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Modeling the Probability of Hazardous Materials Release in Crashes at Highway–Rail Grade Crossings

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Abstract

Crashes at Highway–Rail Grade Crossings (HRGCs) that involve a truck or a train carrying hazardous materials (hazmat) expose people and the environment to potentially severe consequences of hazmat release. This research involved statistical modeling of the probability of hazmat release from trucks and/or trains in crashes at HRGCs to identify factors associated with hazmat release. The Federal Railroad Administration (FRA) HRGC crash dataset (2007–2016) yielded two subsets of crashes: 1) those involving hazmat-carrying trucks, and 2) those involving hazmat-carrying trains. Results from a logistic regression model using data subset 1 (crashes involving hazmat-carrying trucks) with hazmat release/no release as the response variable showed that standard flashing signal lights, railroad crossbucks, and railroad classes II and III (relative to railroad class I) were associated with lower hazmat release probability from hazmat-carrying trucks. Hazmat release probability from trucks was higher with freight train involvement. Results from a logistic regression model using data subset 2 (crashes involving hazmat-carrying trains) revealed that hazmat release probability from trains was lower with warmer temperature. However, the probability of release from trains was greater with railroad class II (relative to railroad class I), type of highway user (different types of trucks and motorcycle relative to automobiles), and weather conditions (fog, sleet or snow, relative to clear). A comparison of the results from this study with HRGC crash severity studies highlighted the importance and usefulness of this study.

Surface transportation carries a substantial volume of hazardous materials (hazmat) transported across the United States. Trucks constitute more than 50% of the total annual hazmat transportation in the United States (*1*), and more than 2.6 million carloads of hazmat was transported by rail in 2016 in North America (*2*). Hazmat-carrying trains and trucks potentially expose people and the environment to infrequent but potentially severe consequences of crashes that result in release of hazmat. For example, 2581 hazmat-carrying train incidents were reported to the Federal Railroad Administration (FRA) in the 2012–2016 time period, while only 84 of those incidents led to hazmat release (*3*). However, the consequences of a train crash and release of chlorine gas in Graniteville, South Carolina in 2005 resulted in 9 fatalities, hundreds of injuries, evacuation of approximately 5400 people, and monetary costs exceeding $6.9 million (*4*). While these crashes may occur anywhere on the transportation system, crashes at highway–rail grade crossings (HRGCs), where the two modes of transportation meet, may lead to hazmat release from either trucks or trains, or both. Identifying the contributing factors to hazmat release in HRGC crashes involving a hazmat-carrying truck or train is important for setting policies and for making more informed public safety related decisions.

With a focus on crashes at HRGCs involving hazmat-carrying trucks and/or trains, the research objective was to identify the effects of highway users' characteristics, truck/train attributes, environment, land-use and HRGC traits on the probability of hazmat release from trucks or trains in these crashes. The FRA's HRGC crash dataset (2007–2016) yielded two crash data subsets: 1) crashes involving hazmat-carrying trucks, and 2) crashes involving hazmat-carrying trains. Logistic regression models were estimated using each data subset with hazmat release/no release as the response variable. Both models provided useful information about the presence and magnitude of effects of explanatory variables on hazmat release from these two transportation modes. Based on

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the results, this paper presents recommendations for countermeasures and for policies toward decreasing hazmat release in HRGC crashes.

Organization of the remainder of this paper is as follows. The next section presents a review of literature on safety of hazmat transportation and HRGCs. Methodology, data and variables, and modeling results are the ensuing sections of this paper. Discussion, conclusions and a list of references complete this paper.

Literature Review

A significant number of studies have focused on safety of hazmat transportation and safety of HRGCs. This section presents a review of the relevant results from those studies. Although findings regarding safety of hazmat transportation and safety of HRGCs are helpful in studying crashes leading to hazmat release at HRGCs, the review of published literature did not uncover studies specifically focused on the safety of hazmat transportation at HRGCs by trucks and trains.

Safety of Hazmat Transportation

Studying safety of hazmat transportation is commonly based on risk-based approaches due to the rarity of hazmat release incidents. The usual definition of risk involves a set of components including occurrence probability of a hazmat-involved incident, exposure measures (e.g., traffic in terms of truck-miles and train-miles, population, environment, etc.), probability of hazmat release in an incident, and consequences of the release. A number of studies focused on the methods for quantification of these components or using risk in different approaches towards reduction of occurrence probability and severity of hazmat incidents. Countermeasures regarding hazmat transportation risk reduction recommended in these studies included routing strategies (*1*, *5–8*), hazmat transportation network design (*9–12*), tank car safety design enhancement in rail transportation (*4*, *13–15*), hazmat-carrying train speed reduction (*16*) and emergency response improvements (*1*, *17*).

