

6th Transport Research Arena April 18-21, 2016



A risk assessment for road transportation of dangerous goods: a routing solution

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Abstract

Improve road traffic safety is one of the most important objectives for transport policy makers in contemporary society, and represents a strategic issue for enhance life quality. Recently ISO 39001 (Road Traffic Safety Management Systems) introduced the guidelines of safety-based activities aimed to decreasing road accidents, in agreement with the Quality Management Systems (ISO 9000). Such guidelines are intended for infrastructure managers, administrators, and private entities, and defines a standard management for reduction of road risk.

In this context, the risk arising by dangerous goods transport represents a particular threat which needs strategies and tools to reduce risk rate of society, property and environment. Several decision making solutions for transport managers and public administration are defined, but two open points still exist. Firstly, there are not applications supporting for dangerous goods carriers in tactical and operational planning. The second point is related to impacts of traffic congestion on road accidents frequency: there is not a common approach for study and assessment these relationships.

The aim of this paper is to analyze the interactions between road traffic flow and frequency of accidents: the paper propose an integrated approach for the study of routing problems considering safety. The first part concerns a brief critical review on literature solutions. Following is presented a new approach to analyze a road accident involving a dangerous goods, focusing on the reason which lead to a leakage of hazardous materials. This paper presents an upgrade of a minimum cost routing problem for a road carrier considering also the risk related to dangerous goods. After a description on how computing risk concerning dangerous goods transportation in a routing choice problem, the paper describes a solution aimed at providing a tactical and operating decision-making tool.

The aim is to enable the carrier that transport dangerous goods to calculate the quantification of the risk for each specific trip in addition to operating cost for each specific transport. The added value of risk quantification could be used by transportation

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carrier in ISO 39001 to numerically prove his own safety-decisions to the control authority. The analysis developed has provided good results. The approach defined, albeit simplified, is a useful tool, especially when ISO 39001 standards will strengthen road safety.

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: dangerous goods transport; road traffic safety; accident road; congestion; routing problem

1. Introduction

Nowadays safety of dangerous goods transport is an interesting transportation planning topic. It regards road safety, goods storage, prevention and security. The key purpose is reducing the risk of hazardous accident (e.g.: harmful contamination, toxic emissions, fire and explosions) during travel or transport operations. The consequences of accidents involving dangerous goods may be very tragic for humans, especially when occur in urban areas densely populated, for environment (both for the life forms that live there and the economy which depends on it), or for property.

The international transport of dangerous goods by road, by rail or by internal water is regulated by European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN) and the Regulations concerning the International Carriage of Dangerous Goods by Rail (RID).

In 2012 ISO 39001 standard on Road Traffic Safety Management Systems (RTSMS) was introduced to enable an organization operating in the road traffic system to reduce consequences (death and serious injuries) of road traffic accidents which it can influence. ISO 39001 defines guidelines to promote and enhance risk management culture in this sector.

As well known, the international regulation framework of dangerous goods carriage (ADR, RID, AND, IMGD code and IATA code) defines safety technical requirements (e.g.: on classification, packaging and vehicles), the quantities allowed to transport, training requirements for personnel, obligations on transport documents, and so on, but provides no specific indications on how manage risk. Although, the Seveso legislation framework defines strictly requirements on risk management these are not applied to transport or to temporary storage (e.g. in a port). Hence, the ISO 39001 leads an added value also in the dangerous goods transport.

The application of the PDCA cycle of risk management could help dangerous goods carriage companies to implement appropriate strategies to prevent accidents, mitigate consequences, and verify the efficiency and effectiveness of the countermeasures adopted. Moreover, the ISO 39001 certification could lead economic benefits in terms of insurance cost reduction (for personnel and vehicles), enhance professional image, and prove responsibilities during lawsuits.

Considering a dangerous goods carriage company, the ISO 39001 standard represents an interesting tool to improve safety and quality in the transport service.

