Multi-criteria prioritization of highway-rail grade crossings for improvements: a case study

Jacob Mathew®, Rahim F. Benekohal®, Mark Berndt®, Jeannie Beckett® and Jeff McKerrow®

©Civil and Environmental Engineering, University of Illinois Urbana-Champaign, Urbana, US; ©Civil Engineering, Quetica, LLC, Bloomington, MN, US; ©Civil Engineering, B Eckett Group, Gig Harbor, WA, US; ©Civil Engineering, Olsson Inc, Lincoln, NE, US

ABSTRACT
This paper presents a multi-criteria methodology for prioritizing highway-rail grade crossings for grade separation or other major improvements. The traditional approach for making grade-crossing investment decisions has been guided primarily by the Federal Highway Administration Railroad–Highway Grade Crossing Handbook, which focuses heavily on traffic and safety-related factors. However, it does not consider other criteria such as economic competitiveness, environmental sustainability, and livability. Due to factors including 1) increasing traffic demands resulting in significant delays at crossings, 2) the high cost of grade separation, 3) the long-lasting impact of grade separation on a community, and 4) funding requirements from grant applications, several factors should be considered in crossing selection. The main contributions of this paper are 1) a novel robust prioritization methodology that considers safety, economic, environmental, and community/livability, 2) a case study that prioritizes crossings at two separate rail corridors and a comparison of the results with the expert judgment. The case studies use data that is readily available to practitioners and implementation is fostered by the provision of an Excel Toolkit.

1. Introduction

In the U.S., highway and railway transportation networks intersect at more than 2,000,000 locations. These locations are critical for traffic in terms of safety and mobility. Each year in the U.S., over the past ten years, there are approximately 2000 grade crossing accidents, and around 10 percent of these accidents involve a fatality (Operation Lifesaver, 2020). Grade crossings often cause delay caused by trains for significant durations, causing economic losses to road users. It is also estimated that the freight tonnage in the United States is to increase at about 1.4% per year through 2045 (Bureau of Transportation Statistics, 2017). In response to growing traffic and congestion problems at highway-rail grade crossings, state and local agencies increasingly view grade separations as an option that not only improves safety but also increases network capacity and enhance livability near railroad operations. However, these projects are expensive (installation of a grade separation on a rural two lane road costs...

CONTACT Jacob Mathew® jmathew7@illinois.edu Civil and Environmental Engineering, University of Illinois Urbana-Champaign, Urbana, US © 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
2. Literature review

Typically, large transportation projects usually require substantial investment and affect the economic and environmental characteristics of the project regions. In these situations, a decision-maker must consider multiple project alternatives and an array of evaluation criteria so that the project is practical, and the stakeholder needs are met as much as possible. This literature review covers previous studies on project evaluation and the methods used to evaluate different alternatives in transportation and other fields.

**Multi criteria decision-making methods**

Multi-criteria methods are widely used because of their simplicity and ability to incorporate multiple factors contributing to the decision-making process. This approach is popular in transportation decision-making and has been used previously by several researchers. Brucker et al. (de Brucker et al., 2011) show that multi-criteria analysis can be applied within the stakeholder-driven approach to transport project evaluation. Broniewicz et al. (Broniewicz & Ogrodnik, 2020) examined the possibility of using a multi-criteria method to select the most favorable project for the environment. Jiang et al. (Jiang & Sinha, 1990) provided a selection approach that combined ranking and optimization techniques using multiple criteria. Nosal et al. (Nosal & Solecka, 2014) presented the main elements of the methodology of Multi-Criteria Decision Aid methods and the possibility of applying it to assess variants of the integrated system of urban public transport. Hamurcu et al. (Hamurcu & Eren, 2018) studied the route selection problem for Turkey’s planned monorail transport system. Saaty details the Analytic Hierarchy Process in his paper (Saaty, 1990), which was later used by Tabucanon et al. (Tabucanon & Lee, 1995) to evaluate rural highway improvement projects in Korea.

There also have been reviews of literature of commonly applied multi-criteria techniques. Tsamboulas et al. (Tsamboulas et al., 1999) presented a comprehensive analysis of the properties of five commonly applied MCA methods (REGIME, ELECTRE, MAUT,
AHP, and ADAM). Aruldoss et al. (Aruldoss et al., 2013) presented nine different multi-criteria methods with their merits and drawbacks and their applications in different domains such as banking, performance elevation, and safety assessment. (Macharis & Bernardini, 2015) reviewed 276 publications on the applications of Multi-Criteria Decision Analysis (MCDA) methods intending to provide an outline of the use of MCDA in the evaluation of transport projects and proposed the Multi Actor Multi-Criteria Analysis. Camargo et al. (Camargo Pérez et al., 2015) presented a review of research papers published between 1982 and 2014 concerning MCDM for the design and operation of urban passenger transport systems. Furthermore, Meyer et al., Triantaphyllou, and Sinha et al. (Keeney et al., 1993; Sinha & Labi, 2011) provided details on various Multi-Criteria Decision-making methods.

In using multi-criteria analysis, each criterion is to be weighed to combine the contributions from each criterion. Speicher et al. (Speicher et al., 2000) compared two different multi-criteria evaluation methods to prioritize projects within the Northeast Area Transportation Study (NEATS). In the first approach, each criterion was scored with each criteria having its unique maximum value. In the second approach, the weights were developed using a collaborative workshop process to reflect needs, issues, and objectives. In this study, both the approaches provided similar results. Site et al. (Site & Filippi, 2009) compared three different weighing approaches for a decision problem relating to layout alternatives for planned metro line in Rome. The selected weights were established by a sample of transport planning professionals. Jamal et al. (Jamal et al., 2019) identified four criteria for the optimal planning of remote area islanded microgrids. In this study the weights for each criterion were determined based on academic, industry, and consultant expert surveys from around the world using an Analytical Hierarchy Process (AHP) based Multi-Criteria Decision making (MCDM) technique.

**Review of prioritization studies specifically for highway-rail grade crossings**

This part of the literature review focuses explicitly on the selection of highway-rail grade crossings for improvements. This section of the literature review identifies the variables and the methodologies used for this purpose. Grade crossing evaluation factors used in the USA are provided in the Railroad Highway Grade Crossing Handbook (FHWA, 2007). According to the handbook, grade separation of the crossing should be considered when one or more of the following conditions exists:

- The highway is part of the designated Interstate Highway System.
- The highway is otherwise designed to have full-control access.
- The posted highway speed is at least 70 mph.
- The Annual Average Daily Traffic (AADT) exceeds 100,000 in urban areas or 50,000 in rural areas.
- The maximum authorized train speed exceeds 110 mph.
- The track carries an average of 150 or more trains per day or 300 million gross tons per year.
- The track carries an average of 75 or more passenger trains per day in urban areas or 30 or more passenger trains per day in rural areas.
• The crossing exposure (the product of the number of trains per day and the AADT) exceeds 1 million in urban areas or 250,000 in rural areas; or
• The passenger train crossing exposure exceeds 800,000 in urban areas or 200,000 in rural areas.
• The expected accident frequency for active devices with gates, as calculated by the USDOT Accident Prediction Formula, including 5-year accident history, exceeds 0.5.
• The daily vehicle delay exceeds 40 vehicle-hours

Several studies have documented the use of other criteria to prioritize grade separations. For example, a 1997 Israeli study found that vehicle delay due to blocked crossings was a primary contributor to economic loss (Gitelman & Hakkert, 1997; Hakkert & Gitelman, 1997). Witkowski’s (Witkowski, 1988) study showed that grade separation could lead to benefits including reduction in travel time and vehicle emissions by as much as fifty percent. Grade separation prioritization in the Peel region of Canada focused upon maximizing the efficiency of goods movement. The Peel Goods Movement Task Force identified the prioritization of grade crossing separation decisions as a critical action item to help maximize freight efficiency (Peel Regional Council, 2014). Prioritization of crossings in Kern County, California, focused on allowing the county to best allocate financial resources to projects which provide the most significant benefit to traffic flow improvements, freight movement, passenger movement, and safety (Kern Council of Governments, 2011)

Forty-four different prioritization variables have been identified in the literature. These variables were grouped into six categories. Three variables were related to safety, seventeen related to traffic, eight related to highway and geometry, three related to environmental variables, nine related to the community’s surrounding region, and four related to economic impacts. These forty-four variables are tabulated in the appendix of this manuscript and were used in the methodologies listed below.

**Multi-criteria analysis**

The review of previous literature showed that multi-criteria analysis (MCA) is a common approach used for grade crossing assessment and prioritization. The most frequently used criterion considered in MCA are road traffic, train traffic, and the number of accidents. The criteria are used as variables in standardized formulas to calculate an index or score for each crossing location. The general approach used in MCA is to assign a consolidated score for each of the crossings. The consolidated scores may be obtained for each of the crossings based on the weighted average of the scores of each variable. Different variables and weights have been used in different studies examined in this literature review and are discussed in the following paragraphs. MCA may also be used in multiple stages. Each stage provides the opportunity to assign additional screening factors and uses more criteria than the previous stage to filter crossings to be selected for grade separation.

The California DOT’s Section 190 Grade Separation Program authorizes approximately $15 million per year for grade separation projects (California Public Utilities Commission Rail Crossings engineering Section, 2013). A funding priority list of grade separation projects is prepared using the following two formulas. Equation 1 is used for the crossings nominated for separation or elimination.
\[ P = \frac{V \times (T + 0.1 \times LRT) \times (AH + 1)}{C} + SCF \]  

Equation 2 is used to evaluate the existing grade separations that require alteration or renovation.

\[ P = \frac{V \times (T + 0.1 \times LRT)}{C} + SF \]  

Where,

- **P** = Priority Index Number
- **V** = Average Daily Vehicle Traffic
- **T** = Average Daily Freight/Commuter Train Traffic
- **LRT** = Average Daily Volume of Light Rail Train Traffic
- **C** = Project Cost Share to be Allocated from Grade Separation Fund
- **AH** = Accident History
- **SCF** = Special Conditions Factor
- **SF** = Separation Factor

As the formula shows, the multiple-criteria approach is used to develop a priority list. The formula weights vehicular and train volumes at a crossing along with project costs, accident history, and special conditions or separation factors that are used to consider issues such as sightlines along with the crossing approaches, the angle of the tracks to the roadway, and traffic delays caused by trains traveling through the crossing.

Other examples of the MCA application included the study conducted for Kern County, California (Kern Council of Governments, 2011), Riverside County in California in 2012 (InfraConsult LLC, 2012), the study by Schrader et al. (Schrader & Hoffpauer, 2001), a study by Minnesota Department of Transportation (MnDOT) (Minnesota Department of Transportation, 2014), and a study by the Texas Transportation Institute (Rex Nichelson et al., 1999). Internationally, MCA approaches include studies for the Peel Region, Canada (Southern Ontario) (Peel Regional Council, 2014), and Melbourne, Australia (Taylor & Crawford, 2009).

**Cost-benefit analysis**

Cost-Benefit Analysis (CBA) involves monetizing the impacts of a project in terms of the costs and benefits. A benefit-cost ratio may also be calculated to compare projects of dissimilar sizes. A benefit-cost ratio greater than one indicates a project is expected to return a net benefit to the location or region. The main benefits of a grade separation project include improvements in safety, improvements to traffic flows (i.e. reductions in delay), elimination of community severance issues, and capacity increases. The costs of a grade separation include the following components: potential loss of connectivity, project cost, delays due to construction, etc.

