



Review

Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S.



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ABSTRACT

This study presents an overview of the challenges of grade crossings to shared high-speed rail (HSR) passenger and heavy-axle-load (HAL) freight operations in the U.S., as well as an in-depth analysis of the relevant research to date, through an extensive literature review. Results from this study are expected to identify principal technical challenges related to grade crossings in developing HSR systems. This will facilitate the planning, development, construction, and operation of new HSR shared corridors in the U.S. The challenges and research needs described in this paper may also be relevant to development of shared passenger and freight operations outside the U.S.

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1. Introduction

In 2010, there were approximately 255,000 highway-rail grade crossings in the U.S., of which 52% were publicly accessible (FRA, 2012a). Each crossing represents the opportunity for a collision between a highway vehicle and a train, which can result in casualties, extensive property damage, and even the release of hazardous materials. Though the safety record of passenger rail in the U.S. compares favorably with other modes of transportation, in the past 20 years, 16 rail passenger fatalities and nearly 950 injuries have occurred in passenger train accidents at grade crossings (FRA, 2011b). Additionally, highway grade crossing users currently represent about 30% of all rail-related fatalities in the U.S. Though grade crossing collision rates have declined 80% in the past 20 years, over 15,000 highway users have been killed over that time period at grade crossings (FRA, 2012b).

The U.S. Department of Transportation is supporting development of substantially expanded and improved passenger rail service on a number of intercity corridors across the US (FRA, 2012c). These corridor development projects will range from incremental improvement of existing tracks to construction of new, dedicated high-speed rail (HSR) lines. Existing lines could already have freight or passenger rail services, necessitating shared operations. As the interest in shared corridors grows, the risk of interoperating heavy-axle-load (HAL) freight and lighter, high-speed passenger trains needs to be understood. One of the most important aspects of this risk involves highway-rail grade crossings.

Many proposed HSR corridors are expected to pass through densely populated areas. This can pose significant challenges as these areas are likely to have many grade crossings. The Federal Railroad Administration (FRA) has issued regulations requiring complete grade separation for HSR operations in excess of 125 mph (201 kph). For higher-speed rail (HrSR) operations between 110 and 125 mph (177–201 kph), crossings may still be used with extra protections, but are not recommended. Table 1 summarizes the regulation related to grade-crossing protection and closure.

It should also be noted that positive train control (PTC) system implementation will be required by law on all intercity and commuter passenger lines by December 31, 2015 (74 FR, 35950, 2009). The industry is required to address highway-rail grade crossing safety in PTC implementation.

The most economical approach to eliminating a crossing is arguably to close it; however, communities are often opposed to closing existing grade crossings in their area because of a perceived loss of convenience, as well as concerns about increased emergency service response time and reduced access to schools and other strategic places. If a crossing cannot be closed, other approaches must be considered. These include grade separation and upgraded warning and protection devices.

The topic of highway-rail grade crossing risk has been extensively researched over the years, primarily with a focus on improving highway user safety. This paper presents an overview of grade crossing challenges to shared HSR and HAL operations in the U.S., as well as an analysis of the relevant research to date. Results from this study are expected to identify principal technical challenges related to grade crossings in developing HSR systems.

This will facilitate the planning, development, construction, and operation of new HSR shared corridors in the U.S.

2. Methods

Papers published through 2011 relevant to this literature review were found using Google Scholar and a multi-database search engine at the University of Illinois at Urbana-Champaign Library. Key words used in the search include highway-rail grade crossings, level crossings, high speed rail, shared corridors, passenger train crashworthiness, grade crossing human factors, driver human factors, low-cost crossing design, and grade crossing technology. The reference section of each paper was reviewed and other potentially relevant papers were identified. Those contributing to a better understanding of grade crossings, especially as pertaining to shared rail corridor operations, were selected for more detailed analysis.

In the following section, we present a review of studies related to HSR or shared corridor operations addressing grade-crossing accident prediction, crashworthiness of passenger train cars, alternative grade-crossing warning strategies, and driver human factors. In the discussion section, the relevance of different shared operation types and research needs are presented.

3. Results

3.1. Grade-crossing accident prediction

Many methods of modeling collision likelihood at grade crossings have been developed, mainly with the goal of understanding the risk posed to highway users by freight trains. These models have traditionally been used to decide how funds for highway-rail grade crossing improvements should be allocated. However, the collision rates predicted by these models can equally be used to quantify passenger train risk.

Faghri and Demetsky (1986) categorized collision likelihood models into two groups: relative formulas and absolute formulas. Relative formulas use crossing data to rank the relative hazards at each crossing, so that improvements can be prioritized from most dangerous to least dangerous crossings. Absolute formulas predict the number of collisions expected to occur at each crossing over a certain time period, allowing for estimation of the number of lives saved by upgrading a crossing.

Formulas for the purpose of ranking grade crossings by their collision risk were being developed in the U.S. as early as the 1940s. Many of these formulas are still widely used by state Departments of Transportation. The four early formulas presented here are the New Hampshire model, the Peabody-Dimmick (or Bureau of Public Roads) formula, the NCHRP Report 50 Hazard Index, and the U.S. Department of Transportation (DOT) Accident Prediction Model. They are presented in order from least complex to most complex.

The New Hampshire model is a relative formula which can be used to rank the importance of crossing upgrades (Austin and Carson, 2002; Faghri and Demetsky, 1986). Due to its simplicity, it has been widely used across the country, either in its original form or in various modified forms. Analysis has shown that the hazard index ranks crossings similarly to more complex formulas,

Table 1
Summary of federal regulation related to grade-crossing protection and closure (CFR, 2012).

