Understanding the risk of level crossing derailments

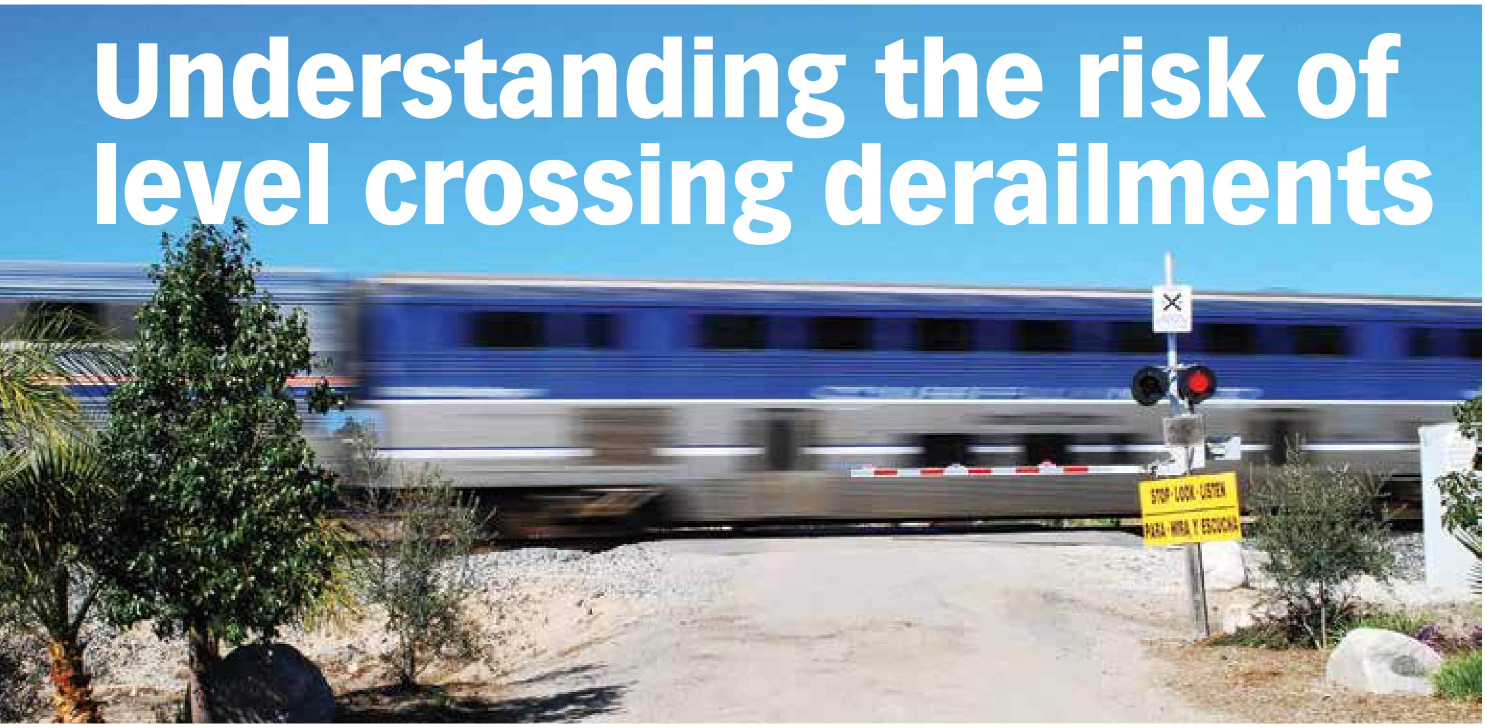

Photo: David Lustig

MODELLING Level crossings pose one of the biggest remaining safety risks to rail operations in many countries. The development of a tool to identify the potential risk of train derailments could help to prioritise investment in the upgrading or removal of crossings.

Investment in level crossing protection is necessary on routes where higher passenger train speeds are envisaged.