Studies using this approach are briefly explained below. Other studies using the CBA approach include the study by J.S. Dodgson in 1984 (Dodgson, 1984), Aoun et al. (Aoun...
et al., 2010), etc. Recently, the USDOT has released Benefit-Cost Analysis Guidance for Discretionary Grant Programs (USDOT, 2020), which guides applicants to USDOT’s discretionary grant programs on conducting benefit-cost analysis for submittal as part of their application. A recent study by Chandra et al. (Chandra et al., 2021) used a BCA methodology incorporating the economic growth potential of candidate at-grade crossings.

**Trade-off analysis**

Trade-off analysis is another approach to facilitate transport decision-making. This approach was used by Bai et al. (Bai et al., 2012), where they provided a general methodology for network level trade-off analysis. At railroad crossings, trade-off analysis was examined in NCHRP report 288, ‘Evaluating Grade Separated Rail and Highway Crossing Alternatives’ (Taggart et al., 1987). The research was conducted to develop a systematic and credible tool to decide on projects related to deteriorated bridges that separate highways and railroads. The approach considered various alternatives, such as Replacement of the structure; rehabilitation of the structure; relocation of the structure; construction of an at-grade crossing in place of the structure; closure of the road; and closure of the rail line. The research found five factors that influence the decision-making process: Safety, Cost, Rail and highway operations, Land use and environmental concerns, and Institutional issues. A recent study by Kavoosii et al. (Kavoosii et al., 2020) viewed resource allocation as an optimization problem where the researchers aimed to minimize the overall hazard or the overall hazard severity at a grade crossing. Their optimization problem is solved by determining a countermeasure among a set of countermeasures that minimizes the overall hazard. The work by Pu et al. (Pu et al., 2021) developed an optimization problem with the objective of finding the optimized design with the lowest construction cost. They solved this optimization model for grade-separated road and railway crossings using a distance-transform approach.

**Other studies related to hazard reduction at highway-rail grade crossings**

The study by Beanland et al. (Beanland et al., 2018) discusses three low-cost solutions to reduce hazard at rail-crossing at rural areas. The suggested solutions from their paper are GPS Average Speed interface, Simple but Strong crossing, and Ecological Interface Design crossing. The study by Lam and Tai (Lam & Tai, 2020) discusses their analysis approach in identifying contributing factors of accidents and finds that technical failure (brake equipment damage and wheel vibrations) are the significant contributing factors. Other accident prediction models are also available in the literature including the latest FRA model which was released in October 2020 (Broad & Gillen, 2020) which is a version of the ZINEBS model developed by the US. The paper by Zhou et al. (Zhou et al., 2020) compares a random forest model to a decision tree model to predict a crash at a location or not. Abioye et al. (Abioye et al., 2020) discusses twenty one different hazard prediction indices in the USA and the same authors (Pasha et al., 2020) evaluates of thirteen different hazard prediction formulas using data from Florida. Keramati et al. (Keramati, Lu, Zhou et al., 2020) used a competing risk model to estimate the likelihood and severity of crash at a highway-rail grade crossing. A practitioner can select the model that is suitable for him/her depending on the location and characteristics of the crossings that are being evaluated.
Shortcomings of literature and needs for a robust methodology

The main shortcomings identified in the literature for railroad crossings evaluation can be summarized as:

1. The cost-benefit analysis only considers those costs that could easily be monetized. Social costs due to environmental impacts and noise impacts were only seen in a few reviewed studies.

2. Determining the weight for each criterion in MCA to calculate a score for each crossing often depends on regional considerations. For instance, the constants used in the study in Arkansas by Schrader et al. ‘A methodology for Evaluating Highway-Rail Grade Separations’ identifies constants in the equations that are specific to the region under investigation.

3. Most of the reviewed literature focused on methodologies developed to address issues particular to a specific region when prioritizing the grade crossings. This procedure allows a user to prioritize a crossing along a corridor in a broader region. For example, a corridor may extend beyond a state boundary. In such a situation, a procedure is needed that is acceptable for both states (or different jurisdictions within a state). NCHRP studies do not set national mandates, and they are done using shared resources from many states.

4. Little has been mentioned in the literature about the change in the economic value of the land after the completion of the grade separation project or social and environmental costs that are not easily monetized. The study by Chandra et al. (Chandra et al., 2021) considers the economic growth potential of candidate grade crossings.

This paper provides a robust methodology including four different factors that consider the traditional factors including safety and costs due to delay and costs due to environmental impacts and community considerations. The developed methodology has adjustable weights for each factor, thereby increasing the usability of the methodology over various regions with their own unique needs. A description of all the factors is given in the next section. This is followed by a discussion on the implementation of the proposed methodology using an Excel Toolkit.

3. Methodology to prioritize highway-rail grade crossings

The methodology proposed in this paper is a multi-criteria approach using four different factors. Each factor is calculated independently. The outcome from the four factors is scaled between one to ten, so all the four outcomes stay within the same range. Weights are used to assign priorities to each of the four factors, which are multiplied by each factor’s outcome. The weighted outcome of all four factors is summed up, which returns the final score for the crossing.

The outcome from four factors is calculated separately.
(a) Safety factors: The USDOT accident prediction formula is used in this procedure. This procedure is widely accepted and therefore is a reasonable way to estimate the safety score. Our procedure also considers site-related adjustment factors to the USDOT accident prediction formula.

(b) Economic factors: The economic score is calculated using both quantitative and qualitative factors. Quantitative factors include vehicle cost of passenger and commercial vehicles based on the delay experienced. Qualitative factors include economic loss, impact on traffic mobility, and impact on land use.

(c) Environmental factors: Thirteen environmental variables are considered in this procedure. The environmental score is calculated based on the presence or absence of each of the thirteen factors considered.

(d) Community livability factors: The calculation of the community/livability score is dependent on the risk of derailment and possibility of exposure to hazmat, both of which are calculated based on proxy variables using available data.

Further details for the calculation are provided in the following sub-sections. This methodology is implemented in an Excel Toolkit called Railroad Crossing Assessment Tool or RCAT.

**Safety factor**

A ‘safety score’ for each crossing. This is based on the safety factors that include the risk of accidents and the severity of accidents (i.e. accidents involving a fatality, accidents involving an injury, or accidents involving property damage only). Therefore, the safety score is composed of two components – the accident prediction value and site-related adjustments. The site-related adjustment changes (increases or decreases) the accident prediction value based on specific factors for the site.

**First component of safety score**

The first component of the safety score, the accident prediction value, is an indicator of the risk of an accident at a given highway-rail grade crossing. Accident prediction models should consider the characteristics of the crossing and the number of observed accidents at the crossing. A widely used accident prediction model in the United States is the USDOT accident prediction formula (Mengert, 1979) which was developed several decades ago and has had very few changes to its model coefficients. Another accident prediction model used is the Zero Inflated Negative Binomial model with Empirial Bayes System (ZINEBS) model developed by the authors (Mathew et. al.) which used more recent data and included variables that were not included in USDOT’s 1979 accident prediction formula.

In this study, the USDOT formula (Edwin H Farr 1987) was used due to its widespread familiarity. The accident prediction using the USDOT formula involves three steps. In the first step, the initial accident prediction value ‘a’ for crossings is computed using Equation 3.

\[
a = K \times EI \times DT \times MS \times MT \times HP \times HL \tag{3}
\]
The formula constant, K, for crossings with different warning device types are given in **Table 1**. Equations 4–21 provides the equations to calculate the rest of the variables in Equation 3.

| Device Type                  | Formula Constant (K) |
|------------------------------|-----------------------|
| Gates                        | 0.0005745             |
| Flashing Lights              | 0.0003351             |
| Crossbucks                   | 0.0006938             |

**Table 1.** Formula constants in the initial accident prediction value in USDOT accident prediction formulae.

\[
EI(\text{Crossings with Gates}) = \left( \frac{Aadt \times TotalTrn + 0.2}{0.2} \right)^{0.2942}
\]

(4)

\[
EI(\text{Crossings with Flashing Lights and No Gates}) = \left( \frac{Aadt \times TotalTrn + 0.2}{0.2} \right)^{0.0416}
\]

(5)

\[
EI(\text{Crossings with Crossbucks}) = \left( \frac{Aadt \times TotalTrn + 0.2}{0.2} \right)^{0.37}
\]

(6)

\[
DT(\text{Crossings with Gates}) = \left( \frac{ThruTrain + 0.2}{0.2} \right)^{0.1781}
\]

(7)

\[
DT(\text{Crossings with Flashing Lights and No Gates}) = \left( \frac{DayThru + 0.2}{0.2} \right)^{0.1131}
\]

(8)

\[
DT(\text{Crossings with Crossbucks}) = \left( \frac{ThruTrain + 0.2}{0.2} \right)^{0.178}
\]

(9)

\[
MS(\text{Crossings with Gates}) = e^{0.0077ms}
\]

(10)

\[
MS(\text{Crossings with Flashing Lights and No Gates}) = 1
\]

(11)

\[
MS(\text{Crossings with Crossbucks}) = 1
\]

(12)

\[
MT(\text{Crossings with Gates}) = 1
\]

(13)

\[
MT(\text{Crossings with Flashing Lights and No Gates}) = e^{0.1917mt}
\]

(14)

\[
MT(\text{Crossings with Crossbucks}) = e^{0.512ms}
\]

(15)
\[ HP(\text{Crossings with Gates}) = e^{-0.5966(hp^{-1})} \]  \hfill (16)

\[ HP(\text{Crossings with Flashing Lights and No Gates}) = 1 \]  \hfill (17)

\[ HP(\text{Crossings with Crossbucks}) = 1 \]  \hfill (18)

\[ HL(\text{Crossings with Gates}) = 1 \]  \hfill (19)

\[ HL(\text{Crossings with Flashing Lights and No Gates}) = e^{0.1826(hl^{-1})} \]  \hfill (20)

\[ HL(\text{Crossings with Crossbucks}) = e^{0.1420(hl^{-1})} \]  \hfill (21)

Where:

- **K** is a formula constant
- **EI** (factor for exposure index based on the product of highway and train traffic)
- **AADT** is the annual average daily traffic at the crossing
- **TotalTrn** is the total number of trains using the crossing
- **DT** factor for the number of through trains per day during daylight
- **DayThru** is the number of daytime thru trains at the crossing
- **MT** factor for the number of main tracks
- **MainTrk** is the number of main tracks at the crossing
- **HL** factor for the number of road lanes
- **TrafficLn** is the number of road lanes at the crossing
- **MS** is the maximum timetable train speed at the crossing in mph
- **HP** factor for road pavement status (1 = yes, 0 = no)

It may be noted that the coefficients in the initial accident prediction formula for calculating ‘a’ in the USDOT formula as mentioned in the Highway-Rail Grade Crossing Handbook (FHWA, 2007) are different from the coefficients given in the Summary of DOT Rail-Highway Resource Allocation Procedures-Revised (E.H. Farr 1987). The FRA uses the coefficients mentioned in the Summary of DOT Rail-Highway Resource Allocation Procedures in their Web Accident Prediction System (Federal Railroad Administration, n.d.).

A ‘B’ value is computed in the second step, a weighted average of ‘a’ value, and the accident history of the crossing.

\[ B = \frac{T_0}{T_0 + T} * a + \frac{T}{T_0 + T} * \left( \frac{N}{T} \right) \]  \hfill (22)

\[ T_0 = \frac{1}{0.05 + a} \]  \hfill (23)

B is called the adjusted accident prediction value, and N is the number of observed accidents in T years, and ‘a’ is the initial accident prediction value.