Maximum passenger train speed	79–110 mph (127–177 kph)	110–125 mph (177–201 kph)	>125 mph (201 kph)
Track class	6	7	8–9+
Grade crossing protection type	Active ^a	Warning/barrier ^b with FRA approval	Grade separate or close

^a FRA recommends but does not require sealed corridor treatment for all grade crossings with train speeds in excess of 79 mph (127 kph).

^b Barrier system must physically prevent incursion of motor vehicle into right-of-way.

but it is limited in that it does not predict the expected number of collisions. The hazard index formula is as follows:

$$\text{Hazard Index} = VTP_f \quad (1)$$

where V = average 24-h (highway) traffic volume; T = average 24-h train volume and P_f = protection factor (0.1 for gates; 0.6 for flashing lights; 1.0 for signs only).

The Peabody–Dimmick formula (also called the Bureau of Public Roads formula), developed in 1941, is an absolute formula which predicts the number of accidents at a crossing over a period of 5 years (Austin and Carson, 2002; Faghri and Demetsky, 1986). The 5-year accident prediction formula is as follows:

$$A_5 = 1.28 \frac{(V^{0.170})(T^{0.151})}{P^{0.171}} + K \quad (2)$$

where A_5 = expected number of accidents in 5 years; V = annual average daily traffic (AADT); T = average daily train traffic; P = protection coefficient and K = additional parameter (smoothing factor).

The NCHRP Report 50 Hazard Index is an absolute formula developed in 1968 by Andrew Voorhees and Associates (Austin and Carson, 2002; Faghri and Demetsky, 1986). It can be expressed as a formula, but is more commonly determined from a series of charts and tables which allow the user to calculate the expected yearly accident rate. It is dependent on factors such as annual average daily traffic (AADT), number of trains per day, the type of warning device in use, the geographic location of the crossing, and geometric aspects of the crossing.

Today, the most commonly used model in the U.S. is the U.S. Department of Transportation (DOT) Accident Prediction Model (Austin and Carson, 2002; Faghri and Demetsky, 1986; Ogden and Korve Engineering, 2007). First developed in the early 1980s, this absolute formula used nonlinear multiple regression techniques on a wide variety of factors, including highway type and train traffic, to predict the expected yearly number of collisions at a crossing. The general expression of the formula is as follows:

$$a = K \times EI \times MT \times DT \times HP \times MS \times HT \times HL \quad (3)$$

$$B = \frac{T_0}{T_0 + T}(a) + \frac{T}{T_0 + T} \left(\frac{N}{T} \right) \quad (4)$$

$$A = \begin{cases} 0.7159B & \text{For passive devices} \\ 0.5292B & \text{For flashing lights} \\ 0.4921B & \text{For gates} \end{cases} \quad (5)$$

where a = initial collision prediction, collisions per year at the crossing; K = formula constant; EI = factor for exposure index based on product of highway and train traffic; MT = factor for number of main tracks; DT = factor for number of through trains per day during daylight; HP = factor for highway paved (yes or no); MS = factor for maximum timetable speed; HT = factor for highway type; HL = factor for number of highway lanes; B = adjusted accident frequency value; T_0 = formula weighting factor; $=1.0/(0.05 + a)$; N = number of observed accidents in T years at a crossing and A = normalized accident frequency value.

A table provides each of the factors, for crossings with passive controls, flashing lights, and gates. U.S. DOT also provided a procedure for using this formula to determine grade crossing upgrade resource allocation (FRA, 1987).

Faghri and Demetsky (1986) tested four absolute formulas and found that the U.S. DOT formula most accurately predicted the number of collisions occurring at grade crossings in Virginia for the 5-year period of study. They recommended that the Virginia DOT use the U.S. DOT formula in combination with site visits to evaluate the importance of grade crossing upgrades.

However, there are some concerns about the U.S. DOT model's accuracy. Since it is based on data from the whole U.S., it may not account for regional differences. As a result, some states have developed specialized formulas using more detailed state-specific data. For example, Benekohal and Elzohairy (2001) examined 10 years of highway-rail grade crossing collisions in Illinois. They found that the U.S. DOT formula only selected 89 of the top 200 grade crossings with collisions for upgrade, and did not reliably identify the most dangerous crossings. They developed a regression model, the Illinois Hazard Index, which suggested a higher percentage of crossings with collisions for improvement; it also selected locations with higher crash rates compared to other equations.

Another concern about the accuracy of the U.S. DOT formula is that crossing conditions and warning/protection technologies may have changed since its development. Austin and Carson (2002) showed that the normalizing coefficients used in Eq. (5), which account for the difference between the model's predicted values and actual observed values, have been steadily reducing in value over time; that is to say, the model's prediction accuracy has declined over time, and the normalizing coefficients have been adjusted to compensate. Austin and Carson propose that the formula's accuracy could be improved if it were re-evaluated using present-day data. However, they also consider the complexity of the U.S. DOT's three-part formula to be problematic, since it is difficult to interpret and prioritize the effects of changing various parameters. To address this concern, Austin and Carson developed an alternate model using negative binomial regression. This model identified many of the same significant variables as the U.S. DOT formula, but as it was developed using only collision data at public grade crossings in six states, further testing would have to be conducted to see if the model would be applicable to all U.S. grade crossings.

Chaudhary et al. (2011) compared the performance of the U.S. DOT Accident Prediction Formula to that of the Transport Canada Accident Model to see which would more effectively identify "hot spots" (high-risk areas) on a network in California. Overall, the U.S. DOT model more closely predicted the yearly number of accidents occurring at a crossing. However, in cases where the crossing had an accident history, the Transport Canada model was more accurate. Chaudhary et al. suggested adapting the Transport Canada model to U.S. crossing data and using it to rank the most dangerous crossings.

