ROAD PRICING IN URBAN HAZARDOUS MATERIALS TRANSPORTATION: A PRACTICAL ASSESSMENT

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ABSTRACT

Many industrial production processes need inputs or generate by-products that pose potential threats to public health or the environment. Those products are called hazardous materials (hazmat). Those hazmat must be safely transported from their origin to destination (e.g. manufacturing/processing or treatment plants) where they are either processed or properly disposed. Unfortunately there are accidents that may result in hazmat spills exposing the population and the environment to the associated risks. Combining available data sources, we designed a methodology to estimate the two main components of the associated risks: the probability of an accident during hazmat transportation, and the consequences associated to such an event. These components allow the estimation of the externality (social cost) imposed by the traffic of hazmat on the society. This social cost can be internalized through an appropriate road price scheme.

This paper presents a methodology to estimate the marginal cost of hazmat trips on a transportation network, based on the estimation of the probability of an accident involving hazmat as well as its associated consequence. The methodology was applied to the case of hazardous waste transportation in Santiago, Chile.

I. INTRODUCTION

Many industrial production processes need to use hazardous materials (hazmat) as manufacturing components and often generate by-products that pose potential threats to public health or the environment. The hazmat must be safely transported from their origin to special facilities (e.g. manufacturing/processing or treatment plants) where they are either used in a production process, modified to decrease their degree of danger, or properly disposed. Hazmat include explosives, flammable liquids and solids, oxidant substances, poisonous and infectious substances, radioactive materials, corrosive substances among others, which must be handled and transported in an efficient and safe manner, from the generating source to the treatment centers and final disposition.

The transportation of hazmat is a strategic decision of enormous social relevance. Indeed, the movement of these materials through populated areas becomes a potential threat to the human health and the environment. In spite of the continuous efforts done to mitigate the harmful effects of hazmat, accidents do occur during their use, handling, and in their transportation and final disposition.

Most of the published literature about hazmat are centered on the elusive concept of *risk*. Nevertheless, researchers do not seem to be in agreement about how to define and model the proper risk. There is agreement though in that the risk associated to transporting dangerous freight depends on the probability of accidents occurrence as well as the derived consequence, being the evaluation of these components the first step in the identification of the risks of this potentially dangerous activity. The above mentioned probability includes the occurrence of an undesirable incident (such as a train derailment or a freight vehicle accident), conditioned on a spill of hazmat. On the other hand, the associated consequences to these spills depend on this probability as well as several other parameters such as the affected area, population density, type of hazmat, and atmospheric conditions among others.

The release of dangerous contents from a vehicle can be caused by an accident or by other incidents such as a leak. To distinguish between these two types of risk generation, the former is known as an "accident risk" and the latter as an "exposure risk" (Erkut and Verter [10]). The exposure risk is described in detail by Saccomanno and Shortreed [2]. This paper deals exclusively with accident risks.

The accidents involving hazmat are uncommon episodes and hence their econometric treatment is difficult. In addition, the actual costs of these episodes are hardly known. Indeed, there are several undesirable consequences associated to a dangerous substance's release, but most of the literature is centered only in the fatalities originated by the accident, neglecting environmental damages, evacuation costs, injured people or animals, and property damages. Thus, the actual costs of a dangerous spill are often underestimated.

Considering fatalities as the only undesirable outcome of a hazmat accident simplifies the evaluation process, but the computed final consequence is far from representing the absolute costs of a potentially risky activity. Even the assessment of the number of fatalities as a result of an incident is quite difficult (e.g. for many hazwaste the direct impact in human lives is not well known). Fortunately, for strategic decisions, it is more convenient to make comparisons between alternatives than focusing on an exact quantification of the absolute consequences of each decision alternative.

To evaluate the risk of different alternatives in hazmat transportation two unknown values must be estimated: probability of an accident involving the dangerous freight, and the consequence associated to that accident. This paper presents a methodology to estimate these two main components.

The rest of the paper is organized as follows. The next chapter summarizes the relevant literature. Chapters III and IV present the methodology to estimate the probabilities, consequences and hence marginal costs associated to catastrophic events. Chapter V presents an application of this methodology to the case of hazwaste transportation in Santiago, Chile. Finally, Chapter VI offers some conclusions and future research lines.