The adjusted accident prediction value is normalized in the third step, as shown in the equation below.
Second component of the safety score

The second component of the safety score is the site-related adjustments made to account for the number and severity of accidents. The severity of the accidents at a crossing can be judged by considering the type of accident based on the degree of severity, i.e., fatal accident, injury accident, or property damage (PDO) only accident. We calculated the severity value for each grade crossing based on each type of accident at a crossing.

We calculated the severity value as:

$$\text{Severity Value for Xing} = F \times (\text{No. of Fatal Accidents at Xing}) + I \times (\text{No. of Injury Accidents at Xing}) + P \times (\text{No. of PDO Only Accidents Xing})$$ (25)

Where

- $F =$ Relative weight for fatal accident
- $I =$ Relative weight for injury accident
- $P =$ Relative weight for PDO accidents

A decision-maker can choose different severity scales to evaluate the accident risk at a crossing depending on the user-specified relative importance assigned to fatal, injury, and PDO accidents. The relative severity of a fatal/injury accident to a PDO accident can be determined in any one of the several ways cited in the literature. Geurts et al. (Geurts & Wets, 2003) use a scale to define priority values for black spots on highways (Scale A in Table 2). The National Safety Council (National Safety Council, 2013) gives the accident costs based on the severity of accidents. A ratio of these severity costs can serve as the basis for a different severity scale (Scale C in Table 2). We chose Scale B as an intermediate scale between scale A and scale C. The scales indicate the relative severity that the user assigns to a fatal accident compared to an injury accident or a PDO accident.

To calculate the safety score at a crossing, the accident prediction value (calculated in the first component) is adjusted based on crossing characteristics. The researchers explored several crossing characteristics, including crossing angle, maximum timetable train speed, highway speed, crossing surface, etc., to find the appropriate combination of adjustments necessary to rank crossings based on the severity values. These adjustments were determined by an exhaustive search using different characteristics and weights. The adjustments may increase or decrease or not change the calculated accident prediction value. These adjustments are made so that the crossings are ranked based on the severity value of the chosen scale.

The default severity scale for the RCAT Toolkit was Scale A. Further details about the adjustments used in the RCAT Toolkit are available in the final report of the NCHRP 25–50 study (Berndt et al., 2019).

| Scale | Fatal (F) | Injury (I) | PDO Only (P) |
|-------|-----------|------------|--------------|
| A     | 5         | 3          | 1            |
| B     | 10        | 4          | 1            |
| C     | 46.5      | 1.7        | 0.1          |
Thus, the safety score of a crossing is calculated as the weighted average of the two components.

\[
\text{Safety Score} = k_1 \times \text{Accident prediction value} + k_2 \times \text{Site related Adjustments} \quad (26)
\]

Where,

- \(k_1\) and \(k_2\) are multipliers that determine the level of adjustment (weight of each component). The default value of these weights is 1.
- The Accident Prediction Value is calculated based on an accident predict model (here, we used the USDOT model). The site-related adjustments depend on the crossing characteristics as follows.

**Gates**

\[
\text{Site related adjustment for gated crossings} = 0.017 \times \text{normalized value for maximum timetable train speed} + 0.017 \\
\times \text{normalized value for distance to nearby highway intersection} + 0.011 \\
\times \text{normalized value for crossing surface} \quad (27)
\]

**Flashing lights**

\[
\text{Site related adjustment for crossings with flashing lights} = 0.047 \times \text{normalized value for maximum timetable train speed} + 0.005 \times \text{normalized value for posted highway speed} \\
+ 0.005 \times \text{normalized value for crossing surface} \quad (28)
\]

**Crossbucks**

\[
\text{Site related adjustment for crossings with crossbucks} = 0.047 \times \text{normalized value for maximum timetable train speed} + 0.005 \\
\times \text{normalized value for Crossing angle} + 0.005 \\
\times \text{normalized value for crossing surface} \quad (29)
\]

Tables 3, 4 and 5 provide the corrective variables and normalized values for the variables for crossings with gates, crossigns with flashing lights and crossings with crossbucks, respectively.

A higher safety score at a crossing indicates a higher safety improvement value from implementing a grade separation project than another crossing with a lower safety score. It is also interesting to note that two of the factors used in this study (Crossing angle and Distance to Nearby HW intersection) was also examined by Keramati et. al. (Keramati, Pan, Tolliver et al., 2020) and was shown to influence the likelihood of fatal crashes.

**Economic factors**

The second factor considered in the proposed methodology is the economic impact. The researchers identified several qualitative and quantitative economic variables which contribute towards an \textit{economic score}. The calculation for the economic factors accounts for the operating cost of passenger and commercial vehicles due to delay experienced,
economic losses due to grade separation of the crossing to the surrounding land users, impact to the mobility of vehicles, and impact to land use. The economic factors considered in this procedure include:

(a) Vehicle operating cost for passenger vehicles: The average cost to a passenger vehicle is calculated based on passenger vehicles’ annual average daily traffic, the average delay that a vehicle faces, and the average travel time cost. The average travel time cost given in the TIGER BCA guidelines is $13 per hour (USDOT, 2015). The vehicle operating cost for passenger vehicles is calculated based on Equation 30.
Vehicle Operating Cost (Passenger Vehicles) = \left( \frac{(Aatt + 2.5) * (Aadt - (Percent Trucks * Aadt))}{60} \right) * 1.5 + Fuel Cost

(30)

Where

AATT is annual average train traffic
AADT is annual average daily traffic
Percent Truck is the percentage of trucks/heavy vehicles using the crossing
Fuel Cost is the cost of fuel in $ per gallon

(a) Vehicle operating cost for commercial vehicles: The TIGER BCA guidelines suggest using $25.80 per hour as the value for travel time for truck drivers (USDOT, 2015). The vehicle operating cost for commercial vehicles is calculated based on this estimate and the percentage of trucks using the crossing. Equation 31 presents vehicle operating cost formula for commercial vehicles:

Vehicle Operating Cost (Passenger Vehicles) = \left( \frac{(Aatt + 2.5) * (Aadt - (Percent Trucks * Aadt))}{60} \right) * 13 \left( \frac{60}{13} \right) + Fuel Cost

(31)

The variables in Equation 31 are defined previously.

The delay calculation is based on available data. If ‘better’ data is available (including train length, train speed, hourly traffic volume), a more accurate delay equation can be developed. The calculation can be updated as more data becomes available.

(a) Economic losses to surrounding landowners: This is treated as a binary variable (Yes or No) as observed based on the adjacent land use.

(b) Impact on traffic mobility. The density near the project measures the impact on mobility due to the grade separation project. Low-density regions would have a low impact on mobility, while densely populated regions like city centers would significantly impact mobility due to the grade separation. This impact is captured using a categorical variable, as shown in Table 6.
(c) Impact on land use. A grade separation project impacts land use in a region depending on population density, similar to how it impacts mobility. It captures the notion that the addition of a grade separation should add value to the nearby property and opportunities for economic development due to the increased mobility and safety provided by such improvements. Table 7 presents the scores for the impact on land use.

(d) Supply chain savings. This involves the cost savings to the supply chain as a result of the grade separation. Grade separation projects result in fewer interruptions in the supply chain network as the highway is physically separated from the rail line. This is captured based on the percentage of truck traffic, as shown in Table 8.

Based on the factors mentioned above, the economic score is calculated. The equation for the calculation of the economic score used in the RCAT Toolkit is

\[
\text{Economic Score} = e_1 \cdot \text{Vehicle operating cost(Passenger)} + e_2 \cdot \text{Vehicle operating cost(Commercial)} + e_3 \cdot \text{Factor for economic losses to surrounding land owners} + e_4 \cdot \text{Factor for traffic mobility improvement} + e_5 \cdot \text{Factor for impact to landuse} + e_6 \cdot \text{Factor for supply chain savings}
\]  

(32)

Where

\[ e_1, e_2, e_3, e_4, e_5 \] are multipliers that determine the weights assigned to each economic factor with a default value of 1.

A higher economic score for a crossing indicates a higher economic impact due to grade separating that crossing.

---

**Table 6. Calculation of Impact to Traffic Mobility.**

| Density Near Project                                      | Score |
|----------------------------------------------------------|-------|
| Low: rural/industrial                                    | 1     |
| Medium suburban/medium residential density               | 3     |
| High: urban (city center, high population density)       | 5     |

**Table 7. Calculation of Impact to Land Use.**

| Density Near Project                                      | Score |
|----------------------------------------------------------|-------|
| Low: (industrial area)                                    | 1     |
| Medium (suburban residential density)                    | 3     |
| High: (city center, high population density)             | 5     |

**Table 8. Calculation of Supply Chain Savings.**

| Percentage of Truck Traffic | Score |
|-----------------------------|-------|
| <5%                         | 1     |
| 6–10%                       | 2     |
| 11–15%                      | 3     |
| 16–25%                      | 4     |
| >25%                        | 5     |
It may be noted that the model is developed considering the available data. The authors realize that more complex models that could take into account the train length (for which the data is unavailable currently), type of train, etc. could result in a more accurate calculation of the delay and vehicle operating cost experienced at the crossing. As the data becomes available, more reliable models could be developed.

**Environmental factors**

The enactment of the National Environmental Policy Act in January 1970 required all projects utilizing federal-aid funding to undergo an environmental review that documents the impacts of a potential project on the environment (United States Environmental Protection Agency, 2017). This paper’s methodology therefore considers the environmental factors. Environmental factors are categorized as: natural, built, and social.

The natural environment includes the living flora and fauna and naturally occurring geologic features that constitute complex ecosystems besides human-made habitats. The built environment includes the communities, neighborhoods, historical artifacts, parks, recreational regions, and other features of the human-shaped world. Finally, the social environment constitutes the factors that describe the living conditions and characteristics of the population that resides in the built environment. The methodology considers six natural environmental factors, five built environmental factors, and two social, environmental factors to calculate a final environmental score. Other environmental factors including emissions due to vehicles delayed at the crossing should also be considered. However, this calculation cannot be carried out without data on hourly traffic volume, train length, train speed, etc. The procedure can be improved as the data becomes readily available.

The 13 environmental factors considered in this methodology are:

1. Coastal management areas
2. Critical habitat for threatened and endangered species
3. Wetlands
4. Wild and scenic rivers
5. Air quality non-attainment areas
6. Superfund sites
7. Tribal lands
8. Federal or state-owned lands
9. Military installations
10. Historical properties
11. Parks and recreational areas
12. Environmental justice
13. Community severance

The environmental score is calculated based on the proximity of the crossing to the 13 environmental factors, as shown in equation 33.

$$\text{Environmental Score} = \sum_{i=1}^{13} I(\text{Environmental Factor}_i)$$

(33)
Where

Environmental Factor$_i$ represents each of the 13 environmental factors considered in this study.

$I(\text{Environmental Factor}_i)$ has a value of 1 if Environmental Factor$_i$ is present within a one-mile buffer of the crossing and 0 otherwise.

A higher environmental score is indicative of higher environmental impact as a result of the grade separation project.

**Community and livability factors**

FHWA defines livability as: ‘...tying the quality and location of transportation facilities to broader opportunities such as access to good jobs, affordable housing, quality schools, and safe streets’. (Federal Highway Administration, 2010). Livability factors considered for grade separations include factors related to safety in terms of risk of derailment and release of hazardous materials, and time savings, especially for emergency vehicles. For scoring, the community and livability evaluation criteria were viewed as factors that affected citizenry’s security without being directly involved in a train accident/collision.

The community and livability factors are used to calculate the ‘community score’, which involves two components. The first component, the risk of the derailment, is captured based on the posted highway speed limit, train speed, and percentage of large vehicles using the crossing. These variables are chosen based on Chadwick et al. (Chadwick et al., 2013).

