exploits the topological relationship between two triangles. This allows drawing a pattern for each situation from which we can deduce in 70% of cases the Inclusion Index.

II.2.2. Fuzzy weight

We denote the Fuzzy Weight by $\widetilde{w}$, and we introduce its definition hereinafter:

Definition 5-9. A fuzzy time-dependent graph $G(V,E,\mathcal{T})$ is defined with the same topology as graph $G(V,E,T)$. Where the weight of each edge $\widetilde{w}_{i,j}(\tau)$ is a Triangular Fuzzy Number, such $\tau \in \mathcal{T}$ is an element of the set of fuzzy time distance $\mathcal{T}$.

$\widetilde{w}_{i,j}^{-}(\tau)$, $\widetilde{w}_{i,j}^{0}(\tau)$ and $\widetilde{w}_{i,j}^{+}(\tau)$ are defined and constructed by estimation as suggested by the author in (Baruah, 2014).

II.2.3. Fuzzy travel time

We introduce the definition of the Fuzzy travel time, denoted by $\widetilde{TT}$, along a path from a source to a destination. The fuzzy time-dependent travel time $\widetilde{TT}(s,d,\tau_s)$ at the departure time τ_s is computed as follows:

$$\widetilde{TT}(s,d,\tau_s) = \bigoplus_{i=1}^{k-1} \widetilde{w}_{i,i+1}(\tau_i) \tag{11}$$

Where $\tau_1 = \tau_s$, $\tau_{i+1} = \tau_i \oplus \widetilde{w}_{i,i+1}(\tau_i)$ with $i \in \{1,\ldots,k\}$. With $\oplus$ and $\bigoplus$ denote respectively the fuzzy addition and summation operators.

II.3. Pre-computation stage

II.3.1. Definitions

The main factors of comparison between different path search algorithms are the reliability and the performance of finding the optimal solution within a reasonable amount of time. For that reason, several speed-up techniques exist, and in this work, we use a heuristic function based on the method proposed by (Demiryurek et al., 2011). The role of this heuristic function is to direct the search towards the goal avoiding thereby unnecessary scan of vertices that are far from being part of the fastest path. That is considered as reliable indicator of the potential nodes. This can be done by performing a pre-processing consisting in:

- Subdividing the network to non-overlapping regions, as defined in Definition 5-4 using a specific metric;
- Computing of the lower bound graph represented by the node-to-border, border-to-border, and border-to-node optimal travel time/risk labels, which shall never overestimate either travel time or risk on any road segment;

a. Graph subdivision

The definition of graph subdivision is as follows:

Definition 5-10. The breaking down of the lower bound graph $G(V,E)$ is a set of sub-graphs $\{S_1,S_2,\dots,S_k\}$ where a $V_i \in S_i = (V_i,E_i)$ with $V_i \cap V_j = \emptyset$ and $\bigcup_{i=1}^{k} V_i = V$, for all $i \neq j$.

b. Minimum fuzzy weight

Hereinafter we define the minimum fuzzy weight for the computation of the lower bound graph $G(V,E)$:

Definition 5-11. Considering a $G(V,E,\mathcal{T})$, the corresponding lower bound graph $G(V,E)$, is a graph having same topology as the graph $G(V,E,T)$, where the edge weight $\widetilde{w}_{i,j}$ is not time-dependent and is equal to the minimum possible fuzzy weight $\widetilde{w}^{\varepsilon}_{i,j}$ where

$$\forall\ e_{i,j} \in E,\quad \tau \in \mathcal{T},\quad \widetilde{w}^{\varepsilon}_{i,j} \preccurlyeq \widetilde{w}_{i,j}(\tau)$$

c. Lower bound fuzzy travel time

Having the minimum fuzzy weight for each road segment, we can compute the fuzzy lower bound travel time $L\widetilde{TT}$ by calculating the lower travel time path from a source s to a destination d. The $L\widetilde{TT}$ is then defined hereafter:

Definition 5-12. The fuzzy lower bound travel time $L\widetilde{TT}(s,d)$ over the (s,d)-path, will never overestimate the travel time at any moment along the same path and is computed as the following

$$L\widetilde{TT}(s,d) = \bigoplus_{i=1}^{k-1} \widetilde{w}_{i,i+1}^{\varepsilon}, \qquad i \in \{1,\dots,k\} \tag{12}$$

Where $L\widetilde{TT}(s,d) \preccurlyeq \widetilde{TT}(s,d,\tau_s)$, with $\bigoplus$ denotes the fuzzy summation operator.

II.3.2. Graph subdivision using Network Voronoi

Network subdivision with Voronoi diagram, consists in dividing the space into a number of regions. This done by specifying beforehand a set of seeds (or generator points) that match each region. A region is constructed by considering all points closer to one seed than to any other. The metrics on which is based "closer", can be defined according to ones needs: Euclidean, Manhattan. (Okabe and Sugihara, 2012) summarizes the work done over the last decades on the network Voronoi diagrams that defines the metrics as weighted shortest path distances, to overcome the limitation of the planar Voronoi diagrams. (Mabrouk et al., 2009) suggests a fuzzy network Voronoi with a fuzzy weighted metrics. In the following, we suggest subdivision of the network using a fuzzy travel time metrics.

We define the Fuzzy Voronoi Graph (F-VG) by breaking down the graph to sub-graphs such that each sub-graph contains the closest, in terms of fuzzy fastest path, vertices and edges to predefined Voronoi seeds. (Mabrouk et al., 2009) exploit fuzzy Dijkstra algorithm proposed by (Boulmakoul, 2004) and (Seda, 2006) to calculate the fuzzy weights of the fastest paths traversed between each fuzzy graph node and the whole of Voronoi seeds.

The Fig. 6-3 represents the flow chart of the algorithm, which uses the Dijkstra's algorithm with multiple sources considered as the Voronoi seeds. It seeks the closest vertices to each seed, in terms of fuzzy travel time. The algorithm can be seen as four steps process, after the "initialization", the three remaining are repeated until the subdivision is achieved. The "Marking" is for labelling the already scanned vertices. The "scan" step has as objective to compute the optimal path to the seeds. Finally, the "control" checks the termination condition that is all vertices have been scanned. Definition 5-7 gives a mathematical formulation of the Fuzzy Voronoi Graph.

