

Decreasing Derailment Occurrence and Severity at Highway-Rail Grade Crossings

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ABSTRACT

Implementation of highway-rail grade crossing warning systems, educational programs and research on crossings have all contributed to a steady reduction in the risk of grade crossings to highway users over the past several decades. Much less attention has been given to understanding the effect of grade crossings on train safety and risk. Incidents at highway-rail grade crossings can have serious consequences for the public and the railroads alike, especially if an incident results in a train derailment involving passengers or hazardous materials. The goal of past research has been to identify and understand the physical factors leading to these derailments. This paper presents an overview of the trends in incident and derailment data which identify the physical factors most likely to cause a grade crossing incident to result in a derailment. These physical factors point to a subset of grade crossings with the highest derailment risk. Traditionally, highway departments prioritize upgrading grade crossings with the highest risk of an incident, but do not account for the likelihood of train derailment. Based on this analysis, we discuss different methods for decreasing the risk of a derailment at grade crossings exhibiting the factors correlated with highest derailment risk. The results of this paper are intended to provide railway decision makers with another metric for prioritizing grade crossing upgrades and closures.

1. INTRODUCTION

Considerable research has been conducted to understand the impact of highway-rail grade crossings on highway users. This has led to improved grade crossing warning systems, integration of grade crossing operations with highway traffic signaling, public education programs such as Operation Lifesaver, and numerous other improvements. These improvements aim to reduce the number of casualties due to train-highway vehicle incidents, and the result has been a steady decline in the number of incidents and casualties over the past several decades (1).

Much less research has focused on understanding the risk that highway users pose to trains at highway-rail grade crossings. In our previous work, we identified the factors that cause grade crossing incidents to result in derailment (2). This paper discusses grade-crossing-caused freight train derailments in a larger risk-analysis context. By incorporating the results of our earlier research with highway-user and hazardous materials safety research, we provide decision makers with an additional tool for prioritizing grade crossings upgrades

2. DEVELOPMENT OF DERAILMENT MODEL

Chadwick et al. (2) identified the physical factors of grade crossing incidents that affect derailment likelihood. The three factors discussed were train speed, highway vehicle speed, and highway vehicle type. A fourth factor was subsequently added to account for incident type. There are two types of incidents: those where the train strikes the vehicle (TSV) and those where the vehicle strikes the train (VST). Characteristics of the four factors are shown in Table 1.

TABLE 1 Definition of Model Variables

Variable Name	Definition (3)	Variable Type	Range of Values
VEHSPD	Highway vehicle estimated speed in mph	Continuous	Range: 0-105 mph Average: 10.50 mph Standard Deviation: 13.57
TRNSPD	Train speed in mph	Continuous	Range: 0-80 mph Average: 31.45 mph Standard Deviation: 15.58
LGVEH	Was a large highway vehicle involved?	Binary	N if no; Y if yes
TRNSTK	Incident type	Binary	VST if highway user struck train; TSV if train struck highway user

Using these four factors, statistical models were developed to predict whether a given grade crossing incident involving a freight train would result in derailment. This procedure is discussed in detail in Chapter 4 of Chadwick (4). In this paper, we will consider only grade crossing incidents involving freight trains, though the methodology can be expanded to passenger trains.

For freight trains, using two statistical models, one for each incident type produced the best statistical fit. These took the following form:

For VST incidents: $p_{VST} = \frac{1}{e^{-x_{VST}} + 1}$

$$x_{VST} = -6.4039 + \begin{cases} 0, & LGVEH = Y \\ -1.5044, & LGVEH = N \end{cases} + 0.00101 VEHSPD^2$$

For TSV incidents: $p_{TSV} = \frac{1}{e^{-x_{TSV}} + 1}$

$$x_{TSV} = -7.1789 + \begin{cases} 0, & LGVEH = Y \\ -1.8687, & LGVEH = N \end{cases} + 0.0166 TRNSPD$$

where VEHSPD, TRNSPD and LGVEH are as described in Table 1.

Using separate equations for each incident type is logical given the physics of a grade crossing incident. In VST incidents, the equation shows that derailment likelihood increases with increased vehicle speed (+ $0.00101 VEHSPD^2$). In TSV incidents, the derailment likelihood increases with increased train speed (+ $0.0166 TRNSPD$). For both incidents, the likelihood of derailment increases if the incident involves a truck.

We will now discuss how this model can be incorporated into the decision making process for allocating grade crossing upgrade funds.

3. MODEL APPLICATION

In its most basic form, risk can be defined as the probability of an event occurring multiplied by the consequence of that event. To develop an overall grade crossing derailment risk model, there are several conditional probabilities that determine the overall likelihood of an event occurring.

In developing a risk model, it is important to understand the chain of events leading to a certain consequence. In this way we can identify individual probabilities of each event occurring. The flow chart in Figure 1 shows a simplified event chain beginning with a train encountering a grade crossing and ending with a consequence event.

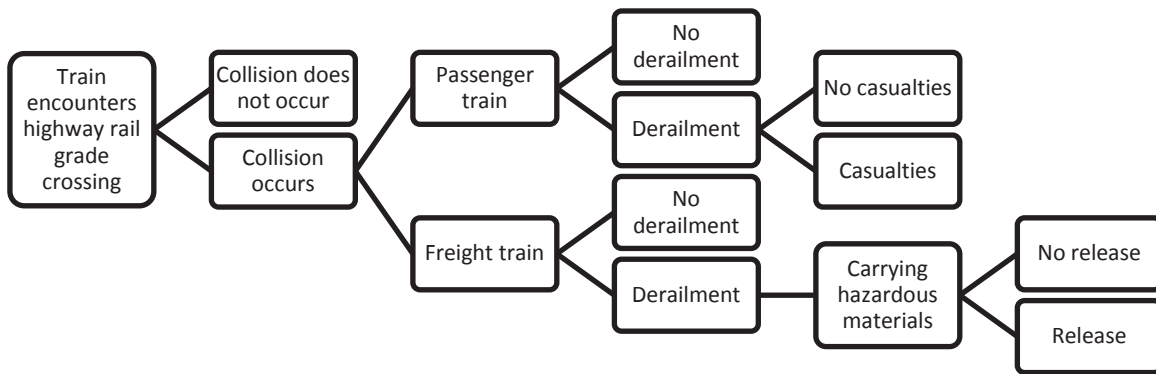


FIGURE 1 Simplified risk flowchart for highway rail grade crossing incidents

For a highway-rail grade crossing incident to occur, the train must first encounter a grade crossing. For every grade crossing encountered, a train has a certain likelihood of being involved in an incident with a highway vehicle. This likelihood is dependent on a range of factors, including traffic, visibility, highway speed limit and warning device type. Several models predicting grade crossing incident likelihood have been developed to evaluate highway safety. An example of an incident prediction model is the U.S. DOT Accident Prediction Model, which calculates the expected incident frequency at a given crossing (5).

If an incident occurs, passenger and freight trains may have different derailment probabilities and are therefore treated differently. We have hypothesized that passenger and freight trains have different derailment likelihoods because of different weight and speed characteristics. This paper discusses applications of the freight derailment model, but this methodology can be similarly applied to a passenger model.

Once the derailment has occurred, the consequence of that event can be determined. The model can be adapted to consider a variety of consequences including financial cost to the railroad as well as train crew casualties. Figure 1 represents the consequence of a freight train derailment as the release of hazardous materials. Hazardous materials release models have been developed that could be combined with the derailment likelihood model to indicate the risk of a

hazardous materials release as a result of a grade crossing incident. This will be summarily discussed in Section 4.