The second component, the exposure to hazmat due to an incident (e.g. a release or spill), is calculated based on the presence of hazardous train cars, population density, presence of vulnerable populations such as hospitals, senior living facilities, schools, etc. and the presence emergency response facilities like a fire station within a half-mile buffer around the crossing. The community score is calculated as

$$
\text{Community Score} = c_1 \times \text{Component for the risk of derailment} + c_2 \times \text{Component for the exposure to hazmat} \\
$$

(34)

Where

$c_1$, $c_2$ are multipliers that determine the weights assigned to each of the community factors.

The component for the risk of the derailment is calculated as

$$
\text{Component for risk of derailment} = c_{11} \times \text{Train Speed Score} + c_{12} \times \text{Highway Speed Score} + c_{13} \times \text{Truck Percentage Score} \\
$$

(35)

$c_{11}$, $c_{12}$, and $c_{13}$ are multipliers with the default value of 1. Train speed score is dependent on the maximum timetable train speed at the crossing as given in Table 9.

Highway speed score is dependent on the posted highway speed limit at the crossing as given in Table 10.

Truck Percentage Score is dependent on the percentage of truck traffic at the crossing as given in Table 11.

The component for exposure to hazmat is calculated as
Component for exposure to hazmat = $c_{21} \times \text{Presence of hazardous vehicles}$

$+ c_{22} \times \text{Population density} + c_{23} \times \text{Vulnerable population} + c_{14}$

$\times \text{Emergency response delays}$

(35)

Where:

$c_{21}, c_{22}, c_{23},$ and $c_{24}$ are multipliers with the default value of 1.

The presence of hazardous vehicles is a binary variable indicating hazmat trains using the crossing.

Population density is a categorical variable with three categories: Low, medium, and high. This is based on the population per square mile measured within $\frac{1}{2}$ square mile of crossing.

Vulnerable population is an indicator variable to show the presence of hospitals, senior living, schools, prisons, measured within $\frac{1}{2}$ square mile of a crossing.

Emergency response delays are an indicator variable to show police station, fire station, or hospital within $\frac{1}{2}$ mile of crossing without access to a grade-separated crossing.

4. Final score

Each scores for the four different factors is normalized to a value between 0 and 10, based on Equations 36 to 39 and Table 12.

Normalized safety score for crossing = $10 \times \frac{\text{Safety score for crossing} - \text{Min Safety score}}{\text{Max Safety Score} - \text{Min Safety Score}}$

(37)
Table 12. Normalized Environmental Score.

| Number of Environmental Factors | Normalized Environmental Scores |
|---------------------------------|---------------------------------|
| 0–3                             | 2                               |
| 4–6                             | 4                               |
| 7–9                             | 6                               |
| 10–12                           | 8                               |
| 13                              | 10                              |

\[
\text{Normalized economic score for crossing} = 10 \\
\frac{\text{Economic score for crossing} - \text{Min Economic score}}{\text{Max Economic Score} - \text{Min Economic Score}} \quad (38)
\]

\[
\text{Normalized community score for crossing} = \\
10 \times \frac{\text{Community score for crossing} - \text{Min Community score}}{\text{Max Community Score} - \text{Min Community Score}} \quad (39)
\]

\[
\text{Final Score for a Crossing} = w_1 \times \text{Normalized safety score} + w_2 \times \text{Normalized economic score} + w_3 \times \text{Normalized environmental score} + w_4 \times \text{Normalized environmental score} \quad (40)
\]

Where \( w_1, w_2, w_3, \) and \( w_4 \) are the weights for the normalized safety score, normalized economic score, normalized environmental score, and normalized community score, respectively. The default values suggested for the weights are 0.5 for \( w_1 \), 0.25 for \( w_2 \), and 0.125 for both \( w_3 \) and \( w_4 \). These default weights were chosen by industry experts and academics. Also the study used two new sets of weight values, and a sensitivity analysis was performed based on the weights. These values can be modified by the user.

5. Data

The data required as inputs of this methodology are obtained from various sources. The major ones are listed below.

1. Crossing inventory and accident data from Federal Railroad Administration’s office of safety. (FRA, 2019)
2. GIS maps. Some examples are listed below.
   a. Coastal and Marine Geology (United States Geological Survey, 2020)
   b. Parks and Rec (ESRI, 2019)
   c. Critical habitat (Conservation Biology Institute, 2019)
   d. Air Quality Non-Attainment Areas (United States Environmental Protection Agency, 2010)
3. Population information from the U.S. census bureau. (United States Census Bureau, 2010)
4. Hazardous material information (Federal Railroad Administration, 2020)
6. Sensitivity analysis

The researchers performed a sensitivity analysis to ensure that the methodology is robust and meets the expectations of potential users. We developed a spreadsheet toolkit to simplify the use of the methodology (TRB, 2019). The toolkit offers a practitioner the ability to download information about the crossings directly from the FRA database. It allows flexibility to a practitioner to edit the values (if required), as well as the weights needed in the methodology. The toolkit is programmed to calculate the scores for each of the four factors as well as the final score for each crossing. It presents a ordered list of ranked crossing based on the methodology, with a higher ranked crossing being the one with the higher priority for major improvements. Further information about the Toolkit is available in the User Guide (“NCHRP” 25-50 RCAT Users Guide” 2018).

First, a sensitivity analysis was conducted to compare the ranking of the crossings using different scales (Table 2). The coefficient established using each of the three scales (Scale A, B, and C) were used to determine the ranking of the crossings, and they are shown in Tables 13–15 below, respectively. The tables present the analysis result for the crossings along the TRRA corridor.

In the above three analysis rankings, seven crossings are the same among the top 10 crossings (From Tables 13–15 or Table 16). The order of the ranking of the crossings changes slightly as the severity scales are changed, as expected. For example, crossing 803,356 C, which appears second while using severity scale A, appears third while using severity scale B, and fifth while using severity scale C. Incidentally, it was also found that crossing 803,090 V was the one with the highest final score using all the three scales. This was the only crossing that witnessed an accident among all the crossings in the corridor during the analysis period. This analysis suggests that each of the severity scales gives a reasonable result for ranking the crossings.

Secondly, the weights of each of the factors were altered to see how the final scores would change. The default values are 50% for safety factors, 25% for economic factors, 12.5% for environmental factors, and 12.5% for community livability factors. Two different alterations were done. They are

1. 60% for safety factors, 20% for economic factors, 10% for environmental factors, and 10% for community livability factors
2. 40% for safety factors, 30% for economic factors, 15% for environmental factors, and 15% for community livability factors.

i.e. the weight for safety factors is changed by +10%, weight for economic factors is changed by +5%, the weight of environmental and community livability factors is changed by +2.5%. The three weight groups used in this sensitivity analysis are:

Weight Group 1: 50% for Safety, 25% for Economic, 12.5% for Environmental and 12.5% for Community livability factors. The result for this is shown in Table 13.

Weight Group 2: 60% for Safety, 40% for Economic, 10% for Environmental, and 10% for Community livability factors. The result for this is shown in Table 17.

Weight Group 3: 40% for Safety, 30% for Economic, 15% for Environmental, and 15% for Community livability factors. The result for this is shown in Table 18.
Safety is still given the highest priority among all four factors. We do not expect the weight for safety to go over 60% or under 40%; however, the user can select the weights as they see appropriate.

The severity score of 5 (fatal) – 3 (injury) and 1 (PDO) were used in this analysis.

With different weights, the top five crossings and their order remain intact even with the weights changed. Among the top 10 crossings, nine are common in the three analyses (Comparing Tables 13, Tables 17, and 18, or Table 19). While the order of the crossings changes slightly, these changes are not drastic. This indicates that the procedure is not very sensitive to the weight of each of the four factors.

Thirdly, a comparison was made to show how the ranking ability of the methodology performs if only one of the four factors was used as opposed to using all four factors. Table 20 shows the ranking of the crossings for each of the four different factors used independently as well as using all four factors. The ranking using all four factors use the weights 50% for safety factors, 25% for economic factors, 12.5% for environmental factors, and 12.5% for community livability factors. The severity scale A (5 for fatal, 3 for injury and 1 for PDO accidents) is used.

The results show that the top crossing selected are different when only safety, economic or environmental factor (or community livability factor) is used alone. This indicates that each crossing has its own priority factor that is unique to it, depending on the features of its location and other factors. The top crossing selected based on environmental factors and community livability factors are the same, but the ranking of other crossings is significantly different. For example, 803,368 W which is ranked second using environmental factors comes only ninth while ranking using community/livability factors. Another observation that can be made from this result is that the top four crossings ranked via safety score are ranked in the same order as the top four crossings ranked using all four criteria. Furthermore, the top six crossings are the same while ranking using these two criteria. This can be explained as safety is the highest

| Rank of Crossing (Based on Final Score) | Crossing ID   | Safety Score | Economic Score | Environmental Score | Community Score | Final Score |
|----------------------------------------|---------------|--------------|----------------|---------------------|----------------|-------------|
| 1                                      | 803,090 V     | 5.00         | 0.98           | 0.38                | 0.83           | 7.19        |
| 2                                      | 803,356 C     | 2.89         | 1.29           | 0.50                | 1.25           | 5.93        |
| 3                                      | 803,085 Y     | 2.03         | 1.58           | 0.38                | 0.83           | 4.81        |
| 4                                      | 803349S       | 2.02         | 1.19           | 0.38                | 1.17           | 4.76        |
| 5                                      | 803,368 W     | 1.59         | 1.27           | 0.50                | 1.08           | 4.44        |
| 6                                      | 803347D       | 1.83         | 1.15           | 0.25                | 1.00           | 4.22        |
| 7                                      | 803,353 G     | 1.38         | 1.12           | 0.50                | 1.17           | 4.16        |
| 8                                      | 803,350 L     | 1.39         | 1.13           | 0.38                | 1.25           | 4.14        |
| 9                                      | 803,364 U     | 1.41         | 1.03           | 0.50                | 1.08           | 4.03        |
| 10                                     | 803,348 K     | 1.42         | 1.18           | 0.25                | 1.17           | 4.02        |
| 11                                     | 803,092 J     | 0.38         | 2.50           | 0.25                | 0.67           | 3.80        |
| 12                                     | 803359X       | 1.23         | 0.86           | 0.50                | 1.17           | 3.76        |
| 13                                     | 803360S       | 1.22         | 0.86           | 0.50                | 1.17           | 3.74        |
| 14                                     | 803,346 W     | 1.53         | 0.87           | 0.25                | 1.08           | 3.73        |
| 15                                     | 803,366 H     | 1.32         | 0.94           | 0.38                | 1.08           | 3.72        |
| 16                                     | 803,354 N     | 1.34         | 0.75           | 0.50                | 1.00           | 3.59        |
| 17                                     | 803,362 F     | 1.03         | 0.75           | 0.50                | 1.25           | 3.53        |
| 18                                     | 803365B       | 1.03         | 0.75           | 0.50                | 1.08           | 3.37        |
| 19                                     | 803,091 C     | 1.00         | 0.44           | 0.25                | 0.67           | 2.35        |
| 20                                     | 803,078 N     | 1.00         | 0.63           | 0.50                | 1.08           | 2.21        |
| 21                                     | 803,077 G     | 0.00         | 0.63           | 0.50                | 1.00           | 2.13        |
| 22                                     | 803,189 F     | 0.36         | 0.00           | 0.38                | 0.00           | 0.74        |
Table 14. Final Scores based on Severity Scale B (10 (fatal)-4 (injury)-1 (PDO)).