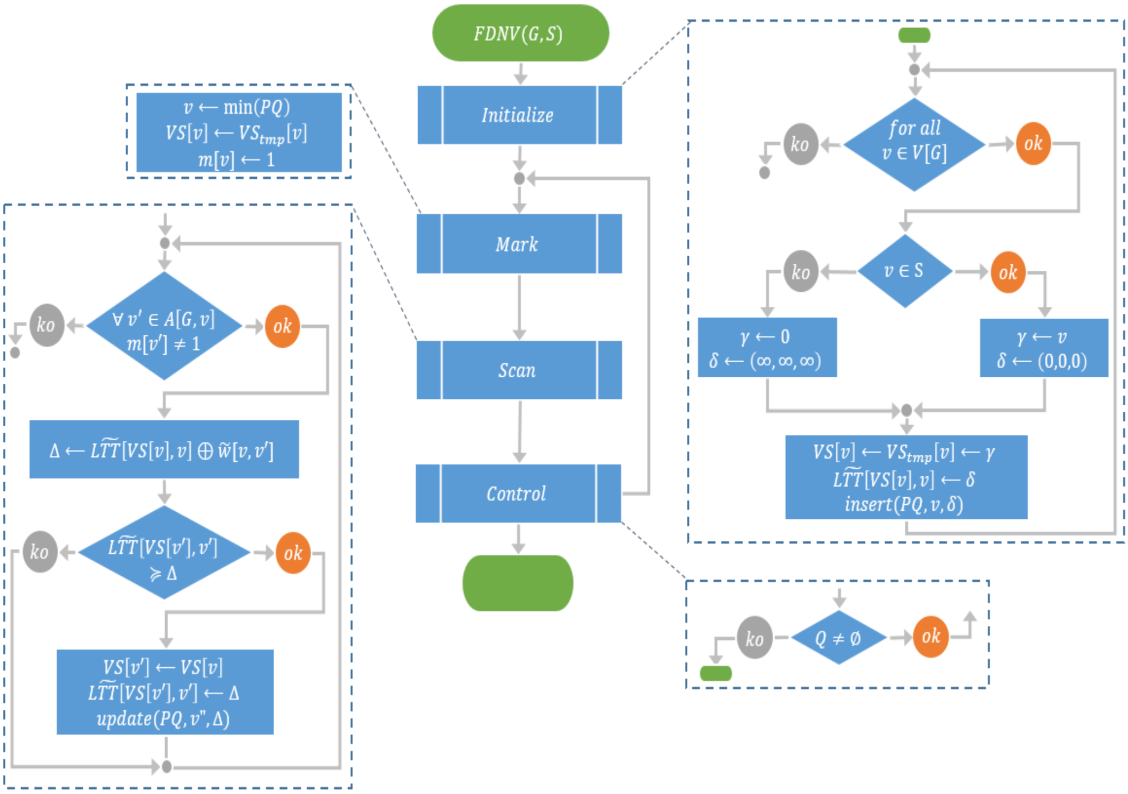

Fig. 6-3 Graph subdivision by Network Voronoi using Fuzzy Dijkstra algorithm

Definition 5-13. *Let $G(V,E)$ be a graph with V and E are respectively a set of vertices and edges. Let $S = \{s_1, \dots, s_k\}$ be the set of Voronoi seeds for the F-VG corresponding to graph G. Consider $\widetilde{LTT}(v, w, t_v)$ as the optimal travel time (fastest path) from a node v to a node w. The F-VG with seeds S breaks down the graph G to k sub-graphs $\{G_1, G_2, \dots, G_k\}$ such as:*

$$G_i = \{\forall\, v \in V \;/\; \widetilde{LTT}(s_i, v) \preccurlyeq \widetilde{LTT}(s_j, v), \forall\, j \in [1,k], i \neq j\,\}$$

G, The graph structure. $V[G]$, The vertices of the graph G. S, The set of seeds. $VS[v]$, The closest seed to the vertex v. $A[G,v]$: The set of adjacent vertices to the vertex v.

PQ, The priority queue ordered using the fuzzy ranking algorithm proposed in chapter 5. The elements of this queue are the vertices and their fuzzy weight.

$\min(PQ)$, extract by pulling off the vertices with the minimum weight. $insert(PQ, v, \delta)$, insert into PQ the vertex v with weight δ. $update(PQ, v, \Delta)$: Replaces the weight of the vertex v by a new one Δ and restructures PQ.

II.3.3. Lower bound travel time computation

As mentioned beforehand, we need to use an estimator $h(v)$ that never overestimates the travel time between a certain node v belonging to the fastest path and the destination node d. For this reason, (Demiryurek et al., 2011) suggests to compute a lower bound heuristic estimator of the start node s to d by the formula (13). The Fig. 6-4 graphically represents the lower bound travel time computation on a subdivided graph.

$$h(s) = L\widetilde{TT}(s, b_s) \oplus L\widetilde{TT}(b_s, b_d) \oplus L\widetilde{TT}(b_d, d) \tag{13}$$

With $\oplus$ denotes the fuzzy addition operator.

Therefore, $h(s)$ will never overestimate the fuzzy time-dependent fastest path from s to d, since $h(s) \preccurlyeq L\widetilde{TT}(s, d) \preccurlyeq \widetilde{TT}(s, d, \tau_s)$, for any $\tau_s \in \mathcal{T}$. In this situation, we will only need to store the lower bound travel time labels of the node-to-border, border-to-border, and border-to-node, instead for every pairs of nodes. By subdividing the Fuzzy Dijkstra for Network Voronoi algorithm, the lower bound travel times is computed implicitly.

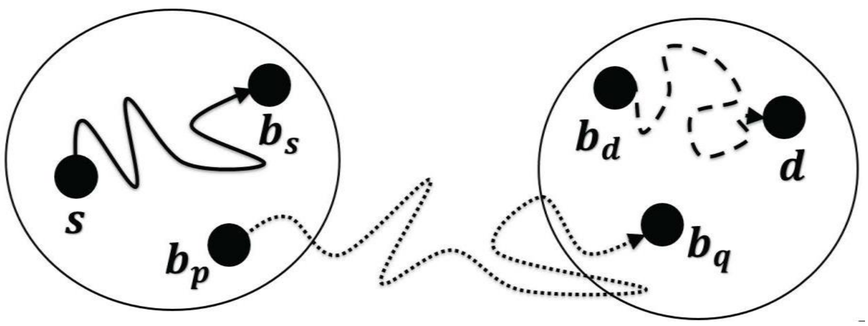

Fig. 6-4. The node-to-border, border-to-border, and border-to-node lower bound travel time labels from source node s to destination node d

II.4. Real-time stage

The time-dependent fastest path algorithm take as input a fuzzy time-dependent network G, a source node s, a destination node d, and a departure time τ_s.The output should be the fuzzy fastest (s, d)-path denoted as F-$TDFP(G, s, d, \tau_s)$.

II.4.1. Point-to-Point (P2P) algorithm

Path finding is a fundamental problem with multiple applications, and have several variations, including single-source, point-to-point, and all-pairs shortest paths. The non-negative cost single-source problem has been most extensively studied (Cherkassky et al., 1996), (Cowen and Wagner, 2000), (Dantzig, 1998), (Denardo and Fox, 1979). The other common variant is the point-to-point shortest path problem applied on non-negative cost directed graphs, also referred by the P2P algorithm. Unlike the single-source variation, where every nodes of the network should be visited, the P2P, hopefully, can often be solved while scanning a small sub-graph. The algorithm performance is then assessed by measuring the ratio of the number of scanned nodes, to the number of nodes within the shortest path.

Single-source algorithms such Dijkstra's, SHARC (Delling and Nannicini, 2008), and Contraction Hierarchies (CH) (Batz et al., 2009), are not as effective with dynamic scenarios as with static ones, unlike authors claim in (Dreyfus, 1969). Multiple Dijkstra's algorithms variations and speed-up techniques exist in order to improve the single-source efficiency, yet remain far behind the performance scored by the Point-to-Point algorithms. The latter uses a heuristic function to direct the search toward the goal, and avoid thereby useless scanning.

Furthermore, speed-up techniques reduce even more the scope of the potential nodes such with Ohshima's Landmark technique (Ohshima, 2008), which uses a pre-calculated landmarks with shortest path distance label. Then the algorithm on the online mode has only to find the closest landmark to the source and the one to the destination. The used algorithm for shortest path search is the ALT algorithm (Goldberg and Harrelson, 2005) that stands for A-star search, Landmarks and Triangle inequality.

(Demiryurek et al., 2011) suggests a different approach that consist in a bidirectional A-star search using the pre-computed lower bound graph for as basis for the A-star heuristic function. The computing of the lower bound travel time on every road network shall not overestimate a travel time on any road segment.

Demiryurek proves that his proposed approach is much more efficient than Ohshima's Landmark technique, in term of computation performance and memory consumption. That is why we use Demiryurek is bidirectional search for our proposed Fuzzy time-dependent travel time algorithm. The considered network shall not violate the First In First Out (FIFO) property. Indeed, the path-finding problem is proven an NP-Hard problem when applied on a non-FIFO network, which means overtaking and waiting at nodes are prohibited.