ISO 39001 is a voluntary standard. Promoting it to companies carrying dangerous goods means providing a tool that allows to accomplish the RTSMS requirements enhancing their competitiveness, in addition to the right training on risk management. Route optimization software for haulage generally provides the best route on transport costs, logistics costs, driver's breaks, traffic conditions, road network's restrictions (for weight, dimensions, goods, or other as "for residents only"). Referring the dangerous goods carriage, route optimization software normally provides data on banned thoroughfares throughout Europe. It takes into account (or provides) no information on travel risk.

In relation to scientific research, the routing problem of dangerous goods transport was generally dealt like a transportation planning issue for Public Administrations by the scientific research. The goal of this paper is to study the interactions between congestion and road accidents proposing a method to consider the risk in the route of vehicles carrying dangerous goods. Starting from an , the method proposed seeks to improve it with the risk quantification.

This paper is presented as a start point of the research. If the method should be received widespread recognition by stakeholders as a reliable guideline to quantify risk, it will provide route optimization software which could lead an added value to the RTSMS.

The paper is structured as follows: literature review; problem description; methodology description; a case study application for motorway; presentation of further developments.

2. Literature review

During the last twenty years, several researchers have dealt the issue of risk assessment on the dangerous goods transport (Yang et al., 2010). These studies were focused especially on safe transportation using pipelines (Citro and Gagliardi, 2012), railway transportation (Liu et al., 2013; Saat et al., 2014), and road transports (Fabiano et al., 2002, 2005; Gheorghe, 2006; Yang et al., 2010).

The research on road transport of HazMat (Hazardous Materials) follows three topics. The first is related to methodologies aimed at improving emergency response based on road properties, weather conditions and traffic factors (Fabiano et al., 2005). The second is based on methodologies for survey and accident risk analysis from historical data aimed at divulging accident characteristics such as frequency of occurrence, accident consequences, and identification of causal factors (Fabiano et al., 2002; Yang et al., 2010; Shen et al., 2013). The last topic focuses on decision making aimed at improving choice of truck capacity (Guo and Verma, 2010) and route (Fabiano et al., 2002).

Generally, a road accident involving dangerous goods can damage road infrastructures, community (for economic and environmental consequences of leakage), and humans. In relation to hazards for humans, road transportation of dangerous goods creates risk for people present on road (users), and people along the routes (surrounding population resident). It is essential therefore get information on frequency and consequences which a road accident involving dangerous goods generates. Frequency and impacts can depend on: the effects of an accident and its duration (Adler et al., 2013); category and dangerousness of goods transported (Amezaga et al., 2015); type of accident, primary or secondary crashes (Hong Yang et al., 2014); road typology (motorway, arterial, urban road, etc.); road sections, for example straight, curved, tunnel, bridge, etc.. (Kinateder et al., 2015); surrounded areas crossed; pavement structure; speed.

A very important issue is relationships between traffic congestion and frequency/impact of road accident. Traffic congestion and road accidents are two important external costs of transports produced by road users (EC, 2008) with relevant impacts on road users and community. The reduction of their impacts is one of the primary objectives for transport policy makers.

Traffic congestion is an omnipresent phenomenon mainly during rush hour in densely-populated areas (Arnott and Small, 1994; Downs, 2005). Literature defines two traffic congestion types: recurrent, if depend on relevant flows and density of traffic; non-recurrent, when it is the result of external events such as an accident. Some authors have studied the problem of interrelationship between traffic congestion and road accident (Shefer, 1994; Shefer and Rietveld, 1997, Quddus et al. 2009). Other authors have defined risk assessment for dangerous goods carriage (Cassini, 1998, Fabiano et al. 2002, Fabiano et al. 2005).

Traffic congestion and road accidents are closely related by an inverse relationship which can pose a potential dilemma for transport policy makers (Shefer and Rietveld, 1997). Shefer (1994) has proposed an inverse relationship between congestion and road fatalities, in which volume over capacity ratio was used to measure the level of congestion. A further study by Shefer and Rietveld (1997) investigated the link between congestion and safety on highways. Starting from the hypothesis previously used, they compared fatality rates throughout the day, and found that during peak hours the fatality rate is lower than that at other times of the day. Due to data unavailability they examined a proposed model, using a simulated dataset rather than real-world data. Quddus (2009) underlined that this studies tend to use an analytical approach and a weak proxy for traffic congestion, so as such, more robust empirical evidence, and a precise congestion measurement, are required. However, collecting data for multiple year to describe the relationship between traffic congestion and road accidents is an expensive and time consuming activity.

