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A Probabilistic Risk Assessment of Truck/Trailer Transportation of Radioactive Material in Canada

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Abstract

There are over one million packages containing radioactive material being safely transported in Canada each year. Canadian regulations for the transportation of radioactive material ensure protection of the environment and the health and safety of people in the course of these transportation activities. Building on this foundation, the Canadian Nuclear Safety Commission (CNSC) initiated a project to develop a Transport Safety Risk Assessment (TSRA) methodology to complement the current review of radioactive material transported in Canada by quantitatively assessing the safety risks associated with this activity.

Lloyd's Register, Sweden, provided technical support to the CNSC to source and analyze transport accident data, on public roadways in Canada, with the objective of developing a truck/trailer accident event tree. The resulting event tree gives the CNSC an idea of the nature and probability of truck/trailer accidents in Canada which could have safety consequences. This work provides confirmation that radiological risks from radioactive material transportation conducted in compliance with Canadian regulations are low and the safety of packages is high. It also provides a useful tool for communicating to and improving public understanding regarding the relative safety risks related to the transport of radioactive material.

This paper describes the development of a truck/trailer accident event tree, in a Canadian context, and the results and conclusions from the TSRA project will be presented.

I. INTRODUCTION

Transportation of radioactive material in Canada is subject to Canadian regulations and is regulated by the Canadian Nuclear Safety Commission (CNSC). The regulations ensure protection of the health and safety of people and the environment. The basic philosophy behind CNSC's transport regulations is that safety relies heavily on the design of the transport package. Package designs are combined with additional regulatory controls including labeling, placarding, quality assurance and maintenance records, and allow for radioactive material to be carried safely in all modes of transport such as road, rail, air and sea transportation.

A study was conducted to quantitatively assess the safety risks associated with radioactive material transport by road in Canada using probabilistic methods. The objective was to gather and analyze relevant Canadian road accident data and develop a generic accident event tree specific to Canadian conditions. Lloyd's Register, Sweden, provided technical support to the CNSC for this study.

The scope was limited to large trucks that could transport Type B packages with a high activity content, as these would pose the highest risk in the event of a traffic accident, and the study covered accident data on public roadways only. Human factors and human risk assessment were assumed to be implicitly included in the accident data. Aspects of security, safeguards or the possibility of malevolent acts were considered out of scope, and no specific transport routes were analyzed.

The generated event tree provides the relative distribution of different traffic accident scenarios and their respective conditional probability of occurrence. Further studies will be needed to determine how the accident scenarios translate into consequences for Type B packages.

II. METHODOLOGY

The overall methodology and assumptions in this study are similar to those applied by Sandia National Laboratories (SNL) in the development of an accident event tree for transport of used fuel casks on U.S. roadways [1]. SNL's event tree is an updated version of an event tree for shipping container response to severe highway and railway accident conditions created by Lawrence Livermore National Laboratory [2]. The methodology in this report also takes into account generic guidance provided by the International Atomic Energy Agency (IAEA) in its report on *Input Data for Quantifying Risks Associated with the Transport of Radioactive Material* [3].

Accidents during radioactive material transport are very rare worldwide. Therefore, it was not meaningful to create the event tree in this study based on statistical data on accidents involving radioactive material alone. Instead, general traffic accident data for large trucks was used where there is sufficient data available as the basis for the event tree. This data is viewed as worst case since the transport of radioactive material is subject to more stringent requirements than general transports, including factors such as vehicle performance and maintenance, driver training and emergency preparedness. The data used in this study was received, managed and calculated using Microsoft Excel.

III. DATA SOURCES

Transport Canada is a federal-level institution that is responsible for transportation policies and programs throughout Canada. Transport Canada maintains the National Collision Database (NCDB) [4] which contains all police-reported motor vehicle collisions on public roads in Canada. The data from the NCDB, including the relative distribution of different accident types involving all large trucks in Canada, was the main data source for this study. In this database, the most severe consequence is reported, along with other information related to the accident. The data provided from this database was for the years 2011-2015 and therefore, this is the time span of the accident data upon which this study has been based. The number of large truck road accidents per year included in the NCDB data for the years 2011-2015 ranged from 41,486 to 45,364 [4].

To enable comparison of traffic accident data with the total number of relevant vehicles on the road, data was gathered from Statistics Canada on the number of large truck registrations [5]. To align with the time period of the NCDB data used in this study, data from 2011-2015 was used.