Samantha Chadwick, **Rapik Saat**,
Tyler Dick and **Chris Barkan**
Rail Transportation & Engineering Center
University of Illinois at Urbana-Champaign

Level crossings are a constant source of danger, with the ever-present risk of a collision between a train and road vehicle or pedestrian. In the majority of cases, the main impact is on the road users, but there is a continuing toll of incidents around the world where the train is damaged or derailed, with potentially significant consequences.

In the USA, there has been a steady decline over several decades in the number of crossing incidents and casualties due to train-vehicle collisions, thanks to crossing closures, investment in improved warning systems and public education programmes such as Operation Lifesaver and the annual International Level Crossing Awareness Day co-ordinated by the International Union of Railways (RG 6.11 p98).

While Federal Railroad Administration data shows that on average level crossing incidents are, in terms of derailments, less severe than accidents from other causes, crossing incidents are by far the most common (Fig 1). Besides the ever-present potential for catastrophic consequences, crossing incidents impose large costs on society because of their cumulative property damage and loss of life.

In 2010, there were approximately 255 000 road-rail crossings in the USA, of which 52% were publicly accessible. Though the safety record of US railroads compares favourably with other modes, and crossing collision rates declined by 80% over the 20 years from 1991 to 2010, more than 15 000 road users were killed at level crossings during that period, excluding pedestrians. In addition, 25 train passengers were killed and nearly 950 injured in level crossing accidents. According to FRA, in 2012 road user fatalities at level crossings represented about 30% of all rail-related fatalities in the USA.

Train speeds rising

One area of concern at this time is the impact of faster train speeds, given the growing interest in expanding inter-city passenger services using existing freight rail corridors. The rail industry is also required to address level crossing safety under the Congressional mandate requiring the implementation of Positive Train Control on all US inter-city and commuter passenger lines by December 31 2015.

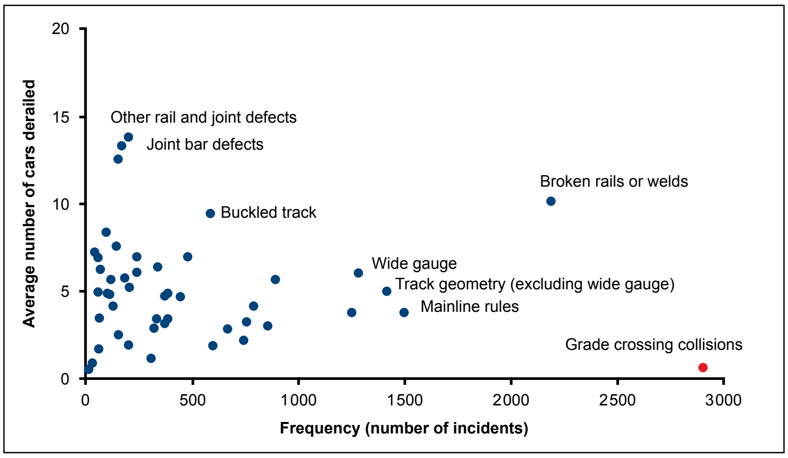

Fig 1. US railroad incidents by cause, severity and frequency, 1991-2010.

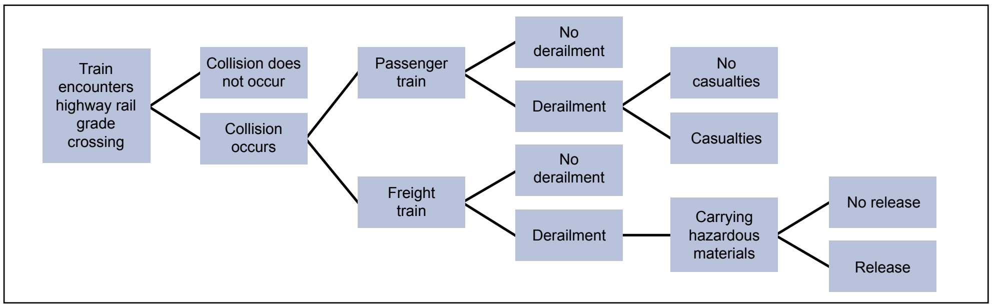

Fig 2. Simplified risk flowchart for road-rail level crossing incidents.