A variety of statistical models have been developed with the goal of improving the accuracy of collision frequency prediction of the earlier models. The following five papers use diverse, advanced statistical methods including Poisson regression, negative binomial regression, gamma probability models, and Bayesian analysis.

Sacomanno et al. (2004) developed models for identifying highway-rail grade crossing black-spots in Canada. They performed both a Poisson regression and a negative binomial (NB) regression on the data, considering 11 variables. For each regression method, three separate models were developed – one for passive crossings, one for crossings with flashing lights, and one for crossings with gates. They found that the NB models performed better. Significant factors varied by crossing treatment. For passive crossings, train speed and exposure were the only significant factors. For crossings with flashing lights, surface width was also found to be significant. For crossings with gates, road speed, number of tracks and exposure were found to be significant. They also found that crossings with the highest collision frequency were located in urban areas, probably because the exposure factor is likely to be higher in urban areas than rural areas.

Other frequency models have been developed abroad. South Korea evaluated the effectiveness of the U.S. DOT Accident Prediction Formula for predicting accidents at Korean grade crossings (Oh et al., 2006). After finding that the U.S. DOT formula did not

accurately predict collision rates in Korea – likely because all grade crossings in Korea are equipped with gates, unlike in the U.S. – they developed a gamma probability model using Korean accident data. Collisions were observed to increase with highway traffic volume, train volume, proximity to commercial areas, distance of train detector from crossing, and time between activation of warning signals and gates. An interesting aspect of this paper is that grade crossing warning device type, which is a critical factor in most other collision prediction models, is eliminated from the analysis because all crossings in Korea have the same warning device. This illuminates some factors such as proximity to commercial areas that likely affect collision rates in the U.S. but are so far not considered in U.S.-based models.

Washington and Oh (2006) and Saccomanno et al. (2007) both used Bayesian methodology to assess the effectiveness under uncertainty of different grade crossing treatments at reducing collision rates. Washington and Oh considered 18 grade crossing treatments in their analysis. For each treatment, a survey of past research findings was conducted to determine a Bayesian prior density. Next, a panel of experts was presented with a random sample of collisions which had occurred at South Korean grade crossings, and were asked to evaluate how each treatment would have affected the occurrence of each collision. This information was aggregated into a best-estimate “current” accident modification factor (AMF). Bayes’ theorem was then used to combine the experts’ AMF with prior knowledge to obtain “posterior” intervals of AMFs. Applying this methodology, Washington and Oh determined that the three treatments which most effectively reduce crashes are (highway-side) in-vehicle warning systems, obstacle detection systems, and constant warning time systems. As the authors point out, the rankings do not consider cost in any way; since cost is a critical factor to consider when upgrading a crossing, it should likely be included in further analysis. Additionally, their ranking of treatments does not account for variation across crossing locations. Saccomanno et al. (2007) took a different approach in their analysis. Their model can be calibrated to a specific crossing and provides a statistical distribution of the expected change in collision likelihood for a given treatment. Since grade crossing collisions are random events, and since there is a lack of before-and-after studies for many grade crossing treatments, engineers have to make decisions about grade crossing upgrades under uncertainty. By considering a range instead of an absolute value for the reduction of risk, engineers will be able to better evaluate the cost-benefit ratio for a given crossing upgrade.

Mok and Savage (2005) took a different approach to analyzing collision rates at grade crossings. They observed that the number of collisions and fatalities at grade crossings has decreased significantly over the past 30 years, despite an increase in both train and highway traffic. Their analysis showed that about 70% of the decrease could be attributed to human factors related aspects (such as educational programs like Operation Lifesaver, and the requirement of ditch/crossing lights on locomotives), and 30% could be attributed to the installation of gates and/or flashing lights, as well as closing crossings. This result suggests that collision prediction models rightly attribute high importance to the type of crossing warning device in use, but should also consider human-factors aspects.

Great Britain and Australia have both developed level crossing incident prediction models for use in determining the priority of crossing upgrades. Rail organizations in Great Britain have been working on grade crossing risk assessment models since the early 1990s. The first model developed in Great Britain was the Automatic Level Crossing Model (ALCM) (ADL, 2010). This model examined a variety of factors relating to a crossing’s condition and environment to determine its risk of experiencing a grade crossing collision. It provided a Microsoft Excel spreadsheet-based

tool that assisted users with creating a detailed crossing assessment and an overall risk estimate. Some consequence estimates were included in the model. While the model proved to be an effective tool for prioritizing grade crossing upgrades, it was primarily designed for assessing automatically-controlled grade crossings, therefore making it less suitable for the evaluation of other crossing types. An expanded model referred to as the All Level Crossing Risk Model (ALCRM) was implemented in 2006 (ADL, 2010). While the ALCM had proved effective at reducing risk for automatic crossings, passive crossings were identified as the largest remaining source of risk. Therefore, ALCRM was designed to be suitable for use at all crossings. It refined the variables considered when determining incident likelihood and expected consequence. ALCRM was designed to be “platform independent”, meaning it was independent of any particular software tools. It was then developed into a web-based database tool to assist in assessing and prioritizing grade crossing upgrades. Rollout of the system was accompanied by user training sessions to ensure proper application of the model.