Some studies applied optimization techniques for reducing the risk of hazmat release in crashes. Zografos and Androutsopoulos (*1*) proposed a decision support system for evaluating routes and implemented the method using hazmat distribution within the area of Thriasion Pedion, Greece. By combining transportation network modeling and risk assessment, Glickman et al. (*5*) concluded that significant risk reductions were achievable with relatively minor alterations in routing patterns. Verter and Kara (*9*, *10*) investigated the possibility of designing a transportation network for transportation of hazmat to minimize population exposure. Similarly, Erkut and Gzara (*11*) modeled the transportation network design problem as a bi-level network flow formulation, and Erkut and Alp (*12*) considered designating hazmat routes in and through a major population center. Saat and Barkan (*13*), and Barkan et al. (*14*, *15*) presented different approaches to tank car safety design via optimization to address the tradeoff between safety design and tank car weight.

Nayak et al. (*18*) presented a number of methods for quantifying the probability of accidents and severity of impacts of hazmat accidents in rail transportation. Saccomanno and El-hage (*19*, *20*) focused on tank car derailment, a common cause of hazmat release in train incidents. Liu et al. (*21*) analyzed number of derailed tank cars as a measure of severity of tank car derailments in freight-train accidents. Verma et al. (*22*) proposed a bi-objective model for planning and managing rail-truck intermodal hazmat transportation.

Safety at Highway-Rail Grade Crossings

The majority of studies on safety of HRGCs focused on analysis of crash frequency and severity at these transportation junctions. Raub (*23*) examined the performance of four specific warning device classes (crossbucks only, STOP signs, flashing lights, and gates) at HRGCs and compared their effects on crash frequency. Hu et al. (*24*) studied and identified factors associated with crash injury severity at HRGCs, which included number of daily trains, number of daily trucks, highway separation, an obstacle detection device, and approaching crossing marks. Other factors that were associated with crash frequency and severity at HRGCs include highway motor vehicle driver's age and behavior, traffic volume, and weather conditions (*25*, *26*). Zhao and Khattak (*27*) found that greater number of highway lanes at HRGCs, the presence of standard flashing-light signals and clear weather decreased the likelihood of severe injuries. Zhao et al. (*28*) showed that higher train speed, female pedestrians and commercial land use were associated with more severe injuries in pedestrian-train crashes at HRGCs. Fan et al. (*29*) identified pick-up trucks, concrete, and rubber surfaces associated with more severe crashes at HRGCs, while truck-trailers, snow and fog, and higher daily traffic volumes were more likely to be observed in less severe crashes.

The contributing factors to crash frequency and severity at HRGCs were relatively consistent in the reviewed studies. However, these results do not necessarily hold in describing probability of hazmat release, which warrants the investigation of hazmat-related crashes at HRGCs. The next section presents the research methodology and a description of the modeling technique.

Methodology

This research involved estimation of two logistic regression models for capturing possible impacts and associations of explanatory variables on the probability of hazmat release from hazmat-carrying trucks (Truck Model) and trains (Train Model) in crashes reported at HRGCs. Occurrences of hazmat release or no release from trucks and trains respectively were binary response variables in the two logistic regression models. Explanatory variables included HRGC-related traits, train and highway user characteristics, type of crash, and environmental and land-use characteristics. The following paragraphs describe the logistic regression model, estimation methods and the tools for model interpretation used in this study.