IV. BOUNDING ASSUMPTIONS OF THE DATA AND ANALYSIS

The NCDB data categories found to contain useful information for creating the accident event tree were vehicle type, vehicle event category, roadway configuration, collision configuration, and vehicle damage severity. The vehicle types from the NCDB database relevant to the scope of this study are heavy unit trucks, with or without a trailer, with a weight greater than 4,536 kg, and tractor-trailers, with or without a semi-trailer.

In creating the event tree, a large truck accident was assigned as the initiating event. In accordance with the event tree developed by SNL [1], the first set of branches following the initiating event were assigned a collision type. The three possible types of accident are ‘collision with non-fixed object,’ ‘collision with fixed object,’ and ‘non-collision.’

For each collision type, a second set of branches were assigned a vehicle event category depending on the object struck, again in accordance with the SNL event tree. The collision type and vehicle event categories are shown in Table 1.

Table 1. Collision Types and Vehicle Event Categories

Collision Type	**Vehicle Event Category – Object Struck**	
Collision with non-fixed object	Train	
	Other moving vehicle	
	Other non-fixed/moving object	
Collision with fixed object	Bridge	Run-off
		Not run-off
	Other fixed road structure	
	Other fixed object	
	Ditch	
	Embankment, dirt pile, rock	
Non-collision	Fire/explosion	
	Other non-collision	

For collisions that occur on bridges, it is of particular interest whether the vehicle is likely to remain on the bridge, due to the potential of an extreme scenario of a truck falling a significant distance. As such, the branch associated with a bridge structure being struck was subdivided into two configurations; “Run-off” and “Not run-off”.

Finally, each vehicle event category was assigned a vehicle damage severity. The four vehicle damage severity classifications, and their description, are listed in Table 2 below.

Table 2: Vehicle Damage Severity Descriptions

Vehicle Damage Severity	**Description**
Light	Superficial, driven away from the scene
Moderate	Still drivable but does not meet requirements of the law for further use without repairs, driven away from the scene
Severe	Not drivable, but worth repairing, towed from the scene
Demolished	Totally destroyed, not worth repairing

Accidents leading to light or moderate vehicle damage severity were consolidated, as it is the accidents that lead to higher impacts (severe and demolished vehicle damage severity), and therefore a potential impact on the transport package, that are of main interest in this study. Note, however, that even if the truck is heavily damaged, it cannot directly be concluded that the transport package is damaged.

Assigning the vehicle damage severity as the last set of branches in the event tree was valuable, as it indicates the degree of impact that the vehicle is subject to as a result of the initiating event. This differs from SNL's accident event tree [1], in which the last two columns relate to speed distribution and surface struck, both of which are indirect indicators of the degree of impact. As such, the vehicle damage severity in the NCDB is a more direct measure of the impact and is deemed to correspond to the intent of the speed distribution and surface struck columns in the SNL event tree.

V. QUANTIFICATION OF THE ACCIDENT EVENT TREE

Using the relevant data from the NCDB, the fractions of the respective branches for the objects struck were calculated. Subsequently, the fractions of the resulting vehicle damage severity for each of the objects struck and the totals for the main collision types were calculated. The fractions were calculated for each of the years (2011-2015), followed by the average ± standard deviation over the five-year period. The results for the "Collision with non-fixed object" collision type are listed in Table 3 as an example of the final event tree calculations.

Table 3. Calculated Fractions of the Large Truck Accident Event Tree for "Collision with non-fixed object" Collision Type

Type and Object Struck	Vehicle Damage Severity	2011	2012	2013	2014	2015	Average	± Std. Dev.
Collision with non-fixed object		0.756	0.723	0.769	0.778	0.786	0.762	0.025
Train	Total	0.001	0.001	0.001	0.001	0.001	0.001	0.0003
	Demolished	0.286	0.400	0.375	0.467	0.333	0.372	0.068
	Severe	0.571	0.200	0.375	0.333	0.500	0.396	0.145
	Light/moderate	0.143	0.400	0.250	0.200	0.167	0.232	0.102
Other moving vehicle	Total	0.921	0.909	0.861	0.854	0.861	0.881	0.031
	Demolished	0.027	0.026	0.025	0.027	0.023	0.026	0.001
	Severe	0.072	0.073	0.081	0.087	0.070	0.076	0.007
	Light/moderate	0.902	0.901	0.894	0.886	0.907	0.898	0.008
Other non-fixed/ moving object	Total	0.079	0.090	0.138	0.144	0.138	0.118	0.031
	Demolished	0.021	0.021	0.223	0.237	0.198	0.140	0.109
	Severe	0.169	0.169	0.105	0.094	0.088	0.125	0.041
	Light/moderate	0.810	0.810	0.672	0.669	0.715	0.735	0.071