Quddus et al. (2009) analyzed road accidents with personal injuries for the M25 motorway (London, UK), and found that in their case study traffic congestion has no impact on the frequency of accidents (either for fatal and serious injury accidents or for slight injury accidents). Although this result, the authors asserted that further research is needed to fully understand the effects of traffic congestion on road accidents. On this topic, Pasidis (2015) started a new work not finished yet. The author has been using new data sources and modern identification techniques to estimate the effect of an accident's occurrence on the observed average speeds using the observed patterns of traffic

flows in England's highways in the period 2007–2013. For the author, these data have never been used before in an academic paper, so the result of his research will be surely interesting.

In relation to the main topic of this paper, Fabiano et al. (2002) defined a method to calculate the frequency of a road accident involving dangerous goods on highway. Fabiano et al. (2002) referred to all types of road accidents, including also the PDO-s (accidents with property damage only). The authors defined that the frequency depends on: geometric factors; slopes; number/width of lanes; types of road section (straight, bend, tunnel or bridge); weather; traffic flow.

Relationship between traffic congestion and road accidents proposed by the formulation of Fabiano et al. (2002) will be discuss in next section .

This paper deals with the risk formulation for dangerous goods transport, and describes the relationship with the traffic flow according to objective criteria, hence depending by the Levels of Service (LoS). In following parts, the parametric method to quantify risk is presented, referring to a common function for routing optimization. The frequency of road accidents and the consequences of road accidents are parameterized for different LoS in case of recurrent congestion, and the risk is set as an added cost in the path choice model.

3. Problem description

Fabiano et al. (2002) argued that a proper evaluation of the expected frequency is the starting point for an effective approach to risk modelling. The frequency of an accident on the i -th road section can be expressed by the following equations:

$$f_i = \gamma_i L_i n_i \quad (1)$$

$$\gamma_i = \gamma_0 \sum_{j=1}^6 h_j \quad (2)$$

where γ_i is the expected frequency on i -th road section (accident km^{-1} per vehicle), 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 enhancing/mitigating parameters.

Referring to a scenario S , the frequency of a road accident on the i -th road section, can be expressed as:

$$f_{i,S} = \gamma_i L_i n_i P_S P_I \quad (3)$$

where P_S is the probability of evolving scenarios of type S , following the accident initializer (i.e. collision; roll-over; failure, etc.), and P_I is the ignition probability for flammable substances involved in the accident.

The parameters h_j identified by Fabiano et al. (2002) are: h_1 , which depends by road section geometry (straight, bend, etc.); h_2 , which depends by slope; h_3 , which depends by number and width of lanes; h_4 , which depends by weather conditions; h_5 , which depends by traffic flow (congestion); h_6 , which depends by road type (tunnel, bridge, etc.).

These parameters are tabulated and assessed arbitrarily as a range of discretionary values by the authors, and used to calculate the frequency of road accident on the i -th road section. Note that the parameters h_1, h_2, h_3, h_5 , are more or less a qualitative expression of the LoS parameter (HCM, 2000). Moreover, it is not clear what is the link between the traffic flow and the probability P_S of evolving scenarios (S). In particular for collisions and roll-over what is the link between the expected vehicle speed due to the traffic flow density on the i -th road section (or geometric characteristic of the i -th road section) and the crash dynamic (or crash energy).

The common evidence would suggest a parabolic relationship between density and crash energy. When densities increase, there would be first a positive relationship due to the increase in the numbers of cars in the system. However, when density becomes so high that speeds are influenced negatively, the crash energy will decrease (Shefer and Rietveld, 1997). Hence, in relation to the resistance characteristics of ADR packaging/ADR tank

truck/ADR tank container, the traffic flow density and the probability of leakage of hazmat should convey this tradeoff.