3.1 Enumeration of Model Branches

To develop a model ranking crossings by derailment risk, the first step is to understand if intrinsic crossing characteristics can be used as proxy variables for the incident-specific variables used in the statistical model. For example, knowing that derailment likelihood increases with increased vehicle speed is not necessarily useful unless crossings where vehicles travel faster can be reliably identified.

For each incident-specific variable used in the model, Table 2 indicates a crossing-specific variable (or variables) that will be investigated as a possible proxy.

TABLE 2 Potential Proxy Variables

Incident-Specific Variable	Crossing-Specific Variable
Vehicle Speed	Highway Speed Limit
Train Speed	Posted Timetable Speed
Large Vehicle Involvement	Percent Truck Traffic Annual Average Daily Traffic (AADT)

A proxy variable will not be discussed for the incident type variable. There are likely many factors that influence whether a crossing is more likely to experience a TSV or VST incident, including many human factors aspects that are outside the scope of this work. A detailed literature review of research into human factors at grade crossings is provided in *Driver Behavior at Highway-Railroad Grade Crossings: A Literature Review from 1990-2006*, by Yeh and Multer (6).

Instead of a proxy variable, we will use a fixed ratio based on historical data to define the relative likelihood of TSV and VST incidents. Based on historical data, 79.95% of incidents are TSV; 20.15% of incidents are VST. Subsequent work could refine this element through a better understanding of which crossing characteristics affect incident type.

3.2 Methodology

For this analysis, data from the U.S. DOT Highway-Rail Grade Crossing Inventory History File (GCI) and the Federal Railroad Administration Highway Rail Grade Crossing Accident/Incident database (HRA) were used (7, 8). For each unique and complete incident record in the HRA database, the GCI record in force at the time of the incident was extracted. This record theoretically contains information about the state of the crossing at that time, such as the posted highway speed limit or the type of crossing warning device in use, and should be updated every time characteristics of the crossing change significantly. However, in practice, the data is only sporadically entered and sometimes contains reporting errors. Of the 44,000 complete records in

the HRA database, only 2,221 had full, accurate records in the grade crossing inventory. Therefore, the following analysis is conducted using only those complete records. This reduced data set will be referred to as Set D.

It should be noted that Set D may not be representative of all grade crossing incidents. There may be reasons that inventory data was collected for these roads and not for others. For example, more complete data may be provided by some states than others. Additionally, some road types, such as major arterials, may be evaluated more frequently due to their importance, resulting in better data quality for these roads compared to local roads. If this is the case then there may be variation that will be reflected in the results.

3.3 Proxy Variables

3.3.1 Highway Speed Limit as a Proxy for Vehicle Speed

For each record in Set D with a valid vehicle speed (VS) and highway speed limit (HSL), a value was calculated comparing the actual speed of the vehicle to the posted HSL. This value, called “percent deviation from highway speed limit” (PDHSL), is defined as follows:

$$PDHSL = \frac{VS - HSL}{HSL}$$

Figure 2 shows the distribution of PDHSL values for Set D. A value of -100% means the vehicle was stopped on the crossing. A value of 0% means the vehicle was traveling at the HSL. A value of 100% means the vehicle was traveling at twice the HSL. Less than 0.2% of all incidents occurred with the vehicle traveling more than twice the posted speed limit, so the chart was cut off at 100%.

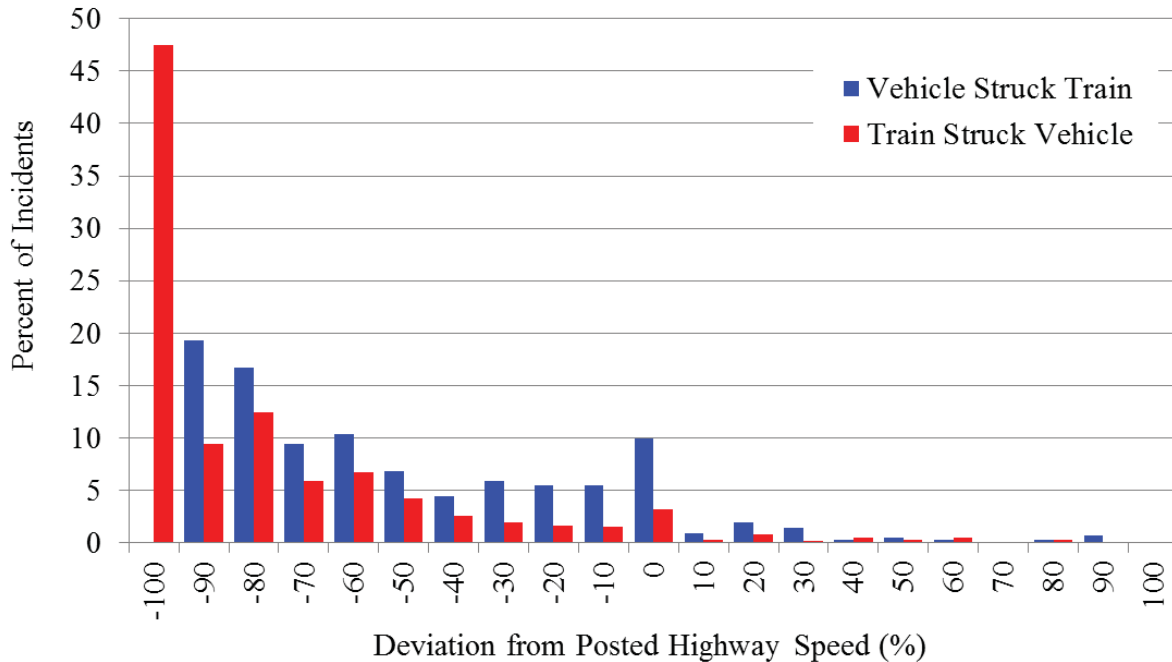


FIGURE 2 Probability density function of percent deviation from posted highway speed

Figure 2 shows that, in cases where the train struck the vehicle, about 47% of incidents involved a vehicle which was stopped on a crossing. Overall, if vehicles were traveling at the speed limit, they were more likely to strike the train than to be struck by the train.

Based on this analysis, the likelihood that any vehicle at any crossing will be traveling at a certain percent of the HSL when involved in an incident was calculated. This speed distribution will be used to calculate the probability of derailment.

3.3.2 Timetable Speed as a Proxy for Train Speed

Similar to the analysis of vehicle speed, for each record in Set D with a valid train speed (TS) and timetable speed (TTS), a value was calculated comparing the actual speed of the train to the timetable speed. This value, called “percent deviation from timetable speed” (PDTTS) is defined as follows:

$$PDTTS = \frac{TS - TTS}{TTS}$$

Figure 3 shows the distribution of deviation from the TTS for Set D. A value of -100% means the train was stopped on the crossing. A value of 0% means the train was traveling at the TTS. A value of 100% means the train was traveling at twice the TTS. While some trains (less than 1%) were reported to be traveling more than twice the timetable speed, these records were excluded from analysis because they are almost certainly the result of reporting errors. For the most part, these records reported a timetable speed of 0 or 1 mph, which is unlikely to reflect the actual timetable speed.