A key feature of an event tree is that the sum of all fractions at a given branch point equals one. Due to rounding of the calculated results to three decimal points, however, some exceptions to this may occur. For instance, the fractions for the vehicle damage severity for the "Other moving vehicle" collision type for 2011 in 3 are; Light/moderate = 0.902, Severe = 0.072, and Demolished = 0.027. Consequently, the equation to verify that the total probability at this branch point, P_{total}, equals 1 is:

$$P_{total} = 0.902 + 0.072 + 0.027 = 1.001$$

For purposes of this study, this is considered acceptable.

To calculate the probabilities of each of the accident scenarios, the branch point fractions for the respective path in the event tree were multiplied. For example, the probability of the first scenario in the event tree, that a truck is demolished as a result of a collision with a train, was calculated by multiplying the following branch point fractions: type – collision with non-fixed object = 0.762, object struck – train = 0.001, and vehicle damage severity – demolished = 0.372. As such, the equation for calculating the probability of the first accident scenario is:

$$P_{\text{accident scenario 1}} = 0.762 \text{ x } 0.001 \text{ x } 0.372 = 0.000283 = 2.83\text{E-4}$$

The resulting accident scenario probability of 2.83E-4 is, consequently, listed as the probability of the associated scenario (Index 1) in Figure 1. Similarly, the probabilities of all other accident scenarios in the transport accident event tree were calculated and are listed in Figure 1. This is the comprehensive event tree for accidents involving large trucks on Canadian Roadways.

Accident	Type	Object struck	Collision configuration	Vehicle damage severity		Probability	Index
Large truck accident 1	Collision with non-fixed object 0.762	Train 0.001		Demolished	0.372	2.83E-04	1
				Severe	0.396	3.02E-04	2
				Light/moderate	0.232	1.77E-04	3
		Other moving vehicle 0.881		Demolished	0.026	1.75E-02	4
				Severe	0.076	5.10E-02	5
				Light/moderate	0.898	6.03E-01	6
		Other non-fixed/moving object 0.118		Demolished	0.140	1.26E-02	7
				Severe	0.125	1.12E-02	8
				Light/moderate	0.735	6.61E-02	9
	Collision with fixed object 0.115	Bridge 0.025	Run-off 0.192	Demolished	0.405	2.24E-04	10
				Severe	0.289	1.60E-04	11
				Light/moderate	0.306	1.69E-04	12
			Not run-off 0.808	Demolished	0.130	3.02E-04	13
				Severe	0.165	3.83E-04	14
				Light/moderate	0.705	1.64E-03	15
		Other fixed road structure 0.042		Demolished	0.035	1.69E-04	16
				Severe	0.189	9.13E-04	17
				Light/moderate	0.776	3.75E-03	18
		Other fixed object 0.720		Demolished	0.142	1.18E-02	19
				Severe	0.136	1.13E-02	20
				Light/moderate	0.722	5.98E-02	21
		Ditch 0.203		Demolished	0.219	5.11E-03	22
				Severe	0.328	7.66E-03	23
				Light/moderate	0.453	1.06E-02	24
		Embankment, dirt pile, rock 0.010		Demolished	0.328	3.77E-04	25
				Severe	0.252	2.90E-04	26
				Light/moderate	0.420	4.83E-04	27
	Non-collision 0.122	Fire/explosion 0.026		Demolished	0.613	1.94E-03	28
				Severe	0.159	5.04E-04	29
				Light/moderate	0.228	7.23E-04	30
		Other non-collision 0.974		Demolished	0.219	2.60E-02	31
				Severe	0.257	3.05E-02	32
				Light/moderate	0.524	6.23E-02	33

Figure 1. Event Tree for Accidents Involving Large Trucks on Canadian Roadways

It is important to emphasize that the accident scenario probabilities in Figure 1 all assume that an accident involving a large truck has occurred. In other words, the probability that a given scenario will actually occur is significantly smaller than the values listed in the probability column in Figure 1 since most transports do not result in an accident.