Logistic regression models are the common binary response regression models (*30*, *31*). These models are a type of generalized linear model with the Bernoulli distribution assumption for the response variable and cumulative density function of a logistic probability distribution as the link function. In binary response models, the quantity that is estimated is the probability of success, π. In the context of this paper, π_i is probability of hazmat release in the i^{th} HRGC crash from trucks and trains in the Truck and Train models, respectively. If $x_{i1}, \ldots, x_{ip}$ are p explanatory variables measured on the i^{th} observation (i^{th} HRGC crash), in logistic regression models π_i is defined as in Equation 1.

$$\pi_i = \frac{exp(\beta_0 + \beta_0 x_{i1} + \ldots + \beta_p x_{ip})}{1 + exp(\beta_0 + \beta_0 x_{i1} + \ldots + \beta_p x_{ip})} \quad (1)$$

In this equation $\beta_0, \ldots, \beta_p$ are the logistic regression parameters or coefficients of the explanatory variables. Equation 1 can be rewritten as shown in Equation 2. The left side of Equation 2 is the natural logarithm for the odds of success (hazmat release) and the right side of this equation is a linear combination of the regression parameters with the explanatory variables, often referred to as linear predictors. This transformation of π_i is referred to as the logit transformation (*31*).

$$log\left(\frac{\pi_i}{1 - \pi_i}\right) = \beta_0 + \beta_0 x_{i1} + \ldots + \beta_p x_{ip} \quad (2)$$

Model interpretation in this study used the odds ratios (OR). For a c-unit increase in a continuous explanatory variable, x, the OR is defined as shown in Equation 3. This measure is interpreted as "the odds of hazmat release from trucks or trains change by OR times for every c-unit increase in x, holding the other variables constant". For a categorical explanatory variable, the value of c is 1 and the interpretation is "the odds of hazmat release from trucks or trains change by OR times as large for $x = 1$ than for $x = 0$, holding the other variables constant" (*30*, *31*).

$$\text{OR} = \frac{\text{Odds}_{x+c}}{\text{Odds}_x} = e^{c\beta_i} \quad (3)$$

Maximum Likelihood (ML) is the most common estimation method for logistic regression models. In some cases this estimator might lead to biased results, e.g., when an outcome of the response variable is rare, or presence of complete or quasi separation (an explanatory variable separates the data between 0 and 1 for the response variable (*31*)). The bias-reduction method developed by Firth (*32*) is a solution for this issue. In this study quasi separation was present in the Truck Model (detected by observing abnormally large estimated standard errors for some of the coefficients (*31*) in case of using ML), and values of 1 (hazmat release) were rare in the response variable of the Train Model (0.13%). Therefore, in both models ML was replaced with the Firth estimation method.

Data and Variables

Ten-year U.S. HRGC accident/incident data (2007–2016) and HRGC history inventory data were obtained from FRA safety database, which included 21,761 total number of reported accidents (*3*). Crashes were matched with the inventory dataset based on unique HRGC identification number and approximate date of crash. Two subsets of crashes were extracted from this dataset: 1) crashes with hazmat-carrying highway users (trucks) containing 75 crashes, and 2) crashes with hazmat-carrying trains, including 3726 crashes. Truck Model and Train Model were estimated using these two subsets, respectively. Table 1 presents the variables and their statistics for the truck subset, while Table 2 shows similar information for the train subset.

Modeling Results

Two logistic regression models were estimated for hazmat release from trucks (Truck Model) and trains (Train Model) in crashes at HRGCs. Variable selection was based on Corrected Akaike's Information Criterion (AICc). Some variables in both models were not statistically significant (at $\alpha = 0.10$ level), but were retained in model specifications, since they contributed to the models according to AICc (via describing small proportions of variations in the response variable and affecting other parameters of the models) (*31*). Table 3 shows the modeling results including estimated coefficients, standard errors, OR, and 90% profile likelihood ratio confidence intervals for OR. The significance of estimated coefficients with 90% confidence can be judged by looking at the OR confidence intervals (if each interval does not contain 1, hypothesis of equality of the coefficient with zero is rejected). Figure 1 shows the point estimates and profile likelihood ratio confidence intervals of OR, for better observation and easier interpretation.