| Rank of Crossing (Based on Final Score) | Crossing ID | Safety Score | Economic Score | Environmental Score | Community Score | Final Score |
|----------------------------------------|-------------|--------------|----------------|---------------------|----------------|-------------|
| 1                                      | 803,090 V   | 5.00         | 0.98           | 0.38                | 0.83           | 7.19        |
| 2                                      | 803085Y     | 2.43         | 1.58           | 0.38                | 0.83           | 5.22        |
| 3                                      | 803,356 C   | 2.15         | 1.29           | 0.50                | 1.25           | 5.19        |
| 4                                      | 803,092 J   | 1.52         | 2.50           | 0.25                | 0.67           | 4.94        |
| 5                                      | 803,368 W   | 2.05         | 1.27           | 0.50                | 1.08           | 4.91        |
| 6                                      | 803,353 G   | 1.87         | 1.12           | 0.50                | 1.17           | 4.66        |
| 7                                      | 803349S     | 1.92         | 1.19           | 0.38                | 1.17           | 4.65        |
| 8                                      | 803,350 L   | 1.88         | 1.13           | 0.38                | 1.25           | 4.64        |
| 9                                      | 803,364 U   | 1.90         | 1.03           | 0.50                | 1.08           | 4.52        |
| 10                                     | 803,348 K   | 1.91         | 1.18           | 0.25                | 1.17           | 4.51        |
| 11                                     | 803359X     | 1.75         | 0.86           | 0.50                | 1.17           | 4.27        |
| 12                                     | 803360S     | 1.74         | 0.86           | 0.50                | 1.17           | 4.26        |
| 13                                     | 803,366 H   | 1.83         | 0.94           | 0.38                | 1.08           | 4.22        |
| 14                                     | 803347D     | 1.75         | 1.15           | 0.25                | 1.00           | 4.15        |
| 15                                     | 803,354 N   | 1.84         | 0.75           | 0.50                | 1.00           | 4.09        |
| 16                                     | 803,362 F   | 1.58         | 0.75           | 0.50                | 1.25           | 4.07        |
| 17                                     | 803365B     | 1.58         | 0.75           | 0.50                | 1.08           | 3.91        |
| 18                                     | 803,346 W   | 1.50         | 0.87           | 0.25                | 1.08           | 3.69        |
| 19                                     | 803,091 C   | 0.87         | 0.44           | 0.25                | 0.67           | 2.22        |
| 20                                     | 803,078 N   | 0.00         | 0.63           | 0.50                | 1.08           | 2.21        |
| 21                                     | 803,077 G   | 0.00         | 0.63           | 0.50                | 1.00           | 2.13        |
| 22                                     | 803,189 F   | 0.38         | 0.00           | 0.38                | 0.00           | 0.76        |

Table 15. Final Scores based on Severity Scale C (46.5 (fatal)-1.7 (injury)-0.1 (PDO)).

| Rank of Crossing (Based on Final Score) | Crossing ID | Safety Score | Economic Score | Environmental Score | Community Score | Final Score |
|----------------------------------------|-------------|--------------|----------------|---------------------|----------------|-------------|
| 1                                      | 803,090 V   | 5.00         | 0.98           | 0.38                | 0.83           | 7.19        |
| 2                                      | 803347D     | 3.66         | 1.15           | 0.25                | 1.00           | 6.06        |
| 3                                      | 803,346 W   | 3.39         | 0.87           | 0.25                | 1.08           | 5.59        |
| 4                                      | 803085Y     | 2.26         | 1.58           | 0.38                | 0.83           | 5.04        |
| 5                                      | 803,356 C   | 1.96         | 1.29           | 0.50                | 1.25           | 5.00        |
| 6                                      | 803,368 W   | 1.85         | 1.27           | 0.50                | 1.08           | 4.71        |
| 7                                      | 803,092 J   | 1.28         | 2.50           | 0.25                | 0.67           | 4.70        |
| 8                                      | 803,333 G   | 1.66         | 1.12           | 0.50                | 1.17           | 4.44        |
| 9                                      | 803349S     | 1.71         | 1.19           | 0.38                | 1.17           | 4.44        |
| 10                                     | 803,350 L   | 1.67         | 1.13           | 0.38                | 1.25           | 4.42        |
| 11                                     | 803,364 U   | 1.69         | 1.03           | 0.50                | 1.08           | 4.31        |
| 12                                     | 803,348 K   | 1.70         | 1.18           | 0.25                | 1.17           | 4.30        |
| 13                                     | 803,077 G   | 1.98         | 0.63           | 0.50                | 1.00           | 4.11        |
| 14                                     | 803359X     | 1.52         | 0.86           | 0.50                | 1.17           | 4.05        |
| 15                                     | 803360S     | 1.52         | 0.86           | 0.50                | 1.17           | 4.04        |
| 16                                     | 803,366 H   | 1.61         | 0.94           | 0.38                | 1.08           | 4.00        |
| 17                                     | 803,354 N   | 1.62         | 0.75           | 0.50                | 1.00           | 3.87        |
| 18                                     | 803,362 F   | 1.34         | 0.75           | 0.50                | 1.25           | 3.84        |
| 19                                     | 803,078 N   | 1.56         | 0.63           | 0.50                | 1.08           | 3.77        |
| 20                                     | 803365B     | 1.34         | 0.75           | 0.50                | 1.08           | 3.67        |
| 21                                     | 803,091 C   | 0.59         | 0.44           | 0.25                | 0.67           | 1.95        |
| 22                                     | 803,189 F   | 0.00         | 0.00           | 0.38                | 0.00           | 0.38        |

A weighed factor in the combined methodology leading to prioritization of those crossings with higher safety scores. This comparison shows how the importance of the inclusion of multiple factors, thus making the proposed methodology robust.
Table 16. Result of Sensitivity Analysis based on Severity Scales.

| Rank of Crossing (Based on Final Score) | Severity Scale A | Severity Scale B | Severity Scale C |
|-----------------------------------------|-----------------|-----------------|-----------------|
| Crossing ID                             | Crossing ID     | Crossing ID     |
| 1                                       | 803,090 V       | 803090 V        | 803090 V        |
| 2                                       | 803,356 C       | 803085Y         | 803347D         |
| 3                                       | 803085Y         | 803356 C        | 803346 W        |
| 4                                       | 8033495         | 803092 J        | 803085Y         |
| 5                                       | 803,368 W       | 803368 W        | 803356 C        |
| 6                                       | 803347D         | 803353 G        | 803368 W        |
| 7                                       | 803,353 G       | 803349S         | 803092 J        |
| 8                                       | 803,350 L       | 803350 L        | 803353 G        |
| 9                                       | 803,364 U       | 803364 U        | 803349 S        |
| 10                                      | 803,348 K       | 803348 K        | 803350 L        |
| 11                                      | 803,092 J       | 803359X         | 803364 U        |
| 12                                      | 803359X         | 803360S         | 803348 K        |
| 13                                      | 803360S         | 803366 H        | 803077 G        |
| 14                                      | 803,346 W       | 803347D         | 803359X         |
| 15                                      | 803,366 H       | 803354 N        | 803360S         |
| 16                                      | 803,354 N       | 803362 F        | 803366 H        |
| 17                                      | 803,362 F       | 803365B         | 803354 N        |
| 18                                      | 803365B         | 803346 W        | 803362 F        |
| 19                                      | 803,091 C       | 803091 C        | 803078 N        |
| 20                                      | 803,078 N       | 803078 N        | 803365B         |
| 21                                      | 803,077 G       | 803077 G        | 803091 C        |
| 22                                      | 803,189 F       | 803189 F        | 803189 F        |

Table 17. Analysis using weights: 60% for safety, 40% for economic, 10% for environmental, and 10% for community livability factors.

| Rank of Crossing (Based on Final Score) | Crossing ID | Safety Score | Economic Score | Environmental Score | Community Score | Final Score |
|-----------------------------------------|-------------|--------------|----------------|---------------------|----------------|-------------|
| 1                                       | 803,090 V   | 6.00         | 0.79           | 0.30                | 0.67           | 7.75        |
| 2                                       | 803,356 C   | 3.47         | 1.03           | 0.40                | 1.00           | 5.90        |
| 3                                       | 803085Y     | 2.43         | 1.26           | 0.30                | 0.67           | 4.66        |
| 4                                       | 8033495     | 2.43         | 0.95           | 0.30                | 0.93           | 4.61        |
| 5                                       | 803,368 W   | 1.91         | 1.02           | 0.40                | 0.87           | 4.19        |
| 6                                       | 803347D     | 2.19         | 0.92           | 0.20                | 0.80           | 4.11        |
| 7                                       | 803,353 G   | 1.65         | 0.89           | 0.40                | 0.93           | 3.88        |
| 8                                       | 803,350 L   | 1.67         | 0.90           | 0.30                | 1.00           | 3.87        |
| 9                                       | 803,364 U   | 1.70         | 0.82           | 0.40                | 0.87           | 3.79        |
| 10                                      | 803,348 K   | 1.71         | 0.94           | 0.20                | 0.93           | 3.78        |
| 11                                      | 803,346 W   | 1.84         | 0.69           | 0.20                | 0.87           | 3.59        |
| 12                                      | 803,366 H   | 1.59         | 0.75           | 0.30                | 0.87           | 3.50        |
| 13                                      | 803359X     | 1.48         | 0.69           | 0.40                | 0.93           | 3.50        |
| 14                                      | 803360S     | 1.47         | 0.68           | 0.40                | 0.93           | 3.48        |
| 15                                      | 803,354 N   | 1.61         | 0.60           | 0.40                | 0.80           | 3.41        |
| 16                                      | 803,362 F   | 1.24         | 0.60           | 0.40                | 1.00           | 3.24        |
| 17                                      | 803,092 J   | 0.46         | 2.00           | 0.20                | 0.53           | 3.19        |
| 18                                      | 803365B     | 1.24         | 0.60           | 0.40                | 0.87           | 3.11        |
| 19                                      | 803,091 C   | 1.20         | 0.35           | 0.20                | 0.53           | 2.28        |
| 20                                      | 803,078 N   | 0.00         | 0.50           | 0.40                | 0.87           | 1.77        |
| 21                                      | 803,077 G   | 0.00         | 0.50           | 0.40                | 0.80           | 1.70        |
| 22                                      | 803,189 F   | 0.44         | 0.00           | 0.30                | 0.00           | 0.74        |

7. Reasonableness of proposed methodology

The ideal way to validate the methodology would be to compare the rank list generated by the procedure to the benchmark model. However, such a benchmark does not exist. Therefore, the next best option to ensure the reasonableness of this procedure is to see if the experts generally agree with the selection of the procedure. Based on their knowledge about the crossings, the experts are the decision makers in selecting new projects. We can
say that a procedure is reasonable if it is developed without input from the experts and can return a priority order of crossings that the experts would generally agree on. Therefore, checking the reasonableness of this procedure was based on providing the experts with the ranked list of crossings (as generated by the procedure) from two corridors and by asking them if they agreed with the results.

The two corridors selected are.
(1) Merchants Subdivision, Terminal Railroad Association (TRRA) of St. Louis includes 49 crossings out of 22 at grade crossings while the remaining are grade-separated crossings.

(2) The BNSF Great Northern Corridor, Seattle Subdivision in Kent, Washington, includes 12 crossings, out of which eight crossings are at grade while the remaining are grade separated crossings.

Generally, the methodology results were in line with the crossings that the practitioners selected as the ones with an immediate need for improvement. These practitioners were familiar with the crossings attributes and outcomes.