This paper presents a proper evaluation of the expected frequency on the i -th road section using the range of traffic flow defined by Highway Capacity Manual (2000), namely LoS. The Level of Service is a quality measure describing operational conditions within a traffic stream, generally in terms of service measures such as speed and travel time, freedom of maneuver, traffic interruptions, and comfort and convenience (HCM, 2000). It is authors' opinion that this single parameter can substitute the parameters h_1, h_2, h_3, h_5 , proposed by Fabiano et al. (2002), and can give more clearness and clarity to the evaluation of expected frequency on the i -th road section. Moreover, the LoS parameter allows to describing better relationship between expected speed of vehicles and the geometry of road section, and the traffic flow density.

This paper refers to motorway sections. In particular, about the risk trend concerning road accidents involving dangerous goods due to collisions, it is important to note that:

- Better LoS (A, B) generates higher speeds, high freedom of maneuver (acceleration, deceleration, lane changing, etc.), and less congestion. So, road accidents are more rare, but in case of dangerous goods carriage the leakage probability is higher. Although, the number of vehicles on road are less, so fewer road users are subject to risk, they are more exposed, like the surrounding population resident.
- Medium LoS (C) generates a more regular speed of the vehicles in relation to the traffic flow, hence less freedom of maneuver. Frequency of road accidents begins higher because there are more vehicles on the road. Speed of vehicles begins to decrease, but the probability of leakage starts to decrease only when crash energy becomes limited.
- Lower LoS (D, E) generates low speeds, limited freedom of maneuver, and a considerable congestion. So, road accidents are more frequent, and there are more road users on the road, but on the other hand the probability of leakage is lower because crash energy is limited. Although, road users and surrounding population resident are less subject to risk, in case of leakage of hazmat traffic congestion leads to a late emergency response. Risk analysis has to take into account also this point.

The frequency of road accidents is evaluated according to LoS, as well as the consequences due to hazmat leakage. The risk is so conveyed in the function of routing optimization as an external cost. Clearly, these elements vary greatly with LoS, producing changes in the total cost of transport.

Common functions of routing optimization refer to the general function of direct cost of freight transport which can be formulated as follows:

$$C_d(A-B) = \sum C_{d|h} n.h(A-B) + \sum C_{d|km} n.km(A-B) + \sum C_{da}(A-B) \quad (4)$$

where:

- ✓ $C_d(A-B)$ is direct cost of freight transport from A to B;
- ✓ $\sum C_{d|h}$ is summation of unit costs (per hour) of use of the transport resources whose use is a function of time;
- ✓ $n.h(A-B)$ is number of hours required for loading, transport, and unloading of goods;
- ✓ $\sum C_{d|km}$ is summation of unit costs (per km) of use of transport resources whose use is a function of distance;
- ✓ $n.km(A-B)$ is number of kilometers (A-B);
- ✓ $\sum C_{da}(A-B)$ is summation of other direct costs (tolls, charges, wear, etc.).

The aim is to consider in the above cost function (see. eq. 4) also a component related to risk that depends by frequency and leakage probability. So, in relation to eq. (4), the cost of transport (meaning the direct cost plus the risk associated to a dangerous goods transport) can be described by eq. (5).

$$C_{DDGR}(A-B) = C_d(A-B) + \sum_1^4 R \quad (5)$$

where:

- ✓ $C_{DDGR}(A-B)$ is direct cost plus dangerous goods risk of transport from A to B;
- ✓ $C_d(A-B)$ is direct cost of freight transport from A to B;

✓ $\sum R$ is summation of risk due to collisions with other vehicles, accident as single vehicle, technical failure and other hazers.

In this way, the carrier can consider risk in the path choice process, and can record it in line with ISO 39001.

Next chapter describes the proposed methodology to analyze risk and to assess $\sum R$ of eq. (5). An important assumption is that speed, density, delay, and flow/congestion are considered in steady-state conditions. Moreover, the function cost defined not considers loading and unloading phases.

