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# Road Users Exposed to Harm from Transportation of Dangerous Goods - Definition and Estimation

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The Italian Interreg Project DESTINATION was intended to acquire data on the transportation of dangerous goods and use them, developing a tool to protect the territory. The Project developed a risk analysis model for examination and assessment of the elements exposed to harm in the event of accident scenarios involving hazardous substances. Defining the risk model, the need emerged for a procedure able of explicitly estimating the number of road users that could be affected in case of dangerous goods accident. After a brief presentation of the risk model, this paper describes the method adopted for the quantification of the possible involved road users, in coherence with the Project's objectives and requirements. Due to the specific nature of the subject, it was necessary to consider parameters not included in traditional vehicle queuing models, such as the possibility of assessing users in transit on roads not directly affected by the accident and of differentiating analyses depending on the temporal development of the event (instantaneous vs. non-instantaneous events).

## 1. Introduction

Project DESTINATION started in 2010 and completed in 2015 and it involved the Piedmont, Lombardy and Valle d'Aosta Regions as well as the Autonomous Province of Bolzano/Bozen, Italy, and Canton Ticino, Switzerland. It deals with the issue of safety of Dangerous Goods Transport (DGT), which can highly benefit from outcomes of research. Different areas of the issue are investigated in recent studies, such as the emergency management in Hemmratian et al. (2017) and the route optimization in Li (2017).
Tools for risk assessment and for data analysis are helpful to increase safety of DGT. DESTINATION project led to the creation of an information system defined GIIS (Global Integrated Information System) for sharing, processing and analysis of environmental, local territorial and technical data on DGT by road.
The GIIS allows the identification of measures designed to mitigate DGT risk, the monitoring of DGT through On-Board Units and Gates and a more efficient emergency management in case of a significant event. The creation of the GIIS required the definition of a DGT risk analysis and assessment model consistent with the classical risk formula (ISO/IEC, 2014) and based on the actual availability of data from the partners.
The risk analysis model, able of considering both the populations and environments affected because of a DGT accident, is presented by Orso Giacone et al. (2012) and by Studer et al. (2012), which provide a detailed description. This paper is intended to illustrate the methodology used to estimate the road users affected by a DGT accident.

## 2. The Affected "Road Users"

The approach used to estimate the number road users affected by a DGT accident is described below.

### 2.1 Affected Populations in Project DESTINATION

The categories of affected populations considered by Project DESTINATION are the resident population, the variable tourist population, the workers and the users of various territorial structures (industry and services, hospitals and schools, medium and large shopping centers) and the road users.

Unlike the affected environments, described in detail in Gandini et al. (2015), which are heterogeneous in nature, the affected populations are homogeneous and therefore "summable", constituting, in their entirety, an exposure indicator defined as "equivalent population".
The number of affected subjects is estimated by overlapping the DGT accident scenario harm zones onto the layers describing the facilities where the various affected populations are located: built-up areas, industrial zones and healthcare, education and commercial facilities. In theory, the definition of road users is not dissimilar to that of the other affected population categories. However, a series of characteristics (their linear, as opposed to aerial, positioning and high dynamicity and the limited availability of data from the Project's partners) necessitated the implementation of a specially-developed methodology.

### 2.2 Methodological Remarks

To estimate the number of affected *road users*, it is necessary to acquire an affected vehicle density value, which relates the total road user value to the unit of road length. By multiplying the said density by the length of the road sections affected by the harm zone and using appropriate vehicle occupation coefficients, it is possible to estimate the number of users potentially harmed. The question of vehicle density definition has been widely examined, and there are numerous queuing models available which are capable of exhaustively and fully simulating the phenomenon of queue formation and of yielding adequate quantification. However, due to the specific nature of the DGT issue, certain original parameters come into play which the Project's partners have deemed significant and worthy of detailed analysis.
The first noteworthy parameter is the need to consider the *temporal duration* of the DGT accident scenarios considered in the risk model:

- Instantaneous scenarios: these occur in an extremely short time, affecting road users in very close temporal proximity to the accident site. Take, for example, an explosion.
- Non-instantaneous scenarios: these occur over a longer period and also affect road users temporally distant from the accident site. Take, for example, the dispersion of toxic substances into the air.

