Accident Analysis and Prevention 51 (2013) 192–201

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

A mathematical modeling approach to resource allocation for railroad-highway crossing safety upgrades

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ARTICLE INFO

Article history:
Received 10 May 2012
Received in revised form 28 October 2012
Accepted 10 November 2012

Keywords:
Railroad-highway crossings
Safety upgrades
Resource allocation

ABSTRACT

State Departments of Transportation (S-DOT's) periodically allocate budget for safety upgrades at railroad-highway crossings. Efficient resource allocation is crucial for reducing accidents at railroad-highway crossings and increasing railroad as well as highway transportation safety. While a specific method is not restricted to S-DOT's, sorting type of procedures are recommended by the Federal Railroad Administration (FRA), United States Department of Transportation for the resource allocation problem. In this study, a generic mathematical model is proposed for the resource allocation problem for railroad-highway crossing safety upgrades. The proposed approach is compared to sorting based methods for safety upgrades of public at-grade railroad-highway crossings in Tennessee. The comparison shows that the proposed mathematical modeling approach is more efficient than sorting methods in reducing accidents and severity.

1. Introduction and literature review

An at-grade railroad-highway crossing (AGRHX) is the intersection where a highway crosses a railroad at the same level or grade. There are more than a quarter million such crossings in the US and safety of these crossings is crucial for secure railroad as well as highway transportation. US DOT Federal Highway Administration (FHWA) notes that accidents at AGRHXs resulted 311 deaths and 859 injuries in 2002 (FHWA, 2002). It is reported that there were over 300 fatal accidents at AGRHXs in 2004 in the US (Ogden, 2007). State Departments of Transportation (S-DOT's) periodically allocate federal funds for safety improvements at AGRHXs. Resource allocation methods are developed as an assisting tool for S-DOT's in selecting the AGRHXs to be improved using the limited budget.

Despite the importance of the resource allocation problem for AGRHX safety upgrades, there has not been a significant amount of study in the academic literature. Most of the studies on AGRHX safety focus on accident prediction, countermeasures and their effectiveness, and human factors involvement.

The main goal of accident prediction models is to provide a statistical tool to associate a risk measure for AGRHX or to estimate the frequency of possible accidents at AGRHXs. The most commonly used accident prediction models are Peabody Dimmick Formula, New Hampshire Index, NCHRP Hazard Index, and US DOT Accident Prediction formula. Austin and Carson (2002) discuss the shortcomings of the aforementioned methods and point out the need for a consistent accident prediction method. Academic literature on accident prediction and risk measurement at AGRHXs focuses on selecting the appropriate statistical method for the data of interest. Defining hazard index (Gitelman and Hakkert, 1997; Kallberg, 2002; Samaranayake et al., 2011), linear regression methods (Schultz, 1965; Berg and Oppenlander, 1969; Belle et al., 1975), Poisson regression methods (Lee et al., 2005; Hu et al., 2011), binomial regression methods (Austin and Carson, 2002; Saccomanno et al., 2004), gama model (Oh et al., 2006), and logit model (McCollister and Pflaum, 2007; Hu et al., 2010) are among the statistical methods used for accident prediction at AGRHXs.

As noted by Park and Saccomanno (2005), accident prediction methods must be studied before examining effectiveness of a specific preemptive practice, which is referred to as a countermeasure. Definitions of a set of countermeasure that are intended to increase safety at AGRHXs can be found in Washington and Oh (2006) and Ogden (2007). Effectiveness of a specific countermeasure is defined as the percent reduction in accidents after installation of the countermeasure (Farr, 1987). Methods to measure countermeasure effectiveness include statistical tools (Park and Saccomanno,

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http://dx.doi.org/10.1016/j.aap.2012.11.011

2005; Saccomanno and Lia, 2005; Raub, 2006; Washington and Oh, 2006; Saccomanno et al., 2007; Yan et al., 2010), before and after studies (Dommasch et al., 1976; Bowman, 1987; Heathington et al., 1989; Ward and Wilde, 1995; Noyce and Fambro, 1998; Ko et al., 2007; Millegan et al., 2009, 2009, 2010), simulation (Coleman and Moon, 1996, 1997; Rudin-Brown et al., 2012), data comparison and on-site observations (Wortman et al., 1972; Wortman and Lipinski, 1974; Lipinski and Wortman, 1976; Russell et al., 1979; Morrissey, 1980; Farr and Hitz, 1984; Eck and Halkias, 1985; Mather, 1991; Burnham, 1995; Russell and Rys, 1996; Raub, 2006; Hellman et al., 2007). The Railroad-Highway Grade Crossing Handbook 2007 of US DOT FHWA (Ogden, 2007) provides a detailed discussion on definition of countermeasures, minimum installation requirements and guidance to selection of countermeasure alternatives for AGRHXs.

Human involvement in the traffic at AGRHXs requires understanding of the effects of human behaviors and developing associated countermeasures or taking human behaviors into account in estimating the effectiveness of countermeasures. Lerner et al. (1990) and Yeh and Multer (2006) provide intense reviews of the studies on driver behaviors prior to 1990 and for years 1990 through 2006, respectively. The studies focusing on driver behaviors at AGRHXs use post-accident data, simulation, surveys, or field studies (see, e.g., Rahimi and Meshkati, 2001; Meshkati et al., 2003; Russell et al., 2007; Davey et al., 2008a,b; Rys et al., 2009; Tey et al., 2011a,b; Lenne et al., 2011; Luoma and Poutanen, 2011). Reinach and Viale (2006), Dorrian et al. (2007), Chang and Ju (2008), Davey et al. (2008a), Baysari et al. (2008), and Baysari et al. (2009) study effects of train operator behaviors on railroad as well as AGRHX safety. Lobb et al. (2001), Siques (2002), Lobb et al. (2003), Lobb (2006), Silla and Louma (2009), and Silla and Louma (2011) analyze pedestrians' contribution to AGRHX safety.