II.4.2. A-star search

The Fig. 6-5 shows the A-star cost function is computed with sum of two path-cost. Let v be an intermediate vertex within the (s, d)-path. We have $f(v) = g(v) \oplus h(v)$:

- $g(v)$ The knowledge function, i.e. the shortest travel time from s to v;
- $h(v)$ The heuristic function, i.e. the estimated shortest travel time from v to the destination d.

The zeroing of $h(v)$, A-star turns into Dijkstra's algorithm. If instead $g(v)$ is zeroed that will be rather the Best First Search algorithm. By balancing properly those two path-cost functions, we get the A-star Point-to-Point algorithm. The challenge is to define a suitable heuristic function $h(v)$ that will fasten the path finding while ensuring the optimality of the solution.

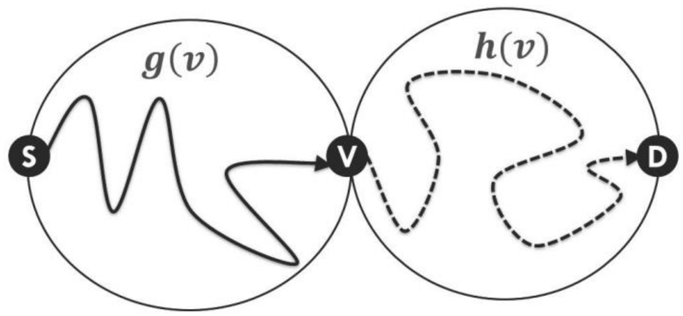

Fig. 6-5 Illustration of the two cost functions of the A-star algorithm: $\boldsymbol{g(v)}$ *and* $\boldsymbol{h(v)}$

Having said that, in our case the $g(v)$ is considered as the optimal time dependent travel time $\widetilde{TT}^*(s, v, \tau_s)$, and the heuristic function $h(v)$ is considered as the lower bound travel time $L\widetilde{TT}(v, d)$.

$$f(v) = g(v) \oplus h(v) = \widetilde{TT}^*(s, v, \tau_s) \oplus L\widetilde{TT}(v, d)$$

II.4.3. A-star bidirectional search

The use of suggested estimator $h(v)$ for an A-star forward search is sufficient to find the TDFP within a reasonable amount of time. However, by applying a bidirectional search we can speed-up further the computation. This technique consists in lowering the size of the potential nodes set by the backward search, as shown in Fig. 6-6. To put it another way, the size of the set of potential nodes that might belong to the fastest path, is continuously shrunken by only considering the intersection of the two sets i.e. Forward and Backward potential nodes sets.

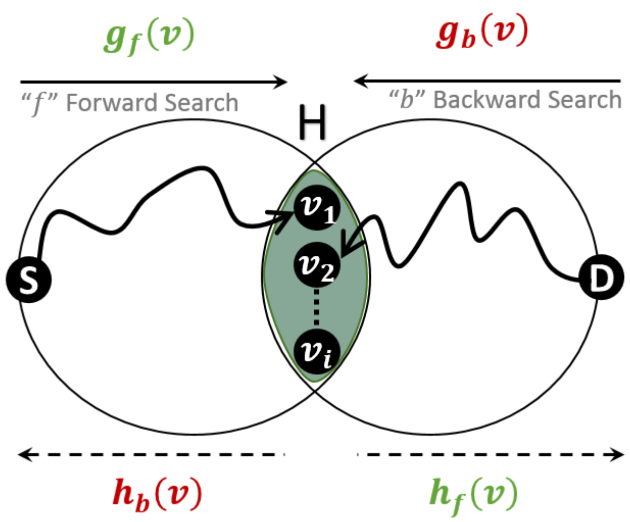

Fig. 6-6. Bidirectional Time-Dependent Fastest Path problem (BTFP)

The challenges with the bidirectional search is the fact that we do not have the arrival time to start the backward search. We solve this by considering the lower bound travel time arrival time since it will never overestimate it.

In addition, satisfying the consistency of the estimator $h(v)$, is not an obvious matter, since the algorithm when running the forward and backward search use inconsistent potential cost function. Let consider $h_f(v)$ the estimated cost function from v to destination d, and $h_b(v)$ be the estimated cost function from v to source s. Each original edge $e(i,j)$ with the backward search is considered as $e(j,i)$ in the reverse graph. h_b is computed by

$$\widetilde{w}_{j,i}(\tau_j) \longleftarrow \widetilde{w}_{i,j}(\tau_j) \ominus h_b(j) \oplus h_b(i)$$

Then h_f and h_b are consistent if for all $e(i,j)$, $\widetilde{w}_{j,i}(\tau_j) \approx \widetilde{w}_{i,j}(\tau_j)$. There is not guarantee that the optimal path can be found in the case of the forward and backward estimated function are not consistent.

To address this challenge, according to (Demiryurek et al., 2011), we need to find:

- A consistent heuristic function and stop the search when forward and backward search meet;
- A new termination condition.

Let consider $v_i \in H$ as set of nodes where the search frontiers meet, and u is the node scanned before v_i by the forward search, with the following termination condition

$$\widetilde{TT}^*(u,d,\tau_u) + h(u) > \widetilde{TT}^*(s,v_i,\tau_s) + \widetilde{TT}^*(v_i,d,\tau_{v_i})$$

Whereas $\widetilde{TT}^*(s,v_i,\tau_s) + \widetilde{TT}^*(v_i,d,\tau_{v_i})$ is the length of the temporary optimal path. Once the searches stop, H will include all the potential nodes that can satisfy the optimality.

To decide which potential node is the one who belongs to the optimal path, we run continue the forward search starting from the nodes in the set H until it reaches the destination d.

III. Multicriteria optimization

The multicriteria optimization is a field in the Multi Criteria Decision Making (MCDM), which is a sub-discipline of Operations Research. It considers explicitly several criteria in a decision making process. In mathematical optimization problems, it consists at optimizing multiple objective function simultaneously. When undertaking this goal, usually one faces conflicts where a single solution does not optimize all the criteria and thus a trade-off is required. The outcomes in these situations are multiple optimal solutions and the decision makers can choose which solution is more suitable for the context of the problem. In the literature, considerable research have been done in the "most preferred" alternative solution, and especially in the case of Fuzzy criteria, such in (Demirtas et al., 2008), (Lu et al., 2007), (Rasmy et al., 2002), (Pohekar et al., 2004) and (Kahraman et al., 2008).

Generally, in the transportation of dangerous goods, stakeholders would prefer a safer route as the economic cost of transport remains attractive. This means the criteria might not have similar stature, as in DGT, the travel time is more interesting than risk.

In single criterion optimization, a scalar weight is affected to each edge of the graph. Whereas in multicriteria optimization, it is rather a vector weight with each dimension refers to a criterion. In the following, I define the vector weight and the multicriteria optimization algorithm, in addition to a case study that clarify the proposed approach.

III.1. Vector weight

The vector weight can be defined as follows

Definition 5-14. Considering *a fuzzy weighted and time-dependent graph* $G(V, E, \mathcal{T})$ *where* $V = \{v_i\}$ *is a set of nodes and* $E \subseteq V \times V$ *is a set of edges that connect nodes. For all* $e(v_i, v_j) \subseteq E$, *and* $v_i \neq v_j$, *we associate a positive vector weight* $\overrightarrow{W}_{i,j}(\tau) = (\omega_1, \omega_2) \in \mathbb{F}^2$, *where* τ *is the time variable in fuzzy time domain* $\mathcal{T}$. *This vector weight represents the pair travel time and risk costs of the edge* $e(v_i, v_j)$ *starting at time* τ, *respectively* ω_1 *and* ω_2, *such*

$$\omega_1 = \widetilde{TT}(v_i, v_j, \tau)$$

$$\omega_2 = \tilde{R}(v_i, v_j, \tau)$$

With $\widetilde{TT}$ and $\tilde{R}$ represent respectively the fuzzy travel time and the fuzzy risk.