The second noteworthy parameter, a consequence of the dichotomy described above, is the occurrence, in the event of a DGT accident, of various *affected road user typologies*. Indeed, when a DGT accident occurs, a harm zone is defined, within which the number of road users involved depends on the temporal duration of the accident scenario. In the case of instantaneous scenarios, which occur in a particularly short time (ignition of an extremely flammable or explosive substance, for instance), vehicle queues potentially exposed to harm from DGT are not determined. All users, both those located on the road directly affected by the event and those on adjacent roads are equally affected at the moment when the event occurs. Road users belonging to this immediately affected category are defined as *local area road users* and constitute the only users exposed.
In the case of non-instantaneous scenarios, on the other hand, a second category must also be taken into account, consisting of users who are stuck in a queue and therefore exposed to the consequences of the non-instantaneous scenario developing. They are the users travelling on the road on which the accident occurs and therefore obliged to stop.

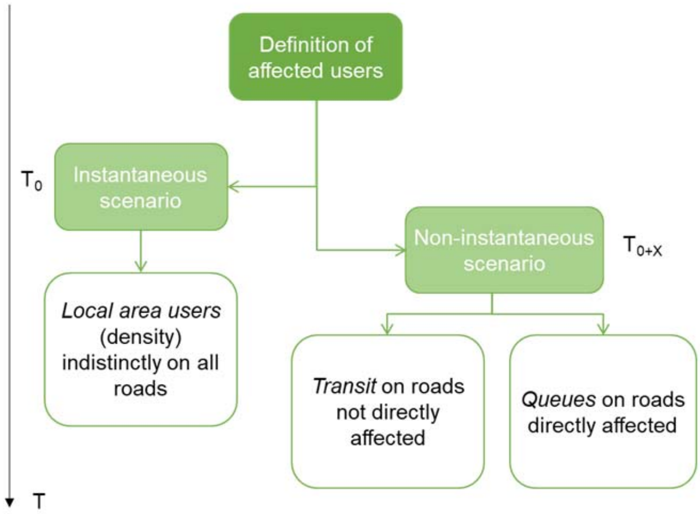


*Figure 1: Affected user typologies depending on the development of the DGT accident scenario.*

These users are defined as *queuing road users*. This category does not, however, include users travelling on parallel roads (even the roadway parallel to the one on which the DGT accident occurs, on a road with separate roadways) or intersecting the road on which the accident occurs and who, even after the accident, continue their movement, thus determining a third category of affected users defined as *users in transit*. Figure 1 illustrates the various affected user possibilities depending on the parameters described in the text.
Whatever the temporal duration of the scenario and the user typology, quantification of the exposed road users requires data capable of describing the traffic on the roads analyzed as well as information on the physical characteristics of the road sections, such as width or number of lanes.

### 2.3 Proposed Calculation Methodology

As illustrated, to define the total number of road users within accident scenario harm zones, it is essential to take into account the temporal development of the accident scenario as this determines the calculation methods and the user typologies affected. Having defined the moment when a scenario develops as $T_0$, it is possible to define in detail the dynamics described above, using different calculation methods depending on whether the scenario is instantaneous or non-instantaneous.

#### Instantaneous Scenarios

All road users located on road sections that fall within the harm zone (buffer) at moment $T_0$, when the accident causes its impact, are considered affected.
The effects of the scenario are immediate and are over in a time period so short as to be deemed negligible. Based on the definitions provided, therefore, instantaneous scenarios only affect local area road users.

#### Non-instantaneous Scenarios

In this second case, the impacts of the DGT accident scenario do not take place immediately but, rather, over a certain time period which varies depending on the scenario (for example, the type of rupture of the container and the substance involved). Using moment $T_{0+1}$, it may be presumed that additional vehicles will continue to arrive in the accident zone. These will travel on the affected roads (i.e. the roads which fall within the harm zone but not the one on which the accident occurs) and will tail back on the road on which the accident occurs, probably obstructed by the vehicles involved in the accident.
For this reason, non-instantaneous scenarios require the definition of a *Queue formation time* - Qt, whose duration depends on the type of accident. This time period may be defined as the interval between release of the load and formation of the queue.
The table below shows the queue formation time on defined intervals based on the scenario considered. In particular, the scenarios implemented under Project DESTINATION can be attributed to the following three classes of scenario, shown in Table 1.

*Table 1: K-th queue formation time for non-instantaneous scenarios*

| Scenario Class | Queue Formation Time - $Qt_k$ |
|---|---|
| Immediate ignition | 20 seconds |
| Delayed ignition | 60 seconds |
| Toxic dispersion into the air | 500 seconds |

Using these temporal hypotheses, two different types of road users within the harm zone can be identified:

- Road users in transit: users travelling on parallel roads, potentially including users of the opposite carriageway in the case of roads with two or more carriageways, or on roads intersecting the one on which the accident occurs and who are, in any case, able to continue moving after the accident. These users may only be located on affected roadways.
- Queuing road users: users travelling on the road on which the accident occurs and who are unable to move because of the accident. These are the users likely to suffer the most serious consequences of a DGT event. Indeed, they are typically near the event with no means of escape, being stuck in the queue created because of the accident. These users may only be located on the accident site roadway.