4. Methodology

4.1. Identification of the hazardous road accidents for dangerous goods transports

Road accidents can be split in collision between vehicles (which include frontal collisions, frontal-lateral collisions, lateral collisions, rear-end collisions and collisions with vehicles in arrest), accidents of single vehicle (as bumps in gear, skidding, etc.), and investment of pedestrians. Weather condition is a negative factor which increases the likelihood of human error and loss of vehicle control, but the occurrence of a mode of road accidents over another in general depends by the traffic flow, road characteristics, and road user's behavior. These elements change significantly both within the same country (e.g. road characteristics), and country by country (e.g. driver behavior). For instance, statistical data published by ISTAT (Italian National Institute of Statistics) in 2014 show that in Italy the collisions between vehicles amount to 72% of road accidents against 28% of accidents of single vehicles.

Dangerous goods carriage by road must satisfy to ADR requirements: this means that three important elements have to be taken into account when analyzing the origin of a road accident involving hazmat. These concern the packages, meaning where and how these materials are transported, the vehicle used, and the drivers.

ADR code imposes specific requirements for vehicle safety systems, in particular for the braking systems and the ABS system. In addition, ADR transports must comply with more restrictive speed limits: e.g. the speed limit on motorway is 100 km/h for vehicles with mass exceeding 3.5 t and up to 12 t, and 80 km/h with mass exceeding 12 t (except Class 1).

Hazardous materials are transported with specific packages, tank truck or tank containers which must respond to ADR technical requirements corresponding to the material hazardousness in terms of stress resistance. Hence, the leakage of hazardous materials can occur for a technical failure to the package or to a component of the trailer or container, as well as for an impact with energy sufficient to cracking them.

Referring to the road accident dynamics and above considerations, a hazard identification was addressed to identify the Events Producing Conditions of Leakage (EPCLs), meaning the circumstances that lead to a functional loss of packaging. In general, the EPCLs can refer to two accident mode: a technological failure or an impact equal or more than the packaging ultimate strength.

The technological failures refer mainly to parcels with mechanical or technological elements that ensure containment and the transport safety. For instance, the tank trucks (or tank containers) have technological systems as temperature and/or pressure sensors (working for monitoring systems to check the state of hazardous material during the transport), and mechanical components (as vapor vents, man holes and covers, discharging valves, safety valves, and so on). Usually these are standard elements which comply with technical codes, and whose reliability could be considered as an input data.

To consider impacts, an EPCL requires a minimum energy, because ADR packaging are designed in order to pass specific stress test (e.g. drop test, leakproofness test, internal pressure test, stacking test). Hence, the minimum energy required by an EPCL impact means that collisions between vehicles, or collisions with external objects, or overturning, have to occur to a minimum speed. Obviously, the minimum speed of impact too gets an EPCL depends to the accident dynamic: impact direction and mass puts into play.

The results of the hazard identification for an ADR vehicle point out that the Events Producing Conditions of Leakage of hazardous materials on the road are:

1. Collisions between vehicles (with another vehicle in gear; with another vehicle in arrest, except vehicle in stop)

2. Accident as single vehicle accident collisions (with external object, included vehicle in stop; overturning, as single vehicle accident)
3. Technical failures (on the vehicle; on the package, tank truck, tank container)
4. Others (unforeseen events).

In the item called “Other”, unforeseen events are taken into account. Unforeseen events should be considered because the nature of the road accidents is strongly empirical, deeply influenced by human factor. Data on driver behavior and dynamic of collisions, which leading to road accidents usually are incomplete. An “unforeseen events” estimation can be made using national road accident statistics which usually record this specific item.

“Collisions between vehicles” and “accident as single vehicle accident” are analyzed in following sections setting forth the approach to estimate the risk of an ADR transport in relation to traffic density, traffic free-flow-speed, traffic average-flow-speed, and weather conditions.

4.2. A new approach for risk assessment in road transport of dangerous goods

As described, the main goal of this paper is to introduce in the eq. (4) the assessment of risk associated to the transport of dangerous goods in order to create a tool to support carriers in ISO 39001. In relation to hazards identified in the previous section 4.1, the cost of transport (meaning the direct cost plus the risk associated to a dangerous goods transport) can be described by eq. (5).