The multicriteria optimization weight vector $\vec{W}$, leads only to a partial order preference relation $\prec$ called *dominance* in the fuzzy set $\mathbb{F}$ such as

$$\forall\, \vec{W}, \vec{W}' \in \mathbb{F}^2 \quad \vec{W} \prec \vec{W}' \iff \forall p \in \{1,2\}, \qquad \omega_p \preccurlyeq \omega'_p \;\; and \;\; \vec{W} \not\approx \vec{W}'$$

Consequently, it is not always possible to rank one as better than the other in the case where no dominance relation exists between two vectors, such as the trade-off travel time/risk conflicting between the two vectors: let us consider these two vector weights (ω_1, ω_2) and (ω'_1, ω'_2), such as $\omega_1 > \omega'_1$ and $\omega_2 < \omega'_2$. In other words, higher travel time and lower risk, versus, lower travel time and higher risk.

III.2. Multiobjective A-star algorithm

The core of the multiobjective optimization is to search for the all non-dominated solutions, which will lead to an analogy to A-star that aims at finding all optimal paths. (Mandow and De la Cruz, 2005) propose a more efficient algorithm by extending the multiobjective A-star search that preserves "path selection" and expansion as the basic operations. Its concept is detailed hereinafter.

III.2.1. An acyclic search graph

The algorithm uses a data structure of an acyclic graph, called the Search Graph (SG), to keep best partial solutions paths. Typically, the A-star search algorithm uses a Search Tree (ST) to store a single partial solution and use it to expand it. However, in the case of multiobjective search, multiple solutions might exist, and in order to store more than one solution, we use the acyclic graph structure.

III.2.2. Expansion of partial solutions

The algorithms uses a list data structure $OPEN$ intended for expansion of partial solutions. For each node $v \in SG$ and each non-dominated weight vector $\overrightarrow{W}$, there will be a corresponding triple $(v, \vec{g}_v, F_v)$ in $OPEN$. $F(v, \vec{g}_v)$ represents the multiobjective analogue to $f(v)$ of A-star cost function such,

$$F(v, \vec{g}_v) = nondom\{\vec{f} \mid \vec{f} = \vec{g}_v + \vec{h}_v\}$$

Where $nondom(X)$ is the set of non-dominated vectors in set X. $\vec{g}_v$ is the knowledge vector from source s to v, such

$$\vec{g}_v = \sum_{i=1}^{k-1} \overrightarrow{W}_{i,i+1}(\tau_i) = (\widetilde{TT}(s, v, \tau), \tilde{R}(s, v, \tau))$$

and $\vec{h}_v$ represents the multiobjective heuristic vector from node v to destination d, such

$$\vec{h}_v = (L\widetilde{TT}(v, d), L\tilde{R}(v, d))$$

With $L\widetilde{TT}$ and $L\tilde{R}$ represent respectively the lower bound travel time and lower bound risk applied on the Fuzzy Voronoi Graph (F-VG) during the pre-computation phase. The $L\widetilde{TT}$ gives an estimation of the travel time required to reach the destination, whereas the $L\tilde{R}$ estimates the lower bound risk.

The algorithm will keep considering, at each iteration, the extension of an open triple $(v, \vec{g}_v, F_v)$.

III.2.3. Filtering

The data set $COSTS$ records all non-dominated cost vectors to destination node. Once a solution is found, the obtained cost vector is used to delete dominated open triples. Finally, the algorithm terminates when the $OPEN$ list becomes empty.

III.2.4. Illustrative example

To illustrate better the operating of this algorithm, the Fig. 6-7 highlights the steps for achieving the desired results.

First, the graph is subdivided into distinct and non-overlapping subgraphs. This is done by the Fuzzy Network Voronoi partitioning. Then, we consider the reversed graph for the backward search. We start the bidirectional search at same time from start node and destination node. The backward search creates the set H, which is supposed to contain all non-dominated costs from the destination. Once the forward and backward iteration meet, the latter is stopped, and the forward search continue only on the potential nodes with non-dominated costs. Once the forward search reach the destination node, the algorithm is stopped.

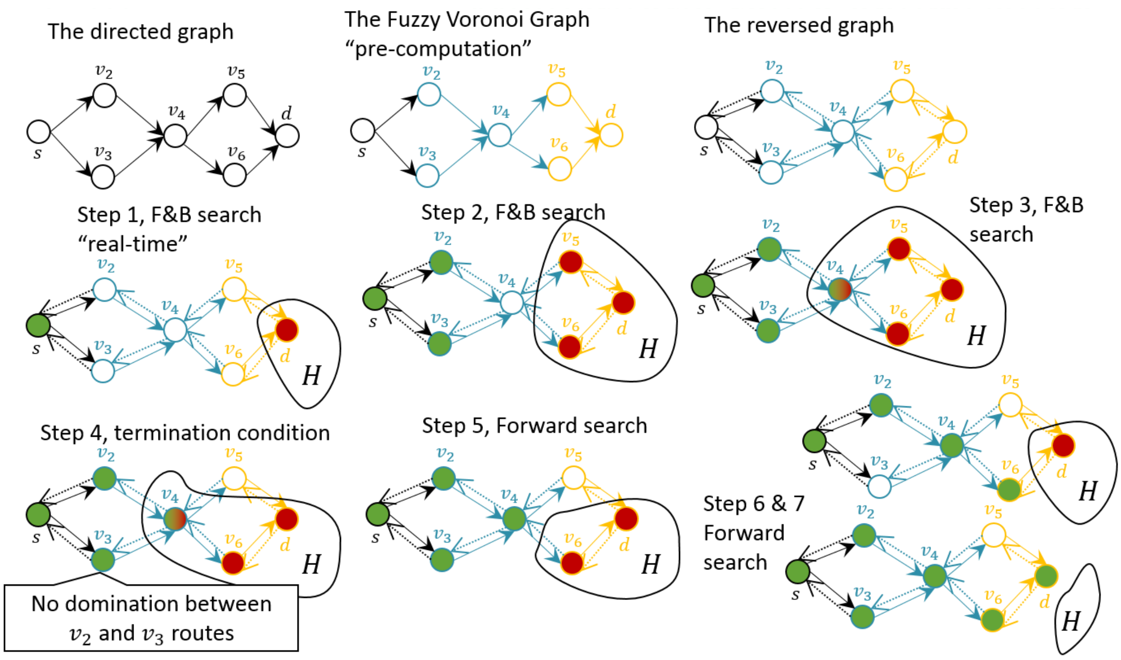

Fig. 6-7. Illustration of the algorithm of Bidirectional and Multi-Objective route search

IV. Implementation with Boost Graph Library

Boost Graph Library (or BGL) is a set of libraries for the C++ programming language that furnishes extensive tools and support for graph structures such: Adjacency List, and algorithms such: Dijkstra, A-star, etc. BGL also provides mechanisms to extend and customize the graph structures and algorithm behaviours. Furthermore, most of the Boost libraries are licensed under the Boost Software License, designed to allow Boost to be used with both free and proprietary software projects.

IV.1. The adjacency list

BGL provides the users with an adjacency list structure to build a graph and browse it. Indeed, one of the common way to model a graph is by using an adjacency list, as shown on Fig. 6-8, where each vertex point to a list containing the adjacent vertices.