Whatever the type of road users being estimated, the number of affected users exposed is estimated through definition of the vehicle density per unit of road length, based on traffic data - i.e., in the first instance, the Average Daily Traffic - ADT, which represents the average of a series of daily surveys conducted on conventionally set days for any road - and on the average speed - s of the vehicles on the roads examined. Only considering the queuing road users, however, is it necessary to extend the exposed vehicle count to the

queue formation time. For this operation, it is also necessary to acquire data on the number of lanes per traffic direction.
Once the vehicle flow, based on the ADT and average travelling speed, is known, it is possible to estimate the linear vehicle density per kilometer, taking into account Eq(1).

$$density[\frac{veh}{Km}] = \frac{flow\ [\frac{veh}{day}]}{speed\ [\frac{Km}{h}]} \times \frac{1}{24[h]} \quad (1)$$

## 3. Calculation of the Number of Road Users

### 3.1 $T_0$: Number of local area vehicles exposed

Therefore, in order to calculate the number of vehicles located on a road at the moment when the accident occurs, it is necessary to acquire specific data on the road involved. In particular, data on the ADT and average travelling speed of the different types of vehicles (light and heavy) are required. The parameters of the road graph used must, therefore, include this information which is used to calculate the density by means of Eq(2):

$$density_{R,T}\ [\frac{veh}{Km}] = \frac{ADT\ _R[\frac{veh}{day}]}{s_{R,T}[\frac{Km}{h}]} \times \frac{1}{24[h]} \quad (2)$$

Where:
*R*: road considered
*T*: vehicle typology (light vehicles and heavy vehicles)
Once the vehicle density on the relevant road sections has been calculated, it is possible to calculate the number of vehicles that fall within the harm zone by multiplying the vehicle density by the length of the road affected by the accident and therefore included in the harm buffer. This operation, described by Eq(3), is performed automatically by the GIIS.

$$local\ area\ vehicles[veh] = density_{R,T}\ [\frac{veh}{Km}] \times L_S[Km] \quad (3)$$

Where:
*R*: road considered
*T*: vehicle typology (light vehicles and heavy vehicles)
$L_S$: length of the road section impacted, obtained as the intersection between the harm zones of the DGT accident scenarios considered in the risk model and the road graph.

### 3.2 $T_{0+x}$: number of exposed vehicles in transit and queuing

**Vehicles in Transit**

It is hypothesized that vehicles travelling on the opposite carriageway to the accident site one, on parallel roads or on roads intersecting the one on which the accident occurs will not stop moving after the event but may be exposed to the accident scenario while they are located within the harm zones resulting from the said event.
The reference time for calculation of the vehicles in transit is the queue formation time shown in Table 1.
The formula used to quantify the vehicles in transit is shown in Eq(4).

$$vehicles\ in\ transit_{R,T}[veh] = density_{R,T}\ \left[\frac{veh}{Km}\right] \times S_{R,T}\ \left[\frac{Km}{h}\right] \times Qt_k[s] \times \frac{1}{3600[s]} \quad (4)$$

Where:
*R*: road considered
*T*: vehicle typology (light vehicles and heavy vehicles)
$Qt_K$: queue formation time associated with the *k*-th scenario

**Queuing Vehicles**

Once the accident involving a specific hazardous substance occurred, it is necessary to consider, for the vehicles travelling on the road directly affected by the scenario, queue formation prior to the initiating event.
As in the previous case, the formula used is shown in Eq(5):

$$exposed\ queuing\ vehicles_{R,T}[veh] = density_{R,T}\ \left[\frac{veh}{Km}\right] \times S_{R,T}\ \left[\frac{Km}{h}\right] \times Qt_k[s] \times \frac{1}{3600[s]} \quad (5)$$

Where:
*R*: road considered
*T*: vehicle typology (light vehicles and heavy vehicles)
$Qt_K$: queue formation time associated with the k-th scenario
However, in the case queuing vehicles, unlike local area vehicles and those in transit, it is necessary to consider that not all the vehicles that tail back in the hypothesized time are necessarily exposed to the accident scenario. Indeed, Eq(5) provides a value of queuing vehicles potentially exposed. In particular, in the case of queue formation after the event, the vehicles affected are exclusively those which fall within the harm zones. For this reason, it is necessary to compare the number of queuing vehicles potentially exposed, as described above, with the maximum number of vehicles that can physically tail back along a roadway within the harm zone, taking into account the accumulation capacity of the road considered. It is therefore necessary to introduce a new parameter denominated storage. Hypothesizing an average distance between vehicles of 6.5 m (defined as the size of the vehicle plus its distance from the one in front), it was assumed that 150 vehicles can tail back on one kilometer of a single lane. Consequently, the total storage of a road section can be calculated using Eq(6).