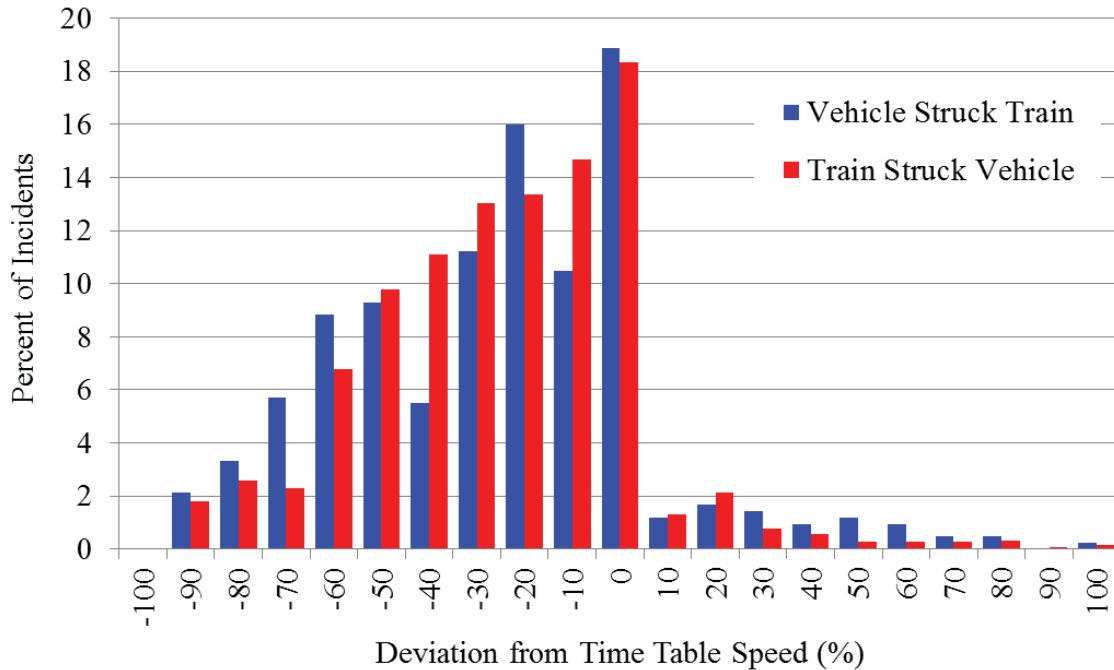


FIGURE 3 Probability density function of percent deviation from timetable speed

Figure 3 shows that the majority of trains were traveling near the TTS when the incident occurred. Interestingly, no trains were stopped on the crossing when the incident occurred (meaning the PDTTS would be -100%). The figure shows that about 8% of incidents involved a train traveling in excess of the timetable speed. If true, this represents about 150 over-speed incidents. While some of these events can be confirmed as over-speed incidents by examining the narrative field, the majority are probably reporting errors. This could be determined on a case-by-case basis if actual historical timetable data was obtained from the railroad.

Based on this analysis, the likelihood that any train at any crossing will be traveling at a certain percent of the TTS when involved in an incident was calculated. This speed distribution will be used to calculate the probability of derailment.

3.3.3 Proxy for Vehicle Type

Results so far have shown that a truck’s involvement in a grade crossing incident increases the likelihood of that incident resulting in derailment. Therefore, it is important to be able to identify crossings where incidents are more likely to involve trucks.

It was hypothesized that crossings with greater truck traffic are more likely to have train-truck incidents. This was tested using percent truck traffic (PTT) to quantify the number of trucks at a crossing.

Figure 4 shows the probability density distribution of PTT for cases involving a large vehicle and for cases without a large vehicle involved. A t-test comparing the two distributions showed that there is a small but statistically significant (p -value = 0.0113, $\alpha=0.025$) difference in

the likelihood of large vehicle involvement based on PTT at a crossing. Specifically, the likelihood that an incident will involve a truck is greater for crossings with higher PTT.

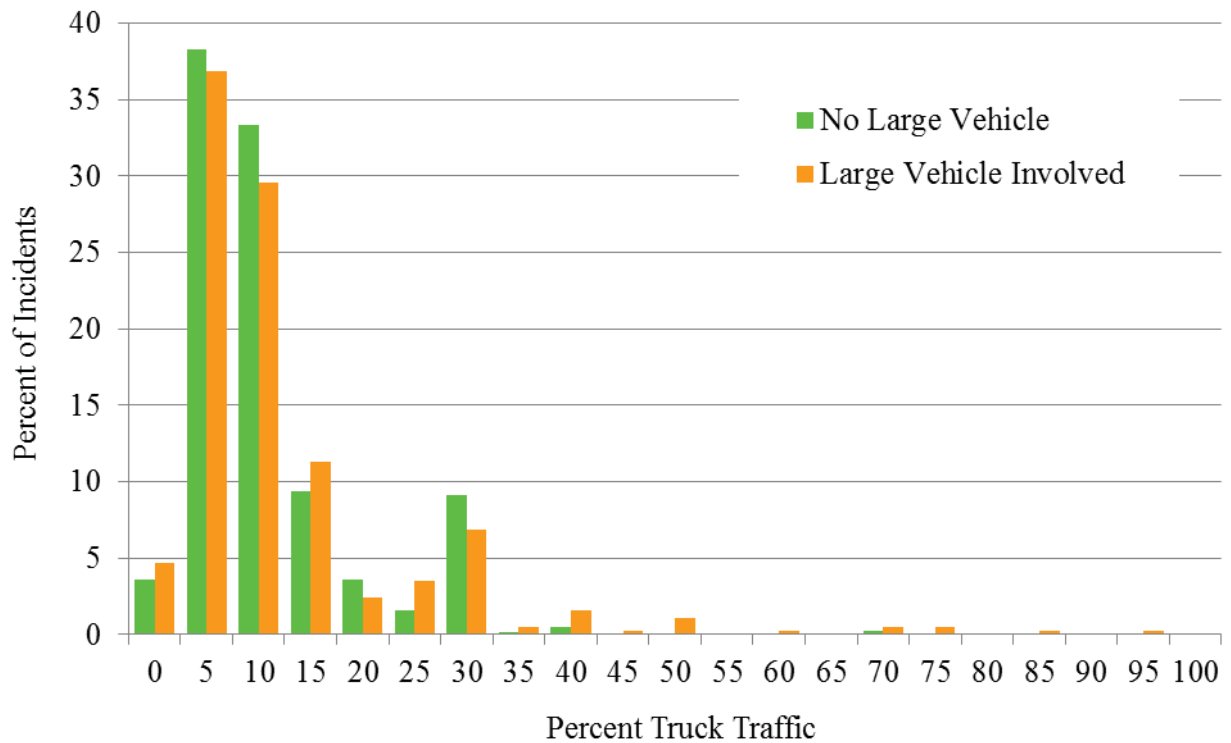


FIGURE 4 Distribution of percent truck traffic for incidents involving cars and trucks

To quantify this relationship for use in the derailment likelihood model, the ratio of truck incidents to car incidents was calculated for each value of PTT, and a linear regression was performed, as shown in Figure 4. If the ratio was zero or undefined, that point was omitted from analysis.

Next, the data was divided according to the warning device type in use at the grade crossing to see if different trends would be observed for different warning device types. Initially, three separate distributions were considered – one each for gates, active excluding gates, and passive. Statistical analysis using JMP software showed that regressions for “gates” and “active excluding gates” were not significantly different; therefore they were grouped into the “active” category and compared to the “passive” category. There is a statistically significant difference between active and passive.