II. LITERATURE REVIEW

Several authors propose and apply different forms of statistical inference to evaluate risk in the context of hazmat transportation (Abkowitz and Cheng [1]). These techniques presume the existence of enough historical data to determine the frequency and the consequences of past incidents to infer future expectations. However, there are considerable criticisms regarding statistic confidence of hazmat accidents databases, due to the lack of information of release events, as well as the uneven quality and quantity of the available data.

One way to estimate the frequency and the consequences of the liberation of hazwaste/hazmat, is using two types of logical graphs: failure trees and event trees. Saccomanno and Shortreed [2] employed failure trees to evaluate the probabilities of a product overflow due to a deficiency in the frame or in the valves of a vehicles' tank. Glickman [3] presented an application of event trees to evaluate the transportation risks on highways for a variety of flammable liquids. An excellent analysis of these methodologies is presented in Paté-Cornell [4]. Patel and Horowitz [5] put forward models that incorporate the effect of the wind in the assessment of the diffusion of gases, due to possible overflows during transportation in broad areas. Saccomanno and Chan [6] presented a model where they assumed that the probabilities of accident and the resulting consequences were affected by random environmental influences.

A complete representation of the danger requires the use of a risk profile, i.e., a cumulative distribution function of the random consequences of a potentially dangerous activity. This profile shows the probability that the a consequence exceeds a given level. Saccomanno and Shortreed [2] presented risk profiles for the social danger in the chlorine transportation by railway and freight vehicle. Although the use of risk profiles enrich the evaluation of the danger associated to some decision alternatives, it is not clear how to use these profiles in optimization models.
Some authors point out that the consequences of an overflow of dangerous substances can be reduced through an effective emergency response system and also preparing the community for possible accidents. Accordingly, Saccomanno and Allen [7] presented

models to locate specialized equipment on a transportation network, to efficiently react against hazwaste/hazmat accidents. List and Mirchandani [8] followed another path, analyzing the trade-offs between the response time, risk, cost and equity of the danger when locating response equipments. Other authors (such as Pijawka et al. [9]) state that an effective risks reduction in the transportation of dangerous substances is improving the level of the community's knowledge and training. In this sense, the aim centers in the evaluation of the "vulnerability" (or degree of threat of a hazwaste/hazmat) of a population and its the ability to mitigate the consequences of possible incidents.

III. A METHODOLOGY TO ESTIMATE PROBABILITIES OF ACCIDENTS

Previous to the estimation of the probability of an accident, it is necessary to identify and evaluate the different scenarios for the occurrence of an incident involving hazwaste/hazmat. The scenarios can be described as a sequence of events. The events can be graphically represented in a tree structure, showing a sequential progression of branched options. One of such structures is known as *event tree*, which represents sequences of joint events with conditional probabilities. These trees are typically constructed through deductive logic, i.e., starting with an initial event, fixing all the possible sequences of the following episodes, and determining the result (payoff) of each considered sequence. As each event is conditional in the occurrence of previous events, the joint probability of the intersection of episodes that form a sequence (or scenario) is found by the multiplication of all the probabilities associated to a sequence.

Our aim is the definition of the probability of occurrence of a catastrophic accident in the hazmat/hazwaste transportation. A catastrophic event is one that, given a liberation of a dangerous substance to the environment, the exposure of that material will produce damage (fatalities, injuries or value loss) to the surrounding inhabitants and/or environment. With this aim in mind, let $G\ (N.A)$ be a directed graph representing a transportation network where A is the set of arcs and N the set of nodes. Let R be the set of different hazwaste/hazmat to be transported.

The episodes that form the event tree are defined as follows:

B_a : a traffic accident occurs in the arc $a \in A$.

C : a traffic accident corresponds to a fall, collision, crash or overturn of the affected vehicle.

D_a: an accidented vehicle in arc $a \in A$ is a freight vehicle.

E_a : a freight vehicle accidented in arc $a \in A$ is carrying hazmat.

F_r : the hazmat carried by an accidented freight vehicle, is of type r.

G_r : an accident that involves a freight vehicle carrying hazmat of type r has catastrophic characteristics.