Table 1. Variables and Statistics of the Hazmat-Carrying Truck Data Subset

Variable	Variable name	Values and statistics
Response variable		
Hazmat release	HAZREL	1 = No (45.33%), 2 = Yes (54.67%)
Explanatory variables		
Highway user characteristics		
Type of vehicle	TYPVEH	1 = Truck (20.00%), 2 = Truck-trailer (72.00%), 3 = Pick-up Truck (08.00%)
Vehicle speed	VEHSPD	Mean = 8.3467, Variance = 164.5268
Driver age	DRIVAGE	Mean = 47.3467, Variance = 169.0944
Driver gender	DRIVGEN	1 = Male (98.67%), 2 = Female (1.33%)
Train characteristics		
Railroad class	TYPRR	1 = Class I (81.33%), 2 = Class II (01.33%), 3 = Class III (17.33%)
Freight train	FREIGHT	1 = No (21.33%), 2 = Yes (78.67%)
Train speed	TRNSPD	Mean = 32.4110, Variance = 326.5510
Number of cars	NBRCARS	Mean = 51.5135, Variance = 1615.2670
Crash characteristics		
Type of crash	TYPACC	1 = Train struck highway user (92.00%), 2 = Train struck by highway user (08.00%)
Environment and land-use characteristics		
Temperature	TEMP	Mean = 63.1600, Variance = 473.4335
Weather	WEATHER	1 = Clear (64.00%), 2 = Cloudy (30.67%), 3 = Rain (05.33%), 4 = Fog, sleet, snow (00.00%)
Visibility	VISIBLTY	1 = Dawn (06.67%), 2 = Day (70.67%), 3 = Dusk (08.00%), 4 = Dark (14.67%)
Type of land use	DEVELTYPE	1 = Open space (41.33%), 2 = Residential (09.33%), 3 = Commercial (10.67%), 4 = Industrial (30.67%), 5 = Other (08.00%)
HRGC characteristics		
Cantilever flashing-light signals	CANTALIVERFLS	1 = No (94.67%), 2 = Yes (05.33%)
Standard flashing-light signals	STANDARDFLS	1 = No (69.33%), 2 = Yes (30.67%)
Bells	BELLS	1 = No (58.67%), 2 = Yes (41.33%)
Crossbucks	CROSSBUCKS	1 = No (32.00%), 2 = Yes (68.00%)
Gates	GATES	1 = No (70.67%), 2 = Yes (29.33%)
Highway traffic signal	HWYTRFICSIG	1 = No (98.67%), 2 = Yes (01.33%)
Audible	AUDIBLE	1 = No (80.00%), 2 = Yes (20.00%)
Stop sign	STOPSIGNS	1 = No (64.00%), 2 = Yes (36.00%)
Other control devices	OTHER	1 = No (82.67%), 2 = Yes (17.33%)
Public/Private HRGC	PUBLIC	1 = No (29.33%), 2 = Yes (70.67%)

In hazmat-carrying truck crashes at HRGCs, with 90% confidence and holding all the other variables constant except the variable being interpreted, it can be said that presence of standard flashing-light signals decreased the odds of hazmat release from trucks by an amount between 0.0475 to 0.4716 times, relative to its absence. Railroad crossbucks decreased the odds of release from trucks by 0.0461 to 0.4065 times and public crossings increased these odds by 1.6148 to 15.8892 times, compared with private crossings. Railroad classes II and III decreased the odds of release from trucks by amounts between 0.0013 and 0.9781 and between 0.0496 and 0.4631, respectively, relative to railroad class I. Freight trains increased truck release odds by 1.9958 to 17.4551 times, compared with non-freight trains. Crossing control devices introduced as "Other control devices" (in Table 1) decreased the odds of release from trucks by 0.0907 to 0.8836 times, compared with absence of these control devices. Sufficient statistical evidence was not available to support the existence of effects of any other variables that were considered in this study on the release of hazmat from trucks in HRGC crashes.

In hazmat-carrying train crashes at HRGCs, again, with 90% confidence and holding all the other variables constant except the variable being interpreted, railroad class II increased the odds of hazmat release from trains by 1.3266 to 62.4336 times, relative to railroad class I. Railroad class III did not have any significant difference from railroad class I regarding the probability of hazmat release from trains. Type of highway user changed the probability of hazmat release from trains: trucks, truck-trailers and pick-up trucks increased the odds of release by an amount between 1.6463 to 57.1876 times, compared with automobiles; crashes with motorcycles, other motor vehicles and other objects increased these odds by 2.1248 to 112.5912 times, relative to automobiles; hazmat release probability did not change in crashes with vans, buses and school buses, and pedestrians relative to automobiles. An increase in temperature by 5^{o} F decreased the odds of hazmat release from trains by an amount