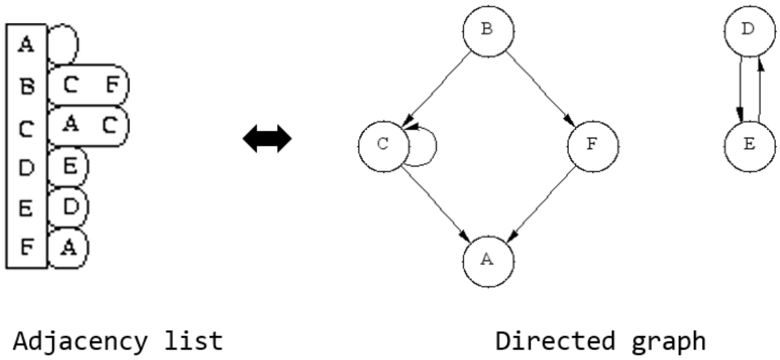

Fig. 6-8 A graph can be modelled with an adjacency list structure

IV.2. The multilevel graph (Network of Networks)

The graph can be easily subdivided to multiple sub graphs, when using the adjacency list within a `sub_graph` structure. In other words, subdividing the graph, using Fuzzy Network Voronoi, amounts to create a multilevel graph (a network of networks), where each partition is a sub graph of the main graph. The Fig. 6-9 shows a graphical representation of multilevel graph using the Boost Graph Library.

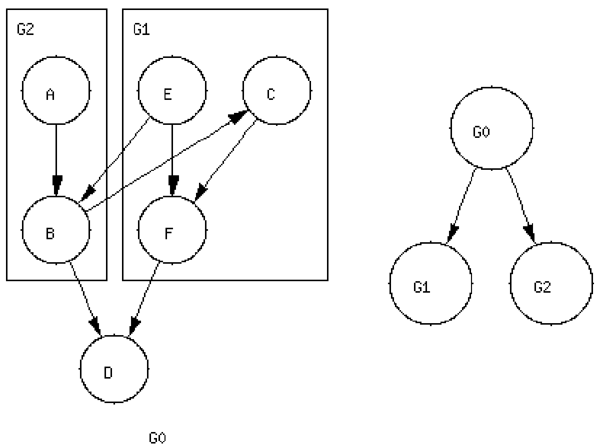

Fig. 6-9 A multilevel graph using sub_graph structure in BGL

IV.3. The vector weighted graph

A weighted graph is a graph in which a real number is associated to every edge in the graph. These real numbers represents weights accumulated, and in some condition positive real numbers.

The Fig. 6-10 shows an `adjacency_list` encapsulated in a `sub_graph` structure. Then `adjacency_list` attributes are mentioned such:

- data structure of vertices `VertexList` and edges `OutEdgeList`;
- directed, undirected or bidirectional;
- properties to inject in vertices, edges and subgraphs.

In the case of `EdgeProperties` that is a `property_map`, which binds the tag `edge_weight_t` with the `weight_vector` entity. This entity represents the multicriteria weight and its two coordinates are the `travel_time` and `risk` using triangular fuzzy number `tfn` as data type.

As a result, we obtain a hyper weighted graph with a fuzzy weight vector.

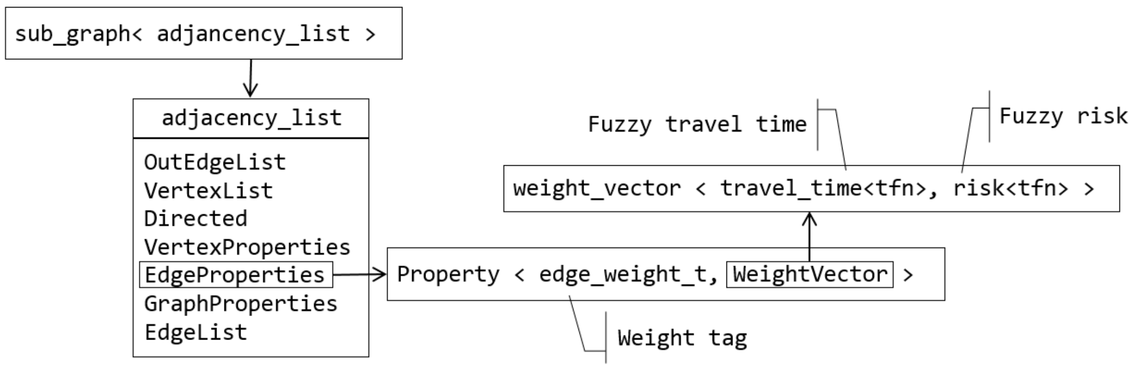

Fig. 6-10 A weighted multi graph using an adjacency list structure with multicriteria weight

V. Chapter summary

To summarize, the objective of this work is to suggest a multiobjective bidirectional A-star search algorithm applied on a fuzzy weighted graph. Two stages are required to get the optimal solution. First, the pre-computation stage that consists in breaking down the graph, using network Voronoi's concept, to non-overlapping sub-graphs, then computing the all pairs lower bound travel time. The second stage, the algorithm executes in real-time a multiobjective bidirectional A-star search. The forward search computes the knowledge function, which is the couple optimal (travel time, risk). While the backward search estimates the travel time and risk to the goal with a heuristic function based on the lower bound (travel time, risk). The bidirectional search asset is the substantial reduction of the set of potential nodes among the optimal path. Travel time and risk factor uncertainty representation are well modelled using the Triangular Fuzzy Numbers. Finally, Boost Graph Library is introduced as a powerful and easy tool for implementing the algorithm.

Yet some issues should be raised and explored: How can we ensure the polynomial growth of the Pareto Curve (or approximate of the Pareto Curve)? Are there any further techniques to speed-up even more the bidirectional Point-to-Point search algorithm? How it can be improved the accuracy of the heuristic cost function?

Bibliography

A

Abkowitz, M., A. Eiger, and S. Srinivasan. Estimating Release Rates and Costs of Transporting Hazardous Waste. In Transportation Research Record 977, TRB, National Research Council, Washington, D.C., 1984, pp. 22–30.

Akgün, V., Parekh, A., Batta, R., Rump, C.M., 2007. Routing of a DG truck in the presence of weather systems. Computers & operations research, Vol. 34, pp. 1351-1373.

Androutsopoulos K. and Zografos K., "Solving the bicriterion routing and scheduling problem for hazardous materials distribution," Transportation Research Part C: Emerging Technologies, vol. 18, no. 5, pp. 713–726, 2010.

Aw A. and Rascle M., "Resurrection of" second order" models of traffic flow," SIAM journal on applied mathematics, vol. 60, no. 3, pp. 916– 938, 2000.

Aydin, G., Qi, Z., Pierce, M., Fox, G., Bock, Y., 2007. Architecture, performance, and scalability of a real-time global positioning system data grid. Physics of the Earth and Planetary Interiors 163 (1-4), 347{359.

B

Basavaraju A., Doddigarla S., Naidu N., Malgatti S. (2014). Vehicle Density Sensor System To Manage Traffic. IJRET: International Journal of Research in Engineering and Technology eISSN: 2319-1163 | pISSN: 2321-7308.

Batta, R., and S. Chiu. Optimal Obnoxious Paths on a Network: Transportation of Hazardous Materials. Operations Research, Vol. 36, 1988, pp. 84–92.

Batz G. V., Delling D., Sanders P., and Vetter C., "Time-dependent contraction hierarchies." in ALENEX, vol. 9, 2009.

Baruah H. K., "Construction of normal fuzzy numbers using the mathematics of partial presence," Mathematics of Uncertainty Modeling in the Analysis of Engineering and Science Problems, p. 109, 2014.

Bell M. G. H., "Mixed routing strategies for hazardous materials: Decision-making under complete uncertainty," International Journal of Sustainable Transportation, vol. 1, no. 2, pp. 133–142, 2007. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/15568310601092013

Benza, M., Bersani, C., D'Inca, M., Roncoli, C., Sacile, R., Trotta, A., Pizzorni,D., Briata, S., Ridolff, R., 2012. Intelligent transport systems (its) applications on dangerous good transport on road in Italy. In: System of Systems Engineering (SoSE), 2012 7th International Conference on. IEEE, pp. 223{228.