The new approach for road accident frequency assessment introduces a correlation between LoS and risk. The use of LoS allows two important improvements in road accident frequency estimate. The first is a more objective description of road characteristics (geometric properties and traffic flow typology). The second is to consider the road accident frequency in relation to traffic density (parameter inversely proportional to road speed), and get a more accurately definition of the road congestion's contribution.

The risk associated to a road accident of an ADR transport on the i -th motorway section can be expressed by the following equation:

$$R_{RA/i} = f^{\lambda_i H_i} (C_{veic} + (d_{p/i} A_i) + (r_O N_{ln} d_{R(i)}) C_{HLL})^{\beta_i} L_i \quad (6)$$

where:

- ✓ $R_{RA/i}$ is the risk associated to a road accident associated of an ADR transport on the i -th motorway section, expressed in €
- ✓ f_{FV} is the road accident frequency for freight vehicles expressed in [n° accident/km];
- ✓ $d_{p/i}$ is the density of population in leaving in the area crossing the i -th motorway section;
- ✓ A_i is area of impact of the dangerous goods release;
- ✓ $d_{R/i}$ is the road density express in terms of number of vehicle per km per line;
- ✓ N_{ln} is the number of line of the motorway;
- ✓ r_O is the occupancy rate of passenger vehicle;
- ✓ C_{HLL} is the cost of human life loss in terms of potentiality to create income per person;
- ✓ L_i is the length of the the i -th motorway section;
- ✓ λ_i is a parameter describing the weather conditions the i -th motorway section;
- ✓ H_i is a parameter describing the variation of the road accident frequency in relation to the traffic density in the i -th motorway section;
- ✓ β_i is a parameter describing the variation of the consequences in relation to the road speed the i -th motorway section.

λ_i , H_i and β_i are modification parameters used to represent the influence of weather, traffic density d_i , average-flow-speed AFS_i and free-flow-speed FFS_i of the i -th motorway section. λ_i is the parameter taking into account weather. H_i and β_i are parameters that describes the mutual relationships between flow and accident frequency.

Concerning weather, λ_i is set equal to 1 if there are ideal travel conditions (meaning sunny). If the ADR transport is carried in weather condition worse than ideal one, the λ_i parameter decreases. The relationship with road accident

frequency shows that if the λ_i parameter decreases of 10%, the frequency f increase ten times. In following pages is describes how assess the λ_i parameter. H_i allows to link the road accident frequency trend with specific traffic density d_j of the i -th motorway section. In particular, it represents the road accident frequency increase during congestion. The H_j parameter is defined by the following equation:

$$H_i = 1 \cdot 10^{-5} d_i^3 - 1 \cdot 10^{-3} d_i^2 + 1,6 \cdot 10^{-2} d_i + 0,95 \tag{7}$$

β_i is the modification parameter of the consequences due to a road accident. In the relation to the transport of dangerous goods, β_i is a function of traffic density d_i , average-flow-speed AFS_i and free-flow-speed FFS_i of the i -th motorway section. These are the variables which determine the occurrence of an impact sufficient to originate a release. The β_i parameter is defined by the following equation:

$$\begin{cases} \beta_i = (-2 \cdot 10^{-5} d_i^3 + 1,2 \cdot 10^{-3} d_i^2 - 2,63 \cdot 10^{-2} d_i + 1,023) - \left(\frac{FFS_i - AFS_i}{100 FFS_i (2 + d_i)} \right) & \text{for } 0 \leq d_i \leq d_{i,max-flow} \\ \beta_i = (-7,3 \cdot 10^{-3} d_i + 0,99) - \left(\frac{FFS_i - AFS_{j,max-flow}}{100 FFS_j (2 + d_{j,max-flow})} \right) & \text{for } d_i > d_{i,max-flow} \end{cases} \tag{8}$$

4.3. Road accident risk assessment for transport of dangerous goods.

In the following part, the risk assessment associated to ADR transport is presented applying the eq. (6) for a case study of motorway section located in Italy. The aim is to describe how the risk of road accident changes the transport cost per kilometers in relation to the traffic density and the traffic speed.