8. Conclusions

This paper presented a multi-criteria methodology for prioritizing highway-rail grade crossings for grade separation or major improvements. The traditional approach for making grade-crossing investment decisions has been guided primarily by the USDOT, Federal Highway Administration Railroad–Highway Grade Crossing Handbook, which focuses heavily on traffic and safety factors. While safety continues to be a high priority in the development of road-rail grade separation projects, state and local decision-makers need more robust criteria when competing against other projects for funding and construction. This methodology meets the needs of providing more robust criteria for the prioritization of projects for grade separation.

The main contributions of this research work are:

(1) Development of a new robust, multi-criteria prioritization technique.
The prioritization methodology proposed in this paper is a multi-criteria approach and includes four different factors: safety, economic, environmental, and community, and livability. The safety score used in this methodology includes the calculation of the accident prediction value at the crossing and relevant site-related adjustment specific to the crossing. The safety score also includes the severity of the accidents at the crossing by considering the different weights for fatal, injury, and property damage only accidents. The economic score considers the vehicle operating costs and delay costs for vehicles, accounting for losses to surrounding landowners, impact on land use, traffic mobility improvement, and supply chain savings. The environmental score encompasses any impact on the natural environment, built environment, and social environment. The community score encompasses the risk of derailment of a train at a crossing and the risk due to exposure to released hazmat from a train. The inclusion of multiple factors enables a decision-maker to provide a comprehensive means of comparing similar grade separation project alternatives. This study takes the research on highway-rail grade crossing prioritization one step further by including environmental and social costs that are not easily monetized.

(2) Establish the reasonableness of the methodology in its ability to rank crossings

The reasonableness of the procedure was established by prioritizing crossings on two different corridors and comparing the results with the ranking of appropriate experts in the field. The results were consistent with the expert opinion of the practitioners.

(3) Ensure that the methodology is easily usable

The procedure developed in this paper considers the data that is available easily to a practitioner. Also, along with the methodology, we developed a spreadsheet toolkit to facilitate the implementation of the methodology. This was done in an Excel Toolkit, and it is designed to make it easier to use the methodology, but the methodology can be used stand-alone.

The main limitation of this study is the lack of an ideal way to validate the procedure by comparing the results of this procedure to an ‘ideal’ benchmark, as such a benchmark doesn’t exist. However, we used the next best option available to established the reasonableness of this procedure. For future work, as and when data becomes readily available, the procedure should be updated. Some of the suggestions are a) improving calculation of delay and b) improving the emissions calculation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Cooperative Highway Research Program (NCHRP 25-50).
References

Abioye, O. F., Dulebenets, M. A., Pasha, J., Kavoosi, M., Moses, R., Sobanjo, J., & Ozguven, E. E. (2020). Accident and hazard prediction models for highway–rail grade crossings: A state-of-the-practice review for the USA. Railway Engineering Science, 28(3), 251–274. https://doi.org/10.1007/s40534-020-00215-w

Aoun, R. B., El Kouri, E., & Lemaire, E. 2010. “The cost benefit analysis of level crossing safety measures.” 12th International Conference on Computer System Design and Operation in Railways and Other Transit Systems. Beijing, China. https://doi.org/10.2495/CR100

Aruldoss, M. T., Lakshmi, M., & Prasanna Venkatesan, V. (2013). A survey on fuzzy mcdm methods and its applications. American Journal of Information Systems, 1(1), 31–43. https://doi.org/10.12691/ajis-1-1-5

Bai, Q., Labi, S., & Sinha, K. C. (2012). Trade-off analysis for multiobjective optimization in transportation asset management by generating pareto frontiers using extreme points nondominated sorting genetic algorithm II. Journal of Transportation Engineering, 138(6), 798–808. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000369

Beanland, V., Grant, E., Gemma, J. M., Read, N. S., Thomas, M., Lenné, M. G., Stanton, N. A., & Salmon, P. M. (2018). Challenging conventional rural rail level crossing design: Evaluating three new systems thinking-based designs in a driving simulator. Safety Science, 110(December 2017), 100–114. https://doi.org/10.1016/j.ssci.2018.03.002

Berndt, M., Benekohal, R. F., Mathew, J., Beckett, J., McKerrow, J., Worker-Braddock, T., Cathcart, A., & Weander, N. 2019. “Prioritization procedure for proposed road–rail grade separation projects along specific rail corridors.” Washington, DC, USA: Transportation Research Board. https://doi.org/10.17226/25460

Broad, D., & Gillen, D. 2020. “A new model for highway–rail grade crossing accident prediction and severity.” Washington, DC, USA: U.S. Department of Transportation.

Broniewicz, E., & Ogrodnik, K. (2020). Multi-criteria analysis of transport infrastructure projects. Transportation Research Part D: Transport and Environment, 83(April), 102351. https://doi.org/10.1016/j.trd.2020.102351

Brucker, K. D., Macharis, C., & Verbeke, A. (2011). Multi-criteria analysis in transport project evaluation: An institutional approach. European Transport - Trasporti Europei, 47(47), 3–24. https://econpapers.repec.org/article/sotjournal/y_3a2011_3ai_3a47_3ap_3a3-24.htm

Bureau of Transportation Statistics. 2017. “Freight facts and figures 2017.” https://www.bts.gov/sites/bts.dot.gov/files/docs/FFF_2017_Full_June2018revision.pdf

California Public Utilities Commission Rail Crossings engineering Section. 2013. “Grade separation program,” no. February.

Camargo Pérez, J., Carrillo, M. H., & Montoya-Torres, J. R. (2015). Multi-criteria approaches for urban passenger transport systems: A literature review. Annals of Operations Research, 226(1), 69–87. https://doi.org/10.1007/s10479-014-1681-8

Chadwick, S. G., Rapik Saat, M., Tyler Dick, C., & Barkan, C. P. L. (2013). “Decreasing derailment occurrence and severity at highway–rail grade crossings.” In Proceedings of the AREMA 2013 Annual Conference, 2013:2–26. Indianapolis, IN: AREMA.

Chandra, S., Rahmani, M., Thai, T., Mishra, V., & Camacho, J. (2021). “Evaluating financing mechanisms and economic benefits to fund grade separation projects.” San José State University, USA: MINETA TRANSPORTATION INSTITUTE PUBLICATIONS. http://onlinepubs.trb.org/onlinemedia2/nchrp/nchrp_rpt_901AppendixC.pdf

Conservation Biology Institute. 2019. “Final critical habitat for threatened and endangered species, USFWS.” 2019. https://www.arcgis.com/home/item.html?id=2fca597731bb4fe0b15c86b5c2ba879

Crawford, R. 2010. “Prioritising level crossings in Melbourne for grade separation.” Conference on Railway Engineering, 716–722. Wellington, New Zealand. https://doi.org/10.1017/CBO9781107415324.004

Dodgson, J. S. (1984). Benefit-cost analysis and the construction and financing of rail/highway grade separations. Transportation Research Part A: General, 18(5–6), 367–377. https://doi.org/10.1016/0191-2607(84)90012-8
ESRI. 2019. “USA parks.” 2019. https://www.arcgis.com/home/item.html?id=578968f9757774d3fab79f56c8c90941
Farr, E. H. 1987. “Summary of the dot rail-highway crossing resource allocation procedure-revised.” U.S. Department of Transportation.
Federal Highway Administration. 2010. “Webinar on STEP and livability.” https://www.fhwa.dot.gov/hep/step/resources/publications_and_webinars/may_26_2010_webinar/052610webinar.pdf
Federal Railroad Administration. 2020. “RRS hazmat one-time movement approval data.” 2020. https://railroads.dot.gov/divisions/hazardous-materials/rrs-hazmat-one-time-movement-approval-data
Federal Railroad Administration. n.d. “FRA web accident prediction system (WBAPS).” https://safetydata.fra.dot.gov/webaps/
FHWA. 2007. “Railroad-highway grade crossing handbook - revised second edition.” 2007. http://safety.fhwa.dot.gov/xings/com_roaduser/07010/sec05.htm
FHWA. 2019. “Federal railroad administration office of safety.” 2019. https://safetydata.fra.dot.gov/OfficeofSafety/publicsite/on_the_fly_download.aspx
Geurts, K., & Wets, G. 2003. “Black spot analysis methods : Literature review.” Steunpunt Verkeers veiligheid bij Stijgende Mobiliteit. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1090.8472&rep=rep1&type=pdf
Gitelman, V., & Hakkert, A. S. (1997). The evaluation of road-rail crossing safety with limited accident statistics. Accident Analysis and Prevention, 29(2), 171–179. https://doi.org/10.1016/S0001-4575(96)00069-3
Hakkert, A. S., & Gitelman, V. (1997). Development of evaluation tools for road-rail crossing consideration for grade separation. Transportation Research Record: Journal of the Transportation Research Board, 1605(1), 96–105. https://doi.org/10.3141/1605-12
Hakkert, A. S., & Gitelman, V. (1997). Development of evaluation tools for road-rail crossing consideration for grade separation. Transportation Research Record: Journal of the Transportation Research Board, 1605(1), 96–105. https://doi.org/10.3141/1605-12
Hamurcu, M., & Eren, T. (2018). An application of multicriteria decision-making for the evaluation of alternative monorail routes. Mathematics, 7(1), 1. https://doi.org/10.3390/math7010016
Illinois Commerce Commission. 2002. “Motorist delay at public highway – rail grade crossings in Northeastern Illinois.”
InfraConsult LLC (2012). Grade Separation Priority Update Study for Alameda Corridor East (Riverside County). Riverside County Transportation Commission. https://www.rctc.org/wp-content/uploads/2018/03/rctc-gradecrossingpriorityreport-final-withappendix-040612.original.pdf
InfraConsult LLC. 2012. “Grade separation priority update study for Alameda Corridor East (Riverside County),” no. March.
Jamal, T., Tania Urmee, G. M. S., & Shahnia, F. 2019. “Using experts’ opinions and multi-criteria decision analysis to determine the weighing of criteria employed in planning remote area microgrids.” Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE 2018-Octob (October). Thavorn Palm Beach Resort Karon, Phuket, Thailand. https://doi.org/10.23919/ICUE-GESD.2018.8635734
Jiang, Y., & Sinha, K. C. (1990). Approach to combine ranking and optimization techniques in highway project selection. Transportation Research Record: Journal of the Transportation Research Board, 1262, 155–161. Transportation Research Board. https://onlinepubs.trb.org/Onlinepubs/trr/1990/1262/1262-018.pdf
Kavoosi, M., Dulebenets, M. A., Junayed Pasha, O. F., Abioye, R. M., Sobanjo, J., Ozguven, E. E., & Ozguven, E. E. (2020). Development of algorithms for effective resource allocation among highway–rail grade crossings: A case study for the state of Florida. Energies, 13(6), 6. https://doi.org/10.3390/en13061419
Keeney, R. L., Raiffa, H., & Meyer, R. F. (1993). Decisions with Multiple Objectives: Preferences and Value Trade-Offs. Cambridge university press.
Keramati, A., Pan, L., Tolliver, D., & Wang, X. (2020). Geometric effect analysis of highway-rail grade crossing safety performance. Accident Analysis and Prevention, 138(February), 105470. https://doi.org/10.1016/j.aap.2020.105470
Keramati, A., Pan, L., Zhou, X., & Tolliver, D. (2020). A Simultaneous safety analysis of crash frequency and severity for highway-rail grade crossings: The competing risks method. Journal of Advanced Transportation, 2020, 1. https://doi.org/10.1155/2020/8878911

Kern Council of Governments. 2011. “Grade separation prioritization report.”