The most economical approach to eliminating a crossing would be to close it, but many communities oppose this because of a perceived loss of convenience. Alternatives to crossing closures include grade separation, which can be prohibitively expensive, and the provision of better warning and protection devices.

Current FRA regulations require complete grade separation for train speeds in excess of 201 km/h. Level crossings are still permitted at lower speeds, with increasing levels of protection, but are not recommended. Active warning devices must be provided where trains run at more than 127 km/h. For speeds above 177 km/h, crossings must be fitted with full barriers that physically prevent any incursion of the motor vehicle onto the railroad right-of-way.

Targeted improvements

With limited money to spend on upgrading level crossings, state and federal highway departments have traditionally prioritised investment projects according to incident likelihood. However, it would be preferable to target the available resources at those crossings which pose the greatest risk, both in terms of the likelihood of a collision and the consequences that might arise, such as a derailment involving passenger fatalities or a hazardous materials release, for example.

Many methods have been developed for modelling the likelihood of a collision at a level crossing. The most commonly used in the USA is the federal Department of Transportation's Accident Prediction Model, which dates from the early 1980s. This uses nonlinear multiple regression techniques on a wide variety of factors, including highway type and train traffic, to predict the annual number of collisions that can be expected at a given crossing.

However, this model is based on data from the entire country, and there have been concerns that it may not reflect regional variations. As a result, some states have developed their own formulae using more detailed data. In general, there appear to be trade-offs between ease-of-use, accuracy, and specificity.

These models were mainly developed with the goal of understanding the risk posed to road users. But much less research has been done into the impact on the trains, and there is no specific metric for identifying crossings with a high likelihood of derailment. The Rail Transportation & Engineering Center has therefore been researching those factors that may cause crossing incidents to result in a derailment, in order to develop a simple tool that could assist decision-makers. We began by looking at freight trains, which are involved in the vast majority of incidents, and then at passenger trains, which have different speed and weight characteristics.

Chain of events

In its most basic form, risk can be defined as the probability of an event occurring multiplied by the consequence of that event. In developing our crossing derailment prediction model, it was important to understand the chain of events leading to a given consequence and identify the probability of each event occurring (Fig 2).

For a crossing incident to occur, the train must first encounter a crossing. The likelihood of the train being involved in an incident with a vehicle at that crossing is then dependent on a range of factors, including traffic volumes, visibility and the type of warning devices provided. Once a derailment has occurred, it is then necessary to determine the likely consequences.

For our analysis, we used data from the USDoT Highway-Rail Grade Crossing Inventory History File and FRA's Highway-Rail Grade Crossing Accident/Incident database. Data from 1991 to 2010 were used for development of the mathematical models, which were then validated using data from 2011 and 2012.

For each record in the FRA database, the DOT record in force at the time of

Table I. Model variables

Variable	Definition	Range of values
VEHSPD	Highway vehicle estimated speed	0 – 170 km/h. Average 16·9 km/h
TRNSPD	Train speed	0 – 129 km/h. Average 50·6 km/h
LGVEH	Large highway vehicle involved?	Yes/No
TRNSTK	Did train strike highway vehicle?	Yes/No
TRKCLAS	FRA track class	Categories 0 to 9
WARNSIG	Crossing warning connected with highway signals	Yes/No/Unknown
VIEW	Was the driver's view of the track obstructed?	Yes/No
PUBLIC	Did the collision occur at a public crossing?	Yes/No
XTYPE	Type of crossing warning device	1: gates 2: active (excluding gates) 3: passive 4: other 5: none

Many crossings rely on passive warning signs, including the standard crossbucks, but with no indication that a train may be approaching.