Let P_a be the probability that a traffic accident occurs in arc $a \in A$, i.e., $P_a = prob\ (B_a)$.

An expression to estimate this probability is the following frequency approximation:

$$P_a = N_a/F_a \qquad (1)$$

where $\boldsymbol{N_a}$ represents the rate of traffic accidents per unit of time occurred in arc $a \in A$, and $\boldsymbol{F_a}$ denotes the vehicle flow in arc $a \in A$ for the same period of analysis.
Consequently let P_{ya} represent the probability that the event C occurs in arc $a \in A$, conditioned on that an accident has occurred in that arc. So, $P_{ya} = prob(C/B_a)$.
Let P_{fva} be the probability that the accidented vehicle in arc $a \in A$ is a freight vehicle, conditioned on the events B_a and C, then $P_{fva} = prob(D_a /B_a,C)$. Let P_{ha} be the probability that the event E_a occurs, conditioned on that all the precedent events took place. This probability can be represented by the following expression:
$P_{ha} = prob(E_a/B_a,C,D_a) = P_a \cdot P_{ya} \cdot P_{fva} \cdot prob(E_a)$.
Let P_{har} represent the probability that the accidented freight vehicle carries hazmat of type r, conditioned on that all the precedent episodes took place. This probability can be represented by the following expression:
$P_{har} = prob(F_r/ B_a,C,D_a, E_a) \qquad \forall\ r \in R$.
Let P_{char} represent the probability that the event G_r takes place conditioned on that the events B_a,C,D_a, E_a and F_r have occurred. This probability can be expressed as follows:
$P_{char} = prob(G_r/ B_a,C,D_a, E_a,F_r) \qquad \forall\ r \in R$.
Finally, the probability that a catastrophic accident involving a hazmat type r occurs in the arc a is given by the following expression:

$$p_a^r = P_a \cdot P_{ya} \cdot P_{fva} \cdot P_{ha} \cdot P_{har} \cdot P_{char} \qquad \forall\ r \in R \qquad (2)$$

Expression (2) represents the sequential progression of each contiguous episode based on the conditional probabilities as in the leaves of an event tree.

IV. METHODOLOGY FOR THE ESTIMATION OF THE CONSEQUENCES

For our purposes, the consequences of a hazmat liberation is measured in terms of its potential to provoke fatalities and/or injuries to the inhabitants in the vicinity of the event. Batta and Chiu [11] put forward the concept of "*impact area*" defined by a dispersion radius (λ) that depends, among other factors, on the physical and chemical properties of the relieved substance. The population living within the impact area corresponds to the exposed population (those who could be directly affected by the spill). According to Erkut and Verter [10, 12] the latter is a necessary simplification due to the limited information. Figure 1 depicts the impact area and the exposed population.

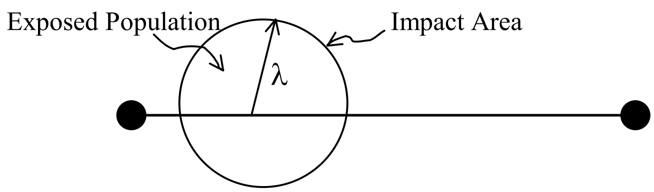

Figure 1: *Impact Area* and *Exposed Population* in a given arc

Let PE_a^r represent the exposed population along the arc a given the occurrence of a catastrophic accident with hazmat of type r. This value can be approximated assuming a uniform population density within the impact area, which can be considered a "worst case scenario", where each person in the impact area is exposed to the same undesirable consequences, disregarding other aspects such as the distance to the accident location, meteorological or topographical conditions. Accordingly, the exposed population along the arc a can be expressed as follows:

$$PE_a^r = A^r \cdot D_a \qquad \textbf{(3)}$$

Where A^r represents the impact area for a hazmat of type r; and D_a is the population density along the arc $a \in A$. Lets assume that an accident involving hazmat of type r provokes (on average) a proportion of seriously injured people (Plg^r), of mildly injured people ($Plng^r$), and deaths (Pmu^r). Then, the expected Affected Population (PA_a^r) after an accident of hazmat type r in arc a can be expressed as follows:

