DEVELOPMENT OF LIGHT RAIL CROSSING SPECIFIC

CRASH PREDICTION MODELS

by

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Development of Light Rail Crossing Specific Crash Prediction Models

Thesis directed by Professor Bruce N. Janson.

ABSTRACT

Existing railroad crossing crash prediction and hazard index equations are analyzed and found to inadequately measure safety at light rail crossings. The operational characteristics of common carrier freight and commuter railroads are different enough from the operational characteristics of light rail to affect the ability of existing railroad equations to accurately predict the number of crashes that occur at light rail crossings. These operational differences require light rail specific crash prediction equations to better predict crash numbers at light rail crossings. The goal of this research is to develop a method to measure safety at light rail crossings.

Through review of the literature describing different statistical methodologies that have been used to develop railroad crossing crash prediction and hazard index equations, the use of a nonlinear regression method to predict initial crash values with an Empirical Bayes Method adjustment to account for the actual crash history at the light crossing is determined to be the optimum model development method.

Operational alignment and configuration of light rail crossings are analyzed, and each is found to have some effect on the prediction of the number of crashes that occur at light rail crossings in addition to light rail vehicle volume, motor vehicle volume, sight obstructions, presence of a residential area near the light rail crossing, and the number of motor vehicle lanes crossing the crossing. Statistically valid models are developed to predict crashes based on light rail crossing alignment type, configuration type, and method of crossing control including traffic signals, flashing lights with gates, and passive signing. Sufficient data to develop a prediction equation for flashing light control is not available for this study.

The use of Geographic Information Systems (GIS) models is determined to be a benefit in use of application of the light rail specific crash number prediction equations. GIS models can be used not only to predict the number of crashes expected to occur at a light rail crossing, but also can be used to identify and analyze light rail crossing crash trends.

The form and content of this abstract are approved. I recommend its publication.

Approved: Bruce N. Janson

DEDICATION

I dedicate this work to transit agencies that work diligently to provide a means of transportation to all who need it, the transit agency safety departments that work tirelessly to make transit the safest mode of transportation in the United States of America, and my fellow State Safety Oversight Program Managers that balance the safety needs of their transit agencies with the regulatory requirements we are charged to administer. May this research provide an additional tool for creating safe rail transit systems.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
ANOVA	Analysis of Variance
APTA	American Public Transportation Association
EB	Empirical Bayes
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
F_{crit}	F distribution critical value
F_{stat}	F distribution statistic
GIS	Geographic Information Systems
LED	Light Emitting Diode
LRV	Light Rail Vehicle
Light rail crossing	Highway-light rail at-grade crossing
MPH	Miles per Hour
NTD	National Transit Database
OCS	Overhead Cantenary System
Railroad crossing	Highway-rail at-grade crossing
RTD	Regional Transportation District
SSE	Sum of Squares Error
SSR	Sum of Squares Regression
SST	Sum of Squares Total
Std Dev	Standard Deviation
t_{crit}	Students t distribution critical value
t_{stat}	Students t distribution statistic
TCRP	Transit Cooperative Research Program
US DOT	United States Department of Transportation

CHAPTER I

INTRODUCTION

Common carrier railroads began to operate in the United States in the 1820's. Shortly thereafter, highway-rail at-grade crossing (railroad crossing) collisions started occurring. As time moved forward, trains became heavier and faster, people moved from transportation by horse and buggy to automobile, and the crashes at railroad crossings became more severe.

Crashes at railroad crossings have long been considered to be some of the most severe crashes that occur. Papers on hazards at railroad crossings have been written as early as 1928. Although railroad crossing crashes at that time represented approximately four percent of the total fatalities and an even smaller percentage of overall injuries, "It is safe to say that the average citizen not familiar with the facts would rate fatalities at railroad grade crossings as one of the most important hazards of the highway" (Eliot 1928, 86).

Light rail as a mode of transit developed as early as 1834 when the first rail line was installed in Cleveland, Ohio, as indicated on the Greater Cleveland Regional Transit Authority website. This website also states that Cleveland had one of the first street railways in 1859 when rail was laid flush with roadways to create smoother rides in vehicles pulled by horses. According to The San Francisco Cable Car Website, cable cars and, according to the Greater Cleveland Regional Transit Authority website, the electric street car was developed in the later 1800's and was a primary mode of transportation used by individuals until the development of private automobiles reduced the demand for fixed-route transportation services.

Modern light rail systems began appearing in the United States with the beginning of the San Diego Trolley operations in 1981, as stated on the San Diego Metropolitan Transit System website. By 1999, 20 light rail systems were in operation in 15 states. By 2009, the number of light rail systems in operation had increased to 33 systems operating in 23 states with three new light rail systems under construction in two additional states. By 2013, the number of light rail systems in operation had increased to 35 systems operating in 24 states with three new light rail systems in planning or under construction in those states and the District of Columbia.

Construction of and countermeasures for highway-light rail at-grade crossings (light rail crossings) have been discussed in the literature as light rail systems are constructed and extended. There have been some attempts to analyze the types of crashes that occur at light rail crossings and to determine types of countermeasures necessary to reduce crashes. However, it does not appear that any papers discussing a statistics-based, objective methodology for measuring safety at light rail crossings have been developed. Such models would provide light rail transit agencies with specific analysis tools, which would allow those agencies to determine how best to use their limited capital funding budgets.

Background

Common carrier freight train operations are substantially different from light rail operations. Common carrier freight trains tend to be long and can travel at slow speeds. When a freight train is traveling at higher speeds (e.g. 55 miles per hour), the distance it takes for the train to stop if there is a collision can be a mile, or more. In addition, the number of freight trains that occupy a railroad crossing is comparatively fewer during a

24-hour period than the number of light rail vehicles that occupy a light rail crossing during the same period of time, although the occupation of a railroad crossing by a freight train tends to be a much longer time per train.

Light rail operations typically involve vehicles that can move through light rail crossings at a faster speed since they are shorter than typical common carrier freight trains.

Railroad crossings throughout the United States (whether near or far from an intersection) can intersect the roadway at various angles from right-angles to severely skewed angles. There are few railroads in the United States where the railroad is street running with motor vehicle traffic. There are also railroads that operate adjacent to urban roadways likely have some type of barrier separation.

In contrast, many light rail systems operate in nonexclusive alignments, such as street running with motor vehicle traffic, or operate in semiexclusive alignments within or adjacent to surface street rights-of-way serving motor vehicle traffic. Although light rail crossings can be configured the same as railroad crossings with standard active warning equipment such as flashing lights, gates and bells, many light rail crossings occur within or directly adjacent to intersections controlled by traffic signals or passive regulatory signs.

The differences between common carrier freight railroad operations and light rail transit operations lead to significant differences in the exposure factor at a crossing and can also lead to differences in driver behavior at a crossing. These differences, in turn, may lead to differences in the number of crashes and the relative hazard indices that may be experienced at railroad crossings versus light rail crossings.

Numerous efforts have been made since the publication of the Peabody-Dimmick formula in 1941 (Peabody and Dimmick 1941) to develop crash prediction and hazard index formulas for use by state and local governments in ranking railroad crossings for safety improvements. In the 35 years following the publication of the Peabody-Dimmick formula, many states and cities developed their own relative hazard index formulas for use in ranking railroad crossings for safety improvements. The Coleman-Stewart formulas, developed in 1976, provided the first predictions of absolute crash number and severities (Coleman and Stewart 1976); and the United States Department of Transportation (US DOT) crash and severity prediction formulas are commonly used today (Farr 1987; Tustin et al. 1986).

For many years, various road authorities (including states, counties, cities, and towns), railroads, and regulatory agencies with safety responsibility over public railroad crossings have used equations to predict the number and severity of crashes expected to occur at railroad crossings, or hazard index equations to provide a relative ranking of railroad crossings from the most dangerous to the least dangerous. These crash prediction and hazard index equations were developed specifically for railroad crossings that accommodate heavy freight rail and/or commuter and intercity passenger rail.

In contrast to railroad crossings where significant research to create crash prediction and hazard index formulas has occurred, a review of the literature found no publications on the development of crash prediction and/or hazard index formulas specifically for light rail crossings. While a number of articles have been written on safety countermeasures for light rail crossings, it appears that all crash prediction and hazard index formulas to date have concentrated specifically on railroad crossings.

The ability to predict the number of crashes at an existing or proposed light rail crossing is necessary given the increasing number of light rail systems in operation, under construction, or for which feasibility studies may be underway. The ability to analyze safety at light rail crossings with a proposed configuration and method of warning would allow designers of new systems, and designers of systems being upgraded, to determine appropriate safety measures to address potential crashes at light rail crossings in a manner that is as systematic, unbiased, and as cost-effective as possible.

Problem Statement

The operational differences between common carrier freight railroads and light rail transit can lead to differences in exposure and driver behavior at railroad crossings as opposed to light rail crossings. However, crash prediction and hazard index equations modeling results of exposure and driver behavior exist only for railroad crossings. Equations specifically modeling results of exposure and driver behavior at light rail crossings will be created. The number of crashes predicted by these equations will be compared to the number of crashes predicted using the existing common carrier railroad crash prediction or hazard index calculations. A comparison of these two calculated values will provide evidence to show whether the operational differences between common carrier railroads and light rail are significant enough to change the safety at or to influence will provide evidence to show whether these operational differences are significant enough to change the safety at or to influence driver behavior at a light rail crossing such that separate light rail crossing specific equations better reflect the outcome of that behavior.

A preliminary review of the literature indicates that a number of articles have been written about light rail crossing construction and countermeasures and about operational analysis of at-grade light rail transit. However, to date, no papers have been published that develop crash prediction equations or hazard index calculations for light rail crossings similar to the equations used for railroad crossings. Additionally, prior to the beginning of this research, no papers had been published that show whether the existing crash prediction equations and hazard index calculations available for railroad crossings provide statistically significant results when used to model crashes and hazards at light rail crossings.

While crash prediction and hazard index equations exist for railroad crossings, there is a question as to how well these equations predict crashes specifically for light rail crossings. There is a need to know if the frequency of crashes is the same or similar at railroad crossings and light rail crossings. With the increasing number of light rail transit systems in the United States, if those systems are not constructed in exclusive rights-of-way with all crossings grade separated, operational issues will likely be experienced.

The purpose of this study is to determine if separate equations to predict crash number or to predict relative hazards for light rail crossings are needed. With this information, transit agencies and state oversight and/or regulatory agencies can better determine the safety needs of light rail crossings and can rank those crossings for safety improvements. Additionally, proposed safety measures can be objectively evaluated during the design phase of a light rail system so that a safe and cost effective light rail transit system is built.

Study Objectives

The objectives of this study are:

1. To determine whether existing railroad crossing crash prediction and hazard index equations adequately predict crashes and hazards at light rail crossings; and
2. If there is a statistically significant difference between crashes predicted by these common carrier railroad crash prediction and hazard index equations and the actual crashes that occur at light rail crossings, to develop crash prediction or hazard index equations specifically for light rail crossings.

Significance of Study

The significance of this study is that it will fill in the gap of knowledge regarding crash number prediction specifically for light rail crossings. This study will determine if the existing railroad crossing crash prediction and hazard index calculations adequately predict the number of crashes at light rail crossings. If they do not, this study will develop light rail crossing specific crash prediction or hazard index equations.

Hypothesis

The null hypothesis of this study is that railroad crossing crash prediction and hazard index equations adequately predict crash number to measure safety at light rail crossings. The null hypothesis is also that a comparison of the number of crashes at light rail crossings predicted using light rail crossing-specific equations will not be significantly different statistically from the number of crashes at light rail crossings predicted using equations for railroad crossings.

Research Questions

The questions to be answered by this research include:

1. Are the operational characteristics of common carrier railroads (freight and commuter rail) different enough from the operational characteristics of light rail to affect the number of crashes that are predicted to occur at railroad crossings and those that are predicted to occur at light rail crossings when the same crash prediction equations are used?
2. If there are differences, would development of crash prediction or hazard index equations specifically for light rail crossings provide a better model to predict the number of crashes at light rail crossings and thus better determine the safety at the light rail crossings?
3. If there should be a separate model, what statistical method or methods should be used to develop crash number prediction equations?
4. If separate models are developed, is there a significant statistical difference between the number of crashes predicted by the equations developed to predict crash number specifically at light rail crossings and the number of crashes predicted specifically at light rail crossings by existing railroad crossing crash prediction equations?
5. Can Geographic Information System (GIS) models be used in the development or application of crash number prediction equations?

Study Delimitations

The following are the delimitations of this study:

1. Time of the study: calendar years 2000 through 2009;

2. Light rail lines used in the study to develop equations were in continuous operation from 2000 through 2009;

3. Freight rail train volumes will not be included in the total train volume for any shared railroad/light rail crossings;

4. Freight rail train crashes will not be included in the total number of crossing crashes used in the model development;

5. Only vehicle crashes will be used in the analysis.

Study Limitations

The following are limitations of this study:

1. Availability of average daily traffic (ADT) volumes at the light rail crossings used in this study was limited due to economic downturn during the late 2000's and road authorities reducing or eliminating traffic count programs during this time period;

2. Data sample size is limited due to study delimitations that light rail lines be in continuous operation during the study period and due to limited availability of light rail crossing ADT volumes;

3. Each transit agency gathers and reports its data in a different manner; and, as a result, accuracy of data will not be able to be verified;

4. No light rail crossings in nonexclusive rights-of-way where light rail vehicles and motor vehicles share the same lane (nonexclusive c1) are included in the study.

Study Assumptions

The following are assumptions of this study:

1. Driver behavior at light rail crossings does not vary dramatically based on the location of the light rail crossing;
2. Driver behavior and reaction to traffic control devices does not vary dramatically based on the location of the light rail crossing;
3. Driver behavior at shared railroad/light rail crossings does not vary dramatically from driver behavior at light rail crossings;
4. Crash data provided by transit agencies are complete and accurate.

Study Terminology

There are a number of terms that will be used throughout this study that may be new to the reader. For the purposes of this study, the following terms have the following meanings:

Active warning is warning to motor vehicles about the presence of a railroad or light rail crossing and consists of equipment that starts to operate upon detection of a train and that can include flashing lights, bells, gates, cantilever flashing light signals, standard traffic signals, or wigwag signals.

Alignment is how the light rail line is separated from motor vehicle and pedestrian traffic and is exclusive, semiexclusive, or nonexclusive.

Configuration is the light rail track positioning and running direction relative to motor vehicle traffic position and running direction.

Consist is the number of locomotive engines and railroad cars or the number of light rail vehicles that are used in the makeup of a train.

Exposure factor is the product of the ADT volume using a crossing and the volume of trains using that same crossing during the same day.

Heteroscedasticity is described by Isaaks and Srivastava as "data values in some regions are more variable than in others" (Isaaks and Srivastava 1989, 46).

Overdispersion is when the variance of crash counts exceeds the mean of the crash counts (Lord and Mannering 2010).

Passive warning is warning to motor vehicles about the presence of a railroad or light rail crossing and consists only of signs including crossbucks, advance warning signs, and possibly yield or stop signs.

Road authority is the governmental or quasi-governmental entity that owns, operates, and maintains the roadway that is crossed by railroad or light rail tracks. Road authorities include states, counties, cities, towns, metropolitan districts, and special districts.

Switching operation involves moving a train back and forth through a crossing while railroad cars from customers being served are either removed from or added to the train consist.

Underdispersion is when the mean of the crash counts exceeds the variance of the crash counts (Lord and Mannering 2010).

Organization of Dissertation

Chapter I of the dissertation introduced and provided a background of the research issues. Chapter I also (1) provided the problem statement, (2) outlined the purpose of the study including the significance of the study, (3) stated the hypothesis being tested, (4) outlined the major research questions, (5) discussed the delimitations and limitations of the research, (6) listed the study assumptions, and (7) defined the study terminology.

Chapter II presents a review of the related literature in four areas. These are: (1) hazard index and crash prediction equation development; (2) statistical and other modeling methods reviewed in the development of light rail specific crash prediction and/or hazard index equations; (3) existing literature relevant to light rail crossings and light rail operations, and (4) existing literature related to the use of GIS in development and/or use with crash prediction and/or hazard index calculations in the study.

Chapter III outlines the methodology and procedures used in this study. A preliminary analysis of crashes on the Denver Regional Transportation District (Denver RTD) Light Rail System will be used to determine whether the number of crashes predicted by two existing railroad crossing hazard index and crash prediction equations adequately predict crashes at these light rail crossings. Next, the methodology for this study is outlined in detail and the study procedures are determined and discussed.

Chapter IV analyzes the various data elements that have been used in railroad specific crash prediction and hazard index models over time and will determine which data elements are appropriate to gather for this study. Data collected and data collection methods will be discussed. The data collected will be analyzed for light rail crossing crash patterns to determine possible ways to group light rail crossings as part of the equation development. Light rail crossing specific equations are developed. Finally, these developed models are analyzed and results are presented.

Chapter V discusses the development and use of a pilot GIS-based method flow chart that can be used to analyze light rail crossing safety. Finally, Chapter VI provides a discussion of the research conclusions and recommendations of the study.

CHAPTER II

LITERATURE REVIEW

Many papers and reports have been written on the development of hazard index and crash prediction equations for railroad crossings. The relevant literature regarding the development of hazard index and crash prediction equations is conducted for this research. Existing hazard index and crash prediction formulas are discussed and model parameters that have been used in previous crash prediction and hazard index calculations are catalogued for this research. In addition, various statistical methodologies and other modeling methodologies have been reviewed. Publications specific to light rail crossings and operations that discuss useful countermeasures are discussed. Finally, papers discussing the potential use of GIS in the created modeling efforts are reviewed. For purposes of this study, the literature review is divided into the following four areas:

- Railroad Crossing Hazard Index and Crash Prediction Equations
- Statistical and Other Methodologies
- Light Rail Specific Publications
- Use of GIS

Railroad Crossing Hazard Index and Crash Prediction Equations[1]

Existing railroad crossing crash prediction and hazard index models are reviewed. From a review of the literature, an inventory of model inputs that have been used in these equations is provided.

[1] The literature review regarding railroad crossing hazard index and crash prediction equations and summary of data elements was presented in a poster session at the 2012 American Public Transportation Association (APTA) Rail Conference in Dallas, Texas. (Fischhaber and Janson 2012).