Photo: Operation Lifesaver Inc

The Operation Lifesaver campaign uses photographs of actual and staged collisions to illustrate the issue of level crossing safety.

Photos: Operation Lifesaver Inc

Photo: RCMP

the incident was consulted. This theoretically holds information about the state of the crossing at the time, such as the posted road speed limit and the type of crossing warning device. The database should be updated when the crossing characteristics are changed, but in many cases there were no records or the data was not updated. Out of 44 000 complete incident records in the FRA database, only 2 221 had full, accurate records in the DOT inventory which we could use. As a result, this reduced data set may not be representative of all crossing incidents. For example, more complete data may be provided by some states than others, or the quality of data could be better for more important roads.

Table I lists the variables we used to predict whether a given crossing incident would result in a derailment. Within this list, we identified four main factors that most affect the likelihood of derailment: train speed, road vehicle speed, large vehicle involvement, and the incident type. This last distinguishes those incidents where the train strikes the vehicle from those where the vehicle strikes the train.

Reactive to predictive

Our model was developed using recorded data, but we wanted to be able to predict the likelihood of a future crossing incident resulting in a derailment. So we needed to understand whether the intrinsic characteristics of the crossings could be used as proxies for the incident-specific variables (Table II). For example, knowing that the derailment likelihood increases with vehicle speed is not necessarily useful unless it is possible to identify those crossings where vehicles travel faster.

As there are many factors which influence the incident type, including human factors, we did not use a proxy variable. Our model uses a fixed ratio based on historical data, which showed that the train struck the vehicle in around 80% of incidents, although it may be possible to refine this element through further work.

In order to use the road speed limit as a proxy for vehicle speed, we compared the actual speed of the vehicle in each incident to the posted limit. In almost half of all 'train strikes vehicle' incidents the vehicle was stopped on the crossing.

A similar analysis was undertaken to relate the actual speed of the train to the permitted line speed. The majority of trains in our sample were travelling near the line speed when the incident occurred, and none were struck while stopped on a crossing. In 8% of incidents, or 150 cases, the data suggested the train was travelling faster than the line speed, which seemed unlikely. While some could be confirmed as overspeed incidents by examining the narrative record, the majority were probably reporting errors.

Thus we could calculate the likelihood that any train or road vehicle at any crossing would be travelling at a given percentage of the permitted speed when involved in an incident. These speed distributions were used to determine the probability of derailment.

The impact of heavy trucks

The data shows that large highway vehicles were involved in 31% of all main line crossing incidents but 91% of reportable crossing derailments (Fig 3). However, statistical analysis found that the actual severity of a derailment was little affected by the size of the vehicle that caused it.

Our analysis did not find a 1:1 relationship between the percentage of truck traffic using a crossing and truck involvement in a crossing incident. One possible explanation is the difference in exposure time, as the average US truck is about five times as long as the average car, and would thus occupy the crossing for longer at a given speed. We therefore developed a 'truck exposure' metric relating the total length of trucks to the total length of all vehicles using a crossing (Fig 4), to produce a series of regression equations which could be used as a proxy for the 'large vehicle involvement' variable.

The figures suggested that, for a low percentage of truck traffic, incidents at crossings with passive warnings are more likely to involve trucks than those at crossings with active warnings such as flashing lights or gates. It could be that roads used by few trucks may not have been maintained with them in mind, which could lead to the danger of a long truck becoming

Fig 3. Level crossing incidents on main line tracks involving large highway vehicles, 1991-2010.