Firstly, the estimate of the road accident frequency for motorway f_{HV} and the cost of human life loss C_{HLL} is required. In this case study were used Italian national statistics. It's important to note that eq. (6) application must be strictly linked to the country where the motorway is located. Consider data from statistics of other countries can lead to important assessment errors. Nevertheless, the presented methodology is replicable.

Looking at statistical data from 2004 to 2014 supplied by AISCAT (Associazione Italiana Società Concessionarie Autostrade e Trafori), the freight vehicles' accidents on Italian motorways amount to 17.819, for 2,053E11 number of vehicle kilometers (VKT). Hence, the road accident frequency for freight vehicles on the Italian motorway (see the term f_{HV} in the eq. 6) can be estimate 8,68E-8 road accidents per kilometers travelled.

To estimate the cost of the human life loss the paper used statistical data supplied on the average cost of human death (CM). This measure is provided by Ministry of Infrastructure and Transport of Italy (MIT, 2012). Referring to eq. (9), CM is calculated as the sum of the average cost of human life (CVU), resulting from the average lost productivity, and the average non-pecuniary damage, and the average healthcare cost (CS).

$$CM = CV_u + CS \tag{9}$$

The study (made in 2010) is based on ISTAT data, and shows that the CVU is 1,502,025 EUR per human death, composed of 940,291 EUR of average lost productivity, and 561,734 EUR of average non-pecuniary damage. CS is 1,965 EUR per person.

So, the cost of human death (CM) is equal to 1,503,990 EUR per human death. This data is used to estimate the human life loss in economic terms (see the term C_{HLL} in the eq. 6).

To compute the people involved in an ADR accident a tanker truck transporting Ammonia is considered. For this type of dangerous goods transport the release is assumed for 300 meters extended, equal to an exposed area of 2,83E5 square meters.

As mentioned above, λ_i (see eq. 6) provides a measure of how the weather conditions affecting road accident frequency. The estimate is carried on analyzing the number of road accident occurred and number of deaths-injured during different weather conditions (sunny, rainy, snow, wind, hail, fog, others). However, this data (supplied by ISTAT) must be correlated to the number of sunny day, rainy days, etc., recorded in the area where the i -th motorway section is located. Hence, the number of deaths-injured per accident per day can be estimated, and the λ_i parameter can be linked to the severity variation. Table 1 presents an instance of the λ_i parameter definition.

Table 1. An instance of the λ_j assessment for a j-th motorway stretch located in Italy.

Weather conditions	Days	Number of road accidents	Number of deaths-injured	Number of deaths-injured/accident*day	λ_j
Sunny	230	6,678	11,353	6,76E-3	1
Rainy/snow	80	1,257	2,122	2,16E-2	0.9
Others	55	1,469	2,391	1,16E-1	0.8

Following chapter describes the results of case study referring to a sunny day ($\lambda_j = 1$).

5. Results

This chapter describes the results of direct cost plus road accidents cost per kilometer for a case study.

The case study assumes that road section can be assimilated to a multilane motorway; hence the risk assessment was conducted in relation to LoS parameter.