The Australian Level Crossing Assessment Model (ALCAM) was developed in the early 2000s and updated in 2009 (Australian Transport Council, 2010). ALCAM considers a wide range of factors including physical characteristics of the crossing as well as many human factors aspects. Each factor is assigned a weight according to numbers developed by a panel of experts. These factors combine to assign the crossing a likelihood factor, indicating the likelihood of that crossing experiencing a collision. Each crossing also has an exposure factor which is the product of the vehicle (or pedestrian) traffic and the train volume. Additionally, a consequence factor is assigned based on environmental factors at the crossing and train speed. The ALCAM Risk Score is a product of these three factors. Each crossing’s score is classified into one of three Likelihood Bands: high, medium or low. Crossings in the “high” category are generally prioritized for upgrade. The ALCAM system also uses “flags” to target specific crossing situations that may be more dangerous than their risk score would suggest. To facilitate use of this system and ensure it is uniformly applied to all crossings, a “total data management system” called the Level Crossing Management System is used.

Overall, a wide variety of models for the prediction of collision rates at highway-rail grade crossings have been developed. In general, there appear to be trade-offs between ease-of-use, accuracy, and specificity. The most accurate models are generally developed for a small set of all collisions – for example, considering data from only one state in the U.S. This may mean that each individual state would have to create its own model using its own data – a task which may be worthwhile to more correctly identify the most dangerous crossings. Additionally, the more accurate models may be more difficult to use for engineers who do not have a statistical background. This problem could likely be avoided if a straightforward procedural document were developed, as was done for the U.S. DOT Accident Prediction Formula.

3.2. Accident severity

The previous section reviewed the variety of efforts which have been made to quantify grade crossing collision frequency. In terms of overall risk, the frequency of an event occurring is half the equation; the other half is the consequence of that event occurring. To date, the majority of researchers have focused on the risk posed to highway users by grade crossings, which represent a large percentage of railroad fatalities. It is important to understand the impact that adding high-speed trains to an existing network would have on collision severity. It is also important to study the impact this could have on train passenger injuries and fatalities. This section presents statistical models of severity, as well as crashworthiness research, which seeks to understand the physical forces involved in a collision and how to mitigate them.

3.2.1. Statistical modeling of severity

The U.S. Department of Transportation developed equations for predicting the probability of an injury accident given an accident and the probability of a fatal accident given an accident (Ogden and Korve Engineering, 2007). The expressions for these probability equations are as follows:

$$P(IA|A) = \frac{1 - P(FA|A)}{1 + CI \times MS \times TK \times UR} \quad (6)$$

$$P(FA|A) = \frac{1}{1 + CF \times MS \times TT \times TS \times UR} \quad (7)$$

where CI = formula constant = 4280; CF = formula constant = 695; MS = factor for maximum timetable train speed; TK = factor for number of tracks; TT = factor for through trains per day; TS = factor for switch trains per day and UR = factor for urban or rural crossing.

The FHWA Grade Crossing Handbook (Ogden and Korve Engineering, 2007) provides tables listing the value of each factor based on the initial prediction of the base collision likelihood model, as well as the number of observed accidents at the crossing over the past 1–5 years. The results of the injury and fatality likelihood models can be used in conjunction with the accident likelihood model to prioritize the most dangerous crossings.

Research has also been conducted to quantify the consequences of grade crossing collisions from the rail side. Great Britain's ALCRM includes consequence algorithms for a passenger train derailment caused by a grade crossing collision (ADL, 2010). This focuses on the effect second track collisions and the presence of objects near the right of way have on derailment likelihood and passenger casualties. Highway vehicle size was found to significantly affect derailment likelihood, with larger highway vehicles being more likely to cause a train derailment. Chadwick et al. (2012) also identify several key factors which lead to train derailments at highway-rail grade crossings. They also show that involvement of large highway vehicles such as tractor-semitrailers in grade crossing collisions increases the likelihood of the train derailing. Additionally, higher vehicle speeds and lower train speeds were shown to increase derailment likelihood. While the overall incidence of train derailments at grade crossings is very low, previous research has shown that the consequences of derailments can be severe.

3.2.2. Crashworthiness

Researchers in the U.S. have examined the issue of passenger train car crashworthiness. Primarily, this research has focused on American commuter and intercity rail cars traveling at speeds below 100 mph (161 kph). Crashworthiness studies on high speed rail cars are few and far between, possibly because HSR operators tend to focus on accident prevention rather than crashworthiness.

Simons and Kirkpatrick (1998) developed a finite element model of a theoretical generic U.S. high speed train and then used it to understand the safety risks posed to passengers. The train consist was tested in seven different crash scenarios, mimicking head-on collisions with various objects at various speeds. For each scenario, the expected number of casualties was predicted based on primary and secondary impact data. Collisions at speeds of 60 and 100 mph with a 50 ton object reflect what would happen if a typical higher-speed train collided with a large highway vehicle such as a semi-tractor-trailer. While there is variability in any accident, Simons and Kirkpatrick showed that the potential for severe casualty levels in grade crossing collisions exists. Their model could be adapted to study the crashworthiness of proposed HSR train designs, to decide which train set would be best for different operating scenarios.

A 1998 collision in Portage, Indiana between a commuter train and a tractor-trailer carrying steel coils led to new regulation addressing passenger train structural design. Full-scale collision testing of the new passenger cars was conducted to compare their

performance to the pre-1999 car design. Jacobsen et al. (2003) tested the crash performance of the two car designs by colliding them with a steel coil truck to imitate the Portage incident. They found that the 1990's cab car end structure deformed more than 20 in. (50.8 cm) longitudinally, resulting in loss of operator survival space, whereas the new design deformed only 8 in. (20.3 cm), which preserved survival space. Additionally, Martinez et al. (2003) developed a computer model to predict crushing behavior in the cab car. They validated the computer model with the full-scale collision test, and found that the model accurately predicted crush patterns. Samavedam and Kasturi (2011) performed the same full-scale test at higher speeds in order to validate their finite element model (FEM) of train collisions. The model closely predicted the overall damage to the locomotive, as well as predicting the intrusion into operator survival space.