$$PA_a^r = (P\lg^r + P\ln g^r + Pmu^r) \cdot PE_a^r \qquad (4)$$

An economic evaluation of the total consequence of a catastrophic accident involving a hazmat of type r can be done by weighting the cost of all the damages $Cost^r$ (material and non-material) incurred after the event by the ratio between the affected population along the arc a and the total affected population (PA^r) as follows:

$$c_a^r = \frac{PA_a^r \cdot Cost^r}{PA^r} \qquad (5)$$

Substituting expressions (3) and (4) into (5) we obtain the following expression:

$$c_a^r = \frac{\left\{ (P\lg^r + P\ln g^r + Pmu^r) \cdot A^r \cdot D_a \right\} \cdot Cost^r}{PA^r} \qquad (6)$$

Which can be computed and applied to each arc $a \in A$ and for each type of hazmat $r \in R$.

V. METHODOLOGY FOR THE ESTIMATION OF THE MARGINAL COST OF TRANSPORTING HAZARDOUS FREIGHT

Given the probabilities of accident occurrence and the cost involved in each accident, the expected social cost to be generated by a volume V_a^r of traffic with hazmat *r* through the arc *a* is given by:

$$SC_a^r = p_a^r \cdot c_a^r \cdot V_a^r \tag{7}$$

therefore, the marginal cost of each shipment of hazmat *r* through the arc *a* is given by:

$$mgc_a^r = \frac{\partial SC_a^r}{\partial V_a^r} = p_a^r \cdot c_a^r \tag{8}$$

this value corresponds to the optimal charge for the social cost imposed by the traffic of hazmat on each arc of the transportation network. This amount does not consider other social costs such as direct infrastructure and vehicle costs, congestion, noise, etc. which should be considered when an actual road price scheme is adopted, *i.e.* this methodology is only concerned with the effect of the hazmat transportation.

VI. APPLICATION OF THE METHODOLOGY TO A CASE OF HAZARDOUS WASTE TRANSPORTATION

The proposed methodology was applied to the transportation network of Santiago, Chile. Santiago is the capital city with about 6 million people and 34 counties. The main transportation network has 5,790 arcs and 2,030 nodes. The National Institute of Statistics keeps records of accidents at the arc level. We obtained data for the year 1997. The population density surrounding each arc was available from the Bureau of Census. The length of each arc and the borough to which it belongs was obtained from official digital maps. Four types of industrial solid hazardous waste (hazwaste) were considered, and each one was characterized by its level of danger according to international risk classifications (Bronfman [13]). All the hazwaste types were loaded/unloaded and carried using the same technology, hence only one type of vehicle was considered.

VI.1. Estimation of Accident Probabilities

The number accidents in each arc was obtained from INE [14], categorized by type of severity and type of vehicles involved. With these data we computed $P_y = 0.88$ and $P_{fv} = 0.162$ at the network level, i.e., on average, a registered accident has a probability of 0,88 of being a fall, collision, crash or overturn, and any involved vehicle has a probability of 0.162 of being a freight vehicle. The INE data base was complemented with other sources (CONAMA [15], D&M [16], MTT [17] and RSPA [18]) to estimate the rest of the probabilities in expression (2). These values are summarized in Table 1.

Table 1: Summary of estimated conditional probabilities at network level

	Type of Hazmat (r)	P_{hr}	P_{chr}	p_a^r / P_a
P_y = 0.880089	1	0.454316	0.191332	1,40E-05
Pfv = 0.167881	2	0.853648	0.108142	1,50E-05
P_h = 0.001127	3	0.072808	0.018791	2,30E-07
	4	0.479995	0.047433	3,80E-06

VI.2. Estimation of the Consequences

To assess the value of the consequences associated to a catastrophic accident in the transportation of a hazmat of type r, first we need to determine the impact area A^r. No relevant information was available in Chile for this purpose. Therefore, the values were approximated adapting data from the United States sources (DOT [19]). The methodology consisted, in identifying the borough to which each arc belonged to and then assigning them the corresponding population density (assuming that the population of each borough is uniformly distributed over the area); if an arc belonged to more than one borough, the corresponding population density was computed as the weighted average of each borough's population density. The results are summarized in Table 2.