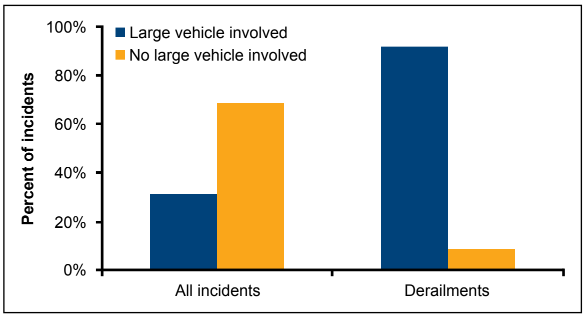

Table II. Proxy variables for the derailment model

Incident-specific	Crossing-specific
Vehicle speed	Road speed limit
Train speed	Line speed
Large vehicle involvement	Percent truck traffic + Annual average daily traffic

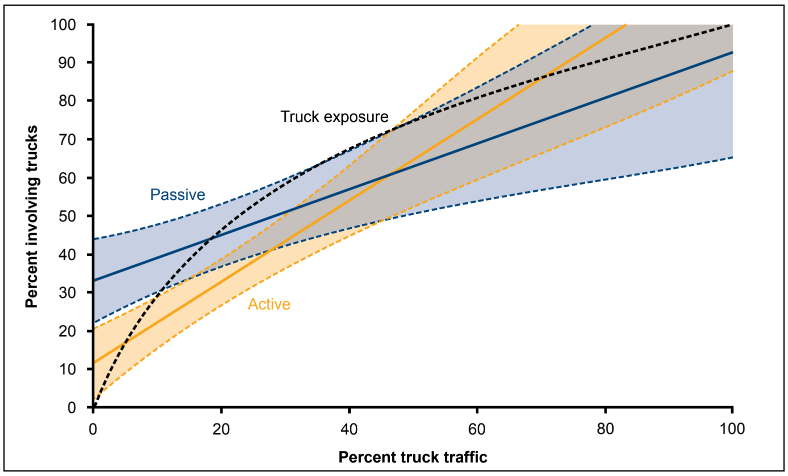

Fig 4. Percentage of incidents involving trucks as a function of percentage truck traffic at crossings with passive and active warning devices. The shaded regions represent the 95% confidence bands for each category.

stuck on a humped crossing, for example. Or it could be that individual truck drivers use such crossings infrequently and are therefore not prepared for the presence of a train.

A case study

Using the available data, we created an Excel 'calculator' to evaluate the derailment risk tree. Users can enter the road speed limit, rail line speed, percent truck traffic and warning device type, and the spreadsheet returns a conditional probability of derailment if an incident has occurred. This is then used in conjunction with an incident probability model to give an overall probability of derailment.

To demonstrate the model, we tested an anonymised 8 km sample track segment with seven crossings (Fig 5). Crossing G is in a small town, while the others are in a rural setting. They represent a variety of speed limits, line speeds, percent truck traffic, and warning devices (Table III). For each crossing, the predicted incident frequency was calculated using the DOT Accident Prediction Model and the FRA Web Accident Prediction System.

Several observations can be made from this analysis. Crossing G is ranked first in all three metrics. Crossing A, which has the second highest risk of an incident, has a comparatively low conditional probability of derailment. While crossing G has gates and A only has flashing lights, the road and rail speeds are lower at A. In reality, G is the only crossing which has actually experienced an incident, and that did not result in a derailment.

Also of interest is crossing C. While it ranked fifth for incident likelihood, it has the second highest likelihood of a derailment. This is because the crossing has 20% truck traffic and a high road speed limit (80 km/h), but does not have gates, probably because it is only used by around 100 vehicles per day.

Crossing D ranks last in all three categories. It has gates, but is only used by 50 vehicles per day and has no truck traffic. This means it is unlikely to experience a crossing incident, or that an incident would result in a derailment, despite the relatively high line speed.

Consider the consequences

While operators clearly need to identify those crossings with a greater derailment risk, the prioritising of investment must also take into account the relative likelihood and severity of the potential consequences.