Peabody-Dimmick Formula

In 1941, Peabody and Dimmick wrote what appears to be the first paper that attempts to develop a methodology for rating railroad crossing hazards (Peabody and Dimmick 1941). Their relative formula provides an index than can associate numbers to crashes on a relative basis with larger numbers representing a higher number of expected crashes; but there is not necessarily a linear relationship to the index numbers generated. This relative formula was developed to calculate the hazard rating of a railroad crossing and could be used as a means of ranking railroad crossings to determine which ones should receive priority in treating safety issues. The formula created by Peabody and Dimmick was designed to determine the number of crashes expected to occur at a railroad crossing over the course of five years. They developed the formula based on crash data collected from 3,563 rural railroad crossings located in 29 states. The data gathered for each railroad crossing included a description or sketch of the railroad crossing, a statement of the train and roadway volumes, and a description of the crashes that had occurred in a five-year period. The Peabody-Dimmick formula is:

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

Equation II.1 The Peabody-Dimmick Formula.

where:

A_5 = expected number of crashes over five years

V = annual average daily traffic (AADT) volume

T = average daily train traffic volume

K = additional parameter

P = protection coefficient

The protection coefficient can be determined from a chart developed by Peabody and Dimmick that provides coefficients for various warning devices on a scale from zero to three.

As noted by Austin and Carson (2002), this formula has a number of limitations due to how and when it was developed. The formula is based only on rural railroad crossings from 29 states. Additionally, advances have been made since 1941 in the designs of railroad crossings (*e.g.*, use of nonmountable medians to prevent vehicles from driving around gates) and the technology of active warning devices (*e.g.*, elimination of crossing watchmen, development of constant warning time detection circuitry).

The New Hampshire Index Formula and Other State and City Hazard Index Formulas

After the Peabody-Dimmick formula was published, a number of cities and states developed their own hazard index formulas and methods for use in ranking railroad crossings for safety improvements. Examples of relative formulas and methods are the New Hampshire Formula, the Mississippi Formula, the Ohio Method, the Wisconsin Method, the Contra Costa County Method, the Oregon Method, the North Dakota Rating System, the Idaho Formula, the Utah Formula, and the City of Detroit Formula (Richards and Bridges 1971). These formulas and methods are shown in Table 13 of the Railroad-Highway Grade Crossing Handbook (Olson et al. 1978). These formulas and methods used various combinations of information regarding crashes, trains, motor vehicle traffic, pedestrians, railroad crossing configuration (number of tracks, number of vehicle lanes, approach gradient, angle of crossing, and condition of crossing surface), warning devices, sight distance, and exposure factors. Each formula and method provided a hazard index for the railroad crossing being analyzed that could be compared and ranked against the hazard index calculated for other railroad crossings in order to prioritize railroad crossings for safety improvements.

Bezkorovainy (1967) performed a study for the City of Lincoln, Nebraska comparing 11 different hazard index formulas. Bezkorovainy determined the New Hampshire formula to be the optimum formula to use as a start towards developing a railroad crossing safety improvement program for Lincoln. Of the formulas reviewed, he determined that the New Hampshire formula is the most straightforward and uses three readily available inputs. The New Hampshire Index formula is:

$$HI = (V)(T)(P_f)$$

Equation II.2 The New Hampshire Index Formula.

where:

- HI = hazard index
- V = AADT volume
- T = average daily train traffic volume
- P_f = protection factor (0.1 for gates, 0.6 for flashing lights, and 1.0 for signs only)

The New Hampshire Index is a very simple hazard index calculation that can give a high level ranking to determine the need and relative priority of railroad crossings for safety improvements. Based on this formula, railroad crossings with higher exposure factors and/or passive warning devices will rank as a higher priority for safety improvements than will railroad crossings with lower exposure factors and/or more active levels of warning devices. The New Hampshire Index does not include as a factor the crashes that may have occurred at the railroad crossing, although some of the other state and city formulas and methods did include crash experience as an input.

Table 17 of the Railroad-Highway Grade Crossing Handbook (Olson et al. 1978) shows the results of a survey that asked the State Highway Agency of each state to identify the data elements included in the hazard index or crash prediction formula used by the State. Forty-two states used number of trains; 42 states used number of vehicles; 27 states included existing traffic control or advance warning devices; 17 states used visibility and sight distance; 12 states used speed; 12 states used number of crashes; 11 states used angle of roadway/railroad intersection; and 10 states used number of tracks through the railroad crossing. Other factors, which were used by six or fewer states, included highway approach grades, highway alignment, number of highway lanes, railroad crossing surface condition, type of train, urban/rural land use, and nearby intersections. Of the 15 data elements noted above, in 1978, the Federal Railroad Administration (FRA) National Inventory data file did not include visibility and sight distance, numbers of crashes, angle of intersection, highway approach grades, highway alignment, and surface conditions.

NCHRP Report 50

In 1968, through the National Cooperative Highway Research Program (NCHRP), the Highway Research Board published Report 50 (NCHRP Report 50) (Schoppert and Hoyt 1968). This report presented a model for quantitatively evaluating hazards at railroad crossings. NCHRP Report 50 determined that development of a single equation that could accurately calculate the frequencies of crashes at railroad crossings would be "too large and clumsy to be of any value" (Schoppert and Hoyt 1968). The

NCHRP Report 50 model, therefore, created a set of equations for calculating expected crashes at crossings based on a number of different input factors.

The simplest statement of the NCHRP Report 50 hazard index formula is:

$$EA = (A)(B)(CTD)$$

Equation II.3 The NCHRP Report 50 Hazard Index Formula.

where:

EA = expected crash frequency

A = vehicles per day factor

B = protection factor indicative of warning devices present

CTD = current trains per day

The A and B factors can be read from tables and graphs in the report or can be calculated based on the equations provided in the report.

The NCHRP Report 50 hazard index provides factors for a greater number of warning devices do than some of the other hazard index formulas and distinguishes between urban and rural railroad crossings, although it provides no guidance on how to distinguish between urban and rural. Thus, if multiple people use these calculations to rank the relative safety of railroad crossings, there could be inconsistency in the application of the urban and rural definitions, which could lead to railroad crossing prioritization ranking errors.

Coleman-Stewart Crash Prediction Equation

In 1976, Coleman and Stewart (1976) developed what appears to be the first set of absolute crash number and severity prediction formulas. Absolute formulas estimate the specific number of crashes and the severities of those crashes. They developed the equation with data collected from 15 states for 37,230 grade crossings at which 9,490 crashes occurred. Railroad crossings were classified according to the number of tracks, urban or rural location, and type of warning device. The stratification created 24 sets of two-way tables from which model coefficients were developed.

The Coleman-Stewart crash number prediction equation is:

$$\log_{10}A = C_0 + C_1 \log_{10}V + C_2 \log_{10}T + C_3 \log_{10}T^2$$

Equation II.4 The Coleman-Stewart Crash Number Prediction Equation.

where:

A = average number of crashes per railroad crossing-years

V = weighted ADT volume for the N railroad crossings

T = weighted average train volume for the N railroad crossings

C_0, C_1, C_2 , and C_3 = model coefficients read from a table based on number of tracks, urban or rural location, and railroad crossing warning device

The Coleman-Stewart formula suffers from some of the same limitations as the Peabody-Dimmick formula in that limited data were available because crash data and railroad crossing data could not always be matched. Also, given the changes over time in the total number of railroad crossings and the types of warning device at railroad crossings, it is likely that the coefficients should be recalculated to properly use this model.

US DOT Crash Prediction Formulas

In April 1986, the US DOT published a set of absolute crash number and severity prediction formulas (Farr 1987; Tustin et al. 1986). The current US DOT formulas are a three step process. The initial equation determines the initial crash prediction. The second equation determines the crash prediction based on the crash history at the railroad crossing. The third and final equation applies a normalizing constant to the second crash prediction.

The FRA's Rail-Highway Crossing Resource Allocation Procedure – User's Guide, Third Edition (Farr 1987), uses three crash prediction equations that are similar to the formulas shown in the various editions of the Railroad-Highway Grade Crossing Handbooks. The formula for the initial crash prediction equation is:

$$a = K*EI*DT*MS*MT*HP*HL$$

Equation II.5 The US DOT Initial Crash Prediction Equation.

where:

a = initial crash prediction (crashes per year at the railroad crossing)

K = formula constant

EI = factor for exposure index based on the product of highway and train traffic

DT = factor for number of through trains per day during daylight

MS = factor for maximum timetable speed

MT = factor for number of main tracks

HP = factor for highway paved (yes or no)

HL = factor for number of highway lanes

The factors are obtained from tables and are based on the type of warning at the railroad crossing (passive signs, flashing lights, or gates). No factors exist for traffic signal control. The second crash prediction equation is:

$$B = \frac{T_0}{T_0 + T}(a) + \frac{T}{T_0 + T}(N/T)$$

Equation II.6 The US DOT Second Crash Prediction Equation.

where:

B = second crash prediction in accidents per year at the railroad crossing

a = initial crash prediction from Equation II.5

N/T = crash history prediction in crashes per year where N is the number of observed crashes in T years at the railroad crossing

T_0 = formula weighting factor = 1.0/(0.05 + a)

The final crash prediction equation is:

$$A = k*B$$

Equation II.7 The US DOT Final Crash Prediction Equation.

where:

A = final crash prediction in crashes per year at the railroad crossing

k = normalizing constant (recalculated every two years for passive devices, active devices, and gates)

B = second crash prediction from Equation II.6

The US DOT formula also includes calculations that determine the probability of a railroad crossing crash being an injury crash or a fatal crash. Every two years, the US

DOT recalculates the formula constants based on the most recent five years of crash data.

Crash severity is determined by the following equations:

$$P(FA|A) = 1/(1+KF*MS*TT*TS*UR)$$

Equation II.8 The US DOT Crash Severity Equation for Fatal Crashes.

where:

P(FA|A) = probability of a fatal crash, given a crash

KF = formula constant (440.9)

MS = factor for maximum timetable train speed = $ms^{-0.9981}$

TT = factor for through trains per day = $(tt+1)^{-0.0872}$

TS = factor for switch trains per day = $(ts+1)^{0.0872}$

UR = factor for urban or rural crossing = $e^{0.3571ur}$

ur = 1 for urban, 0 for rural

$$P(CA|A) = 1/(1+KC*MS*TK*UR)$$

Equation II.9 The US DOT Crash Severity Equation for Casualty Crashes.

where:

P(CA|A) = probability of a casualty crash, given a crash

KC = formula constant (4.481)

MS = factor for maximum timetable train speed = $ms^{-0.343}$

TK = factor for number of tracks = $e^{0.1153tk}$

U = factor for urban or rural crossing = $e^{0.296ur}$

ur = 1 for urban, 0 for rural

The Railroad-Highway Grade Crossing Handbook – Second Edition (Tustin et al. 1986) included only two US DOT crash prediction equations. The first equation was similar to Equation II.5, but included a highway type factor. The second equation was identical to Equation II.6. These formulas were updated in the Railroad-Highway Grade Crossing Handbook – Revised Second Edition (Ogden 2007) to include a third formula where a normalizing constant specific to passive devices, flashing lights, or gates is applied to the final crash prediction in crashes per year at the railroad crossing as shown in Equation II.7 above to obtain the final crash prediction at the railroad crossing.

The US DOT formulas provide the most accurate results if all crash history available is used (Farr 1987). However, the US DOT has determined that improvement in the results is minimal for any data over five years old used in the equations because crash data that are older than five years could be misleading due to changes that occur at railroad crossings over time. As a result, if a substantial change is made at a railroad crossing (*e.g.*, active warning is installed), care needs to be used with these equations; and only data since the change should be used in the formulas.

According to Austin and Carson (2002), the US DOT formula complexity does not make it easy to determine the magnitude of each factor's contribution to the safety of a railroad crossing and makes it difficult to prioritize railroad crossings to address safety-related problems at a railroad crossing. Additionally, with safety improvements at railroad crossings around the country occurring over time, there has been a steady decrease in value of the normalizing coefficients, which correlates to a decrease in the accuracy of results.

US DOT FRA GradeDec.NET 2000 Ver. 2

In 2008, the FRA updated its reference manual for its GradeDec.Net web-based application (Federal Railroad Administration 2008). This program allows a user to calculate the costs and benefits of making specific types of improvements to railroad crossings as a way to provide a standard basis of comparison between railroad crossing improvements. Such a comparison allows agencies spending funds on railroad crossing improvements to get the best safety return for the investment of safety dollars spent.

The crash prediction equations used in the GradeDec.Net program are similar to the US DOT Crash Prediction formulas. The first equation adds an additional factor for highway type. The second and third equations are somewhat combined, and the calculations account for whether a high speed rail model is used. The equations also account for passive warning, flashing lights, and gates, and add a new technology set of equations for calculating the various formula factors. However, the GradeDec.Net program does not model traffic signal warning devices.

Other Hazard Index and Crash Prediction Equations

Over time, other papers and theses have been written proposing other hazard index and crash prediction equation calculations. These include formulas suggested by:

- Crecink, Marsh, and McDonald (1948);
- Coburn (1969);
- Schultz and Oppenheimer (1965);
- Berg, Schultz and Oppenlander (1970, 1970);
- Zalinger, Rogers, and Johri (1977);
- Lavette (1977);

- Ryan and Erdman (1985);
- Hauer and Persaud (1987);
- Nagahama (1987);
- Gitelman and Hakkert (1997);
- Saccomanno, Ren, and Fu (2003);
- Austin and Carson (2002);
- Benekohal and Elzohairy (2001);
- Saccomanno, Fu, and Miranda-Moreno (2004);
- Park and Saccomanno (2005);
- Saccomanno and Lai (2005);
- Qureshi, Avalokita, and Yathapu. (2005);
- Oh, Washington and Nam (2006);
- McCollister and Pflaum (2007); and
- Yan, Richards and Su (2010).

One paper offered a crash severity prediction formula for railroad crossings (Hitz 1984).

Additional factors for consideration have come from these various papers and are included in the following summary of factors.

The statistical and other modeling methodologies suggested by many of these papers will be discussed in the section titled Statistical and Other Modeling Methodologies.

Summary of Factors Used in Railroad Crossing Hazard Index and Crash Prediction Equations

A review of the various crash prediction and hazard index calculations discussed in the literature reveals that each equation requires some combination of railroad crossing configuration and/or railroad crossing operation data. The calculations discussed in the literature include switching movements. Switching movements have been removed from the following lists because light rail operations typically perform switching maneuvers only within their train yards and not on their mainline tracks within their operating areas.

The data used in these equations that could be relevant to light rail crossing calculations include direct inputs or representative factors of:

- Crossing Related Data
    - Crash experience
    - Crash severity
    - Angle of crossing
    - Crossing warning device
    - Crossing width
    - Crossing surface material
    - Condition of crossing
    - Distance to nearest intersection
    - Exposure factor
    - Number of main tracks
    - Number of other tracks
    - Parallel road characteristics
    - Sight distance rating

- Sight obstructions
- Train detector distance
- Urban or rural nature of crossing
- Year of last inspection

- Roadway Related Data
  - Approach gradient
  - Number of traffic lanes
  - Presence of a speed hump
  - Pavement markings
  - Required stopping sight distance on wet pavement
  - Roadway type
  - Roadway paved or not
  - Road pavement width
  - Roadway conditions
  - Shoulder width
  - Shoulder type

- Train Related Data
  - Average daylight train volume
  - Average train volume during dark hours
  - Maximum train timetable speed
  - Number of trains in 24 hour period
  - Number of passenger trains in 24 hours

  - Train speed
  - Time a crossing is blocked

- Vehicle Related Data
  - Average 24 hours traffic volume
  - Average daylight traffic volume
  - Average traffic volume during dark hours
  - Number of pedestrians
  - Number of school buses
  - Percentage of heavy vehicles
  - Vehicle speed

- Miscellaneous Data
  - Distractions at crossing
  - Distance to overhead wires
  - Location of and distance to schools
  - Presence of residential area
  - Presence of commercial area
  - Presence of other land uses (industrial, institutional)
  - Train Horn prohibitions (quiet zones)

The above-listed data elements will be discussed in Chapter IV as to whether the data element should be considered in the development of any light rail specific hazard index and/or crash prediction equations. There may be some data types that, ultimately, will not apply. For example, data on urban versus rural environments may not be necessary since light rail systems tend to operate in urban areas, and data on roadway configurations of paved versus unpaved or shoulders and shoulder types may not be useful as the unpaved roadway configurations tend to occur in more rural areas. There may be limitations on the ability to obtain certain types of data (*e.g.*, the number of pedestrians, percentage of heavy vehicles, number of school buses, time a light rail crossing is blocked) as not all municipalities, counties, and states collect the same information. The road authority may estimate some information (*e.g.*, percentage of heavy vehicles using the roadway). Some information may also be estimated by the roadway authority.

Statistical and Other Modeling Methodologies

A number of statistical and other modeling methodologies have been used in various papers over time in the development of crash prediction and hazard index equations for use in evaluating safety at railroad crossings. Each method has advantages and disadvantages in use, some of which have been mentioned in the previous formula discussions and some of which will briefly be discussed in this section. The following methods will be studied and considered as possible modeling methodologies.

Linear Regression Models

Faghri and Demetsky (1986) performed a study evaluating five hazard indices: the Peabody-Dimmick, the NCHRP Report 50, the Coleman-Stewart, the New Hampshire, and the US DOT Crash Prediction Formula. In this study, Faghri and Demetsky noted that, with the exception of the US DOT model, the studied models employed linear regression techniques for determining the parameters. They also noted that these formulas cannot predict the exact number of crashes that will occur at a railroad crossing, only the mean number of expected crashes at a railroad crossing during an extended time period.

Coburn (1969) used multiple regression and correlation analysis to analyze railroad crossings on the Texas Highway System as part of his doctoral dissertation. This method is fairly simple to use and lends itself to easy calculations of the correlation of variables being used.

Austin and Carson (2002) conducted a review of the Peabody-Dimmick, the New Hampshire, the NCHRP 50, and the US DOT Crash Prediction Formulas. They also provide an analysis of the various model development techniques. In this study, Austin and Carson noted that the Peabody-Dimmick formula is based on only rural railroad crossings from 29 states prior to 1941 and, as a result, has a number of limitations derived from how it was developed. Since the development of the Peabody-Dimmick formula, many advances have been made in railroad crossing designs (*e.g.*, use of nonmountable medians to discourage vehicles from driving around gates) and the technology of active warning devices (*e.g.*, elimination of crossing watchmen, development of constant warning time circuitry). The Peabody-Dimmick formula does not account for these changes.