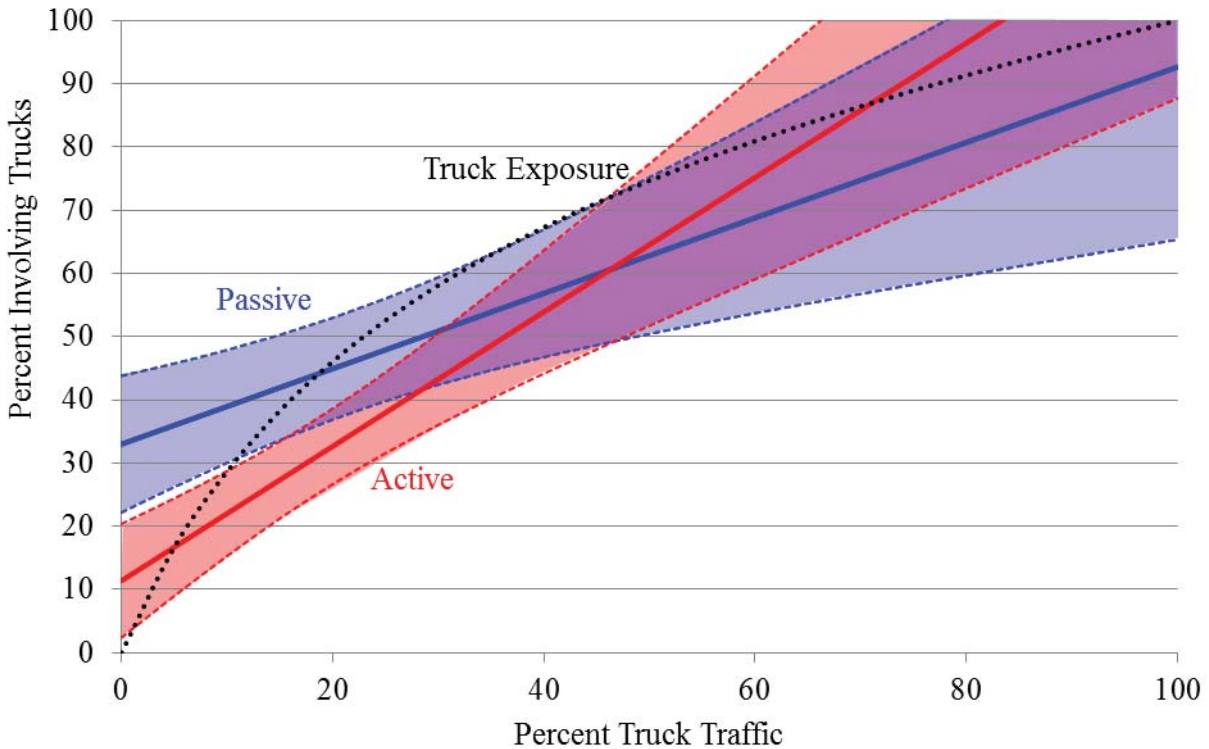


FIGURE 5 Percent of incidents involving trucks as a function of percent truck traffic for passive and active crossing warning device types. Shaded regions represent the 95% confidence bands for each category

Figure 5 shows regression lines for each warning device category. The equations for each line are as follows:

Passive: $y_P = 33.0 + 0.597 PTT$

Active: $y_A = 11.4 + 1.06 PTT$

The figure implies that, for low PTT, incidents at passive crossings are more likely to involve trucks than those at active crossings. However, for roads where trucks constitute more than 50% of traffic, incidents at active crossings are more likely to involve trucks. It should be noted that the confidence bands are distinct at truck traffic levels below 20%, but begin to overlap significantly at higher levels, indicating that the linear trend does not fit as well at the high end of the range. This is likely due to the fact that most crossings in the U.S. have PTT below 20 percent. Therefore, there are many more data points at the low end than at the high end.

It is interesting to note that even roads with reported PTT of zero show trucks involvement in 10 to 30 percent of incidents. It could be that no trucks used the crossing the day of the traffic count; however, the crossing may in fact be used by trucks occasionally. Since the crossing is reported as having a negligible amount of truck traffic, it may not be maintained with trucks in mind. For example, the crossing may be humped, which is not a major problem for

small passenger vehicles but can pose a danger to longer trucks that can become lodged on the crossing. This would affect the likelihood of a TSV incident occurring. Another explanation for the trend could be that individual truck drivers use crossings with low PTT infrequently and are therefore not prepared for the presence of a train when they do use the crossing. This would affect the likelihood of a VST incident occurring.

Another notable factor is that the regression lines in Figure 5 both lie above the diagonal – that is, there is not a 1:1 relationship between percent truck traffic and percent truck involvement. A possible explanation for this is the difference in exposure time for cars and trucks. The average truck in the U.S. is about five times longer than the average car. This means that a truck occupies a crossing for about five times as long as a car, given a constant speed. This indicates that any individual truck has a larger exposure metric than any car. The dotted line in Figure 5 represents truck exposure, a metric representing the total length of trucks using a crossing as a percent of total length of all vehicles at that crossing. This is expressed as:

$$\begin{aligned}
 \text{Truck Exposure} &= 20(\text{PTT}/100) \\
 &+ 80 \left(\frac{\text{AADT} \times \text{PTT} \times 5}{(\text{AADT} \times \text{PTT} \times 5) + (\text{AADT} \times (100 - \text{PTT}))} \right)
 \end{aligned}$$

where AADT is the average annual daily traffic on the intersecting highway.

This value increases exponentially, not linearly, which may partially explain why the regression lines lie above the diagonal. The overall positive trend shows that likelihood of truck involvement does increase as PTT increases. These regression equations are used as a proxy for the large vehicle involvement variable in the derailment model.

3.4 Case Study

Using the results of Section 3.3, an Excel “calculator” was developed to evaluate the derailment risk tree. Users can enter the highway speed limit, timetable speed, percent truck traffic and grade crossing warning device type. The spreadsheet returns a conditional probability of derailment given an incident has occurred.

To demonstrate the use of this model, a sample track segment will be presented. This segment represents a five-mile long section of track with seven grade crossings located in the United States, whose identifying information has been removed. Crossing G is in a rural downtown area, while the other crossings are in a rural setting. These crossings represent a variety of speed limits, timetable speeds, percent truck traffic, and grade crossing warning devices. A diagram of the segment is shown in Figure 6.