Bersani C., Minciardi R., Tomasoni A. M., and Sacile R., "Risk averse routing of hazardous materials with scheduled delays," in Security and Environmental Sustainability of Multimodal Transport, ser. NATO Science for Peace and Security Series C: Environmental Security, M. Bell, S. H. Hosseinloo, and U. Kanturska, Eds., 2010, pp. 23–36.

Boulmakoul, A., Karim, L., Laarabi, M. H., Sacile, R., Garbolino, E., 2014.Mongodb-hadoop distributed and scalable framework for spatio-temporal hazardous materials data warehousing. In: 7th International Congress on Environmental Modelling and Software (iEMSs).

Boulmakoul, A., Laarabi, M.H., Sacile, R., Garbolino, E. (2013). Ranking triangular fuzzy numbers using fuzzy set inclusion index, in Fuzzy Logic and Applications, ser. Lecture Notes in Computer Science, F. Masulli, G. Pasi, and R. Yager, Eds. Springer International Publishing, vol. 8256, pages 100–108. Available: http://dx.doi.org/10.1007/978-3-319-03200-9 11

Boulmakoul, A., Laurini, R., Zeitouni, F., 2001. Spatial monitoring and routing system for the transportation of hazardous materials. In: Environmental information systems in industry and public administration. IGI Publishing ,pp. 227{236.

Boulmakoul A., "Fuzzy graphs modelling for hazmat telegeomonitoring," European journal of operational research, vol. 175, no. 3, pp. 1514–1525, 2006.

C

Cherkassky B. V., Goldberg A. V., and Radzik T., "Shortest paths algorithms: theory and experimental evaluation," Mathematical programming, vol. 73, no. 2, pp. 129–174, 1996.

Chopra A. and Singh M., "An architecture for multiagent systems and approach based on commitments", 2009.

D. Chowdhury, L. Santen, and A. Schadschneider, "Statistical physics of vehicular traffic and some related systems," Physics Reports, vol. 329, no. 4, pp. 199–329, 2000.

Clark, Renee M., and Mary E. Besterfield-Sacre. "A new approach to hazardous materials transportation risk analysis: decision modeling to identify critical variables." Risk Analysis 29, no. 3 (2009): 344-354.

Cowen L. J. and Wagner C. G., "Compact roundtrip routing in directed networks," in Proceedings of the nineteenth annual ACM symposium on Principles of distributed computing. ACM, 2000, pp. 51–59.

Crainic, T. G., Gendreau, M., Potvin, J.-Y., 2009. Intelligent freight transportation systems: Assessment and the contribution of operations research. Transportation Research Part C: Emerging Technologies 17 (6),541 { 557.URL http://www.sciencedirect.com/science/article/pii/S0968090X08000648

Current, J., C. Revell, and J. Cohon. The Minimum-Covering/Shortest-Path Problem. Decision Sciences, Vol. 19, 1988, pp. 490–503.

D

Dadkar, Y., Jones, D., & Nozick, L. (2008). Identifying geographically diverse routes for the transportation of hazardous materials. Transportation Research Part E, 44, 333–349.

Dantzig G. B., Linear programming and extensions. Princeton university press, 1998.

Delis, A., Roussopoulos, N., 1992. Performance and scalability of client-server database architectures. In: Proceedings of the international conference on very large data bases. Institute of Electrical & Electronics Engineers (IEEE),pp. 610{610.

Delling D. and Nannicini G., “Bidirectional core-based routing in dynamic time-dependent road networks,” in Algorithms and Computation. Springer, 2008, pp. 812–823.

Demirtas, E. A., & Üstün, Ö. (2008). An integrated multiobjective decision making process for supplier selection and order allocation. Omega, 36(1), 76-90.

Demiryurek U., Banaei-Kashani F., Shahabi C., Ranganathan A. (2011). Online computation of fastest path in time-dependent spatial networks, in Advances in Spatial and Temporal Databases. Springer, pages 92–111.

Denardo E. V. and Fox B. L., “Shortest-route methods: 1. reaching, pruning, and buckets,” Operations Research, vol. 27, no. 1, pp. 161– 186, 1979.

Dreyfus S. E., “An appraisal of some shortest-path algorithms,” Operations Research, vol. 17, no. 3, pp. 395–412, 1969.

DYNAMIT, M. I. Program. (2004) Mit intelligent transportation systems. [Online]. Available: http://mit.edu/its/dynamit.html

E

Edsger. W. Dijkstra. A note on two problems in connexion with graphs. Numerische Mathematik, 1:269–271, 1959.

Ehlert, P. A., Rothkrantz, L.J. (2001). Microscopic traffic simulation with reactive driving agents. In Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE, pages 860–865.IEEE.

F

Frank, W.C., Thill, J-C, Batta R., 2000. Spatial decision support system for hazardous material truck routing, Transport research Part C, Vol. 8, pp. 337-359.

G

Garbolino, E., Sacile, R., Olampi, S., Bersani, C., Tomasoni, A., Alexandre, N.,Trasforini, E., Benza, M., Giglio, D., et al., 2007. Spatial decision support system prototype for assessing road hazmat accident impacts on the population in a dense urban area: a case study of the city of nice, french riviera. In: Proceedings of the 8th International Conference of Chemical and Process Engineering 2007, in Ischia. pp. 413{41.

Georgeff M. and Lansky A., “Procedural knowledge,” Proceedings of the IEEE, vol. 74, no. 10, pp. 1383–1398, 1986.

Gerlough D. L., “Simulation of freeway traffic on a general-purpose discrete variable computer,” Ph.D. dissertation, University of California, Los Angeles, 1955.

Ghatee M., Hashemi S. M., Zarepisheh M., and Khorram E., “Preemptive priority-based algorithms for fuzzy minimal cost flow problem: An application in hazardous materials transportation,” Computers & Industrial Engineering, vol. 57, no. 1, pp. 341–354, 2009.

Goldberg A. V. and Harrelson C., “Computing the shortest path: A search meets graph theory,” in Proceedings of the sixteenth annual ACM-SIAM symposium on Discrete algorithms. Society for Industrial and Applied Mathematics, 2005, pp. 156–165.

Gopalan, R., K. Kolluri, R. Batta, and M. Karwan. Modeling Equity of Risk in the Transportation of Hazardous Materials. Operations Research 38, 1990, pp. 961–973.

Gudgin, M., et al., April 2007. W3C Recommendation, SOAP Version 1.2 Part1: Messaging Framework (Second Edition). World Wide Web Consortium(W3C).URL http://www.w3.org/TR/soap12-part1/#intro/

H

Hernndez, J. Z., Ossowski, S., Garcia-Serrano, A., 2002. Multiagent architectures for intelligent traffic management systems. Transportation Research Part C: Emerging Technologies 10 (56), 473 { 506.URL http://www.sciencedirect.com/science/article/pii/S0968090X02000323

Holmes A. (2012). Hadoop in Practice. Manning Publications Co.

Hong, S., Heo, J., Vonderohe, A. P., 2013. Simulation-based approach for uncertainty assessment: Integrating gps and gis. Transportation Research Part C: Emerging Technologies 36, 125{137.

Hung Q. Nguyen, B. Johnson, M. H., 2003. Testing Applications on the Web: Test Planning for Mobile and Internet-Based Systems).

I

Ioannou P.A. and Chien C.C.. Autonomous intelligent cruise control. IEEE Transactions on Vehicular Technology, 42(4):657 –672, Nov. 1993.