With respect to modeling issues, Austin and Carson (2002) point to two issues with the use of multiple linear regression. First, with conventional linear regression techniques for modeling crash frequency data, these types of models are not restricted from predicting negative values, which can bias the estimated coefficients. Second, heteroscedasticity problems have been noted when using linear regression to model crash frequency data.

Other examples of railroad crash prediction and hazard index formulas developed using linear regression include Crecink, Marsh, and McDonald (1948), Schultz and Oppenlander (1965), Berg, Schultz, and Oppenlander (1970, 1970), Ryan and Erdman (1985), Gitelman and Hakkert (1997), and Saccomanno and Lai (using a combination of linear regression and cluster analysis) (2005).

Nonlinear Regression Models

Faghri and Demetsky (1986) explain that the US DOT Crash Prediction Formula model was developed using nonlinear regression analysis. According to Austin and Carson (2002), the US DOT Crash Prediction Formula complexity does not make it easy to determine the magnitude of each factor's contribution to the safety of a railroad crossing and makes it difficult to prioritize railroad crossings to address safety-related problems at a railroad crossing. Additionally, with safety improvements at railroad crossings around the country occurring over time, there has been a steady decrease in value of the normalizing coefficients, which correlates to a decrease in the crash prediction model accuracy.

Benekohal and Elzohairy (2001) used nonlinear regression in developing their new hazard index formula for the State of Illinois. They conclude that the percentage of locations with crashes that suggested safety improvements using their formula was higher than the same percentage suggested by other formulas such as the New Hampshire Index Formula and the US DOT Crash Prediction Formula.

Lavette (1977) used a stepwise regression analysis to develop two different crash prediction formulas for railroad crossings in Florida. One formula was developed for railroad crossings with passive warning devices, and a second formula was developed for railroad crossings with active warning devices. Natural logarithm formulas were developed to predict the number of crashes at both passive warning and active warning railroad crossings. The predicted crashes were then included in non-linear formulas (one for passive warning railroad crossings and one for active warning railroad crossings) to calculate the predicted number of crashes per year at a crossing.

Hitz (1984) also used nonlinear regression in developing crash severity prediction formulas. Hitz developed separate formulas to estimate the number of fatal crashes per year at a railroad crossing and to estimate the number of injury crashes per year at a railroad crossing. Hitz found that there were some different influencing factors for each equation.

Poisson Regression Models

Hayter (2007) describes the Poisson distribution as a useful model in situations where there is a need to "define a random variable that counts the number of 'events' that occur within certain specified boundaries". One requirement of the Poisson distribution is that the mean and the variance are equal. (Hayter 2007) According to Austin and Carson (2002), if the mean and variance are not equal, the Poisson model could be over-dispersed or under-dispersed leading to an inadequate fit of the model and a bias in the parameter estimates. Lord and Mannering (2010) note that Poisson regression models can be adversely affected by low sample mean and can produce biased results with small sample sizes.

The model developed by Zalinger, Rogers, and Johri (1977) uses Poisson regression and develops separate equations for urban and rural railroad crossings. Saccomanno, Ren, and Fu (2003) note that Poisson regression models tend to show a problem of underdispersion due to the number of zero collision railroad crossings.

Another example of railroad crash prediction and hazard index formulas developed using Poisson regression include Saccomanno, Fu, and Miranda-Moreno (2004).

Negative Binomial Regression Models

Austin and Carson (2002) discuss negative binomial regression. According to Austin and Carson, this model is more appropriate for over-dispersed data due to relaxing the constraint that the mean and variance are equal, and they used this method in the development of their model. Lord and Mannering (2010) note that the negative binomial regression model has limitations in its inability to handle under-dispersed data and that there can be dispersion-parameter estimation problems when data are characterized by small sample sizes and low sample mean values.

Logit Models

McCollister and Pflaum (2007) used a logit model (logistic regression) in developing their crash prediction model. In comparing their logit model to previously developed models, the Pseudo R^2's for the logit model were more than ten times larger than in previous models, indicating a better fit of the model to the data. This type of model can be used when the probabilities modeled must be between zero and one.

Zalinger, Rogers and Johri (1977) assert that logit models should not be used in analyzing railroad crossing crash data because crash locations are grouped into two categories: crash or no crash. This grouping could skew the model results.

Quantification Methods

Nagahama (1987) used the quantification method in analyzing crashes at railroad crossings. This model appears to have difficulties as a result of the limited information obtained due to the difficulty in collecting human factors data. It also appears that the model as developed needs to be revised to establish higher accuracy.

Empirical Bayes Methodologies

Empirical Bayes (EB) models have been reviewed in a few papers, including those by Saccomanno, Ren, and Fu (2003) and Hauer and Persaud (1987).

Saccomanno, Ren, and Fu (2003) noted that, when using an EB model for crossing crashes, there may not be enough data to realistically represent the historical crash risk at each railroad crossing given the rare nature of these types of collisions. Saccomanno, Ren, and Fu (2003) ultimately chose a Poisson model to predict railroad collisions in Canada, even though the Canadian data were under-dispersed because the authors believed the model was a better fit. They also developed an EB model but found that there was not much improvement over the results of their Poisson model.

Hauer and Persaud (1987) used an EB model to develop a method of estimating safety at railroad crossings that considers both causal factors and crash history of a railroad crossing to estimate the hazard of the railroad crossing. The EB model is used to control the inflation of benefits shown in before-and-after studies as a result of bias-by-selection.

Hierarchical Tree-Based Regression

Yan, Richards and Su (2010) used a hierarchical tree-based regression model to predict crashes at passive railroad crossings. The models created by Yan, Richards and Su are used only to evaluate railroad crossings that were controlled by passive signs, such as crossbucks and stop signs, and to evaluate the effectiveness of adding stop signs to a railroad crossing. The authors note that hierarchical tree-based regression is not always a better tool for crash prediction because while hierarchical tree-based regression models can explore structure or relationships among variables, these models "lack statistical inferences for evaluating the effect of predictors." (2010, 25). Park and Saccomanno (2005) use tree-based data mining using the RPART method in conjunction with a negative binomial prediction model.

Gamma Models

Oh, Washington, and Nam (2006) looked at the gamma model and determined that, given the slight underdispersion with respect to the Poisson model, the gamma model was the most appropriate statistical model of the ones they reviewed to analyze railroad crossing crash data from Korea. They note that the gamma model is relatively new in the transportation safety literature. Lord and Mannering (2010) note that, while the gamma model can handle overdispersion and underdispersion, the gamma model is a dual-state model, meaning that one of the states has a long-term mean equal to zero.

They also note that the gamma model has had limited use since it was introduced by Oh, Washington, and Nam.

Principal Component Analysis

Principal component analysis is defined by Abdi and Williams (2010) as a multivariate technique that analyzes a data table in which observations are described by several inter-correlated quantitative dependent variables with the goal of extracting important information from the table to represent a set of new orthogonal variables (called principal components) and to display the pattern of similarity of the observations and variables as points in maps.

Golob and Recker (2004) used principal component analysis to analyze freeway crash characteristics and traffic flow conditions, and Abdel-Aty and Pemmanaboina (2006) used principal component analysis to identify relatively independent measurements of traffic flow conditions in their study on calibrating a real-time traffic crash-prediction model.

This is not a technique that has been used in the development of any previous railroad crash prediction and hazard index equations. Given the number of model inputs that could potentially be used in the development of a light rail crash prediction or hazard index model, principal component analysis is a technique that could be considered as a method of extracting the information important to the model and should be considered and explored in the development of such a model.

Additional Modeling Data and Methodological Issues

Lord and Mannering (2010) performed a review and assessment of methodological alternatives to consider regarding the statistical analysis of crash-frequency data. Their paper provides detailed discussions and summaries of various data and methodological issues that can be potential sources of error and that have been identified in the crash-frequency literature. In addition to overdispersion and underdispersion of data, Lord and Mannering identify the following issues that should be kept in mind when looking at modeling methodologies: time-varying explanatory variables, temporal and spatial correlation, low sample mean and small sample size, injury severity and crash type correlation, under reporting, omitted variables bias, endogenous variables (variables that may depend on the frequency of crashes), functional form of the model, and fixed parameters.

Lord and Mannering (2010) also discuss a number of other models, including: the Poisson-lognormal model, the zero-inflated Poisson and negative binomial models, the Conway-Maxwell-Poisson model, the generalized estimating equation model, generalized additive models, the random-effects models, negative multinomial models, random-parameters models, bivariate/multivariate models, finite mixture/Markov switching models, duration models, hierarchical/multilevel models, and neural, Bayesian neural network, and support vector machine models. Many of these models appear to have issues with low sample means and small sample sizes or can have complex calculations. These models have not been previously used to create railroad crossing crash prediction and hazard index models and will not be reviewed further in this study.

In developing crash prediction and hazard index formulas specifically modeling light rail operations, the ultimate goal is to develop modeling tools that will be used by transit agencies throughout the country (a) in system design and planning and (b) in determining, as part of the capital improvement budgeting process, if and when mitigation of safety issues at light rail crossings may be needed. The various formulas that have been developed to-date include both formulas that are relatively simple to use and formulas that can be complex to use. If the formulas developed are too complex, it is likely that transit agencies will not use them. However, if the formulas developed do not contain a reasonable degree of accuracy, transit agencies will have no reason to use them. Thus, it is important to find a modeling technique that will balance the need for accuracy with the need for a formula that is not too complex to use.

Another possible issue may be small data sample size and/or low sample mean. Crashes at railroad and light rail crossings tend to be infrequent occurrences when compared to crashes that occur at traffic intersections. Lord and Mannering (2010) discuss a number of models where small sample size and low sample mean can produce biased results or are sources of model error. Data sample size will be an important factor in determining the types of models that should be considered in developing light rail-specific crash prediction or hazard index formulas.

Light Rail Specific Publications

As stated in the introduction, there are a number of papers that have been written regarding light rail operations and crossings. These papers tend to focus on the design and installation of countermeasures at light rail crossings either during the design phase of a project or after-the-fact to mitigate high accident light rail crossings once light rail operations have begun. Although none of these papers discuss any determination or quantification of safety at light rail crossings with actual or proposed operations, these papers do provide various mitigation measures to be considered in this modeling effort. A brief discussion of these papers is presented below.

Morag (1977) developed a methodology to estimate lane capacity and the impacts to traffic due to the implementation of light rail lines that operate in semiexclusive environments. These tools were developed for transportation planners to determine if sufficient motor vehicle capacity existed at a light rail crossing or if the roadway capacity was such that a grade-separated intersection should be considered. Morag noted that the analysis only considered independent light rail crossing situations not involving adjacent intersections with traffic signals and that further consideration would need to be given to these types of intersections, which may require synchronization with a preempted light rail crossing warning system.

Korve (1978) discusses light rail alignment conflicts and potential methods of controlling such conflicts. These conflict control measures can be categorized into four categories: at-grade separation of traffic flows in space, vertical separation of traffic flows in space, separation of traffic flows in time, and reduction in the number of traffic approaches. Korve discusses, for each of four categories, various traffic engineering techniques that can be applied in the design and operations of light rail systems given the types of conflicts that are identified during the design phase.

Quinby and Rogers (1978) summarized the discussions regarding motor vehicle and pedestrian interfaces with light rail transit for the Transportation Research Board Special Report regarding an introduction to light rail transit planning and technology.

The summary discusses issues dealing with the problem of finding the space for developing surface operation light rail systems/ the problem of working light rail systems into arterial roads and other roads of limited width; the methods employed by some transit agencies throughout the United States and abroad; the need to develop light rail design criteria; and the need to work through various trade-offs between physical space, design, operations, and cost alternatives.

Stone and Wild (1982) investigated warrants for priority treatments for light rail vehicles in existing medians and their design considerations. The paper examines warrants for operations through signalized intersections and argues that the use of motor vehicle level of service places a higher priority on motor vehicles than on light rail vehicles. Stone and Wild argue that consideration should be given to the number of people traveling on the light rail vehicle and to the use of total person-delay as an evaluation criterion when determining which mode should receive priority treatment at signalized intersections.

Bates and Lee (1989) focus on light rail planning and its potential impacts on traffic circulation, parking, light rail vehicle priority, and determination of whether to grade-separate light rail vehicles from motor vehicles. Based on their study of empirical data collected from around the country, Bates and Lee provide general guidelines for when light rail crossings should be workable at grade (at 20,000 ADT volume or less), may be workable at-grade if light rail vehicles are not accorded full priority (between 20,000 and 30,000 ADT volume), or when serious consideration should be given to grade separations (greater than 30,000 ADT volume). These guidelines are primarily based on the light rail crossing operations.

The paper by Fehon, Tighe, and Coffey (1989) also discusses techniques that can be used in the operational analysis of at-grade light rail transit. The authors looked at an analysis of six different light rail systems and were presented with a number of challenges given the wide variety of intersection geometry, traffic and light rail control devices, and the operating conditions. The authors also found the sporadic and random nature of the interaction between motor vehicles and light rail vehicles to be challenging, as was the interdependence of events that occur at adjacent light rail crossings during consecutive light rail vehicle arrivals. Fehon, Tighe, and Coffey conclude that the ROADTEST simulator provided the most sophisticated modeling of light rail and motor vehicle operations at light rail crossings. ROADTEST is a microscopic rail and road traffic simulation model that simulates movement of individual road vehicles and rail vehicles through a network of any size and complexity (Fehon, Tighe, and Coffey 1989, 602). This model can be used to simulate light rail vehicle movement, freight trains, buses, pedestrians and other needed vehicle types.

Fox (1989) sets out guidelines that can be used by designers to weigh various alternatives for light rail crossing designs with the goal that more costly design solutions that may not be warranted can be avoided. Fox also discusses what he refers to as light rail crossing protection including stop control, traffic signals, turn prohibition, gated crossings, and grade separations. Further, Fox discusses when general operational guidelines (*e.g.* use of pushbuttons or cab-actuated preempt calls) would be effective.

Korve and Wright (1992) discussed the need for guidelines or standards to govern light rail crossings and their preference that the National Committee on Uniform Traffic Control Devices adopt such guidelines. The authors discuss the three categories: light rail crossing warning signs for roadway traffic; light rail vehicle signal types; and locations for light rail vehicle operators, and midblock light rail crossing gates, locations, and types.

Walters, Venglar, Fambro and Daniel (1993) prepared an interim report on developing analytical tools to evaluate light rail at-grade operations within an urban signal system. The authors research and review various modeling programs that could be used to simulate existing light rail operations. The authors determine that the Federal Highway Administration's NETSIM package is flexible enough to simulate light rail networks. However, because NETSIM can only simulate traffic conditions, they determine that the use of programs such as TRANSYT and/or PASSER would be necessary in order to develop signal timings for proposed or optimized networks.

The Korve and Jones paper (1994) focuses on light rail operations in central business district environments. The authors found that relationships between road authorities and transit operators are important to the successful implementation of light rail operations through downtown central business district areas. In addition, they found that block length and other on-street issues can lead to constraints on the ability to increase headways and capacity of light rail vehicles.

Meadow (1994) conducted a study on safety issues on the Los Angeles Metro Blue Line light rail system and evaluated various means to discourage and/or prevent vehicles and pedestrians from making illegal movements. The measures developed and tested fall into the three Operation Lifesaver categories of engineering, education, and enforcement. Engineering improvements included in the study involved changes at some of the light rail crossings including median construction at gated light rail crossings, the addition of protected left-turn lanes, adjustment of signal phasing for streets parallel to the tracks with the goal of eliminating vehicles maneuvering around down crossing gates and pedestrian inattention near tracks, and a four-quadrant gates and pedestrian gate demonstration project. Education aspects of the study involved the California Rail Transit Safety Act. This act contains a provision where drivers convicted of a grade crossing violation may be ordered to attend traffic school and view film on rail transit safety. This act also requires that the Department of Motor Vehicles include a section in the DMV driver handbook that contains language regarding rail transit safety. Education also involved developing public safety campaigns to provide education to adults, children, and Hispanic audiences. Enforcement activities during the study included a 90-day program of enforcement during which 7,760 citations were issued. This program was so successful that funding for six deputies was authorized, and more than 11,000 citations were issued in the first full year of the program. A photo enforcement demonstration project was conducted at four crossings. The photo enforcement demonstration at two gates light rail crossings in Compton showed an 84% reduction in violations with 364 citations issued during the seven-month demonstration project. The California Rail Transit Safety Act also provides enforcement measures by imposing additional fines and points on those that violate light rail crossing safety laws. No specific safety outcomes resulting from the additional fining authority were discussed.

Korve, Farrán and Mansel (1995) discussed methods of integrating of light rail transit into city streets. This paper discusses the research of the Transit Cooperative Research Program (TCRP) Project A-5, which was later published as TCRP Report 17 (Korve et al. 1996).

Meadow and Curry (1995) discussed some of the new technologies transit agencies could consider for improving safety at light rail crossings. This paper discusses much of what was discussed in the paper by Meadow (Meadow 1994), includes some additional information regarding four-quadrant gates and their design approach and assumptions, and contains a discussion of the way-side horn demonstration project on the Los Angeles Metro Blue Line light rail system.

Coifman and Bertini (1996) focus on crash causation at light rail crossings and mitigation measures for such causal factors. Based on a survey of ten light rail systems, the authors identify left-turning crashes as the most prevalent type of crashes that occurred, and discuss that the apparent cause of many crashes was driver disobedience to warning signs and systems. As an addition to the categories of passive and active warning devices, Coifman and Bertini create a category of warning devices they refer to as reactive devices. As defined by the authors, reactive devices are warning devices that respond to illegal or unsafe motor vehicle movements when light rail trains approach a light rail crossing.

Tennyson (1998) performed an analysis of rail transit safety for the years 1993, 1994, and 1995. The purpose of the analysis is to determine the relative safety of, need for, and room for improvement of rail transit service. Tennyson poses questions in his research about where improvement is most needed, what is the cost of crashes, what is the relative safety among various types of rail transit, and which types of operations best illustrate optimum safety.

Korve et. al. (2001) developed TCRP Report 69 in 2001. The TCRP Report 69 provides information regarding system operating and safety experiences of 11 light rail systems throughout the United States and Canada, gives some application guidelines in design and operation of light rail systems, and provides some field research of the use of presignals at light rail crossings and proposed presignal design criteria.