Table 2: Impact area for each category of hazmat

Type of hazmat	Dispersion Radius (Km)	Impact Area (Km^2)
1	1.2	4.52
2	1.9	11.34
3	0.8	2.01
4	1.9	11.34

The affected population (PAar) within the impact area was approximated using the DOT [18] data, considering average values for accidents registered in the United States during a year for each type of hazmat, its consequences, involved costs, and the total affected people (PA r), for a period between 1993 and 1999 (Tables 3, 4 and 5).

Table 3: Summary of registered accidents, by type of hazmat, period 1993-1999

Type of Hazmat	Number of Accidents Period 1993-1999	Catastrophic Accidents
1	8,588	148
2	16,137	363
3	1,376	26
4	9,074	247

Source: Office of Hazardous Materials Safety, The United States Department of Transportation's Research and Special Programs Administration, 1993-2001

Table 4: Affected people and damage costs due to catastrophic accidents in hazmat transportation, period 1993-1999

Type of hazmat	Catastrophic Accidents	Seriously Injured People	Other Injured People	Fatalities	Exposed People	Total Affected People	Costs in US$
1	148	21	68	0	46,974	89	8,474,057
2	363	34	112	12	288,772	159	26,218,626
3	26	2	17	0	3,659	19	1,812,102
4	247	15	64	12	196,555	91	19,923,031

Source: Office of Hazardous Materials Safety, The United States Department of Transportation's Research and Special Programs Administration, 1993-2001

Table 5: Estimated cost parameters for the period 1993-1999

Type of hazmat	Plg^r	$Plng^r$	Pmu^r	PE^{*r}	PA^{*r}	$Cost^{*r}$ (US$)
1	0.000448	0.001442	0.000004	317.05	0.6	57,196
2	0.000119	0.000389	0.000041	794.826	0.436	72,165
3	0.000447	0.004764	0	140.911	0.734	69,793
4	0.000079	0.000323	0.000059	794.826	0.366	80,564

With the estimated parameters it is possible to estimate the total consequence of a catastrophic accident (expression 6). The results are summarized in

With the data presented in tables 1 and 6, it is possible to compute the road pricing values per borough attributable to each hazmat. The values are presented in Table 7.

Table 6.

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Table 6: Consequences associated to catastrophic accidents in hazmat transportation by type of hazmat

Borough	Demographic Density (Inhab/m^2)	Consequence for hazmat 1 (US$)	Consequence for hazmat 2 (US$)	Consequence for hazmat 3 (US$)	Consequence for hazmat 4 (US$)
Cerrillos	3,68E-03	3,00E+06	3,79E+06	3,66E+06	4,23E+06
Cerro Navia	1,51E-02	1,24E+07	1,56E+07	1,51E+07	1,74E+07
Conchalí	1,42E-02	1,16E+07	1,46E+07	1,41E+07	1,63E+07
Estación Central	9,80E-03	8,00E+06	1,01E+07	9,76E+06	1,13E+07
Huechuraba	1,48E-03	1,21E+06	1,52E+06	1,47E+06	1,70E+06
Independencia	9,89E-03	8,07E+06	1,02E+07	9,85E+06	1,14E+07
La Cisterna	9,32E-03	7,61E+06	9,60E+06	9,28E+06	1,07E+07
La Florida	5,91E-03	4,82E+06	6,09E+06	5,89E+06	6,79E+06
La Granja	1,49E-02	1,22E+07	1,53E+07	1,48E+07	1,71E+07
La Pintana	7,80E-03	6,37E+06	8,03E+06	7,77E+06	8,97E+06
La Reina	4,31E-03	3,52E+06	4,44E+06	4,30E+06	4,96E+06
Lo Prado	1,74E-02	1,42E+07	1,79E+07	1,73E+07	2,00E+07
Macul	1,02E-02	8,30E+06	1,05E+07	1,01E+07	1,17E+07
Maipú	2,65E-03	2,16E+06	2,73E+06	2,64E+06	3,04E+06
Ñuñoa	1,07E-02	8,72E+06	1,10E+07	1,06E+07	1,23E+07
Peñalolén	3,77E-03	3,07E+06	3,88E+06	3,75E+06	4,33E+06
Providencia	7,65E-03	6,24E+06	7,87E+06	7,61E+06	8,79E+06
Pudahuel	8,33E-04	6,80E+05	8,58E+05	8,30E+05	9,58E+05
Puente Alto	4,40E-03	3,59E+06	4,53E+06	4,38E+06	5,06E+06
Quilicura	9,52E-04	7,77E+05	9,80E+05	9,48E+05	1,09E+06
Quinta Normal	8,81E-03	7,19E+06	9,07E+06	8,77E+06	1,01E+07
Recoleta	1,10E-02	9,00E+06	1,14E+07	1,10E+07	1,27E+07
Renca	6,65E-03	5,43E+06	6,85E+06	6,62E+06	7,64E+06
San Bernardo	1,56E-03	1,28E+06	1,61E+06	1,56E+06	1,80E+06
San Joaquín	1,08E-02	8,85E+06	1,12E+07	1,08E+07	1,25E+07
San Miguel	8,35E-03	6,81E+06	8,60E+06	8,31E+06	9,60E+06
Santiago	1,03E-02	8,40E+06	1,06E+07	1,03E+07	1,18E+07