Although the number of level crossing incidents and the number of fatalities have decreased steadily, the fatality rate for road users has remained fairly constant at around 0·12 fatalities per incident. The injury rate has fluctuated more, but averages about 0·38 non-fatal injuries per incident.

To consider more serious effects, we looked at the case of a hazardous materials release from a freight train following a crossing incident. Fortunately, these are extremely rare; FRA's database identified just 30 events in the 20 years to 2010. Only 0·069% of crossing incidents resulted in a hazardous materials release, even though 22·6% of incidents involved a train carrying hazardous materials. But the likelihood of a release was around 10 times greater when the train was derailed.

For our simple case study (Table IV), we looked at the release of a toxic inhalation hazard material such as chlorine. This meant we could use the findings of other studies to assume that 5% of the affected population would suffer fatalities as a result of a TIH release.

We compared two hypothetical crossings. Crossing R is in a rural area with a low population density and has a low incident risk; crossing U is in an urban area with a high population density and has a higher incident risk. The likelihood of a release occurring is calculated by multiplying the predicted incident frequency by the likelihood of a derailment and the likelihood of a release following that derailment. This can then be multiplied by the expected proportion of fatalities.

The results show that rural crossing R is 450 times more likely to experience a road user fatality as a result of a crossing incident than a fatality as a result of a hazardous materials release. While urban crossing U has a higher predicted incident frequency and a much higher population would be

Fig 5. An anonymised 8 km sample track segment with seven crossings was used in the test case.

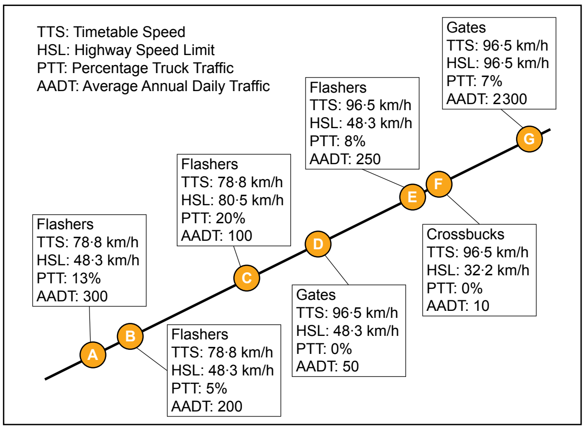

Table III. Sample crossings on 8 km test segment

Crossing	Classification	Incident likelihood Value	Rank	Conditional derailment likelihood Value	Rank	Overall derailment likelihood Value	Rank
G	Rural Major Collector	0·014330	1	0·002684	1	3·846E-05	1
A	Rural Major Collector	0·010532	2	0·000406	4	4·276E-06	3
E	Rural Major Collector	0·009901	3	0·000361	5	3·574E-06	4
B	Rural Local Road	0·009170	4	0·000269	6	2·467E-06	6
C	Rural Local Road	0·006106	5	0·001385	2	8·457E-06	2
F	Rural Local Road	0·005736	6	0·000570	3	3·270E-06	5
D	Rural Local Road	0·002234	7	0·000207	7	4·624E-07	7

Table IV. Example crossings used in hazardous materials case study

	Crossing R	Crossing U
Warning device	Active (gates and flashers)	Active (gates and flashers)
Annual average daily traffic	1 800	29 900
Trains per day	10	14
Road speed *km/h*	88	56
Line speed *km/h*	32	80
Percent truck traffic	10%	6%
Population density *people/ha*	0·77	96·5
Projected fatalities	25	31 250
Incident frequency	0·010317	0·036942
Likelihood of derailment	0·001668	0·000310
Expected number of road user fatalities	0·00124	2·76E-06
Expected number of TIH fatalities	0·00443	0·002294

affected, it is still twice as likely to experience a road user fatality as a fatality from a hazardous materials release.