Boorse (2003) discusses the use of dynamic envelope delineation markings for light rail transit cars and trains. Boorse provides numerous examples of dynamic envelope markings for different light rail system designs through intersections and concludes that there are some isolated situations where such markings might be beneficial, but that widespread use of such markings show the opposite effect.

Li, Wu, Johnston and Shang (2009) conducted an analysis to investigate conflicts and interactions between urban/suburban rail traffic and cross motor vehicle traffic. The proposed light rail priority system discussed in the paper looked to optimize algorithms to minimize intersection delays for trolleys by providing signal priority to the trolleys and to minimize impacts on other traffic incurred by the trolley priority. Their study showed the light rail priority system reduced trolley passenger delay by 89.5% and total intersection passenger delay was reduced by 66.8%.

Farrán (2000) conducted a study regarding controlling vehicles turning in front of light rail vehicles. Farrán identified five crash situations involving left-turning and right-turning vehicles and offers candidate solutions for each situation.

Use of GIS

A paper by Panchanathan and Faghri (1995) provides useful information for using GIS in the safety analysis of railroad crossings. Their paper discusses steps that the State of Delaware took to implement a GIS for safety analysis. The model used various geographic and attribute data sources to develop a knowledge-based expert system. The program used site-specific and qualitative factors in conjunction with information from the US DOT railroad crash index and inventory databases to assign indicators of danger levels at crossings and suggested remedial action safety improvements. The model developed 15 possible safety improvement alternatives and established cost and effectiveness factors for each. Once run, the model used a phase-by-phase evaluation and presented a set of possible actions for safety improvements for each crossing. Figure II.1 shows the inference mechanism of the Panchanathan and Faghri model.

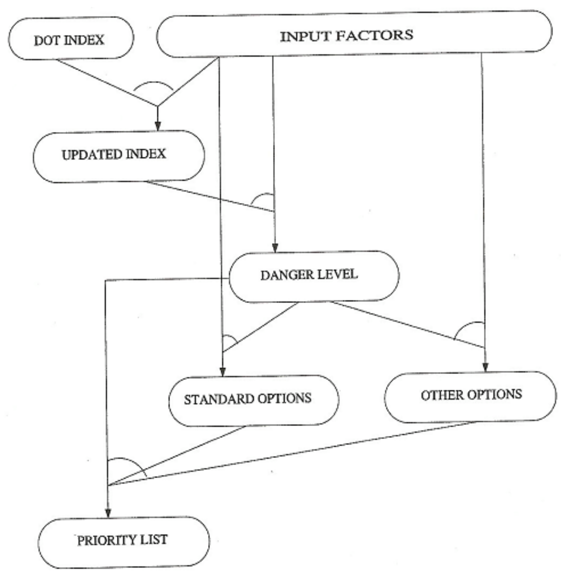

Figure II.1 Panchanathan and Faghri (1995) Model Inference Mechanism.

Souleyrette et. al. (1998) worked on creating a GIS-based crash location and analysis system that provided the query and reporting functions of a personal computer-based crash location and analysis system with the benefits of spatial query and display. The model, developed for the Iowa Department of Transportation, allowed query results to be displayed in both map and tabular form, allowing for easier interpretation of query results and the ability to analyze crash patterns and causal relationships.

Faghri and Harbeson (1999) developed a knowledge-based GIS approach to evaluate design consistency of horizontal roadway alignments that was tested in Delaware. The model was able to evaluate changes in the degree of curve for consecutive elements of a roadway and to evaluate the consistency of the horizontal alignment of the roadway. Faghri and Harbeson successfully applied this model to an actual state highway in Delaware.

Miller (1999, 2000) performed a study similar to Souleyrette et. al. that looked at using GIS for various types of crash data analysis. Miller concluded that, at a macroscopic level, GIS benefits included being able to display and manipulate data in a creative manner; that GIS could be used at a corridor level to identify potential problem sites; that GIS could be used as an analytic tool for crash analysis instead of just as a display tool; and that GIS could be integrated with multiple computer-based methods of obtaining crash locations in the state of Virginia.

Saccomanno, Fu, and Roy (2001) developed a GIS model for the predication and analysis of road crashes. Their model took input from various crash databases as input into an integrated Microsoft Access database. Users were then able to generate various statistics, to select specific locations and specific improvements to those locations, to generate predicted crashes, and to display the results in a GIS. This model used an EB methodology.

Finally, Fischhaber (2007) reviewed various methodologies for geocoding railroad crossing spatial locations and attribute information for use in analysis. Methodologies studied included locating points by hand, by Global Positioning System, by latitude and longitude, and by railroad milepost through the use of dynamic segmentation of the railroad line file. Locating points by hand proved to be the most accurate method.

CHAPTER III

METHODOLOGY AND PROCEDURES

As part of this study, a preliminary analysis was performed on crash data for the Denver RTD Light Rail Central Corridor and Central Platte Valley Corridor to determine if two existing railroad crossing hazard index and crash prediction equations adequately predicted crashes at these light rail crossings and if there was need for this study. The results of the Denver RTD Light Rail crash data analysis were used to help outline and develop the methodology to be used in this study.

The methodology of this study includes reviewing a summary of factors that have been used in railroad crossing hazard index and crash prediction equations over the years and analyzing each element to determine which (if any) of these data elements should be gathered as part of this study. In addition to the review of railroad crossing data elements, two new data elements specific to light rail crossings and operations that will be gathered are discussed and defined. Finally, each model development methodology identified in the literature review is discussed to determine if the methodology is a viable candidate to be used in the equation development.

The study procedures were determined from the outlined methodology for the study. Study procedures include defining the study period, outlining the necessary data collection and data gathering techniques, reviewing the study data, developing the models, outlining statistical testing for the developed models, and developing a GIS model using the newly developed equations.

Preliminary Analysis of Denver RTD Crashes[2]

A preliminary analysis of light rail vehicle crashes with motor vehicles that occurred on the Denver RTD Central Corridor and Central Platte Valley Corridor in Denver, Colorado was conducted to determine whether there are significant differences between light rail configurations and/or operations and those of railroad and/or commuter rail operations that may affect these crash occurrences. A general description of the Denver RTD light rail system is provided. The preliminary analysis involves an analysis of Denver RTD crash data for the years 1999 through 2009 and a preliminary statistical analysis of the Denver RTD crash data compared to the number of crashes predicted by two railroad hazard index and crash prediction formulas.

Description of the Denver RTD Light Rail System in Denver, Colorado

The Denver RTD website contains various Light Rail Corridor Fact Sheets that provide a history of Denver RTD light rail operations (Denver Regional Transportation District 2010). Denver RTD started light rail operations in Denver, Colorado on October 7, 1994 with the opening of the 5.3 mile-long Central Corridor. Denver RTD extended its operations with the addition of the 8.7 mile-long Southwest Corridor on July 17, 2000; the 1.8 mile-long Central Platte Valley Corridor on April 5, 2002; the 19 mile-long Southeast Corridor on November 17, 2006; and the 12.1 mile-long West Corridor on April 24, 2013. Figure III.1 shows the Denver RTD light rail system as of November 2013.

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[2] The preliminary analysis of Denver RTD crashes was presented at the Transportation Research Board 91st Annual Meeting in Washington, D.C. (Fischhaber and Janson 2012) and published in the Transportation Research Record Volume 2275 (Fischhaber and Janson 2012).

The light rail crossings added with the Southwest and Southeast Corridors are all grade-separated crossings. The light rail crossings added with the West Corridor include 23 light rail crossings with active warning devices and 16 grade-separated crossings.

The number of light rail vehicles using the light rail crossings in the Central Corridor increased with the addition of the Southwest and Southeast Corridors as did the total number of crashes occurring at these light rail crossings. The addition of the West Corridor did not add any additional light rail vehicles using the light rail crossings in the Central Corridor, and crash information is not included in this study as the corridor has only been in operation since April 2013.

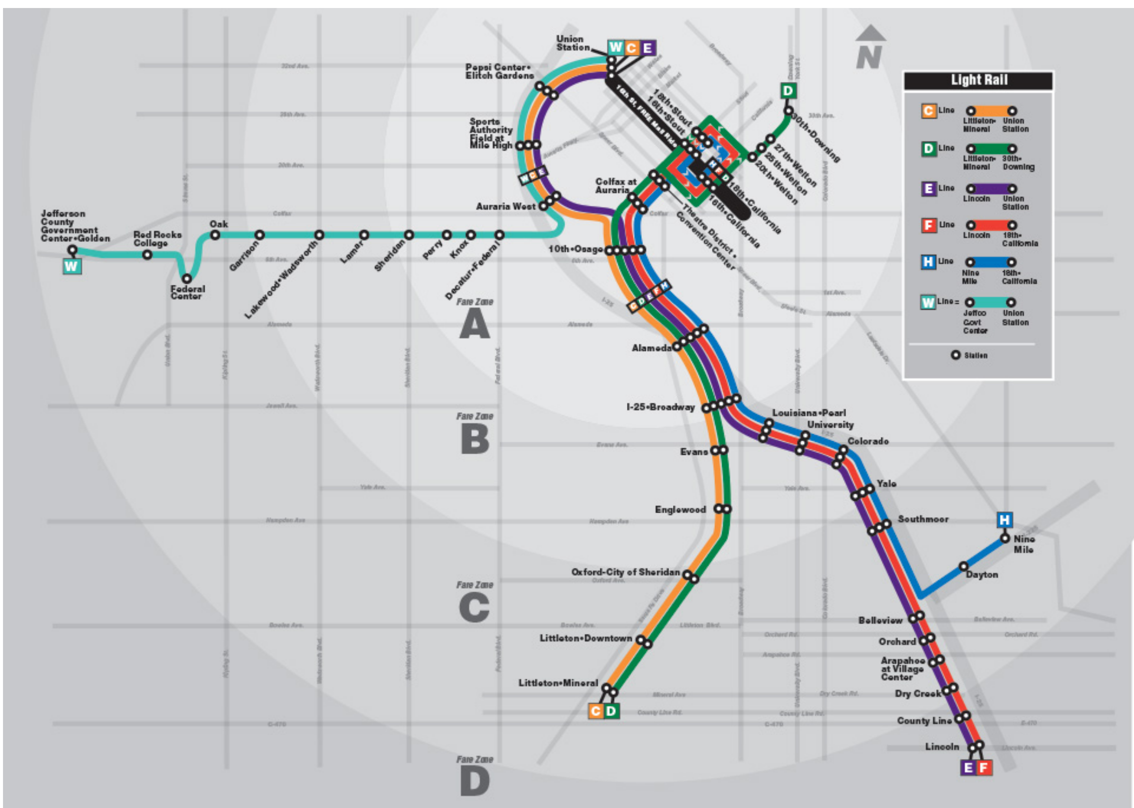


Figure III.1 Denver Regional Transportation District (2013) Light Rail System Map.

Denver RTD currently operates six light rail lines: the C Line from Denver Union Station to the Mineral Station on the Southwest Corridor (83 trains per day); the D Line from the 30th and Downing Station along the Central Corridor to the Mineral Station on the Southwest Corridor (140 trains per day); the E Line from Denver Union Station to the Lincoln Station on the Southeast Corridor (74 trains per day); the F Line from the segment of the Central Corridor in Downtown Denver to the Lincoln Station on the Southeast Corridor (123 trains per day); the H Line from the segment of the Central Corridor in Downtown Denver to the Nine Mile Station on the Southeast Corridor I-225 segment (170 trains per day); and the W Line from Denver Union Station to the Federal Center Station or the Jefferson County Government Center Station on the West Corridor (228 trains per day). When the Southeast Corridor first opened, Denver RTD operated a G Line that ran from the Lincoln Station to the Nine Mile Station on the Southeast Corridor I-225 segment. Denver RTD eliminated the G Line service due to low ridership. To reach any of the stations along the previous G Line, riders must transfer trains at the Southmoor Station. The above information can be found on the Denver RTD website (Denver Regional Transportation District).

The Denver RTD system, prior to the addition of the West Corridor, had 144 street crossings including 76 grade-separated crossings and 68 at-grade crossings. Of the 68 at-grade crossings, eight crossings involve driveways; 54 are at or near traffic intersections; one is a private Denver RTD vehicle access only crossing; and five are traditional crossings not located at or near intersections. The five traditional crossings not near intersections warn drivers with flashing lights, gates, and bells. Eight of the 31 intersection crossings use stop signs to control motor vehicle drivers, pedestrians and bicyclists. The remaining 23 intersections use standard traffic signals to control and warn drivers, pedestrians, and bicyclists. The eight driveway crossings typically warn motorists with passive signs, but a few of these crossings have active warning “No Turn” signs that illuminate when a light rail vehicle is approaching.

With the exception of the private Denver RTD vehicle access only crossing and prior to the addition of the West Corridor, all of the at-grade crossings on the Denver RTD system were along the Central Corridor and Central Platte Valley Corridor. The Central Platte Valley Corridor has one of the intersection crossings, and the remainder of the intersection crossings and driveway crossings are along the Central Corridor. Figure III.2 shows a GIS map enlargement of the Central Corridor and Central Platte Valley Corridor in the downtown Denver area. Figure III.3 shows examples of the types of at-grade crossings on the Denver RTD system.

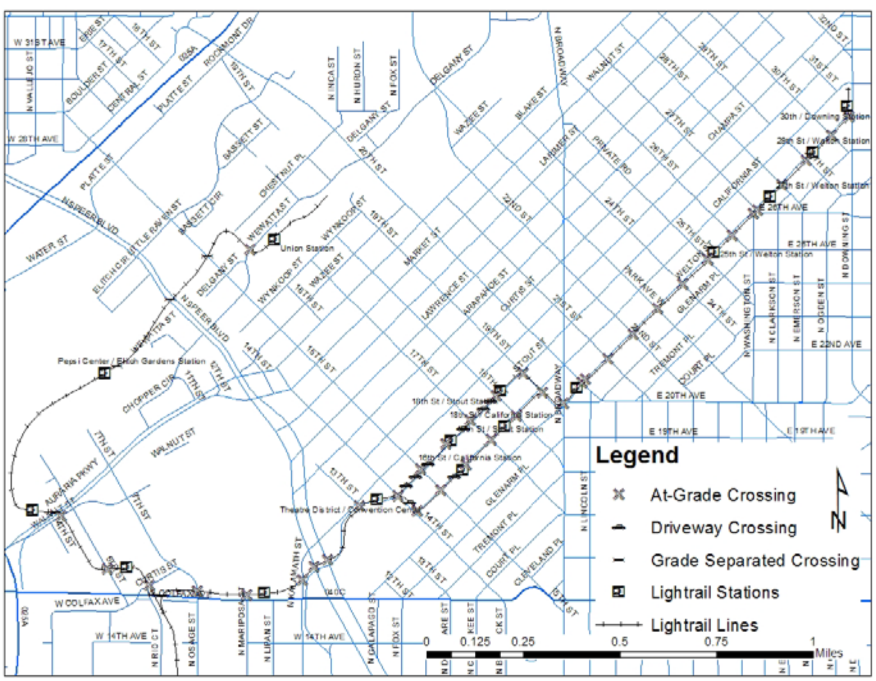
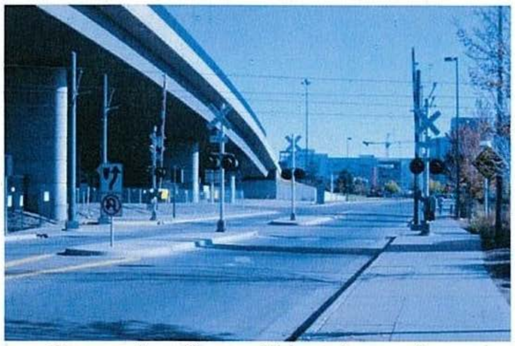


Figure III.2 Denver RTD Light Rail Crossing Locations of the Central Corridor and Central Platte Valley Corridor in the Downtown Denver Area.



Example of a traditional crossing

Example of a traditional signal controlled crossing

Example of a driveway crossing

Figure III.3 Examples of Denver RTD At-Grade Crossings.

The crash analysis used in this study was performed on the Denver RTD Central Corridor and Central Platte Valley Corridor. The majority of Denver RTD's light rail system included in these two corridors is two-track. However, there are areas in downtown Denver and a segment along Welton Street where the light rail operates on single track. In the downtown Denver area, the light rail operates on a single track in a contraflow configuration on California Street, Stout Street, 14th Street and 19th Street. Denver RTD also operates on single track with light rail vehicles traveling in both directions along Welton Street from just south of 25th Street to just south of the 30th and Downing Station.

Denver RTD's operation also has a number of configurations with motor vehicle operations. For this study, seven different configurations of light rail vehicle operations with two-way motor vehicle operations and six different configurations of light rail operations with one-way motor vehicle operations were preliminarily identified. These configurations include both traditional crossing operations that are perpendicular to roadway operations and various parallel light rail vehicle/roadway vehicle operations with light rail vehicles operating either in a one-way or a two-way configuration. These configurations will be defined and described in greater detail later in Chapter III.

Preliminary Denver RTD Crash Data Analysis

A preliminary analysis of Denver RTD light rail crashes in the years 1999 to 2009 was performed to examine their characteristics and to compare their frequencies of occurrence to the frequency of occurrence as predicted by the railroad crash prediction and hazard index formulas. During this period, Denver RTD reported a total of 199 crashes, incidents, and hazards to its State Safety Oversight Agency. After analysis of those crashes/incidents/hazards reported, 20 incidents and hazards were removed from the analysis because they were not intersection crashes. These included one structural failure, seven derailments (six tail track derailments and one derailment due to a Union Pacific Railroad derailment), two brake fires, two situations of overheated bearings, two bomb threats, and six trespasser incidents.

A total of 179 crashes from 1999 through 2009 were analyzed. Of these crashes, 160 occurred at light rail crossings, and 19 occurred at stations. Twenty-eight crashes involved pedestrians: 17 pedestrian crashes at crossings and 11 pedestrian crashes at stations. Two crashes involved bicyclists: one bicycle crash at a crossing and one bicycle crash at a station. More than 75% of the crashes occurred in clear weather conditions. Very few crashes occurred during dawn or dusk hours; of the crashes 62% occurred during daylight hours and about 25% occurred during the dark hours.