In the wake of the 2005 Glendale, California collision between a Metrolink commuter train and an SUV, in which 11 people were killed, the FRA released a report on the safety of push-pull and multiple unit locomotive passenger rail operations (FRA, 2006). This report sought to understand the relative crashworthiness of multiple-unit cars, cab-car leading trains ("push mode"), and conventional locomotive-led trains ("pull mode"). Analysis of 20 years of data showed that, while locomotive-powered trains operated in the push mode had a slightly greater number of fatalities and tendency to derail than those operated in pull mode, the differences were not statistically significant. Multiple-unit service was shown to have a superior safety record, with the lowest fatality rate of all passenger transportation modes, including air travel.

Also in response to the Glendale collision, Metrolink worked with the FRA, the Federal Transit Administration (FTA) and the American Public Transportation Association (APTA) to develop a performance-based technical specification for passenger rail car crashworthiness, focused on crash energy management (CEM). This work produced performance specifications for the overall train consist; for its cab and passenger-carrying cars; and for mechanical components such as couplers (Tyrell et al., 2006). CEM trains are designed to deform in a controlled way during a collision, collapsing unoccupied areas to absorb energy and preserving survival space in the occupied areas. Tyrell and Perlman (2003) compared the crashworthy (or survivable) speeds of CEM and conventional trains, in both train-to-train collisions and highway-rail grade crossing collisions. They found that passengers in CEM trains could experience a much higher primary collision speed and survive, even though their secondary impact velocity would be slightly greater than in a conventional train.

The study of crashworthiness has led to newer, safer passenger trains being developed. These advances are especially critical in the context of shared corridor operation, since passenger trains will operate at even higher speeds. While the focus should be on reducing the likelihood of grade crossing collisions, it is unlikely that collisions can be entirely prevented. Developing trains which better preserve passenger lives will help mitigate the consequence of such collisions.

3.3. Alternative grade crossing warning strategies

The formulas for highway-rail grade crossing collision likelihood and severity discussed above account for existing grade crossing warning devices and strategies. The typical levels of protection in the U.S. are fully passive crossings, including crossbucks or stop signs, active crossings with flashing lights and/or bells, and gated crossings. Crossings with a history of collisions can be upgraded to more restrictive warning devices. If a crossing has full gates and still experiences a high collision rate, railroads and local departments of transportation may work together to close the crossing.

Ideally, any rail line would be completely grade separated. However, due to cost considerations, it is often infeasible to grade

separate an entire line. New thoughts on grade crossing protection include augmented passive systems and sealed corridors. Nelson (2010) summarizes the many strategies currently in use around the world for reducing risk at grade crossings. These include closures and consolidation, upgraded lights and gates, and alternative technologies such as in-pavement flashers. The goal in the U.S. is to develop a strategy that balances cost with risk reduction.

3.3.1. Sealed corridors

The sealed corridor concept has been developed as a way to upgrade conventional rail lines to carry higher-speed passenger trains. For trains operating in the 110–125 mph (177–201 kph) range, grade separation is suggested but not required; instead, the Federal Railroad Administration (FRA) requires crossings to have approved barrier systems which can prevent highway vehicle incursion on the right of way. Obstacle detection systems to alert the train if a vehicle does become stuck on the tracks are also recommended. These requirements and appropriate technologies for use in achieving these goals are summarized in the FRA's "Highway-Rail Grade Crossing Guidelines for High-Speed Passenger Rail" (2009a).

The state of North Carolina has been the first to make aggressive use of the sealed corridor concept (Bien-Aime, 2009; FRA, 2009a, 2009b). The NC DOT Sealed Corridor is part of the Southeast High Speed Rail (SEHSR) Corridor and included 216 grade crossings, 44 of which were private crossings. Between 1987 and 2004, this section experienced 282 collisions, resulting in 74 injuries and 55 fatalities. The program has consolidated as many grade crossings as possible and upgraded the rest to include self-monitoring four-quadrant gates, long-arm gates, and/or traffic channelization devices. NCDOT projects that 19 lives were saved between 2004 and 2009 by implementing the sealed corridor concept due to a sharp decrease in the number of grade crossing collisions (Bien-Aime, 2009; FRA, 2009c).

Illinois DOT (IDOT) has been upgrading sections of track for 110 mph (177 kph) operation between Chicago and St. Louis using a sealed corridor approach (Hellman and Ngamdung, 2009). The route between Chicago and Springfield, IL had 311 grade crossings, of which 68 were proposed for closure. However, only 10 crossings were ultimately closed due to strong opposition from impacted communities. Of the remaining crossings, 69 were equipped with four-quadrant gates and vehicle detection systems. The detection system will be discussed further in the next section (Section 3.3.2). The results in North Carolina suggest that this approach will reduce collisions and fatalities along the route, even with higher speed passenger trains.

3.3.2. Obstacle detection

Glover (2009) summarizes the goal of obstacle detection as "identifying the presence of a vehicle or person on the crossing as the train approaches and communicating this to the train driver in time for him or her to stop before reaching it." Obstacle detection technology should provide a feasible and cost-effective way of mitigating grade crossing risk. However, the main challenge is that these systems have a short amount of time to react to an intrusion and bring the train to a stop. Glover (2009) suggests that there may be only limited reduction in the severity of a collision because the train may still collide with the obstructing highway vehicle. Additionally, there are concerns that these systems could be less reliable than traditional gated crossings; since the devices are fail-safe, an error in the detection system would result in a "false-alarm" closing of the crossing gates. If highway users become accustomed to higher error rates, they may erroneously assume the crossing is out of service when in fact the gates have been activated by the presence of a train. If they attempt to circumvent the gates, a collision could occur.