Lam, C. Y., & Tai, K. (2020). Network topological approach to modeling accident causations and characteristics: Analysis of railway incidents in Japan. Reliability Engineering and System Safety, 193(March 2019), 106626. https://doi.org/10.1016/j.ress.2019.106626

Macharis, C., & Bernardini, A. (2015). Reviewing the use of multi-criteria decision analysis for the evaluation of transport projects: Time for a multi-actor approach. Transport Policy, 37, 177–186. https://doi.org/10.1016/j.tranpol.2014.11.002

Mathew, J., & Benekohal, R. F. (2021). Highway-rail grade crossings accident prediction using zero inflated negative binomial and empirical Bayes method. Journal of Safety Research. (in queue for publication in 2021). https://www.sciencedirect.com/science/article/pii/S0022437521001171

Mengert, P. 1979. “Rail-highway crossing hazard prediction research results.” Cambridge MA, USA: U.S. Department of Transportation.

Minnesota Department of Transportation. 2014. “Improvements to highway-rail grade crossings and rail safety,” no. December.

National Safety Council. 2013. “Estimating the costs of unintentional injuries, 2011,” no. C: 23–25. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Estimating+the+Costs+of+Unintentional+Injuries#5&intitle:Estimating+the+Costs+of+Unintentional+Injuries#5%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Estimating+the+Costs+of+Unintentional+Injuries#5&intitle:Estimating+the+Costs+of+Unintentional+Injuries#5

“NCHRP 25-50 RCAT users guide.” 2018. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_901AppendixC.pdf.

Nosal, K., & Solecka, K. (2014). Application of AHP method for multi-criteria evaluation of variants of the integration of urban public transport. Transportation Research Procedia, 3 (December), 269–278. https://doi.org/10.1016/j.trpro.2014.10.006

Operation Lifesaver. 2020. “Collisions & casualties by year.” 2020. https://oli.org/track-statistics/collisions-casualties-year

Pasha, J., Dulebenets, M. A., Abiye, O. F., Kavoosi, M., Moses, R., Sobanjo, J., & Ozguven, E. E. (2020). A comprehensive assessment of the existing accident and hazard prediction models for the highway–rail grade crossings in the state of Florida. Sustainability (Switzerland), 12(10). https://doi.org/10.3390/su12104291

Peel Regional Council. 2014. “Improvements to at grade rail crossings: Prioritizing crossings for grade separation,” no. November. https://doi.org/10.1002/ejoc.201200111

Protopapas, A., Roop, S. S., Morgan, C. A., Warner, J. E., & Olson, L. E. (2010). Quantifying the impacts of highway–rail grade crossings on surface mobility: Regional impact model. Transportation Research Record: Journal of the Transportation Research Board, 2149(1), 103–107. https://doi.org/10.3141/2149-12

Pu, H., Liang, Z., Schonfeld, P., Wei, L., Wang, J., Zhang, H., Song, T., Wang, J., Jianping, H., & Peng, X. (2021). Optimization of grade-separated road and railway crossings based on a distance transform algorithm. Engineering Optimization, 1–20. https://doi.org/10.1080/0305215X.2020.1861264

Qureshi, M., Virklker, M. R., Sanford Bernhardt, K. L., Spring, G., Avalokita, S., Yatapu, N., Chilukuri, V., King, T., & Gibbons, K. 2003. “Highway/rail crossing project selection.” Washington, DC, USA: Missouri Department of Transportation.

Rex Nichelson, G., Jr., George, J. D., & Reed, L. 1999. “Grade separations when do we separate?” http://d2dl5nlnpfr0.cloudfront.net/tti.tamu.edu/documents/TTI-1999-12.pdf

Roper, B. A., & Keltner, D. M. 1999. “User benefits of railroad grade separation in a small community: Practical techniques for applying MICROBENCOST.” Sixth National Conference on Transportation Planning for Small and Medium Sized Communities 1. Olympia, WA, USA: Texas A&M Transportation Institute. https://doi.org/10.1017/CBO9781107415324.004

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. European Journal of Operational Research, 48(1), 9–26. https://doi.org/10.1016/0377-2217(90)90057-I

Schrader, M. H., & Hoffpauer, J. R. 2001. “A methodology for evaluating highway-railway grade separations.” Transportation Research Board. https://doi.org/10.3141/1754-09
Sinha, K. C., & Labi, S. (2011). Transportation Decision Making: Principles of Project Evaluation and Programming. John Wiley & Sons.

Site, P. D., & Filippi, F. (2009). Weighting methods in multi-attribute assessment of transport projects. European Transport Research Review, 1(4), 199–206. https://doi.org/10.1007/s12544-009-0018-1

Speicher, D., Schwartz, M., & Mar, T. (2000). Prioritizing major transportation improvement projects: Comparison of evaluation criteria. Transportation Research Record: Journal of the Transportation Research Board, 1706(1), 38–45. https://doi.org/10.3141/1706-05

Tabucanon, M. T., & Lee, H. - M. (1995). Multiple criteria evaluation of transportation system improvement projects: The case of Korea. Journal of Advanced Transportation, 29(1), 127–143. https://doi.org/10.1002/atr.5670290110

Taggart, R. C., Laura, P., Groat, G., REES, C., & Brick-Turin, A. 1987. “Evaluating grade-separated rail and highway crossing alternatives, NCHRP report.” 288. Transportation Research Board

Taylor, J., & Crawford, R. 2009. “Prioritising road-rail level crossings for grade separation using a multi-criteria approach” 32: 15p (session Wed 3A). New Zealand: Australasian Transport Research Forum (ATRF). http://atrf.info/papers/2009/2009_Taylor_Crawford.pdf

TRB. 2019. “Prioritization procedure for proposed road–rail grade separation projects along specific rail corridors.” 2019. http://www.trb.org/NCHRP/Blurbs/179092.aspx

Tsamboulas, D., Yiotis, G. S., & Panou, K. D. (1999). Use of multicriteria methods for assessment of transport projects. Journal of Transportation Engineering, 125(5), 407–414. https://doi.org/10.1061/(ASCE)0733-947X(1999)125:5(407)

United States Census Bureau. 2010. “Population.” 2010. https://www.census.gov/topics/population/data.html

United States Environmental Protection Agency. 2010. “Air quality non-attainment areas.” 2010.

United States Environmental Protection Agency. 2017. “What is the national environmental policy act?” 2017. https://www.epa.gov/nepa/what-national-environmental-policy-act

United States Geological Survey. 2020. “Coastal and marine geology program (CMGP) interactive maps.” 2020.

USDOT. 2015. “TIGER benefit-cost analysis resource guide,” 5. https://www.transportation.gov/policy-initiatives/tiger/tiger-benefit-cost-analysis-bca-resource-guide

USDOT. 2020. “Benefit-cost analysis guidance for discretionary grant programs.” https://www.transportation.gov/sites/dot.gov/files/docs/mission/office-policy/transportation-policy/284031/benefit-cost-analysis-guidance-2018_0.pdf

Vana, B. (2008). Criteria for Grade Separation for RR Crossing (Right of Way). Arizona Department of Transportation Utility and Railroad Engineering Section. http://sp.rightofway.transportation.org/Documents/AZUTGradeSeparationRRCrossingCriteria.doc

Weissmann, A., J., Weissmann, J., Kunisette, J. L., Warner, J., Park, E. S., Sunkari, S., Protopapas, A., & Venglar, S. 2013. “Integrated prioritization method for active and passive highway-rail crossings.” USA: Texas A&M Transportation Institute. http://d2d15mnlpfr0r.cloudfront.net/tti.tamu.edu/documents/0-6642-1.pdf

Witkowski, J. M. (1988). Benefit analysis for urban grade separated interchanges. Journal of Transportation Engineering, 114(1), 93–109. https://doi.org/10.1061/(ASCE)0733-947X(1988)114:1(93)

Zhou, X., Pan, L., Zheng, Z., Tolliver, D., & Keramati, A. (2020). Accident prediction accuracy assessment for highway-rail grade crossings using random forest algorithm compared with decision tree. Reliability Engineering and System Safety, 200(January), 106931. https://doi.org/10.1016/j.ress.2020.106931
### APPENDIX: List of Variables identified from Literature Review

Table A – 1: Safety factors identified in the literature

| Literature                                                                 | Accident Prediction Value | FRA Safety Record (Accident History) | Near Misses |
|----------------------------------------------------------------------------|---------------------------|-------------------------------------|-------------|
| 1 Railroad-Highway Grade Crossing Handbook (FHWA, 2007)                   | X                         |                                     |             |
| 2 Grade Separation Prioritization Report (Kern Council of Governments, 2011) |                           |                                     | X           |
| 3 Development of Evaluation Tools for Road Rail Grade Separation (Hakker & Gitelman, 1997) | (Not used in the equation) | (Not used in the equation)          |             |
| 4 Grade Separation Priority Update Study for Alameda Corridor East (Riverside County Transportation Commission, 2012) |                           |                                     | X           |
| 5 Prioritizing Level Crossings in Melbourne for Grade Separation (Crawford, 2010) |                           | X                                   | X           |
| 6 Improvement to Highway-Rail Grade Crossing and Rail Safety (Minnesota Department of Transportation, 2014) | X                         | X                                   | X           |
| 7 Grade Separation Program (California Public Utilities Commission Rail Crossings engineering Section, 2013) |                           |                                     | X           |
| 8 Grade Separations: When do we Separate? (Rex Nichelson et al., 1999)     | X                         |                                     |             |
| 9 A Methodology for Evaluating Highway-Rail Grade Separations (Schrader & Hoffpauer, 2001) | X                         | X                                   |             |
| 10 Integrated Prioritization Method for Active and Passive Highway-Rail Crossings (Weissmann et al., 2013) |                           | X                                   |             |
| 11 Highway-Rail Crossing Project Selection (Qureshi et al., 2003)           | X                         |                                     | (The output of the model) |
| 12 Criteria for Grade Separation for R.R. Crossing (Right of Way) – Arizona (AASHTO, 2008) |                           | X                                   |             |
| 13 Criteria for Grade Separation for R.R. Crossing (Right of Way) – Minnesota (AASHTO, 2008) |                           | X                                   |             |
| 14 Criteria for Grade Separation for R.R. Crossing (Right of Way) – Arkansas (AASHTO, 2008) |                           |                                     | X           |
| 15 Criteria for Grade Separation for R.R. Crossing (Right of Way) – New Hampshire (AASHTO, 2008) |                           |                                     | X           |
| 16 User Benefits of Railroad Grade Separation in a Small Community (Roper & Kelner, 1999) |                           | X                                   |             |
| 17 Benefit-Cost Analysis and the Construction and Financing of Rail/ Highway Grade Separations (Dodgson, 1984) |                           | X                                   |             |
| 18 Quantifying the Public Impact of Highway-Rail Grade Crossing on Surface Mobility (Protopapas et al., 2010) |                           | X                                   |             |
Table A-2: Traffic and delay related factors identified in the literature

| Literature                                                                 | Current road delay | Future road delay | Rail delay | Posted highway speed | Speed reduction | AADT | AATT | Train distribution | Passenger train count | Train speed | Train length | Exposure | Traffic growth | Duration of crossing closure | LOS | Queue length | Binary Var: Through Train? |
|---------------------------------------------------------------------------|--------------------|-------------------|------------|----------------------|----------------|------|------|-------------------|------------------------|-------------|--------------|----------|----------------|--------------------------|------|-------------|------------------------|
| 1  Railroad-Highway Grade Crossing Handbook (FHWA, 2007)                  | X                  |                  |            |                      |                | X    | X    | X                 | X                      | X  | X  | X  | X  | X                       | X  |             |                        |
| 2  Grade Separation Prioritization Report (Kern Council of Governments, 2011) | X                  |                  |            |                      |                | X    | X    | X                 | X                      | X  | X  | X  | X  | X                       | X  |             |                        |
| 3  Development of Evaluation Tools for Road Rail Grade Separation (Hakkert and Gitelman, 1997) | X                  |                  |            |                      |                | X    | X    | X                 | X                      | X  | X  | X  | X  | X                       | X  |             |                        |
| 4  Grade Separation Priority Update Study for Alameda Corridor East (Riverside County Transportation Commission, 2012) | X                  |                  |            |                      |                | X    | X    | X                 | X                      | X  | X  | X  | X  | X                       | X  |             |                        |
| 5  Improvements to at Road Rail Crossings: Prioritizing Crossings for Grade Separation (Peel Regional Council, 2014) | X                  |                  |            |                      |                | X    | X    | X                 | X                      | X  | X  | X  | X  | X                       | X  |             |                        |