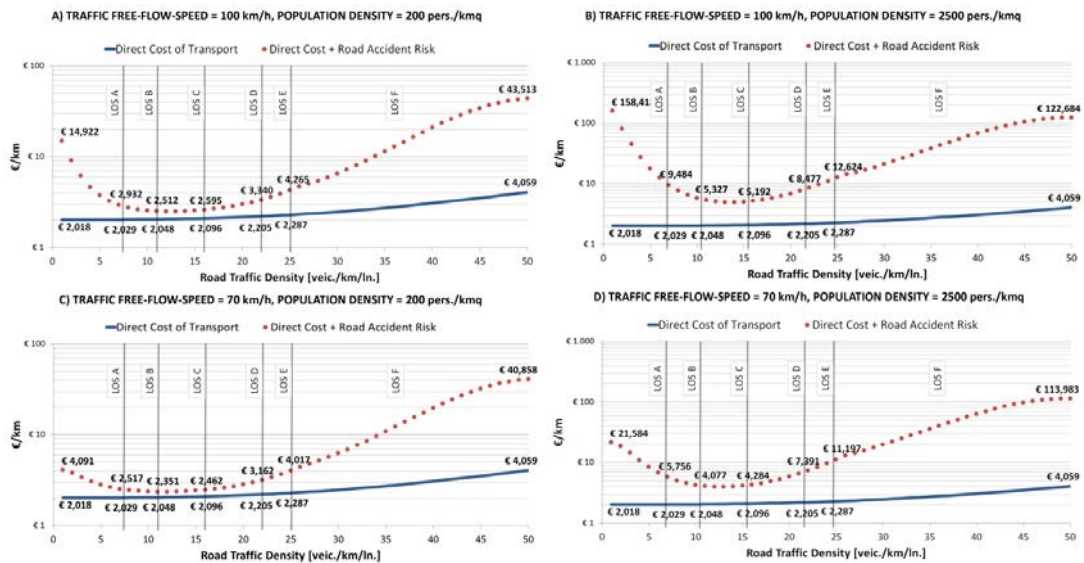


Fig. 1. Direct cost + Risk road accident cost for: A) TFF = 100 km/h and Dab = 200 pers./kmq, B) TFF = 100 km/h and Dab = 2500 pers./kmq, C) TFF = 70 km/h and Dab = 200 pers./kmq, D) TFF = 70 km/h and Dab = 2500 pers./kmq.

Figure 1 shows the graphs of the cost per kilometer in relation to the traffic density in terms of veic./km/ln. Different scenarios are presented, for sparsely populated areas (d = 200 pers./kmq, see fig. 1-A and 1-C) and for densely populated areas (d = 2500 pers./kmq, see fig. 1-B and 1-D). Moreover different FFS values are considered in accordance to the HCM2000: 100 km/h (see fig. 1-B and 1-D), and 70 km/h (see fig. 1-A and 1-C).

The results underline how the cost of transport has a more highlighted minimum corresponding to the LoS C for the densely populated scenario, while for the sparsely populated scenarios the variations between one LoS area to another are lower. As predictably, the reduction of free-flow-speed produces a reduction of transportation cost in particular for the LoS A. For LoS F congestion area the results are more or less the same for all scenarios.

6. Conclusions

The purpose of this paper is to identify the components correlated to the risk of dangerous goods carriage by road. These components are very difficult to define in detail. The paper proposes some simplifications, and for sure it leaves many open points for future developments.

The cost function proposed in eq. (6) represents a first step of study to model the risk, and introduce it in the function of routing optimization for dangerous goods transportation. The method proposed for a motorway case

study describes risk on the i -th road section using LoS parameter, the AFP, and the FFP. This gives more clearness and clarity to the evaluation of expected frequency of road accident on the i -th road section. Moreover, the correlation between risk of road accident involving dangerous goods and traffic density, traffic FFS, and traffic AFP qualitatively fulfil the trend waited by the described tradeoff of traffic congestion and frequency of road accidents. The result achieved represents a step forward against the previous formulations, and responds to the open points mentioned in the problem description.

Hence, next step will be the validation with a real case study of the parameters composing the eq. (6). In this phase an empirical confirmation of the hypothesis assumed will be sought considering various goods type and analyzing accidents and energies involved (speed, mass loaded, leakage possibility, etc.).

The final goal of the paper's topic concerns the realization of a solid decision-making tool with the objective to offer the model as risk assessment technique in route optimization software. This will allow to record the risk associated to the ADR truck's route, and hence support a PDCA process to reduce risk and enhance safety of the dangerous goods carriage by road, in compliance with the ISO 39001. For the road carrier, this tool could represent an opportunity to publicize to the market, to the authority, and to the stakeholders, the transportation service quality in terms of residual risk.

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