Table 7: Marginal cost associated to each hazmat in US$

Borough	Hazmat 1	Hazmat 2	Hazmat 3	Hazmat 4
Cerrillos	42,0	56,9	0,8	16,1
Cerro Navia	173,6	234,0	3,5	66,1
Conchalí	162,4	219,0	3,2	61,9
Est. Central	112,0	151,5	2,2	42,9
Huechuraba	16,9	22,8	0,3	6,5
Independenc	113,0	153,0	2,3	43,3
La Cisterna	106,5	144,0	2,1	40,7
La Florida	67,5	91,4	1,4	25,8
La Granja	170,8	229,5	3,4	65,0
La Pintana	89,2	120,5	1,8	34,1
La Reina	49,3	66,6	1,0	18,8
Lo Prado	198,8	268,5	4,0	76,0
Macul	116,2	157,5	2,3	44,5
Maipú	30,2	41,0	0,6	11,6
Ñuñoa	122,1	165,0	2,4	46,7
Peñalolén	43,0	58,2	0,9	16,5
Providencia	87,4	118,1	1,8	33,4
Pudahuel	9,5	12,9	0,2	3,6
Puente Alto	50,3	68,0	1,0	19,2
Quilicura	10,9	14,7	0,2	4,1
Qta Normal	100,7	136,1	2,0	38,4
Recoleta	126,0	171,0	2,5	48,3
Renca	76,0	102,8	1,5	29,0
San Bdo	17,9	24,2	0,4	6,8
San Joaquín	123,9	168,0	2,5	47,5
San Miguel	95,3	129,0	1,9	36,5
Santiago	117,6	159,0	2,4	44,8

It can be observed in Table 7 that the internalization price to be paid by a hazmat shipment ranges from US$0,2 to US$234, depending on the degree of risk presented by the hazmat, the population density in the borough and the probability of an accident occurrence in that borough. Note however, that in an actual application of a road price scheme, other social costs must be included into the price, such as congestion costs, direct infrastructure deterioration, noise, etc.

VII. FINAL REMARKS

In this study, we have shown a methodology to estimate the probability that an accident occurs while transporting hazmat, as well as an approach to assess the consequences associated to this event with catastrophic characteristics (fatalities and injuries in the adjacent population). With these values we computed marginal costs associated to a given hazmat being transported through an urban network.

The consequence of this type of incidents was estimated according to the dispersion radius of each spilled hazmat, assuming that each person living within the impact area was exposed to the same consequences (death in the worst case).

The methodology was applied to the case of hazardous waste transportation in Santiago, Chile. These hazmat road pricing estimates represent a valuable starting point for the analysis of the social and economic impact of different logistic strategies for hazmat transportation, specially in urban areas.

One of the promising lines of research in this topic is the link between physical characteristics of the network (arcs and nodes) and the values of the accident probabilities as well as the impact of the passengers vehicles sharing the same capacity with hazmat vehicles. On the other hand, the assumption of uniformity in the risk distribution within the impact area may also be generalized to incorporate more realistic approaches depending not only on the type of hazmat but also on the topographic profile of the area.

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