J

K

Kahraman, C. (2008). Fuzzy multi-criteria decision making: theory and applications with recent developments (Vol. 16). Springer.

Kazantzi V., Kazantzis N., and Gerogiannis V. C., "Risk informed optimization of a hazardous material multi-periodic transportation model," Journal of Loss Prevention in the Process Industries, vol. 24, no. 6, pp. 767 – 773, 2011.

Klir G. J. and Yuan B., Fuzzy sets and fuzzy logic. Prentice Hall New Jersey, 1995.

Kuchin, S., 2012. Oracle, Odbc and DB2-CLI Template Library Programmer'sGuide.URL http://otl.sourceforge.net/

L

Laarabi, M. H., Boulmakoul, A., Mabrouk, A., Sacile, R., Garbolino, E., 2014.Real-time fastest path algorithm using bidirectional point-to-point search on a fuzzy time-dependent transportation network. In: Advanced Logistics and Transport (ICALT), 2014 International Conference on. IEEE, pp. 78{84.

Laarabi, M. H., Boulmakoul, A., Sacile, R., Garbolino, E., 2013a. An overview on an intelligent transportation system (its) based on agents, time-dependent network and fuzzy travel time cost. In: 3rd Edition On Innovation and News Trends in Information Systems (INTIS 2013). pp. 191{202.

Laarabi, M. H., Sacile, R., Boulmakoul, A., Garbolino, E., et al., April 2013b.An overview of a multiagent-based simulation system for dynamic management of risk related to dangerous goods transport. In: Proceedings IEEE International Systems Conference in Engineering of Complex Systems. pp.830{835.

Leonelli, P., Bonvicini, S., Spadoni, G., 1999. New detailed numerical procedures for calculating risk measures in hazardous materials transport. Journal of Loss Prevention in the process industries, Vol.12, pp. 507-515.

Library, M., 2012. Microsoft: I/O Completion Ports.URL http://msdn.microsoft.com/en-us/library/aa365198(VS.85).aspxLiu, H. H., 2009. Software Performance and Scalability: A Quantitative Approach(Quantitative Software Engineering Series). Wiley.

Lighthill M. J. and Whitham G. B., "On kinematic waves. ii. a theory of traffic flow on long crowded roads," Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, vol. 229, no. 1178, pp. 317–345, 1955.

Lipsa G. M. and Martins N. C., Finite horizon optimal memoryless control of a delay in gaussian noise: A simple counterexample. In IEEE Conference on Decision and Control, pages 1628–1635, December 2008.

Liu H. H., Software Performance and Scalability: A Quantitative Approach (Quantitative Software Engineering Series), Wiley, 2009.

Lu, Jie, Guangquan Zhang, and Da Ruan. Multi-objective group decision making: methods, software and applications with fuzzy set techniques. Imperial College Press, 2007.

M

Mabrouk, A., Boulmakoul, A., Bielli, M. (2009). Fuzzy spatial network voronoi diagram: a spatial decision support for transportation planning, International Journal of Services Sciences, vol. 2, no. 3, pages 265–280.

Mabrouk, A., Boulmakoul, A., Laarabi, M. H., Sacile, R., Garbolino, E., 2013. Graphes de Voronoï Flous basés sur un nouvel opérateur de Tri des Nombres Flous Triangulaires. In: 3rd Edition On Innovation and News Trends in Information Systems (INTIS 2013). pp. 155{166.

Mallikarjuna C., "Analysis and modelling of heterogeneous traffic," Ph.D. dissertation, Ph D thesis, 2007.

Mandow, L., & de la Cruz, J. P. (2005, July). A New Approach to Multiobjective A* Search. In IJCAI (pp. 218-223).

MATSIM, T. S. Planning, T. T. at the Institute for Land, and S. T. S. T. U. Berlin. (2003) Multi-agent transport simulation. [Online]. Available: http://www.matsim.org/

Meister I. K., Balmer I. M., K. W. Axhausen, E. IVT, and V. Kai Nagel, "planomat: A comprehensive scheduler for a large-scale multi-agent transportation simulation," education, vol. 200, p. 250, 2006.

MicrosoftTechNet, 2012. Network Load Balancing Technical Overview.URL http://technet.microsoft.com/en-us/library/bb742455.aspxMSDNLibrary, 2012. Chapter 14 - Improving SQL Server Performance.URL http://msdn.microsoft.com/en-us/library/ms998577.aspx#scalenetchapt14topic10/

MongoDB 10gen. (2013). Available from: http://www.mongodb.org.

N

Nagel K. and Schreckenberg M., “A cellular automaton model for freeway traffic,” Journal de Physique I, vol. 2, no. 12, pp. 2221–2229, 1992.

Nannicini, Giacomo. "Point-to-point shortest paths on dynamic time-dependent road networks." 4OR 8.3 (2010): 327-330.

Newell G. F., “Nonlinear effects in the dynamics of car following,” Operations Research, vol. 9, no. 2, pp. 209–229, 1961.

O

Ohshima T., “A landmark algorithm for the time-dependent shortest path problem,” Ph.D. dissertation, Kyoto University, 2008.

Okabe, A., Sugihara, K. (2012). Network Voronoi Diagrams. John Wiley & Sons, Ltd. pages 81–100. Available: http://dx.doi.org/10.1002/9781119967101.ch4

P

Pal D. and Mallikarjuna C., “Cellular automata cell structure for modeling heterogeneous traffic,” European Transport, no. 45, pp. 50–63, 2012

Panwhar, S. T., Pitt, R., & Anderson, M. D. (2000). Development of a GIS-based Hazardous Materials Transportation Management System: A Demonstration Project. UTCA Report 99244. Tuscaloosa, Alabama: University Transportation Center for Alabama.

Payne, H. J. (1971). Models of freeway traffic and control. Mathematical models of public systems.

Pettre J., Kallmann M., and M. C. Lin, “Motion planning and autonomy for virtual humans,” in ACM SIGGRAPH 2008 classes. ACM, 2008, p. 42.

Pelechano N., Allbeck J. M., and Badler N. I., “Virtual crowds: Methods, simulation, and control,” Synthesis Lectures on Computer Graphics and Animation, vol. 3, no. 1, pp. 1–176, 2008.

Pnueli A., “Specification and development of reactive systems,” Information Processing, vol. 86, pp. 845–858, 1986.

Pohekar, S. D., & Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—a review. Renewable and Sustainable Energy Reviews, 8(4), 365-381.

Pradhananga R., Taniguchi E., and Yamada T., “Ant colony system based routing and scheduling for hazardous material transportation,” Procedia- Social and Behavioral Sciences, vol. 2, no. 3, pp. 6097–6108, 2010.

PRIM, “Le transport de marchandises dangereuses“, Prim.net, 2010. – Introduction, available at http://www.prim.net/citoyen/definition_risque_majeur/dossier_risq_transport/pageintroduction.htm

Q

Qiao Y., Keren N., and Mannan M. S., “Utilization of accident databases and fuzzy sets to estimate frequency of hazmat transport accidents,” Journal of hazardous materials, vol. 167, no. 1, pp. 374–382, 2009.

R

Radner R.. Team decision problems. Ann. Math. Statist., 33(3):857–881, 1962.

Raney B. and Nagel K., “An improved framework for large-scale multiagent simulations of travel behavior,” in 4th Swiss Transport Research Conference: Towards better performing European Transportation Systems. STRC, 2006, p. 305347.

Rasmy, M. H., Lee, S. M., Abd El-Wahed, W. F., Ragab, A. M., & El-Sherbiny, M. M. (2002). An expert system for multiobjective decision making: application of fuzzy linguistic preferences and goal programming. Fuzzy Sets and Systems, 127(2), 209-220.