Accident prediction and countermeasure effectiveness calculations are preliminary steps required for safety upgrades at AGRHXs. The objective of resource allocation methods is to select safety upgrade choices, among a set of alternatives, so that the maximum safety improvement/risk reduction is achieved with a given budget. As noted in the Railroad-Highway Grade Crossing Handbook 2007 of US DOT FHA (Ogden, 2007), economic analysis procedures can be used in selection of alternative projects for safety improvement. Cost-effectiveness analysis (ranking alternatives based on cost per unit accident reduction), benefit–cost ratio analysis (ranking alternatives with respect to the ratio of benefit achieved to cost of the alternative), and net annual benefit (ranking alternatives based on their net annual benefits achieved) are the economic analysis procedures discussed in Ogden (2007). However, it is noted that different methods can produce different suggestions (Ogden, 2007). Throughout this paper, these methods are referred to as the *sorting methods* since they sort safety upgrade alternatives with respect to some predefined ratios. Section 2 explains the details of the sorting methods.

The resource allocation method developed by US DOT, to achieve selection of improvements with greatest benefits out of a given budget, is a sorting method as well. Details of the US DOT resource allocation procedure are as follows (Farr, 1987). Three categories of AGRHXs are considered: AGRHXs with passive warning devices (no signs, stop signs, crossbucks, and other signs), AGRHXs with flashing lights (flashing lights, highway signals, wig-wags or bells, flagman), and AGRHXs with gates. The procedure only considers upgrades for AGRHXs with passive warning devices or flashing lights as AGRHXs with gates are regarded as safe; hence, there is no need to upgrade AGRHXs with gates. The following upgrades are the predefined alternatives:

- Single track passive crossings can be upgraded using flashing lights or gates
- Multiple track passive crossings can be upgraded using gates
- Flashing light crossings can be upgrades using gates

The inputs to the procedure are the accident predictions, countermeasure effectiveness, and budget limit. The costs of the alternative countermeasures are also required. Using these data, the resource allocation procedure returns a set of recommended installation of countermeasures. It is noted that the resource allocation procedure is an assisting tool for state and railroad planners for safety improvement decisions. The Railroad-Highway Grade Crossing Handbook 2007 of US DOT FHA (Ogden, 2007) states how field evaluations should be conducted when it is decided to revisit the recommendations of the US DOT resource allocation procedure.

In the literature, a limited number studies are conducted on resource allocation methods for AGRHX safety upgrades. Volmer et al. (2006) apply benefit–cost ratio for project selection to improve the safety of AGRHXs in Iowa. Cooper et al. (2007) discuss a cost–benefit analysis for selecting countermeasures to improve safety of AGRHXs in California. They consider 2Q gates and long-arm gates, median separators, 4Q gates, and photo enforcement as alternative countermeasures.

It is observed from the review of the literature that an efficient and easy-to-modify generic resource allocation method is not available. To the best knowledge of the authors, mathematical modeling has not been used in the analysis of resource allocation problem for AGRHXs safety upgrades. This paper contributes to the state-of-art and practice by developing a generic mathematical model for the resource allocation problem for AGRHX safety upgrades faced by S-DOT's periodically. As will be discussed later in the current paper, through application of the proposed model for safety upgrades of public AGRHXs in Tennessee, the proposed model can be a more efficient resource allocation tool compared to the sorting based resource allocation methods approved by US DOT and FRA.

The rest of the paper is organized as follows. Section 2 summarizes and gives the algorithmic descriptions for the sorting methods used for resource allocation. Then, the proposed modeling approach is explained, where the details of the mathematical model are explained. In Section 3, the proposed model is applied to public AGRHXs in Tennessee and the efficiency of the mathematical modeling approach is compared to sorting methods. The paper is finalized with concluding remarks and possible future research directions in Section 4.

2. Sorting methods and the mathematical model for resource allocation

In this section, first, the sorting methods are explained. Then, the details of the mathematical formulation for the resource allocation problem are documented. Before proceeding with the details, a definition of the resource allocation problem for safety upgrades at AGHRXs is given.

Suppose that n AGRHXs are considered for safety upgrades and let $I = \{1, 2, \ldots, n\}$ be the set of AGRHXs and let AGRHXs be indexed by i. There is a limited budget for safety upgrades and let B denote the available budget. A set of m countermeasures can be implemented at AGRHXs and let $J = \{1, 2, \ldots, m\}$ be the set of countermeasures and let countermeasures be indexed by j. Each countermeasure j has a specific implementation cost, c_j. Furthermore, let p_{ij} be the safety benefit achieved through implementing countermeasure j at AGRHX i. A further discussion on the definition of p_{ij} will be given when the sorting methods are compared to the mathematical modeling approach. The ultimate goal of the resource allocation problem is to find the countermeasures to be implemented at each AGRHX using the available budget so that the total safety benefits at AGRHXs are maximized.