The severity of the crashes was recorded for 176 crashes. Of these, three crashes resulted in fatalities (all fatalities were pedestrian fatalities); 83 crashes resulted in injuries or transport of individuals away from the scene; 89 crashes involved property damage only; and one crash was a hit and run. Motor vehicle drivers were cited by the police in approximately 41% of the 160 at-grade crossing crashes (police did not respond to all light rail crashes), and motor vehicle driver actions were found to be the contributing factor in more than 76% of the crashes.

Five of the 160 light rail crossing crashes occurred at light rail crossings with flashing lights, gates, and bells as the warning device; 21 occurred at driveways with no traffic control; 32 occurred at stop sign-controlled intersections; and 102 occurred at intersections controlled by traffic signals.

No significant crash trends were identified in the above analysis of the 160 light rail crossing crashes.

Figure III.4 shows the number of crashes per year on the Denver RTD system from 1999 through 2009. There was a slight increase in crashes when the Southwest Corridor started revenue service in 2000, but there was a much greater increase in crashes when the Southeast Corridor started service toward the end of 2006. Reviewing the crashes in 2006 and 2007, the number of trains running through the Central Corridor more than doubled in late 2006 when the Southeast Corridor began operations, which explains some of the increase in crashes for 2006 and 2007. Weather appears to be another reason for the crash increase during this period. Figure III.5 shows the weather conditions at the time of crashes on the Denver RTD light rail system for 1999 through 2009. The Denver metropolitan area experienced major blizzards and snow storms every week for approximately seven weeks in the end of 2006 and the beginning of 2007. More than half of the crashes that occurred during the first three months of the Southeast Corridor operations occurred in snowy conditions during that time period.

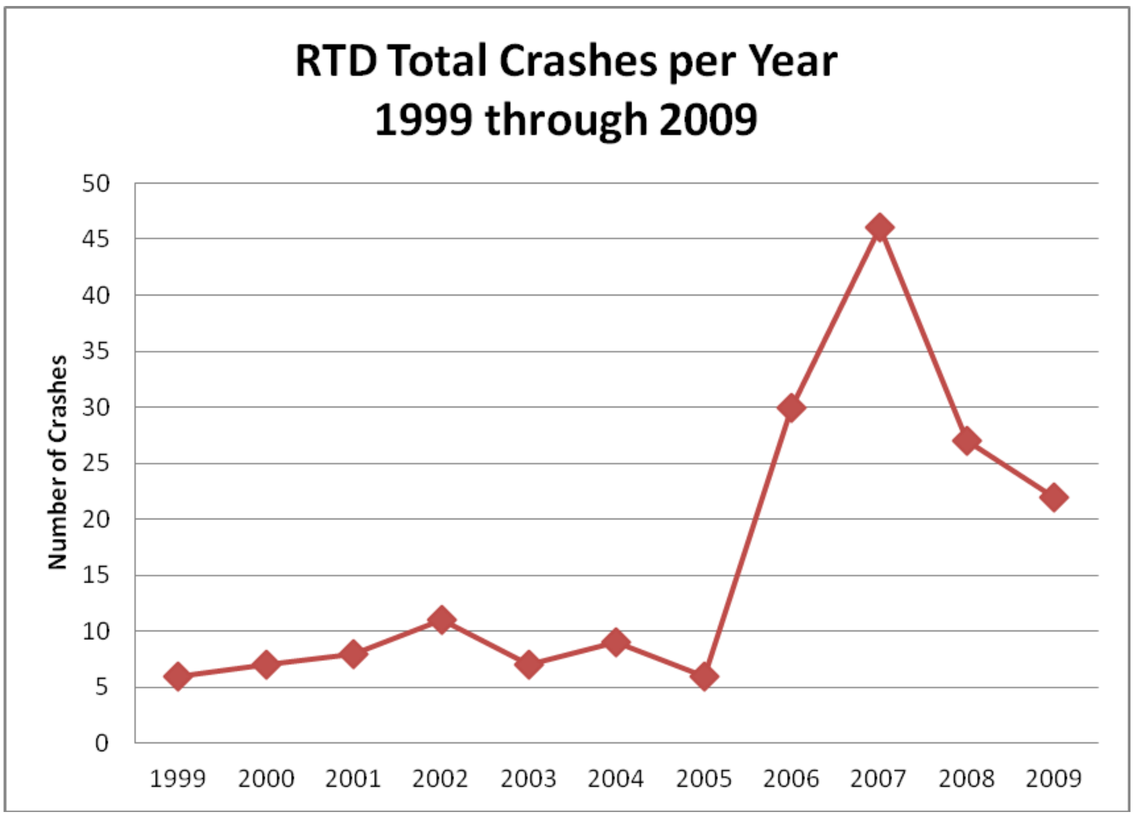


Figure III.4 Denver RTD Total Crashes Per Year from 1999 Through 2009.

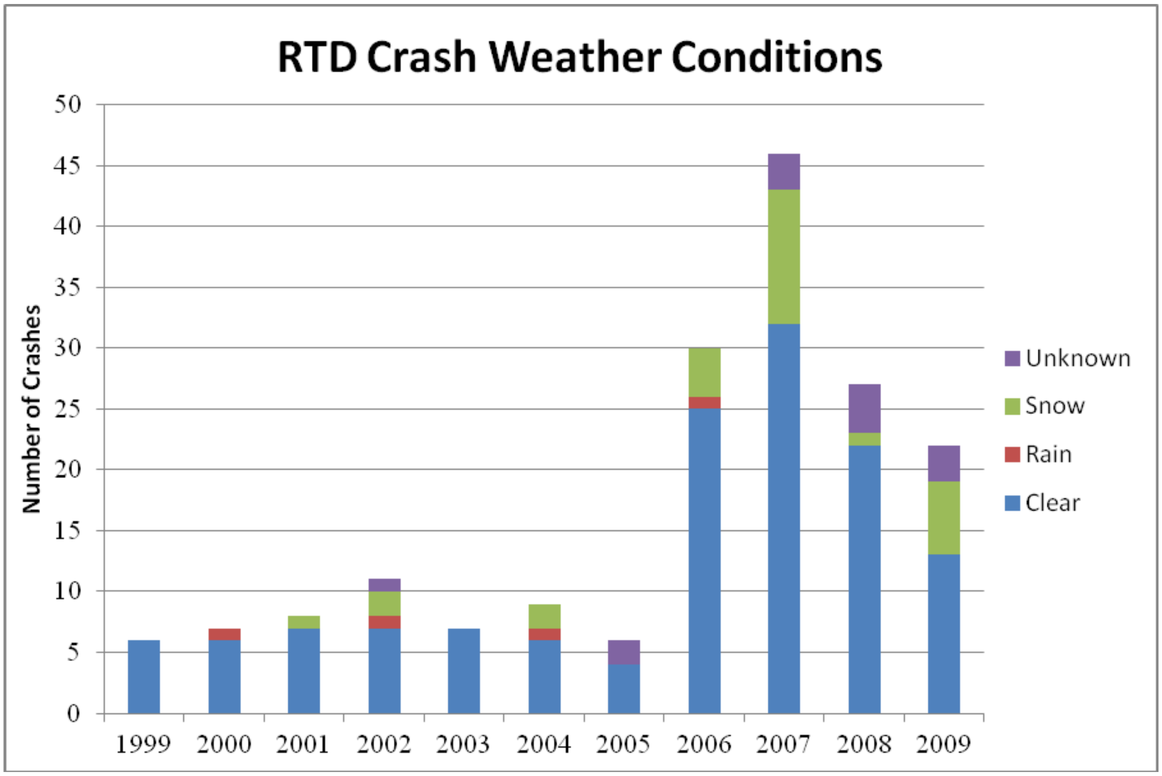


Figure III.5 Denver RTD Crash Weather Conditions.

There are two areas on the Denver RTD light rail system where there are higher concentrations of crashes: the Cascades area by the Auraria Campus and the Welton Street Corridor. Both areas are located on the Central Corridor. Of the 160 crashes that occurred at light rail crossings from 1999 to 2009, 43% occurred at the five light rail crossings adjacent to the Auraria Campus (7th Street, 9th Street, Kalamath Street north of Colfax Avenue, Speer Boulevard Northbound, and Speer Boulevard Southbound), and 30% occurred at crossings located along the Welton Street corridor on the north end of the Central Corridor alignment. Figure III.6 shows the crashes for 1999 through 2009 on the Denver RTD system along the Central Corridor.

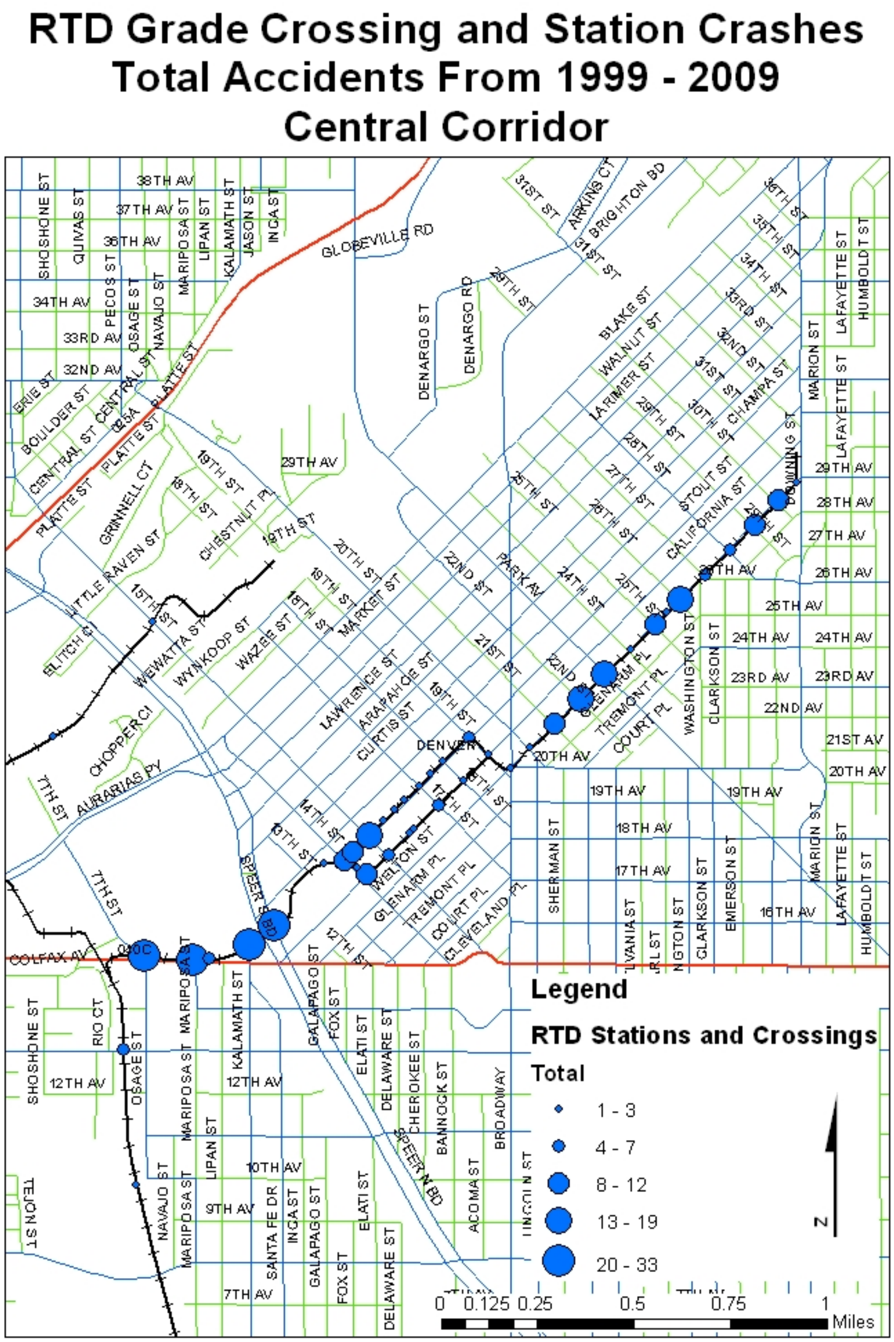


Figure III.6 Denver RTD System Central Corridor Crashes 1999 Through 2009.

The University of Colorado Denver, Metropolitan State University of Denver, and the Community College of Denver are all located on the Auraria Campus. The five light rail crossings near the Auraria campus experience high traffic conditions with many pedestrians and bicyclists. Thus, motor vehicle drivers must keep track of many traffic movements in this area.

In addition, 7th Street and 9th Street serve as vehicle access for the Auraria Campus. There may be a higher rate of light rail and motor vehicle crashes at these two crossings due to students rushing to and from classes. However, specific driver age information is not available for the crashes reviewed to confirm this theory.

Further, light rail vehicles make a near 90 degree turn from under a bridge structure before traversing the 7th Street crossing. This configuration could lead to sight distance issues for motor vehicle drivers approaching this crossing from the west or south legs of the intersection with Colfax Avenue. Grechka and Janson (2006) studied the driver behavior effects of certain countermeasures installed at the 7th Street crossing of Colfax. That study found a significant decrease in risky maneuvers by motor vehicle drivers (such as stopping on the light rail tracks) when the stop bar line and light rail warning signs were placed further back from the light rail crossing.

The Central and Central Platte Valley Corridors contain a number of different configurations with the direction of train flow and the direction of motor vehicle traffic flow. Figure III.7 shows the number of crashes in the Central and Central Platte Valley Corridors with respect to the direction of train flow versus traffic flow. A review of Figure III.7 shows that 65% of the crashes occurred either at light rail crossings where the light rail vehicles were moving counter to the one-way vehicle traffic flow or in locations where light rail vehicles moved in two directions with one-way vehicle traffic flow. From the Central Corridor end-of-line station at 30th and Downing Streets through the Downtown Denver area to the Convention Center Station, motor vehicles travel one-way while light rail vehicles either travel one way in the opposite direction of motor vehicles or light rail vehicles travel in both directions adjacent to one-way motor vehicle travel. For the Welton Street corridor on the north end of the Central Corridor where motor vehicles move one-way northbound and light rail vehicles travel in both directions. With these two locations, almost two-thirds of the 160 crashes involved a southbound moving light rail vehicle. For the majority of the crashes along the Welton Corridor, and all of the driveway crashes, drivers were looking south for gaps in northbound motor vehicle traffic. When the driver found a gap in motor vehicle traffic while looking south, the driver failed to look north to see if a light rail vehicle was approaching the light rail crossing. These crash numbers support to the discussion on page 67 of TCRP Report 17 that explains why contraflow light rail operations should be avoided and what types of accidents could occur as a result of constructing a light rail system with contraflow (Korve et al. 1996).

Thirty-eight crashes occurred primarily at traditional crossings, and one crash occurred at the wye crossing with 14th and Stout Streets. A wye crossing is a triangle of track that allows trains to turn around in order to travel in a different direction.

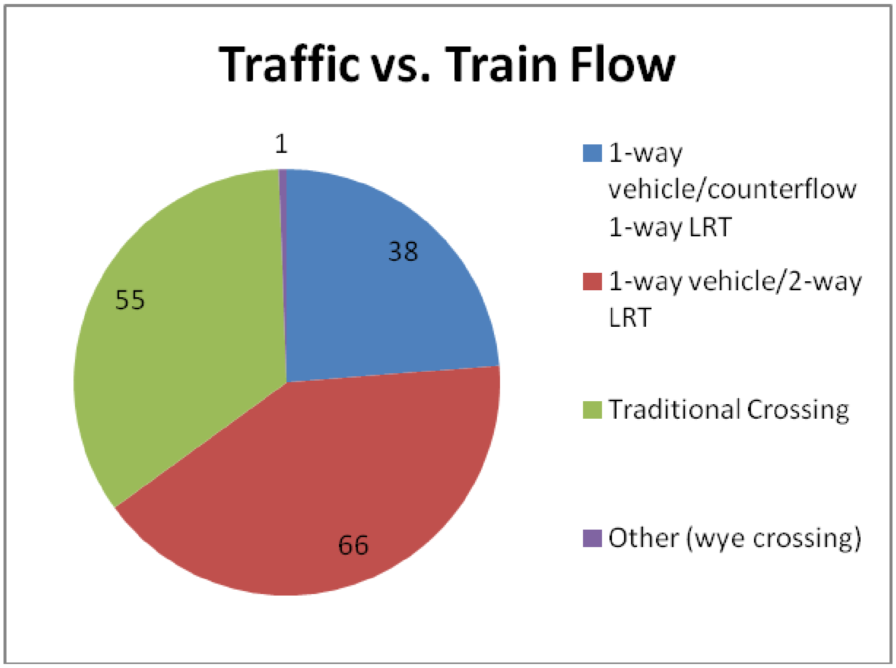


Figure III.7 Number of Crashes on Denver RTD Central and Central Platte Valley Corridors Compared to Traffic and Train Flow Directions.

Preliminary Statistical Analysis of Denver RTD Crash Data

A preliminary statistical analysis was performed comparing the number of crashes predicted by the Peabody-Dimmick formula (shown in Equation II.1.), and the US DOT Accident Prediction formulas (shown in Equations II.5 to II.7) with the actual crashes experienced at Denver RTD's light rail crossings.

The protection coefficient P used in the Peabody-Dimmick formula is determined from a table of coefficients for different types of crossing warning devices, and the additional parameter K can be determined based on a figure presented by Peabody and Dimmick (1941) that was created based on the empirical data as opposed to graphed with an equation. No protection coefficient exists for railroad crossings for which warning is provided by traffic signal operations.

Neither the Peabody Dimmick hazard index formula nor the US DOT crash prediction formula includes information that allow the prediction of crashes at railroad crossings with a traffic signal warning device. The likely reason these prediction models have not been calibrated to account for crossings with traffic signal control is the fact that, of the approximately 133,000 public railroad crossings in the United States of America, only about 350, or 0.27% of the total number of railroad crossings, are controlled by traffic signals. In contrast, 74% of Denver RTD light rail crossings on the Central and Central Platte Valley Corridors are controlled by traffic signals. The lack of information for railroad crossings controlled by traffic signals in the railroad crash prediction equations may be one reason that light rail specific equations may need to be developed.

For purposes of performing a statistical comparison of actual Denver RTD light rail crashes at light rail crossings controlled by traffic signals, the predicted number of crashes at each light rail crossing was calculated for both flashing light and bell crossing operations and for gate operations. Because no updates to these formulas have been developed to account for traffic signals, it is currently unknown how representative this comparison will be.