$$Storage[veh] = 150\left[\frac{veh}{Km}\right] \times no.lanes \times L_S[Km] \qquad (6)$$

Where:
*no.lanes:* number of lanes of the road section affected by the harm zone.
$L_S$: length of the road section impacted, obtained as the intersection between the harm zone of the DGT accident scenario and the road graph.
Once the storage value corresponding to the road section $L_R$ affected by the accidental damage has been defined, it is possible to obtain the actual number of queuing vehicles exposed using a system of equations:

$$If\ Queue > Storage \Longrightarrow Vehicles\ Affected = Storage$$

$$If\ Queue < Storage \Longrightarrow Vehicles\ Affected = Queue$$

If the road is the accident site then it is necessary to distinguish two cases, depending on whether or not it has separate carriageways, as shown below.

**Dual Carriageways**

Where the road has separate carriageways, it is reasonable to assume that the vehicles on the carriageway on which the accident occurs are effectively in a stationary queue and can, therefore, be estimated using the above procedure. The vehicles on the parallel carriageway, on the other hand, can continue to travel and must, therefore be estimated using the procedure described in point 3.1 of this section, on vehicles in transit.

**Single Carriageways**

Where the road has a single carriageway with one or more lanes per traffic direction, both directions will probably be blocked by the accident. Consequently, it is necessary, as a precaution, to apply the calculation procedure developed for definition of the number of queuing vehicles, described in point 3.2 of this section, for both lanes.
Table 2, below, summarizes the procedure for calculating the number of vehicles exposed to the accident scenario.

*Table 2: Summary of possible combinations*

| Temporal scenario | Roadway typology | Vehicle typology |
|---|---|---|
| Instantaneous | affected roadways<br>accident site roadway | Local area vehicles |
| Non-instantaneous | accident site roadway<br>affected roadways | Queuing vehicles<br>Vehicles in transit |

### 3.3 Number of affected users

After the calculation of the number of vehicles affected, it is necessary to convert this into the number of road users, to estimate an accident's anthropic consequences. This operation can be easily performed by applying occupation coefficients for the two vehicle categories considered: light vehicles and heavy vehicles. In view of the road typologies belonging to Project DESTINATION's road graph, which almost exclusively examines motorways and extra-urban roads, the average occupation coefficients were considered equal to 1.5 for light vehicles and 1.1 for heavy vehicles. These are typical indicative values used for data processing and studies relating to transport in non-urban settings in the areas involved in Project DESTINATION. It is therefore possible to estimate the total number of users affected by applying Eq(7):

$$users_{R} = \sum_{T} vehicles\ exposed_{R,T} \times\ Occ.Coeff._{T} \quad (7)$$

Where:
*R*: road considered
*T*: vehicle typology (light vehicles and heavy vehicles)
*Occ.Coeff.*: Occupation Coefficient

### 3.4 Application of the Methodology in Project DESTINATION

The methodology presented in this paper was applied in the Regions which participated to the Project. For this purpose, after the definition of a common standard, each partner collected the necessary data and subsequently processed it so that it adequately met the requirements of the method. For definition of the "road user" affected population, the principal data processing concerned the traffic (Average Daily Traffic DGT and speed) and the road graph. A detailed presentation of an actual application of the GIIS, and thus of the methodology presented in this paper, is deeply described by Borghetti et al. (2015).

## 4. Conclusions

The method developed made it possible to meet a need strongly perceived by the Project's partners and to examine, through the risk analysis model involving the GIIS, an affected population typology (road users) which should not be overlooked. Indeed, road users, particularly in rural areas, can constitute the quantitatively most significant fraction of the exposed population. It should be noted that the lack of traffic data for most of the Project's roads and a level of uncertainty as to the hypotheses make it difficult to precisely quantify this exposed population. A higher level of detail on traffic flow and travelling speed would significantly increase the accuracy of the results obtained through application of the method. The ADT data and travelling speeds used in this initial phase could easily be substituted with data, including that of a time-variant nature, acquirable or commercially obtainable from external providers, or could be the result of assignment of OD matrices to the transport network. These approaches were not adopted during this phase of Project DESTINATION as it was the partnership's explicit intention to use data already available in the Project partners' databases during the start-up phase.

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