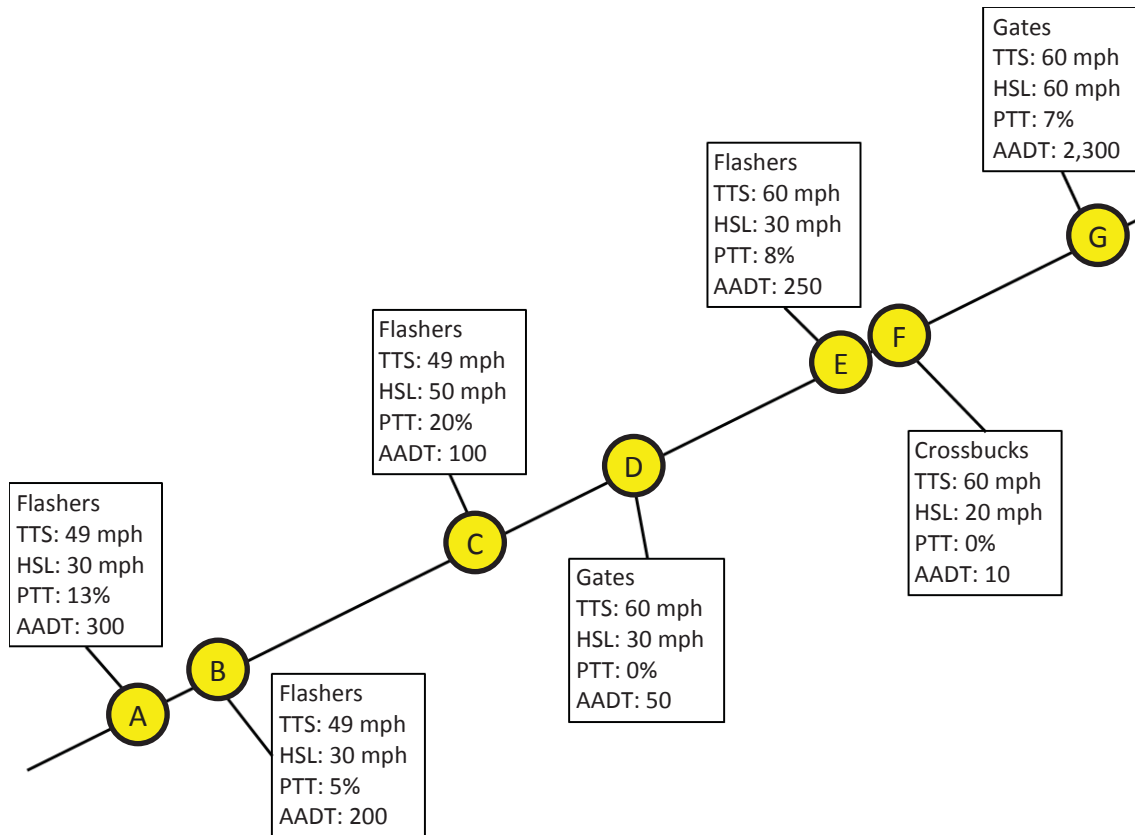


FIGURE 6 Diagram of sample track segment

For each crossing, the predicted incident frequency, or $f(I)$, was calculated using the U.S. DOT Accident Prediction Formula. Specifically, this frequency was generated using the FRA Web Accident Prediction System (WBAPS) (9). These values are shown in the third column of Table 3. Next, the conditional probability of derailment, $p(D/I)$, was calculated using the Excel calculator. These values are shown in the fourth column. Lastly, the product of these two values was calculated to give the overall probability of derailment, $p(D)$, at the crossing.

TABLE 3 Example Crossings Ranked by $f(I)$, $p(D/I)$, $p(D)$

Crossing	Crossing Classification	Value			Ranking		
		$f(I)$ (9)	$p(D/I)$	$p(D)$	$f(I)$	$p(D/I)$	$p(D)$
G	Rural Major Collector	0.014330	0.002684	3.846E-05	1	1	1
A	Rural Major Collector	0.010532	0.000406	4.276E-06	2	4	3
E	Rural Major Collector	0.009901	0.000361	3.574E-06	3	5	4
B	Rural Local Road	0.009170	0.000269	2.467E-06	4	6	6
C	Rural Local Road	0.006106	0.001385	8.457E-06	5	2	2
F	Rural Local Road	0.005736	0.000570	3.270E-06	6	3	5
D	Rural Local Road	0.002234	0.000207	4.624E-07	7	7	7

Several observations can be made from this analysis. Crossing G is ranked first in all three metrics. Crossing A, which has the second highest $f(I)$, has the third highest $p(D)$ due to a comparatively low conditional probability of derailment. While crossing G has gates, which would reduce its derailment likelihood relative to crossing A, which has only flashers, the TTS and HSL are lower at crossing A, which has a strong effect on the derailment likelihood. It is also interesting to note that crossing G is the only crossing on this segment which has actually experienced an incident. The incident did not result in a derailment. Since the U.S. DOT Accident Prediction Formula adjusts a crossing's incident likelihood based on historical incident data (5), this could also explain why crossing G ranks highest in this metric.

Also of interest is crossing C. While it ranked fifth in importance when only incident likelihood is considered, it has the second largest $p(D/I)$ value, giving it the second highest derailment likelihood. This crossing has a large PTT (20%) and a high speed limit (50 mph), but does not have gates, likely because of the low highway traffic (100 vehicles per day). This means it is vulnerable to factors identified as high-derailment risk, but does not have a very high incident risk.

Crossing D has the same rank in all three categories, ranking last. It has gates despite low highway traffic (50 vehicles per day) and no truck traffic. This makes it not only unlikely to experience a grade crossing incident, but also unlikely for that incident to result in a derailment, despite its relatively high timetable speed.

4. INCORPORATION OF CONSEQUENCE DATA

While it is of interest to railroad operators to identify crossings with greater derailment risk, the prioritization of crossing upgrades has to take into account the relative likelihood and severity of different events. As an example, we will consider one potential consequence of a grade crossing incident involving a freight train – a hazardous materials release. Such an incident is extremely rare, with only a handful occurring in the U.S. over the past 30 years (8). However, if one were to occur, the consequence could be enormous depending on its location. In contrast, from the highway side, the expected number of casualties for any one incident is comparatively small, but these incidents occur more frequently (approximately 2,000 incidents in 2012 (10)). Therefore, it is likely inaccurate to consider these risks equally.

Looking at data from the past 20 years collected by the FRA, the number of grade crossing incidents and the number of fatalities has decreased steadily (10). However, the fatality rate for highway users in grade crossing incidents has remained fairly constant around 0.12 fatalities per incident. The injury rate has fluctuated more, but averages about 0.38 non-fatal injuries per incident. This means that in almost half of all incidents, a casualty will occur.

Considering hazardous materials release as a potential consequence of a grade crossing incident, we can use information collected in the FRA's Highway-Rail Grade Crossing Incident database (8) to make general observations about incident rates. Inspection of freight rail data from 1991-2010 shows that 0.069% of all grade crossing incidents resulted in a hazardous materials release (a total of 30 release events in 20 years). It should be noted that 22.6% of all grade crossing incidents involved a train carrying hazardous materials.

The likelihood of release also appears dependent on derailment, as 0.641% of all derailments result in release and 0.063% of all non-derailments result in release. In this example, we will focus only on derailment-related release incidents, as there is evidence that the most severe releases occur as the result of derailment events (11).

Next, we must determine the impact a release would have on the surrounding population. It is reasonable to assume that the worst incidents would involve a toxic inhalation hazard (TIH) material, so this example will consider a release of chlorine, a highly toxic chemical which can be lethal if inhaled (12). Chlorine has been involved in multiple release events in the U.S. (13, 14, 15) including the Graniteville, SC train collision that resulted in the deaths of nine people (16). A large chlorine release, occurring at night, can affect an area of up to 4.9 miles downwind of the release and 1,500 feet in any direction (12). This means an area of about 25 mi² could be affected by one release in a worst-case scenario.

If a release were to occur in a densely-populated area, there would be the potential for significant casualties. Several cities in the Midwest and Northeastern U.S. have population densities well in excess of 15,000 people per square mile (17). If the worst-case scenario were to occur in one of these locations, upwards of 375,000 people could theoretically be affected through evacuation, injury or fatality. Barrett studied the predicted number of fatalities due to a chlorine tank release in a densely populated urban area (with a local population density of 0.01 person/m², or roughly 26,000 people/mi²); he found that the variety of fatality estimate models available yielded a range of results, from approximately 4,000 fatalities to 33,000 fatalities (18).

4.1 Case Study

Consider two hypothetical grade crossings. One is a rural crossing (Crossing R) with lower incident risk and population density; the other is an urban crossing (Crossing U) with higher incident risk and population density. Characteristics of the crossings are shown in Table 4. It is assumed that 5% of the affected population will suffer fatalities as a result of a single incident. This is very simplistic, but will serve for illustrative purposes.

TABLE 4 Characteristics of Example Crossings

Characteristic	Crossing R	Crossing U
Warning Device	Active (Gates and Flashers)	Active (Gates and Flashers)
AADT	1,800	29,900
Number of Through Trains	10	14
Highway Speed	55 mph	35 mph
Timetable Speed	20 mph	50 mph
Percent Truck Traffic	10%	6%
Population Density	20 ppl/mi ²	25,000 ppl/mi ²
Projected Fatalities	25 fatalities	31,250 fatalities
$f(I)$ (9)	0.010317	0.036942
$p(D/I)$ (Derailment Calculator)	0.001668	0.000310

For each case, we will identify a “trade off point” between the expected consequence from the highway and rail perspectives.