Table 2. Variables and Statistics of the Hazmat-Carrying Train Data Subset

Variable	Variable names	Values and statistics
Response variable		
Hazmat release	HAZREL	1 = No (99.86%), 2 = Yes (0.13%)
Explanatory variables		
Highway user characteristics		
Type of vehicle	TYPVEH	1 = Auto (42.53%), 2 = Truck/truck-trailer/pick-up truck (40.55%), 3 = Van/bus/school bus (03.43%), 4 = Pedestrian (04.85%), 5 = Motorcycle/other (08.64%)
Vehicle speed	VEHSPD	Mean = 7.2321, Variance = 128.9675
Driver age	DRIVAGE	Mean = 42.3601, Variance = 299.6472
Driver gender	DRIVGEN	1 = Male (75.46%), 2 = Female (24.54%)
Train characteristics		
Railroad class	TYPRR	1 = Class I (86.23%), 2 = Class II (02.60%), 3 = Class III (11.16%)
Train speed	TRNSPD	Mean = 32.7384, Variance = 243.8642
Number of cars	NBRCARS	Mean = 69.1539, Variance = 1322.8460
Crash characteristics		
Type of crash	TYPACC	1 = Train struck highway user (82.54%), 2 = Train struck by highway user (17.46%)
Environment and land-use characteristics		
Temperature	TEMP	Mean = 60.8345, Variance = 491.5737
Weather	WEATHER	1 = Clear (69.78%), 2 = Cloudy (20.33%), 3 = Rain (05.60%), 4 = Fog, sleet, snow (04.29%)
Visibility	VISIBLTY	1 = Dawn (05.17%), 2 = Day (57.11%), 3 = Dusk (05.52%), 4 = Dark (23.18%)
Type of land use	DEVELTYPE	1 = Open space (28.35%), 2 = Residential (21.08%), 3 = Commercial (26.79%), 4 = Industrial (16.30%), 5 = Other (07.48%)
HRGC characteristics		
Cantilever flashing-light signals	CANTALIVERFLS	1 = No (80.69%), 2 = Yes (19.31%)
Standard flashing-light signals	STANDARDFLS	1 = No (54.30%), 2 = Yes (45.70%)
Bells	BELLS	1 = No (41.88%), 2 = Yes (58.12%)
Crossbucks	CROSSBUCKS	1 = No (32.00%), 2 = Yes (68.00%)
Gates	GATES	1 = No (70.67%), 2 = Yes (29.33%)
Highway traffic signal	HWYTRFICSIG	1 = No (97.61%), 2 = Yes (02.39%)
Audible	AUDIBLE	1 = No (63.88%), 2 = Yes (36.12%)
Stop sign	STOPSIGNS	1 = No (78.98%), 2 = Yes (21.02%)
Other control devices	OTHER	1 = No (83.75%), 2 = Yes (16.25%)
Public/Private HRGC	PUBLIC	1 = No (12.82%), 2 = Yes (87.18%)

between 0.7990 to 0.9863 times. Fog, sleet, and snow increased the odds of release by 1.3229 to 24.0584 times, relative to clear weather. There was not enough statistical evidence toward the existence of any impacts or association of any other variables on the release of hazmat from trains in HRGC crashes.

Discussion and Conclusion

Standard flashing-light signals, railroad crossbucks and "other crossing control devices" (as is in Table 1) were effective in reducing the probability of hazmat release from trucks in truck-train HRGC crashes. The use of such control devices is recommended at HRGCs with high hazmat-carrying truck traffic. Prioritization of safety countermeasures implementation may be given to public HRGCs since hazmat release is more probable at these locations relative to private crossings. Freight trains were associated with higher probability of hazmat release from trucks. This finding is reasonable as freight trains are usually longer and heavier relative to other (e.g., passenger) trains. HRGCs with more frequent passage of trains that belong to railroad classes II and III, and less frequent passage of freight trains were safer for hazmat-carrying trucks. Routes that minimize the interaction between these trucks with class I railroads and freight trains may be preferred and considered in the route selection of hazmat-carrying trucks.

Hazmat-carrying class II railroads were more vulnerable in HRGC crashes relative to class I railroads in terms of hazmat release. Extra train hazmat safety consideration is recommended for hazmat-carrying trains on routes with HRGCs that carry high volumes of trucks, truck-trailers and pick-up trucks, and also motorcycle and other vehicles (relative to automobiles). With the exception of motorcycles, different types of trucks and