Reilly, A., Nozick, L., Ningxiong, X., & Jones, D. (2012). Game theory-based identification of facility use restrictions for the movement of hazardous materials under terrorist threat. Transportation Research Part E, 48, 115–131.

Reynolds C. W., “Flocks, herds and schools: A distributed behavioral model,” in ACM SIGGRAPH Computer Graphics, vol. 21, no. 4. ACM, 1987, pp. 25–34.

Richards P. I., “Shock waves on the highway,” Operations research, vol. 4, no. 1, pp. 42–51, 1956.

Risk Assessment – Recommended Practices for Municipalities and Industry: available at http://psm.chemeng.ca/Products/Risk_Assessment_Recommended_Practices_0406292.pdf

Roncoli C., Bersani C., and Sacile R., “A risk-based system of systems approach to control the transport flows of dangerous goods by road,” Systems Journal, IEEE, vol. PP, no. 99, p. 1, 2012.

Russell S., Norvig P., J. Canny, J. Malik, and D. Edwards, Artificial intelligence: a modern approach. Prentice hall Englewood Cliffs, NJ, 1995, vol. 2.

S

Serafini, P., 2006. Dynamic programming and minimum risk paths. European Journal of Operational Research. Vol. 175, pp. 224-237.

Sewall J., Wilkie D., and Lin M. C., “Interactive hybrid simulation of large-scale traffic,” in ACM Transactions on Graphics (TOG), vol. 30, no. 6. ACM, 2011, p. 135.

Snedaker, S., 2004. The Best Damn Windows Server 2003 Book Period. Elsevier, Ch. Chapter 26 - Managing Web Servers with IIS 6.0, p. 895928.

Spaccapietra, S., Parent, C., Damiani, M.D., Macedo, J.A., Porto, F., Vangenot, C. (2008). A Conceptual view on trajectories. Data and Knowledge Engineering, pages 26–146.

Stewart, B. S., & White III, C. C. (1991). Multiobjective a*. Journal of the ACM (JACM), 38(4), 775-814.

T

Taniguchi, E., Shimamoto, H., 2004. Intelligent transportation system based dynamic vehicle routing and scheduling with variable travel times. Transportation Research Part C: Emerging Technologies 12 (34), 235 { 250,intelligent Transport Systems: Emerging Technologies and Methods in Transportation and Trafic.URL http://www.sciencedirect.com/science/article/pii/S0968090X04000221

Tomasoni, A. M., April 2010. Models and methods of risk assessment and control in dangerous goods transportation (dgt) systems, using innovative information and communication technologies. Ph.D. thesis, école Nationale Supérieure des Mines de Paris.

Tomasoni, A.M., Garbolino, E., Rovatti, M., Sacile, R. (2010). Risk evaluation of real-time accident scenarios in the transport of hazardous material on road. Management of Environmental Quality: An International Journal 21(5) 69-711.

TRANSIMS, T. R. of the University of California. (2003) Transportation analysis and simulation system (transims). [Online]. Available: http://ndssl.vbi.vt.edu/transims.php

Treiber M. and Helbing D., "Microsimulations of freeway traffic including control measures," arXiv preprint condmat/0210096, 2002.

U

V

Van Raemdonck, Koen, Cathy Macharis, and Olivier Mairesse. "Risk analysis system for the transport of hazardous materials." Journal of safety research (2013).

Verma, M. (2009). A cost and expected consequence approach to planning andmanaging tailroad transportation of hazardous materials. Transportation Research Part D, 14, 300–308.

Verma, M., Verter, V., & Zufferey, N. (2012). A bi-objective model for planning and managing rail-truck intermodal transportation of hazardousmaterials. Transportation Research Part E, 48, 132–149.

W

Whitham G. B., Linear and nonlinear waves. Wiley-interscience, 2011, vol. 42.

Wiley.Ji, B., Ji, S., Zhang, C., 2011. Gprs-based data real-time transmission system of water-quality monitoring. In: Electronics, Communications and Control(ICECC), 2011 International Conference on. IEEE, pp. 2072{2075.

Witsenhausen H. S. A counterexample in stochastic optimum control. SIAM Journal on Control, 6(1):138–147, 1968.

Wooldridge, M. (2009). An introduction to multiagent systems. Wiley.com.

Wooldridge, M., Jennings, N.R. (1995). Intelligent agents: Theory and practice. Knowledge engineering review 10(2), pages 115–152.

X

Xu, Z., Fang, Z. (2008). A clustered real-time remote monitoring system for out-of-hospital cardiac patients. In: BioMedical Engineering and Informatics, 2008. BMEI 2008. International Conference on. Volume 1., IEEE 610-614.

Y

Z

Zadeh, L. A. (1965). Fuzzy sets. Information and control 8(3), pages 338–353

Zhang H. M., “A non-equilibrium traffic model devoid of gas-like behavior,” Transportation Research Part B: Methodological, vol. 36, no. 3, pp. 275–290, 2002.

Zhang, J., Hodgson, J., Erkut, E., 2000. Using GIS to assess the risks of hazardous materials transport in networks. European Journal of Operational Research, Vol. 121, pp. 316-329.

Zilske M., Schroder S., Nagel K., and Liedtke G., “Adding freight traffic to matsim,” 2012. [Online]. Available: http://svn.vsp.tu-berlin.de

Zografos K. and Androutsopoulos K., “A decision support system for integrated hazardous materials routing and emergency response decisions,” Transportation Research Part C: Emerging Technologies, vol. 16, no. 6, pp. 684–703, 2008.

Optimisation multicritère des itinéraires pour transport des marchandises dangereuses en employant une évaluation en logique floue du risque et la simulation du trafic à base d'agents

Résumé: Le transport routier de marchandises dangereuses (TMD) est considéré comme l'activité la plus critique et complexe dans l'industrie du transport. Pourtant, il est l'un des facteurs les plus pertinents dans l'économie de chaque pays. Dans le but de soutenir les règlements et les normes sécuritaires régissant le TMD, cette thèse s'inscrit dans le cadre de développement d'un système de transport intelligent. Sa contribution principale est orientée vers l'optimisation multicritères d'itinéraires. Alors que le premier critère est le temps de déplacement, le second représente le risque d'accident entrainant la fuite de substance dangereuse. L'incertitude dans l'évaluation des risques est quantifiée utilisant le concept d'ensembles flous. Par ailleurs, un système de collecte de données a été mis en œuvre, pour la surveillance en temps réel des véhicules TMD. Enfin, pour le besoin de la simulation de trafic, des véhicules virtuels sont injectés dans le système de surveillance en temps réel.

Mots clés: Transport de marchandises dangereuses, Systèmes de transport intelligents, Système de surveillance en temps réel, Évaluation floue des risques, Optimisation multicritère des itinéraires, Simulation multiagent du trafic routier

Multi-criteria route optimization for dangerous goods transport using fuzzy risk assessment and agent-based traffic simulation

Abstract: The road transportation of dangerous goods (DGT) is considered as the most critical and complex activity in the transport industry. Yet, it is one of the most relevant factor in the economy of every country. With the aim to support the implemented regulations and safety standards governing the DGT, this thesis falls within the context of development of an Intelligent Transport System. Its main contribution is oriented towards the multi-criteria route optimization problems. While the first criterion is travel time, the second one is the risk of accident leading to hazardous substance release. The uncertainty within risk assessment is quantified using fuzzy sets concept. Besides, a data collection system, for real-time monitoring of DGT vehicles, was implemented as to be reliable, efficient and scalable. Finally, for the need of traffic simulation, virtual vehicles are injected into the real-time monitoring system.

Keywords: Dangerous Goods Transport, Intelligent Transportation Systems, Real-time monitoring system, Fuzzy Risk Assessment, Multicriteria route optimization, Multiagent-based traffic simulation