VI. ASSESSMENT AND DISCUSSION OF THE ACCIDENT PROBABILITIES

The event tree probabilities of the event tree in Figure 1 and the SNL tree [1] were compared and found to align to a large degree for the collision type and object struck branches. For the last branch, however, vehicle damage severity was used in this study, instead of speed distribution and surface struck as in SNL's study. For this reason, a comparison of overall accident scenario probabilities in the two studies is not applicable.

While the focus of this current study was conditional failure probabilities, it was assessed whether an indication could be obtained of the frequency that a large truck accident occurs in the first place. This was done by comparing the NCDB data [4] with the number of vehicle registrations for a given year from Statistics Canada [5]. The average annual frequency that an accident involving a large truck occurs was calculated as 0.014 per year and truck. Accidents associated with alcohol, drugs or disobeying traffic controls were not included in this calculation since drivers of large trucks transporting radioactive material can be assumed to be specially trained and subject to much more rigorous requirements regarding being fit for duty.

This estimated annual frequency was then combined with the conditional probability for the specific sequences in the event tree. The highest conditional failure probability leading to a severe or demolished vehicle, which would be most likely to damage the package, is collision with another moving vehicle leading to severe vehicle damage, at 5.1E-02 (Index 5 in Figure 1). Multiplying this probability by the average annual frequency, yields a frequency for this accident scenario of; 5.1E-02 x 0.014 = 7.1E-4 per year and truck. And it would be expected that a truck used for transportation of Type B packages would travel less miles per year than an average truck, and hence the frequency for an accident would be expected to be even lower. Therefore, since the probability of an accident ever occurring is very low, the radiological risks from radioactive material transportation conducted in compliance with Canadian regulations are considered low and the safety of packages high.

Based on the average branch fractions and standard deviations (see Table 3), a sensitivity analysis was performed for a selection of scenarios. The associated averages for the brank point probabilities plus the standard deviations were used as an estimate of an upper bound (i.e. the worst-case accident scenario probability). The event sequences that were deemed to have potential to lead to the worst consequences were determined to be:

- Collision with a train – resulting in demolished or severe vehicle damage
- Collision with a bridge that leads to run-off – resulting in demolished or severe vehicle damage
- Collision with a bridge that does not lead to run-off – resulting in demolished or severe vehicle damage
- Collision with other fixed road structure – resulting in demolished or severe vehicle damage
- Collision with embankment, dirt pile, rock – resulting in demolished or severe vehicle damage
- Fire/explosion – resulting in demolished or severe vehicle damage

The data in the NCDB also includes information on the condition of the road surface at the time of the accident and classification of the road as urban or rural. This information was not used in the event tree, but it was observed that the likelihood of demolished or severely damaged vehicles is roughly a factor of 10 higher on icy/packed snow roads and more accidents occur on rural than urban roadways, around 55% vs 36%, respectively [4].

VII. CONCLUSION AND RECOMMENDATIONS

Sufficiently comprehensive and detailed data exists for the creation and use of event trees that are specific to accident probabilities on Canadian roadways. The truck/trailer accident event tree developed gives the CNSC an idea of the nature and probability of truck/trailer accidents in Canada which could have safety consequences. The study found that the probability of a truck/trailer accident involving high activity radioactive material occurring are very low, and therefore, radiological risks from radioactive material transportation conducted in compliance with Canadian regulations are low and the safety of packages is high.

Possible studies that could be pursued in the future include:

- Determining how vehicle damage severity translates into consequences for Type B packages and which sequences could potentially affect the Type B packages
- Investigating how the generic accident event tree could be tailored for assessment of transport along specific routes
- Developing a framework with guidance on how to reduce probability of accidents that are more likely to lead to vehicle damage that is severe or demolished
- Developing reliable accident event trees for other modes of transport

The generic accident event tree developed in this study can be used to inform the CNSC, waste owners and other stakeholders of the relative transport accident risks, and as a basis for future studies, plans and priorities. Given its graphical form and relative simplicity, the event tree can also serve as a tool for communicating general transport accident risks associated with road transport in Canada more broadly.

VIII. REFERENCES

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