Hall (2007) suggests that benefits of obstacle detection may exist even if the system is not capable of entirely preventing collisions. Advance warning of a track obstruction could allow the train to decelerate sufficiently to prevent train passenger deaths, especially when combined with crashworthy passenger train designs. Additionally, Hall states that obstacle detection systems will have the greatest benefit when information can be communicated directly between the grade crossing and an approaching locomotive, as in Positive Train Control (PTC) or the European Rail Traffic Management System (ERTMS).

Obstacle detection systems are being used both nationally and abroad. On the section of track between Chicago and St. Louis which is being upgraded for 110 mph operation, Illinois DOT (IDOT) and Union Pacific (UP) use a detection system consisting of an inductive loop embedded in the pavement on either side of a railway track. It is capable of detecting the presence of a vehicle within the crossing gates and alerting the approaching train through in-cab signaling (Hellman and Ngamdung, 2009). This system could also be integrated with a PTC-equipped train consist.

The system usually operates in "dynamic" mode, meaning the exit gates function based on the presence of highway vehicles within the grade crossing. However, in the fail-safe condition, it operates in a "timed" mode which closes the exit gates after a specified amount of time. The FRA and the Volpe Center conducted tests of this equipment to verify its reliability. They found that the average total delay to five scheduled high-speed passenger round-trips was approximately 38.5 min. They also found that this equipment had a "minimal impact on the frequency and duration of grade crossing malfunctions" (Hellman and Ngamdung, 2009).

3.3.3. Traffic channelization

Traffic channelization devices direct or separate traffic flow. In the context of highway-rail grade crossings, these devices are intended to prevent drivers from using a grade crossing in an unsafe manner by confining them in controlled lanes (FRA, 2010). An example is a raised median.

Research has suggested that channelization discourages risky driving behavior around grade crossings, such as "zig-zagging" past closed gates (FRA, 2010). Several states have already begun to employ channelization in an effort to improve grade crossing safety.

3.3.4. Low-cost level crossing warning devices

An emerging trend in grade crossing warning devices is the development of low-cost devices that provide a level of safety comparable to conventional devices. These systems generally cost between 5% and 30% of conventional technologies and often rely on wireless communications and solar power (FRA, 2011a). Wullems (2011) summarizes the state-of-the-art of this technology and considers its potential for large rural networks such as the Australian railway. Hellman and Ngamdung (2010) presented several low-cost warning devices which satisfy the FRA's minimum performance requirements for grade crossing warning devices. They emphasized the importance of reducing annual maintenance costs, not just installation costs.

While low-cost level crossing warning devices may be interesting from a cost-efficiency point of view, it is unlikely any of the devices currently on the market will be used in the U.S. for high-speed shared corridor applications, as none of the devices incorporate gates and instead rely on augmented passive systems (adding lights or advance warnings to areas around crossings). Additionally, there are significant legal concerns stemming from public perception of the devices, fail-safe requirements and liability to both the public and private sector (Hellman and Ngamdung, 2010; Wullems, 2011). However, the concept will likely continue to develop and may expand to include gate technology.

3.3.5. Conclusions

The innovative grade crossing warning devices and strategies presented here have the potential to improve the safety of both highway users and train passengers. One major obstacle to a wider implementation of higher-speed passenger service is the cost of upgrading warning devices along the route, so designing the safest possible crossing at a reasonable cost is critical. As these systems are put into use along the initial shared operations corridors, their performance should be monitored to inform future decisions about their implementation.

3.4. Human factors and driver behavior

Understanding driver behavior and identifying human factor causes for accidents at highway grade crossings can help us develop better accident-prevention strategies. This section provides an overview of literature relating to human factors and driver behavior at grade crossings, as they might pertain to shared corridor operations. Yeh and Multer (2008) provide an excellent in-depth review of all literature on driver behavior at grade crossings.

Caird et al. (2002) developed a taxonomy of human factor accident contributors to highway-rail grade crossing accidents. The taxonomy groups common accident contributors into 6 categories: unsafe actions, individual differences, train visibility, passive signs and markings, active warning systems and physical constraints.

Different people react differently to warning signs at grade crossings. Several studies have been conducted with the goal of identifying the source of this variation (Lenné et al., 2011; Jeng, 2005; Tey et al., 2011a,b; Caird et al., 2002). On average, males are involved in crossing fatalities more than females (Raub, 2007; Caird et al., 2002). The age group of 26–64 accounted for the most fatalities (Caird et al., 2002); however, this age group proportionally drives the most and thus has the greatest exposure (Evans, 1991). Different age ranges within this group might have different results. Taylor (2008) stated that 16–25 year-old drivers were identified as the group most at risk at grade crossings, as they were the most likely to knowingly engage in risky crossing behavior.

In response to warning signs at grade crossings, drivers showed lower compliance rates at passive crossings than at active crossings (Lenné et al., 2011; Tey et al., 2011a,b). Additional warnings, especially the addition of active warning devices, should result in increased crossing compliance. But due to limited budgets, it is impossible to update all passive signs to active warning systems. Alternative ways of augmenting passive crossings are being studied (Cairney, 2003; Tey et al., 2011b; Wullems, 2011; also see Section 3.3.4). Caird et al. (2002) summarized the effectiveness and cost of different countermeasures at grade crossings (Table 2). The costs have been given in 2013 dollars, though other factors such as the increased cost of materials and labor or advances in technology may mean that these cost estimates do not reflect the current cost of countermeasures.