However, our examples used a simple Net Present Value assessment which does not account for the risk preferences of decision-makers. A risk-neutral approach views the loss of 10 lives in 10 individual incidents as the same as 10 lives in a single incident. In reality a catastrophic incident has a much higher public profile, as we saw with the recent tragedy at Lac-Mégantic in Québec. A risk-averse decision-maker would consider such a catastrophic incident as 'worse' than several smaller incidents with the same cumulative cost.

Passenger model

Developing a passenger model was made more difficult by the very small number of events that have taken place over the past 20 years. Using 'rare events logistic regression' produced a much more complicated model for the passenger data, including interaction and second-order terms that do not appear in the freight model. A simplified model proved to be a poor fit to the data, and another that focused on the four variables from the freight derailment model performed even worse. This may indicate the need to include a factor such as the weight of the rail equipment involved.

The significant variables in the freight train model were directly analogous to the calculation of kinetic energy. However, the model formulation for passenger trains does not have the same structure. Train striking vehicle incidents logically depend on train speed, but 'vehicle strikes train' incidents were not found to be dependent on either vehicle size or speed. However, this may reflect the lack of data. Only six passenger train derailments occurred as a result of vehicle strikes, of which only one involved a large vehicle, and three had a reported vehicle speed of 50 km/h.

In terms of consequences, information from the FRA database can be used to make general observations about the frequency of casualty-causing passenger train incidents, as well as their severity. In 1991-2010 only 3·29% of all passenger train crossing incidents resulted in passenger casualties, with 0·07% of incidents resulting in 138 passenger fatalities.

However, 58·9% of derailment incidents resulted in passenger casualties and 5·3% resulted in a passenger fatality. Only 2·5% of non-derailment incidents resulted in passenger casualties, and there were no fatalities. These findings are not surprising, as a derailment requires significant amounts of energy to be dissipated in a very short time. In fact, of the 25 fatalities suffered by train passengers in level crossing collisions, just two incidents accounted for 11 fatalities each, at Bourbonnais, Illinois, in 1999, and Glendale, California, in 2005. Both of these were aggravated by the presence of trains on adjacent tracks, with which the derailed passenger trains collided.

The two derailment prediction models assume that rail traffic is either 100% freight or 100% passenger, but they can be combined to predict the overall derailment likelihood at crossings carrying both types of traffic. As well as the percentage of rail freight traffic, we use an 'exposure factor' accounting for the difference in train length. As any given freight train is likely to be much longer than any given passenger train, there is a larger window of opportunity for a highway vehicle to strike the train.

Further development

Further development of this work could provide decision-makers with a better risk mitigation strategy, not just for level crossings but for the whole rail network. When it comes to prioritising upgrading projects, it is likely that any improvements to a crossing would affect both the incident likelihood and the derailment likelihood, as the factors affecting the likelihood of a derailment are essentially intrinsic to a given crossing. Thus the best way to reduce the likelihood of a derailment is to reduce the probability of an incident occurring in the first place.

However, the model should really be expanded to include other consequences of crossing incidents and derailments, such as crew casualties, the cost of infrastructure and equipment damage, lost earnings due to track outages, and environmental impact.

While our consequence assessment was very rudimentary, the analysis showed that the weighting assigned to each aspect of risk varies widely. For example, as well as location, a thorough analysis of hazardous material releases would also examine route-specific factors such as the type of commodities shipped through a given crossing and the time of day.

Combining the level crossing model and models for other risks into a system-wide analysis tool would help the rail industry and surrounding communities to create better risk mitigation strategies. This could provide a powerful tool for deciding where to spend the finite amount of money that is available each year for infrastructure improvements.

Rail-TEC will be hosting the 2014 Global Level Crossing Safety & Trespass Prevention Symposium at the University of Illinois at Urbana-Champaign on August 3-8. For further information visit **http://go.illinois.edu/GLXS2014**

Four-quadrant gates are provided to augment the flashing lights at busy crossings or where rail speeds are higher than 177 km/h.

Photo: David Lustig