Crossing R

According to WBAPS (9), Crossing R has a predicted incident frequency of 0.010317 incidents. The historical fatality rate for all U.S. grade crossings was calculated to be 0.12 fatalities per incident. This gives an expected number of highway user fatalities of 0.00124 fatalities for Crossing R.

If there is a derailment, then the likelihood of a release occurring is 0.00641. We multiply this by the predicted incident frequency (0.010317), and by the likelihood of a derailment occurring given an incident has occurred (0.001668). Finally, we multiply by the expected number of fatalities should a release occur, in this case 25 fatalities. This gives an expected number of 2.76×10^{-6} fatalities.

This indicates that Crossing R is approximately 450 times more likely to experience a highway user fatality than a fatality as a result of a hazardous materials release.

Crossing U

According to the U.S. DOT Accident Prediction formula, Crossing U has a predicted incident frequency of 0.036942 incidents. The historical fatality rate for all U.S. grade crossings was calculated to be 0.12 fatalities per incident. This gives an expected number of highway user fatalities of 0.00443 fatalities for Crossing U.

If there is a derailment, then the likelihood of a release occurring is 0.00641. We multiply this by the predicted incident frequency (0.036942), and the likelihood of a derailment occurring

given an incident has occurred (0.000310). Finally, we multiply by the expected number of fatalities should a release occur, in this case 31,250 fatalities. This gives an expected number of 0.002294 fatalities.

This indicates that Crossing U is approximately 2 times more likely to experience a highway user fatality than a fatality as a result of a hazardous materials release.

5. DISCUSSION

5.1 Risk Model Application

The methodology presented in Section 3.4 can be used by practitioners as an extra decision-making tool when prioritizing crossing upgrades. With limited money to spend on crossing upgrades, highway departments have traditionally prioritized projects using an incident-likelihood metric such as the U.S. DOT Accident Prediction Formula, or other formulas such as the New Hampshire Index, Illinois Hazard Index, and many others. The derailment likelihood model can be used in combination with an incident likelihood model, yielding a ranking of a state's crossings according to their derailment risk. Alternatively, the derailment likelihood model can be used as a "tie-breaker" in cases where multiple crossings in the state have the same incident likelihood but cannot all be upgraded at the time.

5.2 Incorporation of Consequence Data

While very rudimentary, the analysis in Section 4 shows that the weight assigned to each aspect of risk varies widely even if only location is considered. A thorough analysis would also examine route-specific factors such as the type of commodities that are shipped through a given crossing and the time of day when they are shipped. For example, if no TIH materials are shipped over the crossing in question, there is no risk to the adjacent population from such materials. However, there could be other risk factors such as the damage to structures from explosive materials, or damage to the environment from environmentally hazardous materials.

Hazardous materials releases caused by grade crossing incidents are extremely rare, and it would be even rarer for one to occur in a densely populated area. Fatalities to highway users are comparatively common. This is reflected in the example of Crossing R, for which a fatality is 450 times more likely to occur as a result of the collision. It is likely that, in the majority of cases, the risk posed to a highway user at a grade crossing outweighs the risk to the surrounding population. The example of Crossing U is quite telling. Despite the very high population density, the likelihood of a hazardous materials release fatality is still less likely than a highway user fatality, though only slightly.

This example does not account for the risk preferences of the agents involved in the decision making process. A simple Net Present Value (NPV) assessment was used. However, NPV assumes that the agents are risk-neutral, meaning that they view the loss of ten lives in ten individual incidents the same as the loss of ten lives in one single incident (19). In reality, it is often the case that decision makers are risk adverse, so a single catastrophic incident is less preferable than several smaller incidents, even if the cumulative cost is the same in both cases. If the decision maker is strongly risk averse, then prioritizing crossing upgrades based on derailment rate may be preferable.

Lastly, it is likely that any improvement done to a crossing would affect both incident likelihood and derailment likelihood, not just one or the other. The factors affecting derailment likelihood – train speed, highway vehicle speed, highway vehicle type, and incident type – are essentially intrinsic to the crossing, and for various practical reasons are unlikely to change. In fact, the best way to reduce the risk of derailment is to reduce the risk of the grade crossing incident occurring in the first place, since the likelihood of derailment is conditional on the incident frequency.

6. FUTURE WORK

The model presented here can be incorporated into a system-wide risk analysis tool to help railroads and communities identify the best risk mitigation strategies. This is only one component of such a tool, and should be expanded to include other consequences of grade crossing incidents and derailments, including crew member casualties, costs due to infrastructure and equipment damage, lost earnings due to track outages, and environmental damage.

A similar model is also being developed for passenger trains, and will examine the tradeoff between casualties to train passengers and casualties to highway users. This can be incorporated with the freight model to fully quantify the risk posed by crossings that serve both freight and passenger train traffic.

Combining the grade crossing component with models for other railroad risk components can help the industry and surrounding communities create better risk mitigation strategies. It could be a powerful tool for deciding where to spend the finite amount of money that is available each year for improvements to infrastructure.

7. CONCLUSIONS

This paper presented a derailment likelihood model for freight trains at highway-rail grade crossings based on U.S. railroad incident data from 1991-2010. The factors statistically shown to affect derailment likelihood – train speed, highway vehicle speed, highway vehicle type, and incident type – were correlated with proxy variables such as timetable speed, posted highway speed limit, and percent truck traffic. A case study demonstrating the model was presented and discussed. Finally, a rudimentary discussion of how to incorporate consequence data to create a risk model was presented. Continued development of this work could provide decision makers with a better risk mitigation strategy, not just for highway-rail grade crossings but for the rail network as a whole.

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LIST OF FIGURES

- FIGURE 1 Simplified risk flowchart for highway rail grade crossing incidents
- FIGURE 2 Probability density function of percent deviation from posted highway speed
- FIGURE 3 Probability density function of percent deviation from timetable speed.
- FIGURE 4 Distribution of percent truck traffic for incidents involving cars and trucks
- FIGURE 5 Percent of incidents involving trucks as a function of percent truck traffic for passive and active crossing warning device types. Shaded regions represent the 95% confidence bands for each category
- FIGURE 6 Diagram of sample track segment

LIST OF TABLES

- TABLE 1 Definition of Model Variables
- TABLE 2 Potential Proxy Variables
- TABLE 3 Example Crossings Ranked by $f(I)$, $p(D/I)$, $p(D)$
- TABLE 4 Characteristics of Example Crossings

Analysis of Factors Affecting Freight Train Derailments at Highway-Rail Grade Crossings

Samantha G. Chadwick, M. Rapik Saat, C. Tyler Dick
and Christopher P. L. Barkan



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Outline

- Research Goals
- Risk Model Development
- Identification of Proxy Variables
- Derailment Likelihood Calculator and Example
- Incorporating Consequence Data
- Future Work



Grade Crossings

- Trains pose a risk to small vehicles such as cars
 - Vast body of research into reducing risks for highway users has resulted in improved crossing warning systems, etc.
 - Fatalities have decreased over the past 30 years



There is another side to the story...