Table 3. Results of Truck and Train Logistic Regression Models

		Truck model					Train model				
					OR 90% confidence interval					OR 90% confidence interval	
Variable	c	Estimated coefficient	Standard error	OR	Lower level	Upper level	Estimated coefficient	Standard error	OR	Lower level	Upper level
(Intercept)	NA	0.1276	0.6314	NA	NA	NA	−7.52731	1.44417	NA	NA	NA
TYPACC2	1	−1.5033	1.0194	0.2224	0.0409	1.0216	0.94787	0.66771	2.5802	0.8604	7.738
STANDARDFLS	1	−1.8406	0.7061	0.1587	0.0475	0.4716	—	—	—	—	—
CROSSBUCKS	1	−1.9297	0.6706	0.1452	0.0461	0.4065	—	—	—	—	—
PUBLIC	1	1.5747	0.7058	4.8294	1.6148	15.8892	—	—	—	—	—
TYPRR2	1	−2.6878	2.4092	0.0680	0.0013	0.9781	2.20836	1.17077	9.1008	1.3266	62.4336
TYPRR3	1	−1.8332	0.6919	0.1599	0.0496	0.4634	−0.84804	1.12983	0.4283	0.0668	2.7466
FREIGHT	1	1.7275	0.6682	5.6267	1.9958	17.4551	NA	NA	NA	NA	NA
OTHER	1	−1.2336	0.7053	0.2912	0.0907	0.8836	—	—	—	—	—
TYPVEH2	1	—	—	—	—	—	2.27244	1.07845	9.7031	1.6463	57.1876
TYPVEH3	1	—	—	—	—	—	2.32472	1.51188	10.2238	0.8503	122.9214
TYPVEH4	1	NA	NA	NA	NA	NA	2.31776	1.50243	10.1529	0.8577	120.1858
TYPVEH5	1	NA	NA	NA	NA	NA	2.73871	1.20683	15.467	2.1248	112.5912
TEMP	5	—	—	—	—	—	−0.02382	0.01281	0.8877	0.799	0.9863
WEATHER2	1	—	—	—	—	—	1.00773	0.68463	2.7394	0.8883	8.4473
WEATHER3	1	—	—	—	—	—	0.80258	1.16608	2.2313	0.3278	15.1896
WEATHER4	1	—	—	—	—	—	1.73017	0.88173	5.6416	1.3229	24.0584
DEVELTYPE2	1	—	—	—	—	—	−0.42363	1.22511	0.6547	0.0873	4.9111
DEVELTYPE3	1	—	—	—	—	—	0.42381	0.89897	1.5278	0.3482	6.7025
DEVELTYPE4	1	—	—	—	—	—	1.18478	0.84209	3.27	0.8185	13.0645
DEVELTYPE5	1	—	—	—	—	—	1.53165	0.97012	4.6258	0.9379	22.8138

Note: — = not used in the final model; NA = not applicable.