Predicted crashes were calculated for each Denver RTD light rail crossing using both the Peabody Dimmick and the US DOT crash prediction formulas. The Peabody Dimmick formula K table data were extrapolated for all unbalanced hazard ratings past five in order to accommodate the 430 trains per day that pass through some light rail crossings on the Denver RTD system; these were not based on empirical data from the Peabody Dimmick study. Since the Peabody Dimmick formula predicts crashes for five years, the results were divided by five to show expected crashes on a per year basis. Total crashes at each light rail crossing location were divided by the 11-year study period to determine the average number of crashes per year. Light rail crossing locations were grouped into those controlled by traffic signals and those controlled by warning signs.

Fischhaber and Janson (2012) performed a paired t-test between the actual and predicted crashes at each light rail crossing according to these two formulas with the null hypotheses being that the mean of the sample of predicted crashes is equal to the mean of the sample of actual crashes. While this statistical test showed that the mean of the actual crash volumes was statistically different from the means calculated by the Peabody-Dimmick and US DOT Formulas, upon further reflection of the data, calculation of the F-statistic R, and R^2 values was determined to be the more appropriate statistical model to analyze the data. The F-statistic shows how well the proposed model fits the actual data, and this is the better statistical test for this research. For the F-statistic, the null hypothesis is that equation coefficients are equal to zero, meaning that the calculated value is not related to any of the input variables. Table III.1 shows the results of this comparison for the eight sign-controlled light rail crossings and Table III.2 and Table III.3 shows results of this comparison for the 23 light rail crossings controlled by traffic signals using proxy models for flashing lights (Table III.2) and gates (Table III.3). This comparison was not performed for the 21 driveway light rail crossings or for the one light rail crossing controlled by flashing lights, gates, and bells that is not a shared crossing with any railroad crossings.

Table III.1 Statistical Analysis of Actual RTD Crossing Crashes versus Peabody-Dimmick and US DOT Formula Predicted Crashes for Sign Control.

	Crashes per Year			Peabody-Dimmick Signs			US DOT Signs		
Sign Control	Actual	Peabody Dimmick Signs	US DOT Signs	SST	SSR	SSE	SST	SSR	SSE
21st St./Welton St.	0.55	4.178	0.36	0.30	17.46	13.20	0.30	0.13	0.04
22nd St./Welton St.	0.73	4.178	0.46	0.53	17.46	11.91	0.53	0.21	0.07
24th St./Welton St.	0.18	4.178	0.15	0.03	17.46	15.97	0.03	0.02	0.00
25th St./Welton St.	0.27	4.178	0.2	0.07	17.46	15.25	0.07	0.04	0.01
26th St./Welton St.	0.27	4.178	0.2	0.07	17.46	15.25	0.07	0.04	0.01
28th St./Welton St.	0.09	4.178	0.1	0.01	17.46	16.70	0.01	0.01	0.00
29th St./Welton St.	0.55	4.178	0.35	0.30	17.46	13.20	0.30	0.12	0.04
30th St./Welton St.	0.27	4.178	0.2	0.07	17.46	15.25	0.07	0.04	0.01
Sample Average	0.36		Sum	1.39	139.6	116.7	1.39	0.60	0.17
			R^2=	0.54			0.43		
			R =	0.74			0.66		
			n=	8			8		
			k=	3			3		
			F_{stat} =	1.59			4.81		
			p-value =	0.32			0.08		
			F_{crit} =	5.78			5.78		
			H0 : $\beta1=\beta2=\ldots\beta k=0$	Accept			Accept		

Table III.2 Statistical Analysis of Actual RTD Crossing Crashes versus Peabody-Dimmick and US DOT Formula Predicted Crashes for Traffic Signal Control Using Flashing Light Equations as a Proxy.

	Crashes Per Year					Peabody Dimmick			US DOT		
		Peabody Dimmick		US DOT		Flashing Lights			Flashing Lights		
Traffic Signal Control	Actual	Flashing Lights	Gates	Flashing Lights	Gates	SST	SSR	SSE	SST	SSR	SSE
14th/California	0.18	3.16	2.02	0.12	0.11	0.05	7.59	8.86	0.05	0.08	0.00
14th/Stout	0.09	5.19	3.06	0.08	0.09	0.10	22.88	25.96	0.10	0.10	0.00
15th/California	0.09	6.81	3.79	0.08	0.08	0.10	41.05	45.15	0.10	0.10	0.00
15th/Stout	0.36	6.49	3.65	0.21	0.21	0.00	37.10	37.58	0.00	0.04	0.02
16th/California	0.00	2.20	1.33	0.04	0.03	0.16	3.21	4.82	0.16	0.13	0.00
16th/Stout	0.00	2.20	1.33	0.04	0.03	0.16	3.21	4.82	0.16	0.13	0.00
17th/California	0.18	6.81	3.79	0.13	0.13	0.05	41.05	43.93	0.05	0.08	0.00
17th/Stout	0.18	6.06	3.46	0.13	0.13	0.05	32.05	34.60	0.05	0.08	0.00
18th/California	0.00	5.81	3.35	0.04	0.04	0.16	29.21	33.73	0.16	0.13	0.00
18th/Stout	0.00	6.44	3.63	0.04	0.04	0.16	36.44	41.47	0.16	0.13	0.00
19th/California	0.00	7.58	0.52	0.04	0.04	0.16	51.45	57.40	0.16	0.13	0.00
19th/Stout	0.45	5.17	3.05	0.24	0.23	0.00	22.70	22.22	0.00	0.03	0.04
19th/Broadway	0.09	10.16	5.24	0.08	0.08	0.10	95.16	101.35	0.10	0.10	0.00
20th/Welton	0.18	7.75	4.20	0.13	0.13	0.05	53.92	57.22	0.05	0.08	0.00
27th/Welton	0.18	2.54	1.61	0.12	0.11	0.05	4.58	5.58	0.05	0.08	0.00
7th St.	1.36	6.90	3.83	0.70	0.74	0.92	42.18	30.63	0.92	0.09	0.44
9th St.	0.36	3.04	1.95	0.20	0.20	0.00	6.96	7.17	0.00	0.04	0.03
N. Kalamath St.	1.73	8.17	4.38	0.86	0.92	1.75	60.39	41.56	1.75	0.21	0.75
N. Speer Blvd. NB	0.91	11.43	5.78	0.48	0.51	0.26	121.64	110.73	0.26	0.01	0.19
N. Speer Blvd. SB	1.91	9.64	5.01	0.96	1.04	2.27	85.28	59.74	2.27	0.31	0.89
Park Ave. West/Welton	0.91	6.44	3.63	0.46	0.47	0.26	36.44	30.59	0.26	0.00	0.20
Welton/N. Downing	0.09	3.45	2.19	0.08	0.07	0.10	9.27	11.27	0.10	0.11	0.00
16th/Wewatta	0.00	2.94	1.88	0.04	0.03	0.16	6.44	8.64	0.16	0.13	0.00
Sample Average	0.40				Sum	7.1	850.2	825.0	7.1	2.3	2.6
					R^2=	0.51			0.33		
					R =	0.71			0.57		
					n=	23			23		
					k=	3			12		
					F_{stat} =	6.53			0.75		
					p-value =	0.00			0.69		
					F_{crit} =	3.49			2.82		
					$H_0 : \beta_1=\beta_2=\ldots\beta_k=0$	Reject			Accept		

Table III.3 Statistical Analysis of Actual RTD Crossing Crashes versus Peabody-Dimmick and US DOT Formula Predicted Crashes for Traffic Signal Control Using Gates Equations as a Proxy.

	Crashes Per Year					Peabody Dimmick			US DOT		
		Peabody Dimmick		US DOT		Gates			Gates		
Traffic Signal Control	Actual	Flashing Lights	Gates	Flashing Lights	Gates	SST	SSR	SSE	SST	SSR	SSE
14th/California	0.18	3.16	2.02	0.12	0.11	0.05	2.61	3.38	0.05	0.09	0.01
14th/Stout	0.09	5.19	3.06	0.08	0.09	0.10	7.07	8.83	0.10	0.10	0.00
15th/California	0.09	6.81	3.79	0.08	0.08	0.10	11.47	13.68	0.10	0.10	0.00
15th/Stout	0.36	6.49	3.65	0.21	0.21	0.00	10.54	10.80	0.00	0.04	0.02
16th/California	0.00	2.20	1.33	0.04	0.03	0.16	0.86	1.77	0.16	0.14	0.00
16th/Stout	0.00	2.20	1.33	0.04	0.03	0.16	0.86	1.77	0.16	0.14	0.00
17th/California	0.18	6.81	3.79	0.13	0.13	0.05	11.47	13.02	0.05	0.08	0.00
17th/Stout	0.18	6.06	3.46	0.13	0.13	0.05	9.34	10.75	0.05	0.08	0.00
18th/California	0.00	5.81	3.35	0.04	0.04	0.16	8.66	11.20	0.16	0.13	0.00
18th/Stout	0.00	6.44	3.63	0.04	0.04	0.16	10.39	13.15	0.16	0.13	0.00
19th/California	0.00	7.58	0.52	0.04	0.04	0.16	0.01	0.27	0.16	0.13	0.00
19th/Stout	0.45	5.17	3.05	0.24	0.23	0.00	7.03	6.76	0.00	0.03	0.05
19th/Broadway	0.09	10.16	5.24	0.08	0.08	0.10	23.36	26.47	0.10	0.10	0.00
20th/Welton	0.18	7.75	4.20	0.13	0.13	0.05	14.39	16.11	0.05	0.07	0.00
27th/Welton	0.18	2.54	1.61	0.12	0.11	0.05	1.45	2.03	0.05	0.09	0.01
7th St.	1.36	6.90	3.83	0.70	0.74	0.92	11.73	6.07	0.92	0.11	0.39
9th St.	0.36	3.04	1.95	0.20	0.20	0.00	2.39	2.52	0.00	0.04	0.03
N. Kalamath St.	1.73	8.17	4.38	0.86	0.92	1.75	15.83	7.05	1.75	0.26	0.66
N. Speer Blvd. NB	0.91	11.43	5.78	0.48	0.51	0.26	28.95	23.76	0.26	0.01	0.16
N. Speer Blvd. SB	1.91	9.64	5.01	0.96	1.04	2.27	21.24	9.63	2.27	0.40	0.76
Park Ave. West/Welton	0.91	6.44	3.63	0.46	0.47	0.26	10.39	7.38	0.26	0.01	0.19
Welton/N. Downing	0.09	3.45	2.19	0.08	0.07	0.10	3.20	4.41	0.10	0.11	0.00
16th/Wewatta	0.00	2.94	1.88	0.04	0.03	0.16	2.19	3.55	0.16	0.14	0.00
Sample Average	0.40				Sum	7.1	215.4	204.4	7.1	2.5	2.3
					R^2=	0.5			0.4		
					R =	0.7			0.6		
					n=	23			23		
					k=	3			12		
					F_{stat} =	6.7			0.9		
					p-value =	0.0			0.6		
					F_{crit} =	3.5			2.8		
					$H_0 : \beta_1=\beta_2=...\beta_k=0$	Reject			Accept		

The US DOT crash prediction formulas have a greater number of inputs that better represent the operations at the light rail crossing. Although there is a significant difference statistically between the actual number of Denver RTD crashes and the number of crashes predicted by the US DOT formulas, the number of crashes predicted by the US DOT formulas is much closer to the actual Denver RTD crash data than is the number of crashes predicted by the Peabody Dimmick formula. Contraflow operations, which occur at the majority of the study light rail crossings under traffic signal control and at all of the study light rail crossings under passive control, need to be investigated as one of the factors for the increased crash risk at these light rail crossings. Differences between these two crash prediction formulas should be considered in determining the types of light rail crossing information to be included in developing light rail specific crash equations.

Conclusions Based on Preliminary Denver RTD Crash Data Analysis

Based on a preliminary analysis of crash data from 1999 through 2009 for the Denver RTD light rail Central and Central Platte Valley Corridors, it appears there are characteristics of light rail crossing configurations and/or operations that are different enough from those of railroads/commuter rail to affect the number and severity of crashes that occur at light rail crossings versus railroad crossings. A review of the Denver RTD data shows some areas of configuration and operational differences that experience a higher number of crashes than in areas that resemble traditional railroad/commuter rail configurations and operations. One such difference is: there are higher numbers of crashes in areas where there is one-way motor vehicle flow and either contraflow or two-way light rail vehicle flow. The preliminary analysis results indicate that, based on statistical comparison and on existing equations not being calibrated or developed to determine crashes at light rail crossings controlled by traffic signals or in areas of light rail vehicle contraflow, the railroad crossing hazard index and crash prediction equations are significantly different statistically. Therefore, this research to develop crash prediction and/or hazard index equations specific to light rail is necessary.

While specific differences have been identified on the Denver RTD system, there are likely other differences with other light rail systems throughout the country. When reviewing data from other light rail systems, special consideration will need to be given to types of warning devices, light rail vehicle flow versus traffic flow, and operational characteristics. These factors may lead to differences in predicted crashes and indicate that there may be statistically significant differences in crashes that occur at these various types of light rail crossings.

Research Questions Answered by Preliminary Denver RTD Crash Data Analysis

Based on the preliminary analysis of the 1999 through 2009 crash data for the Denver RTD system, the answer to research question one appears to be that there are operational characteristics of light rail that are different enough from common carrier railroads to affect the number and severity of crashes that occur at light rail crossings compared to railroad crossings given the use of the same crash prediction and hazard index equations. The statistical analysis of the Denver RTD system shows that at a 99% confidence interval, the actual number of crashes that occurred at the Denver RTD light rail crossings was significantly different statistically than the number of crashes predicted by the Peabody Dimmick formula and the US DOT crash prediction formula for both light rail crossings with active traffic signal warnings and light rail crossings with passive sign warnings. While there may be some question regarding the validity of the statistical comparison of the traffic signal-controlled light rail crossings, the fact is that the number of predicted crashes for light rail crossings with signs as warning devices was significantly different statistically from the number or actual crashes when using formulas that needed no changes or assumptions when using the formula. This preliminary analysis supports the hypothesis that the answer to research question two is: development of crash prediction or hazard index analysis equations specifically for light rail crossings will provide a better model to predict the number and severity of crashes at light rail crossings and thus will better determine the safety at the light rail crossings.

Study Methodology

The methodology used in this study will consist of two main areas: data collection and determination of modeling methodologies to use. Data collection will involve a review and analysis of data elements used in the various railroad crossing hazard index and crash prediction models to determine what types of data to gather as part of this study. Additionally, two new data elements specific to light rail crossings and light rail operations will be defined and discussed. These two data elements are the alignment of the light rail tracks to surrounding roadways and environments (exclusive, semiexclusive, and nonexclusive) and the configuration of light rail tracks relative to surrounding roadways (median running, side running, and perpendicular running).

In regards to modeling methodologies to use, modeling methodologies that have been used to develop the various railroad crossing hazard index and crash prediction models reviewed as part of this study will be reviewed for feasibility of use in this study. Additionally, other modeling methodologies will be reviewed that, while not previously used to develop railroad crossing-specific equations, should be considered as possible new techniques. These model development methodologies will be analyzed and discussed in light of probable data available for this study to determine which methodologies are viable candidates for use in study equation development.

Data Collection

Five major areas of data collection were identified based on a review of the literature for railroad crossing hazard index and accident prediction calculations. As summarized in Chapter II, these areas are data related to light rail crossings, roadways, trains, vehicles, and miscellaneous items. Additionally, Table 17 of the Railroad-Highway Grade Crossing Handbook (Olson et al. 1978), which summarizes the frequency of use of data elements in hazard index or accident prediction formulas used by State Highway Agencies at that time, will be reviewed. This list and Table 17 will be referenced when considering which factors may be relevant to light rail crossings and light rail operational environments and for which data should be collected, if available, for use in developing light rail crossing specific hazard index or crash prediction equations.

Crossing Related Data. Crossing related data that have been used in various hazard index and crash prediction calculations include crash experience, crash severity, angle of crossing, crossing warning device, crossing width, crossing surface material, condition of the crossing, distance to nearest intersection, exposure factor, number of main tracks, number of other tracks, parallel road characteristics, sight distance rating, sight obstructions, train detector distance, urban or rural nature of the crossing, and year of last inspection.

Crash experience is a data input into two of the specific formulas discussed in this study, and has been used in 12 state formulas. Crash experience data should be included in the initial light rail crossing model development as the equations being developed will be predicting this number. Crash experience data should be relatively straightforward to obtain from transit agencies that are willing to share such data.

The angle of crossing is a data factor that has not been used in any of the specific formulas discussed in this study and has been used in11 state formulas. While it is currently unknown if or how this data factor will be included in any model developed, this information should be collected for this study because of the relative simplicity of gathering the information from aerial photos.

Crossing warning devices is a data input through a protection coefficient or protection factor to three of the specific formulas discussed in this study and is a data factor included in 27 state formulas. This information should be included in the initial light rail crossing model development because a review of railroad crash prediction and hazard index equations generally shows that warning devices are either an input into these models through a factor or are a category under which model results are reported. This data factor should be relatively easy to obtain from aerial photos and from ground view photos of each light rail crossing.

Crossing width information is not an input to any of the specific formulas discussed for this study and is not included in any state formulas. While this data element has been used in some existing hazard index and crash prediction equations, it is unknown at this time how important this data element will be in the development of a light rail crossing specific crash prediction model. This data element should be relatively easy to obtain by measuring crossing width from aerial photos of crossings and should be collected for this study.

Crossing surface material and condition are not inputs in any of the specific formulas discussed in this study, but have been included in three state formulas. It is likely that most light rail crossing surfaces are in acceptable condition and that this data element will not be a factor in any light rail crossing specific crash prediction equation. However, information regarding the crossing surface material and the condition of the crossing surface can be easily obtained from aerial photos and ground view photos of crossings and should be collected for this study.

Distance to nearby intersections is a data factor that has not been used as an input in any of the specific formulas discussed for this study and has been used in only one state formula. Parallel road characteristics have not been used in any formula discussed for this study or in any state formulas. While it is currently unknown if these data elements will be included in light rail crossing specific crash prediction equations, this data should be easy to obtain by measuring from the centerline of the nearest track to the centerline of the roadway from aerial photos and by recording the characteristics of those roadways and should be collected for this study.