(Continued)
| Literature                                                                 | Current road delay | Future road delay | Rail delay | Posted highway speed | Speed reduction | AADT | AATT | Train distribution | Passenger train count | Train speed | Train length | Exposure | Traffic growth | Duration of crossing closure | LOS | Queue length | Through Train? |
|---------------------------------------------------------------------------|--------------------|-------------------|------------|---------------------|----------------|-------|------|-------------------|----------------------|-------------|---------------|----------|----------------|--------------------------|------|--------------|----------------|
| 6 Prioritizing Level Crossings in Melbourne for Grade Separation         | X                  |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| (Crawford, 2010)                                                         |                    |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| 7 Improvement to Highway-Rail Grade Crossing and Rail Safety             | X                  |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| (Minnesota Department of Transportation, 2014)                           |                    |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| 8 Grade Separation Program                                               | X                  |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| (California Public Utilities Commission Rail Crossings engineering Section, 2013) |                    |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| 9 Highway-Rail Crossing Project Selection                                | X                  |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| (Qureshi et al., 2003)                                                   |                    |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| 10 Criteria for Grade Separation for R. R. Crossing (Night of Way) –     | X                  | X                 |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| Arkansas (AASHTO, 2008)                                                  |                    |                   |            |                     |                |       |      |                   |                      |             |               |          |                |                          |      |              |                |
| Literature                                                                 | Current road delay | Future road delay | Rail delay | Posted highway speed | Speed reduction | AADT | AATT | Train distribution | Passenger train count | Train speed | Train length | Exposure | Traffic growth | Duration of crossing closure | LOS | Queue length | Binary Var. | Through Train? |
|--------------------------------------------------------------------------|--------------------|-------------------|------------|----------------------|-----------------|------|------|-------------------|---------------------|------------|-------------|----------|----------------|--------------------------|------|--------------|------------|----------------|
| 11 Criteria for Grade Separation for R. R. Crossing (Right of Way) – Michigan (AASHTO, 2008) | X                  | X                 |            |                      |                 |      |      |                   |                     |            |             |          |                |                          |      |              |            |                |
| 12 Grade Separations, When do we separate (Rex Nicholson et al., 1999) | X                  |                   |            |                      |                 |      | X    |                   |                     |            |             |          |                |                          |      |              |            |                |
| 13 User Benefits of Railroad Grade Separation in a Small Community (Roper & Keltner, 1999) | X                  | X                 | X          |                      | X                | X    |      |                   |                     |            |             |          |                |                          |      |              |            |                |
| 14 Motorist Delay at Public Highway-Rail Grade Crossings in Northeastern Illinois (Illinois Commerce Commission (2002)) | X                  |                   |            |                      |                 |      |      |                   |                     |            |             |          |                |                          |      |              |            |                |
| 15 Benefit-Cost Analysis and the Construction and Financing of Rail/Highway Grade Separations (Dodgson, 1984) | X                  |                   |            |                      |                 |      |      |                   |                     |            |             |          |                |                          |      |              |            |                |
| Literature                                                                 | Current road delay | Future road delay | Rail  delay |Posted highway speed | Speed reduction | AADT | AATT |Train distribution | Passenger train count | Train speed | Train length | Exposure | Traffic growth | Duration of crossing closure | LOS | Queue length | Binary Var: Through Train? |
|---------------------------------------------------------------------------|--------------------|------------------|-------------|---------------------|-----------------|------|------|-------------------|-----------------------|-------------|--------------|----------|----------------|---------------------------|------|-------------|--------------------------|
| 16  Quantifying the Public Impact of Highway-Rail Grade Crossing on Surface Mobility (Protopapas et al., 2010) | X                  |                  |             |                     |                 |      |      |                   |                       |             |              |          |               |                           |      |             |                          |
| 17  A Methodology for Evaluating Highway-Rail Grade Separations (Schrader and Hoffpauer, 2001) | X                  | X                | X           |                     |                 |      | X    |                   |                       |             |              |          |               |                           |      |             |                          |

# Not used in the equation
+ heavy vehicles also
# peak trains per day
Table A – 3: Geometry and location-related factors

| Literature | Land Use | Spread of crossings in region | The geometry of Crossing/sight distance/clearance time for road vehicles | Number of Highway Lanes/Highway Paved? | Number of Rail Tracks | Adjacent Grade Separation | Warning Device | Constructability |
|------------|----------|-------------------------------|------------------------------------------------------------------------|-------------------------------------|-----------------------|---------------------------|----------------|-----------------|
| 1 Grade Separation Prioritization Report (Kern Council of Governments, 2011) | | X | | | | | | X |
| 2 Grade Separation Priority Update Study for Alameda Corridor East (Riverside County Transportation Commission, 2012) | | | | | | | | X |
| 3 Grade Separation Program (California Public Utilities Commission Rail Crossings engineering Section, 2013) | | | | | | | X* | |
| 4 Improvements to at Grade Rail Crossings: Prioritizing Crossings for Grade Separation (Peel Regional Council, 2014) | | | X | X | X | X | | X |
| 5 Integrated Prioritization Method for Active and Passive Highway-Rail Crossings (Weissmann et al., 2013) | | | X | | | | | X |
| 6 Highway-Rail Crossing Project Selection (Qureshi et al., 2003) | | | | | | | | X |

(Continued)
The geometry of Crossing/sight distance/clearance time for road vehicles

| Literature | Land Use | Spread of crossings in region | Number of Highway Lanes/Paved? | Number of Rail Tracks | Adjacent Grade Separation | Warning Device | Constructability |
|------------|---------|-------------------------------|-------------------------------|------------------------|---------------------------|----------------|-----------------|
| 7 | Criteria for Grade Separation for R.R. Crossing (Right of Way) – Michigan (AASHTO, 2008) | X | | | | | |
| 8 | User Benefits of Railroad Grade Separation in a Small Community (Roper & Keltner, 1999) | | | | | | |
| 9 | Motorist Delay at Public Highway-Rail Grade Crossings in Northeastern Illinois (Illinois Commerce Commission, 2002) | | | | | | |
| 10 | A Methodology for Evaluating Highway-Rail Grade Separations (Schrader & Hoffpauer, 2001) | | | | | | |
| 11 | Grade Separations: When do we Separate? (Rex Nicholson et al., 1999) | | | | | | |

*Under special conditions factors
Table A – 4: Environmental factors

| Literature                                                                 | Noise | Air Quality/Emissions and Fuel Savings | Sites of Environmental Significance |
|---------------------------------------------------------------------------|-------|----------------------------------------|------------------------------------|
| Grade Separation Prioritization Report (Kern Council of Governments, 2011)|       | X                                      |                                    |
| Grade Separation Priority Update Study for Alameda Corridor East (Riverside County Transportation Commission, 2012) | X     | X                                      |                                    |
| Prioritizing Level Crossings in Melbourne for Grade Separation (Crawford, 2010) | X     | X                                      | X                                  |
| A Methodology for Evaluating Highway-Rail Grade Separations (Schrader & Hoffpauer, 2001) |       | X                                      |                                    |
| Criteria for Grade Separation for R.R. Crossing (Right of Way) – New Hampshire (AASHTO, 2008) |       | X                                      |                                    |
| Benefit-Cost Analysis and the Construction and Financing of Rail/Highway Grade Separations (Dodgson, 1984) |       | X                                      |                                    |
| Literature                                                                 | Population | Vulnerable Population | Transit/Emergency / School bus Vehicle Routes | Social Significance (local development) | Community Cohesion / Accessibility / Connectivity | Quiet Zone | Strategic Fit | Isolated Location | Visual Amenity |
|---------------------------------------------------------------------------|------------|-----------------------|----------------------------------------------|------------------------------------------|------------------------------------------------|------------|---------------|-------------------|----------------|
| 1 Grade Separation Prioritization Report (Kern Council of Governments, 2011) | X          |                       | X                                            | X                                        | X                                              |            |               |                   |                |
| 2 Improvements to at Grade Rail Crossings: Prioritizing Crossings for Grade Separation (Peel Regional Council, 2014) | X          | X                     | X                                            | X                                        | X                                              |            |               |                   |                |
| 3 Grade Separation Priority Update Study for Alameda Corridor East (Riverside County Transportation Commission, 2012) | X          | X                     | X                                            | X                                        | X                                              |            |               |                   |                |
| 4 Prioritizing Level Crossings in Melbourne for Grade Separation (Crawford, 2010) | X          | X                     | X                                            | X                                        | X                                              | X          | X             | X                 |                |
| 5 Improvement to Highway-Rail Grade Crossing and Rail Safety (Minnesota Department of Transportation, 2014) | X          | X                     | X                                            | X                                        | X*                                             |            |               |                   |                |
| 6 A Methodology for Evaluating Highway-Rail Grade Separations (Schrader & Hoffpauer, 2001) | X          |                       | X                                            | X                                        | X                                              |            |               |                   |                |
| 7 Criteria for Grade Separation for R.R. Crossing (Right of Way) – Michigan (AASHTO, 2008) | X          |                       |                                               |                                          |                                                |            |               |                   |                |
| 8 Grade Separations, When do we separate (Rex Nicholson et al., 1999)     | X          |                       |                                               |                                          |                                                |            |               |                   |                |

*XNearby traffic generator*
Table A – 6: Economic Considerations

| Literature                                                                 | Vehicle Operating Cost/Delay and Accident Cost | Crossing Operating Cost/Life cycle cost | Construction Cost | Economic Losses |
|---------------------------------------------------------------------------|-----------------------------------------------|----------------------------------------|-------------------|-----------------|
| 1 Development of Evaluation Tools for Road Rail Grade Separation (Hakkert and Gitelman, 1997) | X                                             | X                                      |                   | X               |
| 2 Grade Separation Prioritization Report (Kern Council of Governments, 2011) | X                                             |                                        |                   |                 |
| 3 Prioritizing Level Crossings in Melbourne for Grade Separation (Crawford, 2010) |                                        |                                        |                   |                 |
| 4 Grade Separations, When do we separate (Rex Nicholson et al., 1999)       | X                                             | X                                      |                   |                 |
| 5 User Benefits of Railroad Grade Separation in a Small Community (Roper & Keltner, 1999) | X                                             |                                        |                   |                 |
| 6 Motorist Delay at Public Highway-Rail Grade Crossings in Northeastern Illinois (Illinois Commerce Commission, 2002) | X                                             |                                        |                   |                 |
| 7 Benefit-Cost Analysis and the Construction and Financing of Rail/Highway Grade Separations (Dodgson, 1984) | X                                             |                                        |                   |                 |