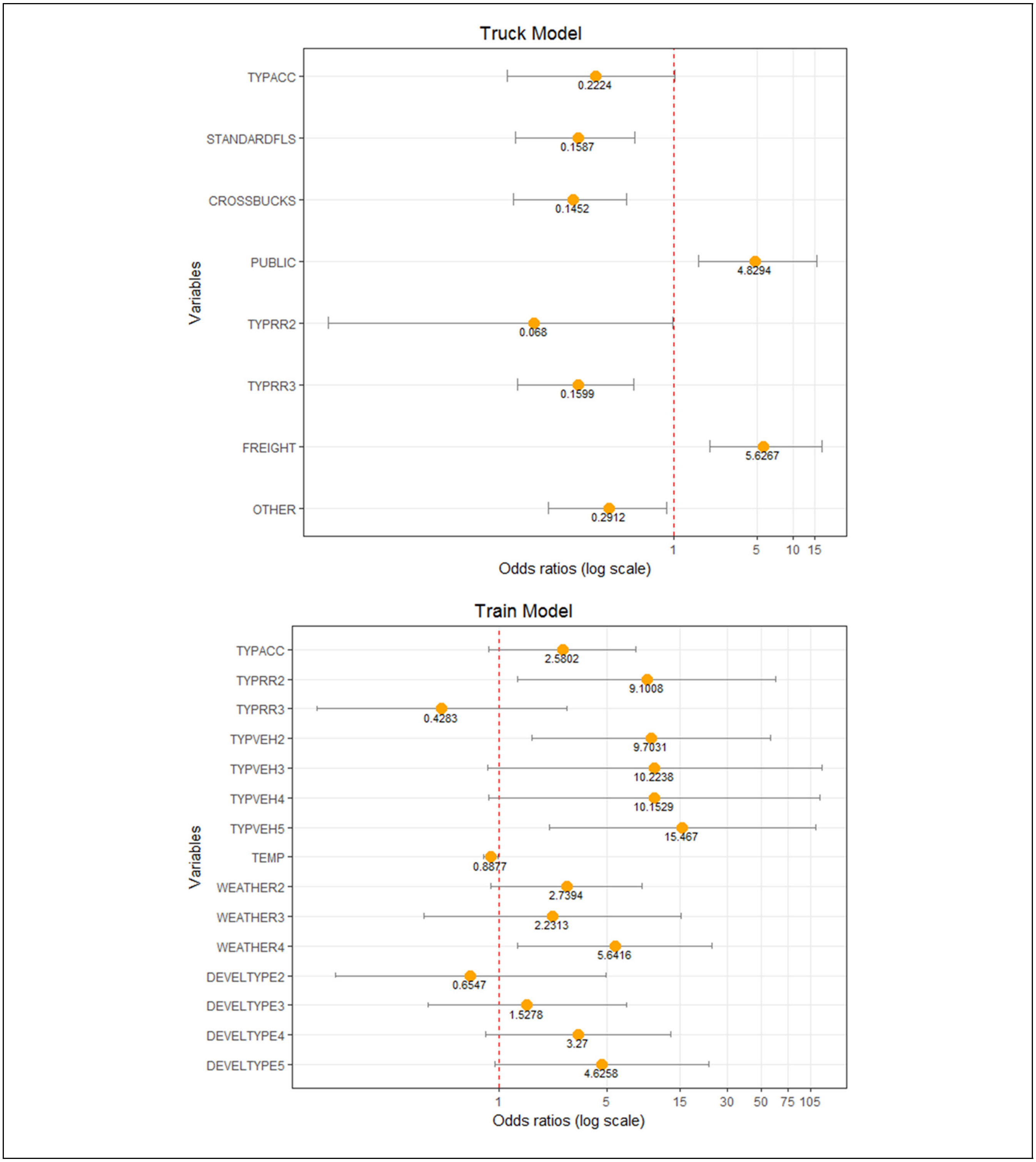

Figure 1. OR and profile likelihood ratio confidence intervals for truck and train models.

other vehicles (e.g., recreational vehicles) are heavier than automobiles on average, leading to potentially more severe collisions and higher probability of hazmat release from trains. Since higher temperature and presence of fog, sleet or snow were associated with smaller and larger probability of hazmat release, respectively, weather considerations are recommended in shipping of hazmat by rail and may be used in relevant policy-making.

Table 4. Comparison of the Results of Six HRGC Crash Severity Studies with Hazmat Release Results

Variables	Crash severity						Hazmat release	
	(Hao & Daniel (*25*))	(Haleem & Gan (*35*))	(Eluru et al. (*36*))	(Zhao et al. (*28*))	(Kang & Khattak (*37*))	(Zhao & Khattak (*27*))	Highway user	Train
TYPACC2	—	Increase	Increase	Increase	Increase	Increase	NS	NS
STANDARDFLS	—	—	NS	NS	Increase	—	Decrease	NS
CROSSBUCKS	—	—	Decrease	NS	Increase	—	Decrease	NS
PUBLIC	—	—	—	—	—	—	Increase	NS
TYPRR2	—	—	—	—	—	—	Decrease	Increase
TYPRR3	—	—	—	—	—	—	Decrease	NS
FREIGHT	—	—	—	Increase	—	Increase	Increase	NA
OTHER	—	—	NS	—	—	—	Decrease	NS
TYPVEH2	Increase	Decrease	NS	NA	Decrease	Decrease	NS	Increase
TYPVEH3	Increase	Decrease	Decrease	NA	NS	—	NS	NS
TYPVEH4	NA	NS	—	NA	—	—	NA	NS
TYPVEH5	Increase	NS	—	NA	Increase	—	NA	Increase
TEMP	—	—	Decrease	NS	—	—	NS	Decrease
WEATHER2	Increase	NS	NS	NS	Increase	—	NS	NS
WEATHER3	Increase	NS	Decrease	Increase	NS	—	NS	NS
WEATHER4	Increase	Decrease	Decrease	Increase	Decrease	—	NS	Increase
DEVELTYPE2	Decrease	NS	—	NS	NS	—	NS	NS
DEVELTYPE3	Decrease	NS	—	Increase	NS	—	NS	NS
DEVELTYPE4	Decrease	Decrease	—	NS	Decrease	—	NS	NS
DEVELTYPE5	Decrease	NS	—	NS	NS	—	NS	NS
OFFPEAK	Decrease	—	—	—	—	—	—	—
VEHSPD	Increase	—	—	NA	Increase	Increase	NS	NS
VISIBLTY1	Increase	—	—	—	NS	NS	NS	NS
VISIBLTY3	Increase	—	—	—	Increase	Decrease	NS	NS
VISIBLTY4	Increase	—	—	—	Increase	NS	NS	NS
TRNSPD	Increase	Increase	Increase	Increase	Increase	Increase	NS	NS
DRIVAGE	Increase	Increase	Increase	Increase	Increase	Increase	NS	NS
NONPAVED	Increase	—	—	—	—	—	—	—
AADT	Increase	Decrease	—	NS	Decrease	—	—	—
DRIVGEN	—	Increase	Increase	Increase	Increase	Increase	NS	NS
BELLS	—	Decrease	—	Increase	—	—	NS	NS
GATES	—	—	Increase	NS	NS	—	NS	NS
HWYTRFICSIG	—	—	NS	—	NS	—	NS	NS
AUDIBLE	—	—	NS	—	NS	—	NS	NS
STOPSIGNS	—	—	Increase	—	Decrease	—	NS	NS
NBRCARS	—	—	—	—	Increase	—	NS	NS