Caird et al. (2002) and Sussman and Raslear (2007) classified the primary reasons for accidents at grade crossings as intentional, distraction-caused or other (visibility issues or driver confusion) for both passive and active grade crossings. Each of these issues requires slightly different approaches for reducing occurrences.

Three main approaches are commonly used to address these problems. These are referred to as the “Three Es”: engineering, education, and enforcement (Sussman and Raslear, 2007; Jeng, 2005). “Engineering” involves using better devices or systems to alert people to the presence of a grade crossing, or to prevent them from entering it. “Education” aims to increase public awareness of the hazards of train movements, as well as reduce dangerous behaviors. “Enforcement” seeks to enforce compliance with laws at grade crossings. The most prominent educational and outreach effort for grade crossing safety in the U.S. is Operation Lifesaver (OL). OL’s network includes certified volunteer speakers and trained instructors offering free rail safety education programs to school groups, driver education classes, community audiences, commercial drivers, law enforcement officers, and emergency responders (Savage, 2006). Proving the program’s effectiveness, Mok and Savage (2005) found that the introduction of Operation Lifesaver programs in a state results in a 15% decrease in the number of grade crossing incidents, and a 19% decrease in the number of fatalities.

Table 2
Caird et al. (2002) summary of effectiveness and cost of countermeasures.

Countermeasure	Effectiveness	Cost (US\$)	Cost (2013 US\$)	References
Stop signs at passive crossings	Unknown	\$1.2–2 K	\$1.7–2.9 K	NTSB (1998)
Intersection lighting	52% reduction in nighttime accidents over no lighting	Unknown	Unknown	Walker and Roberts (1975)
Flashing lights	64% reduction in accidents over crossbucks alone; 84% reduction in injuries over crossbucks; 83% reduction in deaths over crossbucks	\$20–30 K in 1988	\$40–60 K	Schulte (1975) and Morrissey (1980)
Lights and gates (2) + flashing lights	88% reduction in accidents over crossbucks alone; 93% reduction in injuries over crossbucks; 100% reduction in deaths over crossbucks 44% reduction in accidents over flashing lights alone	\$150 K	\$296 K	NTSB (1998), Schulte (1975) and Morrissey (1980)
Median barriers	80% reduction in violations over 2-gate system	\$10 K	\$13 K	Hauer and Persaud (1986)
Long arm gates (3/4 of roadway covered)	67 to 84% reduction in violations over 2-gate system	Unknown	Unknown	Carroll and Haines (2002a)
4-quadrant gate systems	82% reduction in violations over 2-gate system	\$125 K from standard gates; \$250 K from passive crossing	\$163 K from standard gates; \$325 K from passive crossing	Carroll and Haines (2002a), Hellman and Carroll (2002)
4-quadrant gate system + median barriers	92% reduction in violations over 2-gate system	\$135 K	\$176 K	Carroll and Haines (2002a)
Crossing closure	100% reduction in violations, accidents, injuries and deaths	\$15 K	\$20 K	Carroll and Haines (2002a), NTSB (1998)
Photo/video enforcement	34–94% reduction in violations	\$40–70 K per installation	\$52–91 K per installation	Carroll and Haines (2002b)
In-Vehicle Crossing Safety Advisory Warning Systems (ICSAWS)	Unknown	\$5–10 K per crossing + \$50–250 per receiver	\$7–14 K per crossing + \$70–360 per receiver	NTSB (1998)

Jeng (2005) drafted an additional section in the New Jersey driver's manual about railroad safety, and then performed an experimental driver's test on the draft section. The drivers who studied the manual with the additional section performed significantly better on the test. The result suggested that an accurate, easy-to-read and comprehensible driver's manual could improve drivers' response at grade crossings.

Research into driver human factors has shown that engineering solutions solve only part of the problem. Education is also a critical component for reducing collisions at grade crossings. It is important to study the response of drivers to any new type of grade crossing and, if necessary, implement education and awareness initiatives. This is especially the case at shared corridor crossings, where drivers may be accustomed to train movements, but do not expect the more frequent, faster passenger trains.

4. Discussion and conclusions

4.1. Implications for different shared operation types

The Federal Railroad Administration (FRA) classifies passenger and freight train shared operations into (1) shared track, where passenger and freight trains use the same trackage on single or multiple tracks for all or part of their operation; (2) shared right of way, where passenger and freight trains use separate tracks but with adjacent track centers of 25 ft (7.6 m) or less; and (3) shared corridor, which is similar to shared right of way, but with adjacent track centers of more than 25 ft (7.6 m) but less than 200 ft (61 m) apart (Resor, 2003). In addition, "hybrid" systems exist, in which HSR trains operate on dedicated, high-speed infrastructure on some sections and conventional infrastructure on others.