The exposure factor of a crossing is the product of the number of trains per day using the crossing and the ADT of the crossing. This data factor is not gathered directly and would be calculated based on any train volume and traffic volume information gathered for the crossing.

The number of tracks at a crossing is a data input for one of the specific formulas discussed in this study and has been used in 11 state formulas. Some equations look at the total number of tracks, and some divide the tracks into the number of main tracks and the number of other tracks (such as siding tracks and switching tracks). These data should be relatively easy to obtain by looking at aerial photos and following light rail alignments to determine the use of the tracks (main tracks or other uses such as turnaround tracks or tracks leading back to vehicle maintenance facilities) and should be collected for this study.

Sight distance limitations is not a data input in any of the specific formulas discussed in this study, but has been used in 17 state formulas. Specific sight distance information (*e.g.* actual measured sight distance) would be very difficult information to obtain without making site visits to each crossing being studied. However, determining if there are sight distance limitations in any of the four quadrants of the crossing should be relatively easy to obtain by viewing ground level crossing photos and should be collected for this study.

Train detector distance information has not been used as a data input to any of the specific formulas discussed in this study or in any of the state formulas. This information would only be available directly from the transit agencies, and could be burdensome information for transit agencies to provide. Therefore, this information will not be requested from transit agencies for this study.

Information regarding the urban or rural nature of a crossing has not been used as a data input in any of the specific formulas discussed in this study and has been used in two state formulas. Modern light rail systems tend to be located in urban and suburban environments rather than in rural environments where roadways may not be paved and may have shoulders as opposed to being paved with curb, gutter and sidewalks as part of the roadway cross-section in an urban environment. Given the likelihood that light rail crossings will not be located in rural areas, it is not necessary to gather this information for purposes of this study.

Year of last inspection data has not been used as a data input in any of the specific formulas reviewed as part of this study or in any state formulas. With the large number of railroad crossings nationwide, it is likely that State agencies do not regularly inspect all crossings within the state. Railroads may inspect crossings as part of required track inspection or crossing signal inspection. Light rail systems likely perform the same types of track inspection and signal inspection on a regular basis, so it is reasonable to conclude that this data element should not be included in any light rail crossing specific equation.

Roadway Related Data. Roadway related data that have been used in various hazard index and accident prediction calculations include approach gradient, number of traffic lanes, presence of a speed hump, pavement markings, required stopping sight distance on wet pavement, roadway type, whether the roadway was paved or unpaved, road pavement width, roadway conditions, shoulder width, and shoulder type.

Approach gradient is not a data input to any of the specific formulas reviewed for this study and has been used in six state formulas. These data would be difficult to gather without requesting information either from the various road authorities or from the transit agencies, which would be burdensome information for these agencies to provide. These measurements could be made at site visits to the crossing, but this is an expensive and time-consuming way to gather data. Given that approach gradients have not been used in any of the major hazard index and crash prediction formulas reviewed as part of this study, it is likely that approach gradient would not be a data input into the final developed equations. Therefore, this information will not be collected for this study.

The number of traffic lanes, the pavement markings, the road pavement width, and the roadway conditions have not been used as data inputs in any state formula, and only the number of traffic lanes is included as a data input in one of the specific formulas reviewed for this study. While it is unknown whether these data elements will be included as part of the final developed equations, this information would be relatively easy to obtain from aerial photos and ground view photos and will be collected for this study.

The presence of a speed hump, the required stopping sight distance on wet pavement, and the roadway type have not been used as data inputs for any of the specific formulas reviewed for this study and are not data inputs in any state formulas. Speed hump information may be available from ground view photos of crossings. To determine stopping sight distance on wet pavement would require that specific information regarding coefficients of friction of the various roadway materials used at the crossings be requested from road authorities, and such information would be burdensome to obtain. Roadway type classifications would also need to be requested from road authorities and could impose a burden on these agencies. With the lack of use of these data elements in the major equations reviewed, it is likely that these data elements would not be included in any developed equations. Therefore, these data elements will not be collected for this study.

Light rail systems are typically built in urban and suburban environments; and, as discussed in the crossing related data section, it is doubtful that roadways crossing light rail tracks would be unpaved with shoulders. Consequently, data regarding whether a roadway is paved or unpaved, shoulder widths, and shoulder types will not be collected for this study.

Train Related Data. Train related data that have been used in various hazard index and accident prediction calculations include average daylight train volume, average train volume during dark hours, maximum train timetable speed, number of trains in a 24 hour period, number of passenger trains in 24 hours, train speed, and the length of time a crossing is blocked.

Number of trains per day using a crossing is a data input to three of the specific formulas reviewed for this study and has been used in 42 state formulas. These train volumes can be divided based on total trains in a 24 hour period, number of passenger trains in a 24 hour period, train volumes during daylight hours (included in one of the specific formulas reviewed for this study), and train volumes during dark hours. Train volumes can be obtained from schedules published on each transit agency's website. The number of trains during daylight and dark hours can be approximated from these schedules using an assumption that daylight hours are from 6:00 AM to 6:00 PM and dark hours are 6:00 PM to 6:00 AM. Train volumes during daylight and dark hours would likely only be necessary if the corresponding traffic volume information is available so that daylight or dark hour exposure factors could be determined. Regardless, this information can be obtained easily from the published schedules and will be obtained as part of this study.

Maximum train timetable speed was used as a data input in one of the specific formulas reviewed for this study, and speed was used in 12 state formulas.. For railroad hazard index and crash prediction equations, speed is an important input because train speeds at railroad crossings across the country can vary from 10 MPH for Class 1 rated track to 80 MPH for Class 4 rated track. For high speed rated tracks, the maximum train speed can be as high as 200 MPH for Class 9 rated track. Conversely, for light rail track, higher speed track (i.e. between 35 MPH and 65 MPH) will typically be in either an exclusive alignment where all crossings are grade-separated or in a semiexclusive alignment where access by pedestrians, bicycles, and motor vehicles is limited to designated crossing locations. Most semiexclusive and nonexclusive light rail alignments, where there may be easier access across the rail alignment by pedestrians and bicycles, typically will have light rail vehicles operating at speeds less than 35 MPH. To gather this track speed information would require the transit agency to provide track charts with maximum timetable speed information or would require the transit agency to specifically state operational speeds through each crossing, which could be burdensome to provide. Information regarding the light rail alignment will be gathered as part of this study, and that alignment information could be used as a proxy to determine maximum timetable speeds for each of the crossings.

The length of time a crossing is blocked is a data element that has not been used in any of the specific formulas reviewed as part of this study or by in any state formula. For railroad operations, long unit trains and switch operations can occupy a crossing for many minutes at a time. Additionally, depending on the location of railroad crossings relative to train yards, long trains not completely pulled into a yard or waiting to be moved into a train yard can block crossings for substantial periods of time. This will not be the case with light rail operations. Light rail vehicles do not perform switching movements through crossings and typically do not have to block crossings while waiting to move into the yard. Light rail trains tend to be small in consist number (one to four or five vehicles per consist) when compared to unit freight trains (130 cars or more per consist) and occupy crossings for a much shorter periods of time. For these reasons, this data element would not be a necessary input into any light rail specific equation and, therefore, will not be collected as part of this study.

Motor Vehicle Related Data. Motor vehicle related data that have been used in various hazard index and accident prediction calculations include average 24 hour traffic volume, average daylight traffic volume, average traffic volume during dark hours, number of pedestrians, number of school buses, percentage of heavy vehicles, and vehicle speed.

The number of motor vehicles per day using a crossing has been used as a data input to three of the specific formulas discussed in this research and in 42 state formulas. These motor vehicle volumes can be divided based on total vehicles in a 24 hour period, average vehicle volumes during daylight hours, and average vehicle volumes during dark hours. It is possible that many road authorities will not have traffic information available on an hourly count basis, and thus, it will be impossible to obtain traffic volumes for daylight and dark hours in this manner. Motor vehicle volume information will need to be obtained from road authorities. Many road authorities publish this information on their websites, and those road authorities that do not publish ADT volumes on their website can be contacted directly to obtain ADT information. It may be that not all road authorities will have traffic count data for calendar year 2009, which are the data required for this research. If 2009 information is not available, either road authorities will need to be contacted or additional traffic count data will be required to determine growth rates for each area and to adjust the traffic count data to represent 2009 counts. ADT volumes for the calendar year 2009 are required for this research, but it would be both cost prohibitive to obtain traffic counts at every crossing today and time consuming to contact every road authority to determine growth rates in the area since 2009 to adjust count information to 2009 levels. Thus, traffic count data and necessary adjustment data and information will be collected for this research.

Data regarding the number of pedestrians will not be collected for this research for two reasons. First, pedestrian count data are typically not readily available, and it would be cost prohibitive to obtain these data for each crossing in the study. Second, the equations developed for this study will be based on vehicle crashes only. No pedestrian, bicycle, or other types of crashes will be included in the equation development. As such, pedestrian data will not be necessary for this research.

The number of school buses and percentage of heavy vehicles have not been used as inputs in any of the specific formulas reviewed for this study or in any state formulas. To obtain the number of school buses using a crossing would require contact with all school districts in the vicinity of the crossing to obtain school bus route information, which for security reasons, school districts may not be willing to provide. Information regarding the percentage of heavy vehicles using crossings if not obtained directly at the time that traffic counts are taken, would be estimated at best. Because these two data elements would likely not be included in any developed equations and considering the difficulty in obtaining these data, these data elements will not be collected for this study.

Speed was not a data input into any of the specific formulas reviewed for this research, but was included in 12 states formulas although it was not specified if the state used train speed, motor vehicle speed, or a combination of both. Posted speed limits could be gathered from ground level photos along the roadway which is crossed by the light rail crossing. However, some roadways may not be posted for various reasons (for example, short roadway segment, standard speed limit in a jurisdiction is a given speed unless otherwise posted). To the extent this information is available from ground level photos, it should be collected as part of this research.

Miscellaneous Data. Miscellaneous data that have been used in various hazard index and accident prediction calculations include distractions at the crossing, distance to overhead wires, location of and distance to schools, presence of a residential area, presence of a commercial area, presence of other land uses (including, but not limited to, industrial and institutional), and train horn prohibitions/quiet zones.

None of the miscellaneous data elements were used in any of the specific formulas reviewed in this study and none were used in any of the state formulas. Some of this information, such as location of and distance to schools, or presence of residential, commercial, or other land uses such as industrial or institutional, can be collected fairly easily from aerial photos and measurements from aerial photos. Other information, such as distractions at a crossing and distance to overhead wires, cannot be easily collected. Additionally, many light rail vehicles are powered by overhead cantenary systems (OCS) wires through an overhead pantograph affixed to the top of the vehicle. OCS wires are typically not the cause of, or involved in motor vehicle accidents. Finally, train horn prohibitions will be in place only at any shared railroad and light rail crossings as train horn prohibitions are based on FRA rules, which are not applicable to light rail transit. For this study, land use in the vicinity of the light rail crossing and location of and distance to school information will be collected for this study. Information regarding distractions at crossings, distance to overhead wires, and train horn prohibition information will not be collected for this study.

In addition to gathering data elements based on railroad hazard index and crash prediction equations, additional data that may be relevant specifically to light rail operations will also be gathered. These data are information regarding the alignment in which the light rail crossing is located and the configuration of the light rail tracks relative to the roadways at the light rail crossing.

Light rail alignments.[3] A given light rail system can operate in a number of different right-of-way alignments including exclusive, semiexclusive, and nonexclusive. TCRP Reports 17 and 69 define one exclusive, five semiexclusive, and three nonexclusive alignment types. A general description of each alignment type is discussed in TCRP Report 17 (Korve et al. 1996) and TCRP Report 69 (Korve et al. 2001) and is summarized below:

- Exclusive alignment Type a – Right-of-way is grade-separated or, at ground level, is protected by fencing or other barriers, and does not include at-grade crossings. Light rail vehicles typically operate at higher speeds (between 35 MPH and 65 MPH) in these corridors;
- Semiexclusive alignment Type b1 – Similar to an exclusive alignment, but has at-grade motor vehicle, bicycle, and/or pedestrian crossing openings between fencing or

[3] Light rail alignment information was presented in a poster session at the 2012 APTA Rail Conference in Dallas, Texas. (Fischhaber and Janson 2012).

other barriers at appropriate locations. Light rail vehicles typically operate at higher speeds in these corridors;

- Semiexclusive alignment Type b2 – Located within a street right-of-way, but separated from regular traffic by nonmountable barrier curbs or fences between at-grade crossings. Motor vehicles, bicycles, and pedestrians can only cross the alignment at designated locations. Light rail vehicles typically operate at higher speeds in these corridors;

- Semiexclusive alignment Type b3 – Located within a street right-of-way, but separated from regular traffic by nonmountable barrier curbs. Fences may be used between a double set of tracks. Motor vehicles, bicycles, and pedestrians should only cross the alignment at designated locations. Light rail vehicles typically operate at speeds less than 35 MPH;

- Semiexclusive alignment Type b4 – Located within a street right-of-way, but separated from regular traffic by mountable curbs, striping, and/or lane designation. Motor vehicles, bicycles, and pedestrians should only cross the alignment at designated locations. Light rail vehicles typically operate at speeds less than 35 MPH;

- Semiexclusive alignment Type b5 – Located within a street right-of-way, but within a light rail vehicle/pedestrian mall located adjacent to a parallel roadway that is physically separated from the light rail vehicle/pedestrian mall by a nonmountable barrier curb. The light rail vehicle alignment is delineated by detectable visual and textural pavement warnings and/or striping. Pedestrians can cross the light rail vehicle alignment freely and should cross the parallel roadway at designated locations only. Motor vehicles and bicycles should cross the light rail vehicle/pedestrian mall right-of-way at designated locations only. Light rail vehicles typically operate at speeds less than 15 MPH;

- Nonexclusive alignment Type c1 – Operates in mixed traffic with motor vehicles, bicycles, and/or pedestrians. Light rail vehicles, motor vehicles, and bicycles operate in the same traffic lanes on the streets; and pedestrians should only cross the mixed traffic right-of-way at designated locations. Light rail vehicles typically operate at speeds less than 35 MPH;

- Nonexclusive alignment Type c2 – Located within a transit mall. Transit vehicles and light rail vehicles may operate in the same lanes that are a transit-exclusive area for transporting, loading, and unloading passengers. Nonmountable barrier curbs separate the transit right-of-way from the pedestrian way. Delivery vehicles may be allowed in the transit right-of-way at certain times of day. Nontransit motor vehicles are prohibited in the right-of-way. Nontransit motor vehicles, bicycles, and pedestrians should cross this right-of-way only at designated locations. Light rail vehicles typically operate at speeds less than 35 MPH; and

- Nonexclusive alignment Type c3 – Located within a light rail vehicle/pedestrian mall in which these two modes freely share the right-of-way. The light rail vehicle right-of-way is delineated by detectable visual and textural pavement warnings and/or striping. Motor vehicles and bicycles are prohibited from operating on or adjacent to the light rail tracks and should cross the right-of-way at designated locations only. Light rail vehicles typically operate at speeds less than 15 MPH.

Light rail operational configurations.[4] A preliminary review of the Denver RTD light rail system by Fischhaber and Janson (2012) shows there are a number of operational configurations that can occur in a light rail system. Each configuration has been assigned a type code for identification in this study. In addition to determining whether a light rail system is operating in an exclusive, semiexclusive, or nonexclusive alignment, the following operational configurations for light rail crossings need to be categorized and considered in this study:

One-Way Motor Vehicle Operations With:

- Type 1A – Two-way light rail vehicle operations with light rail operating in semiexclusive right-of-way perpendicular to roadway with no adjacent intersections;
- Type 1B – Two-way light rail vehicle operations with light rail operating parallel to one side of the motor vehicle alignment;
- Type 1C – Two-way light rail vehicle operations with motor vehicles operating parallel and between light rail vehicles;
- Type 1D – One-way light rail vehicle operations with light rail operating in semiexclusive right-of-way perpendicular to roadway with no adjacent intersections;
- Type 1E – One-way light rail vehicle operations with light rail vehicles operating parallel in the same direction as motor vehicles; and
- Type 1F – One-way light rail vehicle operations with light rail vehicles operating parallel in the opposite direction as motor vehicles.

Two-Way Motor Vehicle Operations With:

[4] Light rail operational configuration information was presented in a poster session at the 2012 APTA Rail Conference in Dallas, Texas. (Fischhaber and Janson 2012).

- Type 2A – Two-way light rail vehicle operations with light rail operating in semiexclusive right-of-way perpendicular to roadway with no adjacent intersections;
- Type 2B – Two-way light rail vehicle operations with light rail located parallel to one side of the motor vehicle alignment;
- Type 2C – Two-way light rail vehicle operations with light rail operating parallel and between the motor vehicle operations;
- Type 2D – Two-way light rail vehicle operations with motor vehicles operating parallel and between light rail vehicle operations;
- Type 2E – One-way light rail vehicle operations with light rail operating in semiexclusive right-of-way perpendicular to roadway with no adjacent intersections;
- Type 2F – One-way light rail vehicle operations with light rail operating parallel to one side of the motor vehicle alignment; and
- Type 2G – One-way light rail vehicle operations with light rail operating parallel and between the motor vehicle operations.

Light rail configuration Types 1C and 2D, while possible, are not likely or practical designs and are included only to provide a complete list of possible configurations. Some of the listed configurations represent what are commonly referred to as median running configurations, some represent what are commonly referred to as side running configurations, and the remaining configurations represent what will be described as perpendicular running configurations.

Median running configurations are defined as configurations in which the light rail vehicles run in the center median area between motor vehicle movements and are represented in the above lists by Types 2C and 2G. Figure III.8 shows an example median running configuration.

Perpendicular running configurations are defined as configurations in which the light rail vehicles run perpendicular to the roadways they cross and are represented in the above lists by Types 1A, 1D, 2A, and 2E. Figure III.9 shows an example perpendicular running configuration.

Side running configurations are defined as configurations in which the light rail vehicles run parallel and to the side of motor vehicle movements and are represented in the above lists by Types 1B, 1E, 1F, 2B, and 2F. Figure III.10 shows an example side running configuration.