- What risks do grade crossing collisions pose to trains?
- The answer to this question is not well understood



Research Goals

- Understanding derailment risk posed to trains by grade crossings has applications across the rail industry
 - Passenger safety
 - Freight safety
 - Time and financial cost
- A model to predict if a derailment is likely to occur due to a grade crossing incident will help understand this risk



Risk Model Development

Train encounters highway rail grade crossing

Incident does not occur

Incident occurs

- A train approaches a highway grade crossing
- Either a collision will occur or it will not occur
- The probability of a collision can be predicted based on a number of factors
- Considerable research has been done on the prediction models on the part of the US DOT
- US DOT Accident Prediction Models
- Development of a derailment risk model is the focus of this research
- Two derailment risk models will be developed: passenger and freight
- Hypothesis: Passenger and freight trains behave differently in a collision and therefore have different probabilities of derailment

sequence metric is number of casualties

sequence metric could be financial cost, train crew casualties, hazardous materials release

Likelihood of hazard release has been researched extensively

Regression Model

Variable	Definition	Variable Type	Range of Values
VEHSPD	Highway vehicle estimated speed in mph	Continuous	Range*: 0-105 mph Average*: 10.50 mph Standard Deviation*: 13.57
TRNSPD	Train speed in mph	Continuous	Range*: 0-80 mph Average*: 31.45 mph Standard Deviation*: 15.58
LGVEH	Large highway vehicle involved?	Binary	N if no; Y if yes
TRNSTK	Incident type	Binary	VST if highway user struck train; TSV if train struck highway user
TRKCLAS	FRA track class	Categorical	0-9 (0 represents X)
WARNSIG	Crossing warning interconnected with highway signals	Categorical	1 if yes; 2 if no; 3 if unknown
VIEW	Was the driver's view of the track obstructed?	Binary	N if not obstructed; Y if obstructed
PUBLIC	Did the collision occur at a public crossing?	Binary	Y if public; N if private
XTYPE	Type of warning device at crossing	Categorical	1: gates; 2: active (excl. gates); 3: passive; 4: other; 5: none

Regression Model

- Initially developed unified model
 - Found incident type significantly affects derailment probability
 - Model had good fit, but could be improved
- Hypothesis: Physics and human factors involved in each type of incident are very different, therefore model is trying to predict two different distributions using only one equation
- Address this issue by developing a "split" model with two regressions based on incident type

Freight Model

- For incidents where the train strikes the highway vehicle:

$$p_{TSV} = \frac{1}{e^{-x_{TSV}} + 1}; \quad x_{TSV} = -7.1789 + \begin{cases} 0, & LGVEH = Y \\ -1.8687, & LGVEH = N \end{cases} + 0.0166 TRNSPD$$

- For incidents where the highway vehicle strikes the train:

$$p_{VST} = \frac{1}{e^{-x_{VST}} + 1}; \quad x_{VST} = -6.4039 + \begin{cases} 0, & LGVEH = Y \\ -1.5044, & LGVEH = N \end{cases} + 0.00101 VEHS PD^2$$

Where $TRNSPD$ is train speed, $VEHS PD$ is highway vehicle speed, and $LGVEH = Y$ indicates the highway vehicle was a truck

- We can combine these using prior probabilities to give an overall grade crossing derailment model

$$p_{Derailment} = 0.80 p_{TSV} + 0.20 p_{VST}$$

Discussion

- Train strikes highway vehicle, $p(D|I)$ increases:
 - As train speed increases
 - If a large highway vehicle such as a semi truck is involved
- Highway vehicle strikes train, $p(D|I)$ increases:
 - As vehicle speed increases
 - If a large highway vehicle such as a semi truck is involved
- This model describes the likelihood of a particular collision resulting in a derailment, but we want to identify crossings with higher derailment rate
 - Identify physical characteristics of crossing that are proxies of model factors

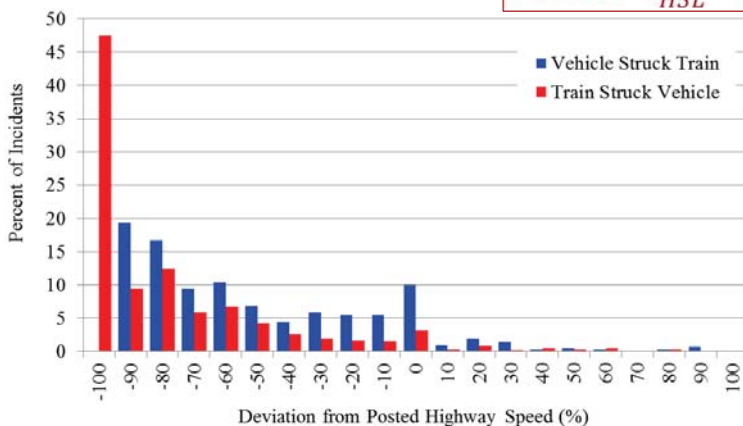
Potential Proxy Variables

Incident-Specific Variable	Crossing-Specific Variable
Vehicle Speed	Highway Speed Limit
Train Speed	Posted Timetable Speed
Large Vehicle Involvement	Percent Truck Traffic Annual Average Daily Traffic (AADT)

- Proxy variable for incident type will not be discussed
 - Many human and design factors influence incident type
 - Use a fixed ratio based on historical data
 - 79.95% TSV
 - 20.15% VST

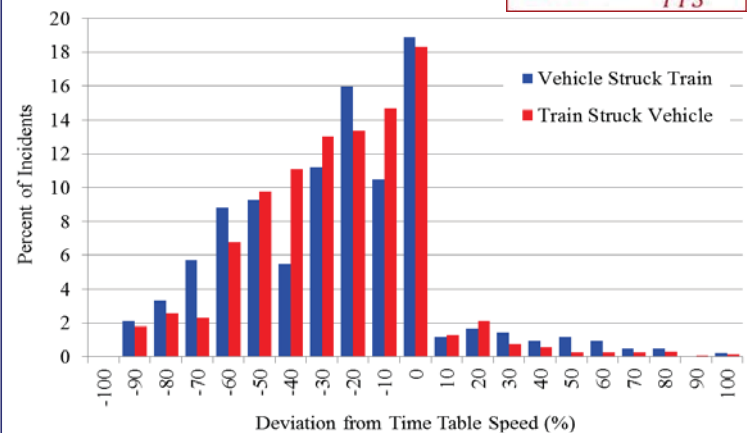
Highway Vehicle Speed

$$PDHSL = \frac{VS - HSL}{HSL}$$

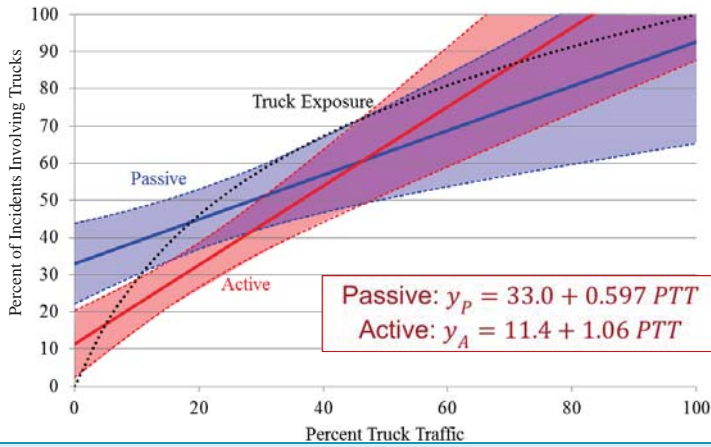


Train Speed

$$PDTTS = \frac{TS - TTS}{TTS}$$



Percent Truck Traffic



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Derailment Likelihood Calculator

P(D I) Calculator	
Enter Crossing Factors	
Posted Highway Speed Limit*	35 mph
Timetable Speed*	45 mph
* values must be greater than 0	
Grade Crossing Type	Other Active
Percent Truck Traffic	8 (0-100)
Results	
Probability of Derailment	0.000380

- Using crossing characteristics, we can calculate an average conditional probability of derailment based on every possible incident scenario
- A "calculator" was developed using Microsoft Excel
- Combined with an incident likelihood model such as the U.S. DOT Accident Prediction Model, can be used to rank grade crossings for improvement

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Derailment Likelihood Example