Shared track	Shared right-of-way shared corridor	Hybrid HSR – conventional
<ul style="list-style-type: none"> • Freight and passenger operate on same track(s) • Increased rail traffic at grade crossings will increase the risk of highway-rail vehicle collisions (exposure metric) 	<ul style="list-style-type: none"> • Freight and passenger operate on separate tracks, but within the same ROW (<25 ft apart) or corridor (25–200 ft) • Correlation between multiple-track territory and higher collision rates • Shared corridor operations will have multi-track grade crossings • Risk of secondary collisions with freight trains on adjacent track 	<ul style="list-style-type: none"> • Passenger service operates mostly on dedicated HSR line, shares existing freight line to access city centers • On dedicated section, crossings would need to be grade separated • On conventional infrastructure section, grade crossing would not necessarily be eliminated, but should be upgraded

In a shared track scenario, adding new HSR or HrSR passenger services will increase the total rail traffic. Increased rail traffic at a crossing has been shown to correlate with an increased number of grade crossing collisions (Austin and Carson, 2002; Faghri and Demetsky, 1986; Ogden and Korve Engineering, 2007). Also, highway users may overestimate the amount of time they have to cross in front of a higher speed train, since they are used to interacting with slower conventional rail. Upgrading passive crossings to active crossings will mitigate this issue provided the crossing warning device does not rely on track circuits. The difference in train speed means track circuited crossings will provide significantly longer warning times for freight than for passenger trains. This can cause "false negative" issues, where highway users believe that the crossing is malfunctioning due to the long wait time; under this assumption, they may decide to ignore the active warning device and proceed, leading to an accident. It is therefore important to consider upgrading any crossing with an increased number of through trains per day. It is also important to inform highway users, through signs and educational programs, that trains at crossings may have higher approach speeds or longer approach times than expected.

Shared right-of-way and shared corridor operations have similar challenges. A correlation has been demonstrated between multiple-track territory and higher collision rates (Austin and Carson, 2002; Faghri and Demetsky, 1986; Ogden and Korve Engineering, 2007). At grade crossings with multiple tracks, drivers may check for trains on one track but forget there is another track to check, and could be struck by an unexpected train on the second track.

Additionally, shared corridor operations could have very long grade crossings, or multiple grade crossings very close together. Both of these are undesirable from a highway driver's point of view as they could limit visibility and reduce the driver's ability to perceive approaching trains.

Shared operations using multiple tracks encounter the additional risk of experiencing secondary collisions with freight trains on adjacent tracks. An example of this is the Glendale, CA collision in 2005. In this incident, a passenger train struck an SUV that had been abandoned on the tracks.¹ The SUV subsequently became lodged on switch equipment, resulting in the train derailling and jackknifing. The passenger train struck a freight train on an adjacent track as well as the tail end of another passenger train. Thus the shared operating scenario increased the severity of the grade crossing collision.

In a hybrid system, the dedicated and conventional sections would require different considerations. On the dedicated section, cost would be the primary obstacle since all grade crossings would need to be grade separated. On the conventional infrastructure section, grade crossings would not necessarily need to be eliminated provided trains were not operating at more than 125 mph (201 kph). However, they would likely need to be upgraded to quad-gate systems or other advanced grade crossing warning devices.

Additionally, hybrid operation could require passenger trains to meet different crashworthiness requirements. On a dedicated HSR line, light-weight train sets would be highly desirable, whereas they could pose an unacceptable safety risk when operated on conventional track. Incorporating the principles of crash energy management could allow train designers to develop a train which is safe enough for a track section with grade crossings, but also light enough to operate efficiently at high speeds on a dedicated section.

¹ The Glendale, CA collision was not technically a grade crossing collision, as the driver of the SUV drove some distance up the track before parking his vehicle. However, the same collision could occur at a grade crossing.

4.2. Research needs

The field of research related to grade crossing safety is vast, as can be seen from this literature review. However, there is room to expand on the existing knowledge base and to explore new techniques for improving safety, especially in the context of shared rail corridor operations.

Collision likelihood modeling should continue to develop and evolve. New research may be conducted to understand if the U.S. DOT Accident Prediction Formula needs to be updated to reflect the current state of technology, or if an entirely new formula needs to be developed. The latter approach has been undertaken by a variety of researchers to date, producing a variety of more accurate models. These may be useful in replacing or augmenting the U.S. DOT formula, but since many use small, regional data sets to develop regression models, it should first be understood if these are applicable on a more global scale. Also, current formulas do not account for a sealed corridor differently than a traditional gated crossing; this would be a critical area to consider as shared corridor usage grows.

In the area of crashworthiness, new research may be conducted to understand the ideal tradeoff between light-weight passenger car design and crashworthiness. Using principles of crash energy management (CEM) design should allow engineers to design trains which could work either in hybrid operations or on shared rights-of-way/shared corridors. In the case of hybrid operations, it would be valuable to study the car designs used abroad, such as in France. Design of the TGV has been informed by collisions at grade crossings on conventional track, and the TGV's designers' understanding of crashworthiness has developed over time (Cleon et al., 1993, 1996; Jacobsen, 2008). In the case of shared right-of-way and shared corridor operations, it is especially important to understand if it is possible to design trains to withstand collisions such as the Glendale, CA accident, where jackknifing of the train resulted in side-swiping a freight train. It may be that improved crashworthiness is insufficient to address this type of accident, and that risk reduction strategies should instead be focusing on accident prevention.

Ultimately, the results of research on collision likelihood, collision severity, and driver behavior can be integrated into a large-scale risk management framework, to be used as a tool to assess the risks and benefits of adding higher-speed rail service to an existing freight network.

4.3. Conclusions

Highway-rail grade crossing risk is a topic which has been researched extensively from the highway perspective, but not as much from the passenger rail perspective. The results of these studies have led to significant safety advancements, especially by improved train crashworthiness, improved grade crossing design, and expanded driver education. These advancements, combined with increased government oversight, have led to a sharp decrease in the number of grade crossing-related casualties in the U.S. Implementation of high-speed rail passenger services on existing freight rail corridors will likely pose new grade crossing safety concerns or amplify existing ones. This paper identified the relevant existing research, potential technical challenges, and future research needs to facilitate the planning, development, construction, and operation of future HSR shared corridors in the U.S.

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