Note: — = not considered in study; NS = not significant; NA = not applicable.

Both models may be used as a part of a risk assessment framework. The framework may include at least two steps: models that predict the occurrence of crashes at HRGCs, based on variables such as highway and rail traffic, land use, control devices, etc. (e.g., (*33*, *34*)); and models, such as those estimated in this study, that predict the probability of hazmat release from trucks, trains, or both, given the occurrence of a crash. The product of these two probabilities can provide a hazmat risk measure for each HRGC, useful to serve as a prioritization tool for countermeasure implementation or resource allocation.

As was mentioned in the literature review, a significant number of papers studied injury severity of HRGC crashes and used this criteria to evaluate control devices and other related factors at HRGCs. It was also mentioned that there was a lack of research on hazmat release crashes reported at HRGCs. The question that may arise is whether the factors that increase/decrease crash severity at HRGCs are consistent with the factors that increase/decrease the probability of hazmat release (positive correlation between crash severity and hazmat release). This consistency may question the importance of this study. To investigate this possibility, Table 4 summarized the results of six studies regarding crash severity at HRGC, and the results of this study for comparison. It should be noted that, although some variables were defined differently in some studies, the final results were consistently reported in this table.

This comparison shows that there were variables that affected crash severity in different studies, almost consistently, but were not associated with hazmat release probability, such as type of crash, train speed, driver age and gender, vehicle speed and some types of land-use. The effects of types of highway user, temperature and weather on crash severity were inconsistent throughout the severity papers. Although these variables were not significant in hazmat release from trucks, some of them affected hazmat release from trains, but not necessarily in the same way (direction) as in the crash severity. The positive effects of standard flashing-light signals, railroad crossbucks and other control devices on hazmat release from trucks were not observed in the majority of the crash severity literature. Public/private HRGCs and type of railroad were not considered in the reviewed crash severity studies, although they were associated with hazmat release. Freight trains increased crash severity and the probability of hazmat release from trucks in crashes at HRGCs. In general, with an exception of some cases, crash severity modeling results were not consistent with hazmat release modeling outcomes, indicating that policies and countermeasures based on crash severity studies may not be relevant to decreasing hazmat release in crashes at HRGCs. Thus, this underscores the necessity of investigating hazmat release in crashes at HRGCs.

The large proportion of missing values in potentially important variables in the dataset and, consequently, not using those variables in the model specifications was a limitation in this research. These variables included details about HRGC control devices, actions of highway users during crashes, sight obstructions, type of hazmat, roadway conditions, etc. For future studies, researchers may address this issue by using more complete datasets (i.e., datasets with few missing values). Other modeling methods can be utilized for analyzing hazmat-related crashes at HRGCs that might lead to further insights. Short-term and long-term costs and damages of hazmat release at HRGCs may be studied to prioritize countermeasures and policies regarding public safety improvements at HRGCs.

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