Crossing	Crossing Classification	Value			Ranking		
		f(I) (9)	p(D I)	p(D)	f(I)	p(D I)	p(D)
G	Rural Collector	0.0143	0.00268	3.8E-05	1	1	1
A	Rural Collector	0.0105	0.00041	4.3E-06	2	4	3
E	Rural Collector	0.0099	0.00036	3.6E-06	3	5	4
B	Rural Local Road	0.0092	0.00027	2.5E-06	4	6	6
C	Rural Local Road	0.0061	0.00139	8.5E-06	5	2	2
F	Rural Local Road	0.0057	0.00057	3.3E-06	6	3	5
D	Rural Local Road	0.0022	0.00021	4.6E-07	7	7	7

$$p(D) = f(I) \times p(D|I)$$

Incorporating Consequence Data

- Prioritization of crossing upgrades should account for relative likelihood and severity of different events
 - Non-derailment GX incident consequence: highway user fatality
 - Derailment GX incident consequence: hazardous materials (HM) release
- While HM releases are much rarer than highway user fatalities, the consequence (number of fatalities) could be much greater

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Incorporating Consequence Data

Characteristic	Rural Crossing	Urban Crossing
Warning Device Type	Active	Active
AADT	1,800	29,900
Percent Truck Traffic	10%	6%
Population Density	20 ppl/mi ²	25,000 ppl/mi ²
Projected Fatalities in HM Release	25 fatalities	31,250 fatalities
f(I)	0.010317	0.036942
p(D I) (Derailment Calculator)	0.001668	0.000310

- Rural Crossing: 450 times more likely to experience a highway user fatality than a fatality caused by HM release
- Urban Crossing: Two (2) times more likely to experience a highway user fatality than a fatality caused by HM release

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Future Work

- Incorporate other consequences of grade crossing incidents and derailments
 - crew member casualties
 - costs due to infrastructure and equipment damage
 - lost earnings
 - environmental damage
- Develop analogous model for passenger trains
- Incorporate these models into the larger risk management framework
 - Implications of shared corridor operations?
 - Routing decisions for hazardous materials trains?

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Conclusions

- Presented a derailment likelihood model for freight trains at highway-rail grade crossings
- A case study demonstrating use of the statistical model was discussed
- Rudimentary discussion of how to incorporate consequence data in the risk model was presented

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Any questions?



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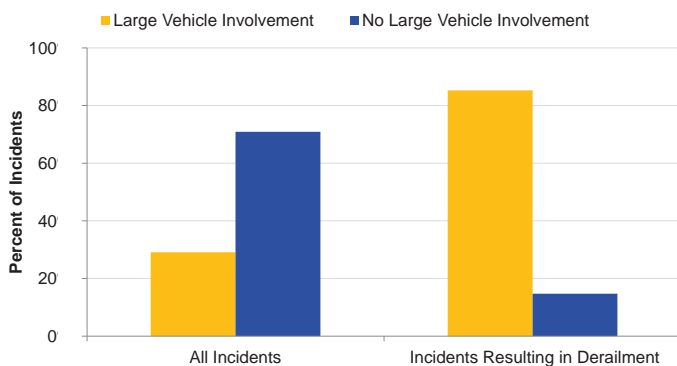
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Thank you!

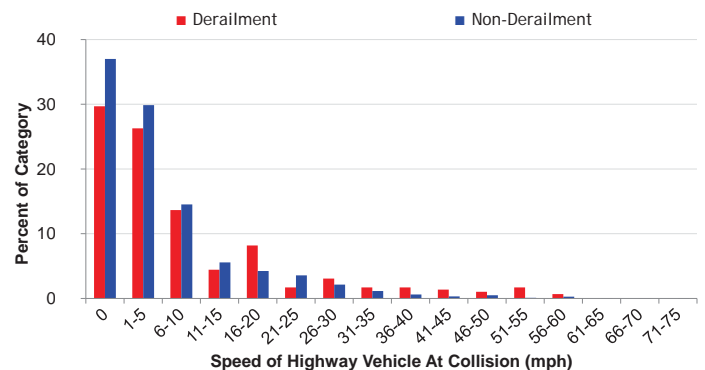
APPENDIX

Incidents Occurring at Grade Crossings on Mainline Track - 1991 to 2010



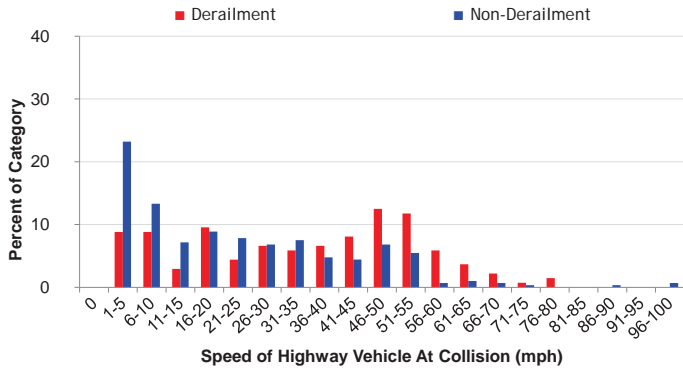
Trains involved in a grade crossing collision with a truck are disproportionately more likely to derail.

Speed at Collision of Highway Users Involved in Grade Crossing Incidents - Train Striking Vehicle, 1991-2010



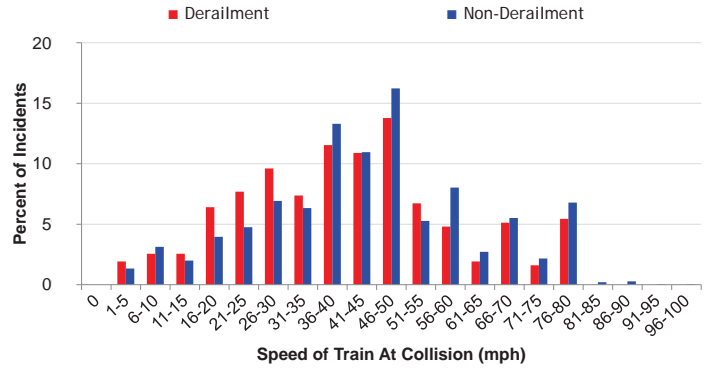
Derailments are more likely to occur at higher vehicle speeds when the train strikes the vehicle.

Speed at Collision of Highway Users Involved in Grade Crossing Incidents - Vehicle Striking Train, 1991-2010



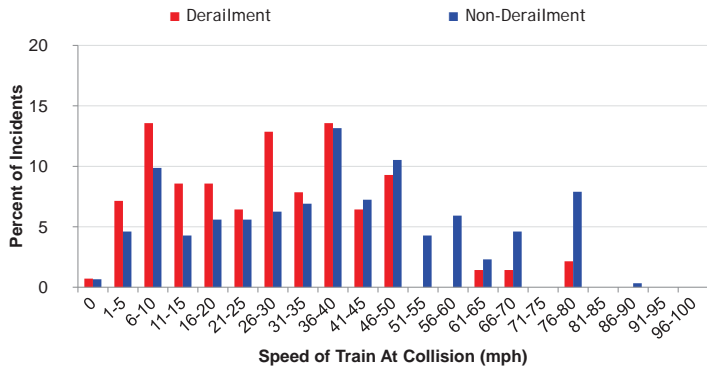
Derailments are more likely to occur at higher vehicle speeds when the vehicle strikes the train.

Speed at Collision of Trains Involved in Grade Crossing Incidents - Train Striking Vehicle, 1991-2010



Derailments are more likely to occur at lower train speeds when the train strikes the vehicle.

Speed at Collision of Trains Involved in Grade Crossing Incidents - Vehicle Striking Train, 1991-2010



Derailments are more likely to occur at lower train speeds when the vehicle strikes the train.