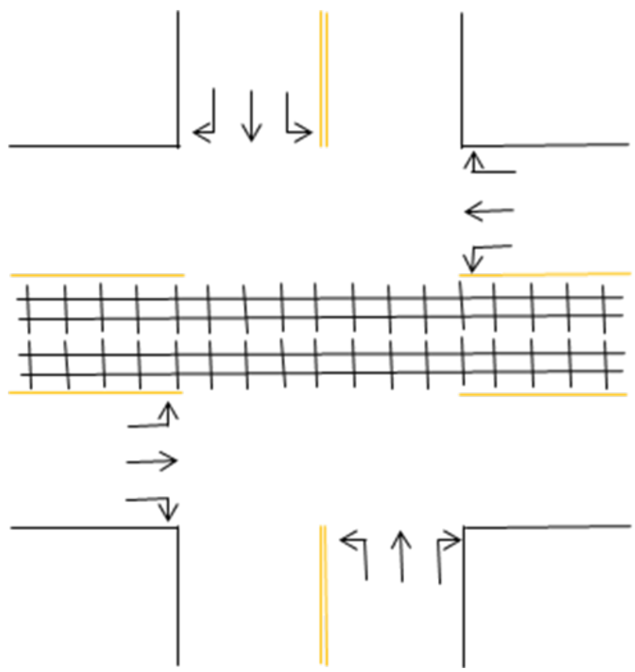


Figure III.8 Example Median Running Configuration.

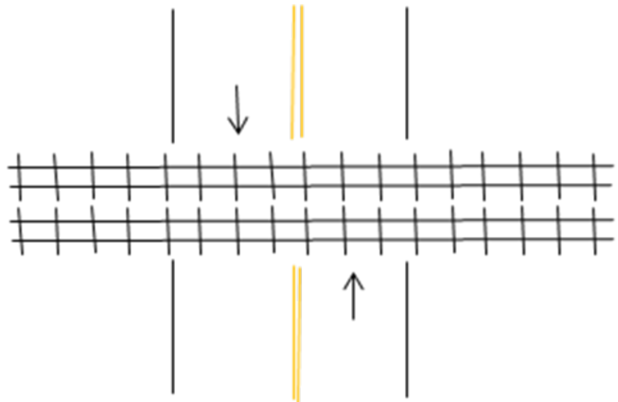


Figure III.9 Example Perpendicular Running Configuration.

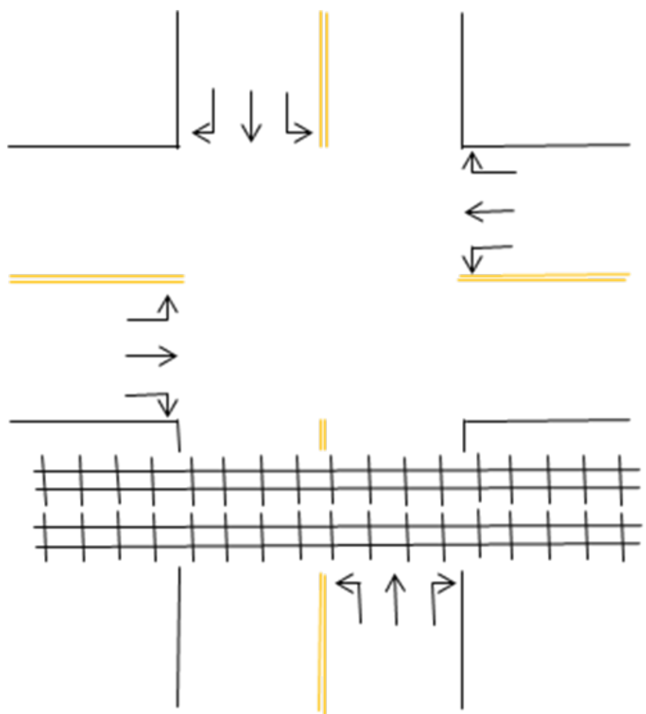


Figure III.10 Example Side Running Configuration.

The preliminary analysis of the Denver RTD light rail system determined that special attention needs to be given to areas on a light rail system where light rail vehicles run contraflow to motor vehicles. A preliminary review of data from other light rail systems indicates that intersection configuration may also need special consideration. At some light rail crossings, there are up to six intersection legs in addition to the light rail vehicle legs that converge at the intersection. These complex intersection configurations may lead to different crash rates and patterns.

Model Methodologies to Analyze

The literature review outlined 10 different statistical and other methodologies that have been used to develop hazard index and crash prediction equations in the past and other possible methodologies to consider in this study. These methodologies include linear regression models, nonlinear regression models, Poisson regression models, negative binomial regression models, logit models, quantification methods, EB methodologies, hierarchical tree-based regression models, gamma models, and principal component analysis. In addition, a paper by Lord and Mannering (2010) that discusses the statistical analysis of crash-frequency data and provides various pros and cons of use of many of these statistical methods is referred to when assessing these various modeling techniques.

The various papers reviewed as part of this study have differing opinions regarding railroad crossing crash data. Some of the papers reviewed in this study indicate that railroad crossing crash data tend to show a problem of underdispersion due to the number of zero collision railroad crossings (Saccomanno, Ren, and Fu 2003; Oh, Washington, and Nam 2006) while other papers indicate that railroad crossing crash data tend to show a problem of overdispersion (Austin and Carson 2002). Until crash data are gathered from transit agencies for this study, it will be unknown whether light rail crossing crash data will show a tendency to be over-dispersed or under-dispersed. The tendency of crash data to be over-dispersed or under-dispersed may limit the methodologies available for use in developing the light rail crossing crash prediction equations.

Additionally, until all crash data and traffic volume data are gathered for this study, the sample size available for this study will be unknown. If the sample size for this study is small, that fact may also serve to limit the methodologies available or that will need to be taken into consideration in use of some methodologies.

Finally, when compared to the number of traffic crashes in general, railroad crossing crashes are rare occurrences. As a result, there are many crossing locations where the crash experience during a study period is zero. This could also be true for the light rail crash data gathered for this study. If there are a significant number of light rail crossing locations where there have been zero crashes during the study period, this has the potential to result in a low sample mean. This potential is another factor that may limit the methodologies available or that will need to be taken into consideration in use of some methodologies.

Linear Regression. Linear regression has been used to develop a number of the hazard index models reviewed as part of this study. Linear regression models are unable to predict the exact number of crashes that will occur at a light rail crossing; they can only determine the mean number of expected crashes. Linear regression models can also predict negative values. The purpose of this study is to develop equations that can estimate the actual number of crashes that will occur at light rail crossings rather than simply rank the safety of crossings based on a hazard index. Additionally, the number of crashes that will occur at a light rail crossing must be either zero or a positive number;

negative estimations are not acceptable. For these reasons, linear regression will not be used to develop equations for this study.

Nonlinear Regression. Nonlinear regression techniques have been used to develop a number of different hazard index and crash prediction models including . The nonlinear regression techniques allow for the development of models that can predict the number and severity of crashes at a railroad crossing. This technique has been used to develop a number of different crash prediction models over the years including the US DOT Crash Prediction Formulas. In addition, because the US DOT Crash Prediction Formulas have been published in the last two editions of the FHWA Rail-Highway Grade Crossing Handbook (Tustin et al. 1986; Ogden 2007), the US DOT Crash Prediction Formulas are more likely to be used by practicing engineers than are some of the other reviewed formulas that have been published solely in various journals. For these reasons, nonlinear regression is a technique that should be further tested and used to develop light rail specific equations for this study.

Poisson Regression. Poisson regression requires that the mean and variance of the data used must be equal. Based on information contained in various papers reviewed for this study, it is unlikely that the mean and variance of the data collected for this study will be equal. It is more likely that the data gathered will be either over-dispersed or under-dispersed. In addition, it is likely that the sample size for this study will be small and that the data could have a low sample mean given the possibility of light rail crossings having zero crashes during the study period. For these reasons, Poisson regression will not be used to develop equations for this study.

Negative Binomial Regression. Negative binomial regression was used by Austin and Carson (2002) to develop a railroad crash prediction model. The authors used this technique because in their opinion, it was more appropriate to use for over-dispersed data. Lord and Mannering (2010) note that negative binomial regression models have limitations in the ability to handle under-dispersed data and there can be dispersion-parameter estimation problems for data characterized by small sample sizes and low sample mean values. It is not known whether the data gathered for this study will prove to be over-dispersed, under-dispersed or will have its mean and variance equal. It is likely, however, that the data will be characterized by a small sample size and a potentially low sample mean given the possibility for a number of crossings in the dataset to have a value of zero crashes during the study period. For this reason, negative binomial regression will not be used to develop equations for this study.

Logit Models. Based on comments from Zalinger, Rogers and Johri (1977), a logit model should not be used to develop a crash prediction equation because of how the model will group the data. With a logit model, light rail crossings would be grouped into two categories: crash and no crash. It is likely that a significant number of light rail crossings will have experienced no crashes during the study period. Use of this methodology would likely skew the overall model results because so many of the subject light rail crossings potentially would fall into the no crash category. Thus, logit models will not be used to develop equations as part of this study.

Quantification Methods. Use of the quantification method would require collecting human factors data to develop the model. While driver behavior can be theorized based on field observations and experience, gathering data to determine this behavior would be a difficult process for both researchers and any transit agency that would use the developed models. For these reasons, the quantification method will not be used to develop equations as part of this study.

Empirical Bayes Methodologies. EB methodologies for railroad crossing crash prediction have been reviewed in a few papers. Hauer and Persaud (1987) used an EB model to develop a method of estimating safety at railroad crossings that considered both causal factors and crash history. Additionally, the Highway Safety Manual (National Research Council (US). Transportation Research Board. Task Force on Development of the Highway Safety Manual 2010) has adopted the use of the EB Method to combine predicted average crash frequencies and observed crash frequencies. The Highway Safety Manual uses this method to compensate for potential bias due to regression-to-the-mean. Based on the paper by Hauer and Persaud (1987) and the discussion in the Highway Safety Manual, an EB methodology is a technique that should be further tested and used to develop light rail specific equations for this study.

Hierarchical Tree-Based Regression. A review of the paper by Yan, Richards and Su (2010) indicates that hierarchical tree-based regression should not be used to develop a crash prediction model. The authors used this method to evaluate railroad crossings controlled by passive signs only and from their study observed that hierarchical tree-based regression is not a better tool for use in crash prediction models. Based on this recommendation, hierarchical tree-based regression will not be used to develop equations as part of this study.

Gamma Models. Gamma models are able to handle data that is either over-dispersed or under-dispersed. However, given that the gamma model is a dual-state model, Lord and Mannering (2010) note that one of the states of this model will have a long-term mean equal to zero. This leads to the skewed model results discussed above with logit models. For these reasons, a gamma model will not be used to develop equations for this study.

Principal Component Analysis. Principal component analysis is described by Abdi and Williams (2010) as a technique that analyzes a data table where observations are described by several inter-correlated quantitative dependent variables. The goal of this technique is to extract information from the table to represent a set of new orthogonal variables and to display the pattern of similarity of the observations and variables as points in maps. Such a transformation would create a linear combination of the original dataset to re-express the dataset (Shlens 2005). Use of this linear re-expressed data would lead to the same issues identified with linear regression models. For this reason, principal component analysis will not be used to develop equations for this study.

Research Questions Answered by Model Methodology Analysis

Based on the analysis of various model methodologies that have been used previously in the development of railroad hazard index and crash prediction equations and other methodologies to consider, the answer to research question three is that nonlinear regression and EB methods should be explored in developing crash number and severity prediction equations for light rail specific operations.

Study Procedures

The general procedures for this study include identification of the study period, collection of necessary study data, calculation of sample statistics, analysis of crash data for patterns, development of light rail specific crash prediction models, testing the models against future year crash data to determine model effectiveness, calculation of predicted crashes for light rail crossings using developed light rail specific equations and US DOT crash prediction equations and testing the statistical significance of the models, calculation of predicted crashes for light rail crossings for years 2005 through 2009 on study light rail crossings using developed light rail specific equations to determine model effectiveness, and development of a sample GIS model flow chart for future use with the light rail specific equations.

Study Period

The study period chosen for this research is a 10-year period using calendar years 2000 through 2009.

Data Collection

Transit agencies with light rail lines in continuous operation from 2000 through 2009 will be identified. Light rail crossing crash data for light rail lines in continuous operation from 2000 through 2009 will be requested from the identified transit agencies. If necessary, crash data for light rail crossings will also be requested from the National Transit Database (NTD) for use in this study. Information regarding train volumes will be determined by downloading train schedules from each transit agency for each of the light rail lines included in the study. Train volumes for each light rail crossing will be determined by counting the number of trains listed on the schedule for those portions of the light rail lines in service from 2000 through 2009.

Traffic volume data for 2009 will be searched for on road authority websites. If traffic volume data for 2009 are available from road authority websites, the data will be recorded. If traffic volume data are not available for 2009, but sufficient data to determine local growth rates are available, the data will be recorded, a local growth rate will be determined and applied to available traffic volumes to forecast or regress 2009 traffic volumes, and 2009 developed traffic volumes for the light rail crossing will be estimated. If traffic count data are not available from road authority websites, the road authority will be contacted directly to request that it provide 2009 traffic volumes or sufficient data to estimate local growth rates and forecast or regress traffic count information to estimate 2009 traffic volumes, and record these estimated traffic volumes.

The Google Earth™ mapping service and Google Street View™ mapping service in the Google Earth™ software (Google 2013) will be used to gather many of the data elements including data that can be visually determined from the aerial mapping information and from street view photographic information. Google Earth™ mapping service ruler tool will be used to measure crossing and roadway widths and to measure the distance to the nearest intersection.

Data Review

The data gathered will be tabulated, organized, and reviewed. Statistics for the data set, including sample size, sample mean and sample, will be calculated. A preliminary analysis of the data set will be performed to identify and to analyze crash patterns, and to determine possible ways of grouping data to develop the models.

Model Development

The data and identified model development methodologies will be used to develop crash prediction equations. Models will be developed using Microsoft Excel computer software and the Microsoft Excel SOLVER function (Microsoft 2007).

Analysis of Developed Model Analysis and Presentation of Results

The models developed will be statistically tested. The developed models will be used to predict crashes for the data set using 2005-2009 actual crashes for the 234 available crossings and comparing predicted crashes to actual crashes. Crashes will also be predicted using the US DOT accident prediction equations and compared to the actual number of crashes. An F-statistic test will be performed comparing these two predicted values with the actual crash volumes at the crossings.

Development of GIS Model Flow Chart

The light rail specific equations will be included in the development of a GIS model flow chart. This GIS model flow chart will be used as a basis for determining future database development and GIS modeling needs to develop a GIS model to apply the developed crash prediction equations to light rail crossing data sets.

CHAPTER IV

DATA COLLECTION, ANALYSIS AND RESULTS

Data for this study was collected for 10 transit agencies for light rail lines that were in continuous operations during calendar years 2000 through 2009. The collected data included light rail crossing configuration data, light rail and roadway operational data, and light rail crossing crash data.

Next, an analysis of light rail crossing crash patterns was performed by type of warning device used at the light rail crossing, by light rail alignment type, by light rail configuration type, and by combination of specific light rail alignment and configuration types. A specific analysis of left-turn and right-turn crash patterns was also conducted. These analyses assisted in determining whether specific alignment and configuration combinations contributed to specific crash patterns and warranted separate analysis and treatment or whether more general alignment (semiexclusive and nonexclusive) and/or configuration types (median running, side running, perpendicular running) were the appropriate level for equation development.

The modeling methodologies to use in the study were selected as discussed above. Following the determination of the level of alignment and/or configuration granularity that are appropriate for this study given the size and makeup of the dataset, an analysis was performed to develop crash prediction equations specific to light rail crossings.

Once the analysis to develop the equations was complete, statistical tests were performed to determine if there is a significant difference statistically between the number of actual crashes that occur at light rail crossings as compared to the number of crashes at light rail crossings as predicted by the developed equations and the number of crashes at light rail crossings predicted by existing railroad crossing crash prediction equations. The new models were tested statistically using 2005-2009 crash data for 234 crossings.

Data Collection and Review of Light Rail Systems

Light rail systems across the country operate on a number of different alignments (exclusive, semiexclusive, and nonexclusive), operate in a number of different configurations (median running, side running, and perpendicular running), and use a number of different types of crossing warning devices, signing, and striping to provide warning to motorists of the presence of a light rail crossing. Various data collection techniques were used and different data elements were gathered as part of this study. Data elements were gathered under the general categories of crossing related data, roadway related data, train related data, motor vehicle related data and miscellaneous data.

Data Collection Techniques

A spreadsheet was created to include the data elements identified in the study methodology section. Data elements included light rail crossing alignments, light rail crossing configurations, crossing warning devices, signing and striping, and other items discussed in each of the general areas. Much of the data was collected using the Google Earth™ mapping service and Google Street View™ mapping service in the Google Earth™ software (Google 2013). Traffic count data were collected from information available on town, city, county and state websites or by contacting road authorities that did not have traffic count data available on websites. Crash data were obtained through contact with the safety departments at the 10 transit agencies identified as having light rail lines in continuous operations during the 2000 through 2009 study time period. Data was collected from August 2010 to August 2013.

Crossing Related Data. Sixteen light rail systems in the United States were in continuous operation from 2000 through 2009. Light rail crossing crash data were requested from each transit agency for these identified systems for the 10-year study period. Nine transit agencies provided crash data for the ten years requested for the lines that were in continuous service during the study period. The data were requested for only those segments of the systems that were in continuous operation during the 10-year study period. The transit agencies that provided crash data and the lines for which crash data were provided are:

- Bi-State Development Agency (East St. Louis, Illinois and St. Louis, Missouri) – Red Line – Lambert Airport Terminal to 5th and Missouri Station;
- Denver Regional Transportation District (Colorado) – Central Corridor and Central Platte Valley Corridor;
- Greater Cleveland Regional Transit Authority (Ohio) – Green Line and Blue Line;
- Los Angeles County Metropolitan Transportation Authority (California) – Blue Line;
- Niagara Frontier Transportation Authority (Buffalo, New York) – at-grade portion of system;

- San Diego Trolley, Inc. (California) – Blue Line, Green Line – Old Town Transit Center to Mission San Diego Station, Orange Line – El Cajon Transit Center Station to 12th & Imperial Transit Center;
- Santa Clara Valley Transportation Authority (California) – Mountain View-Winchester - Downtown Mountain View Station to Tasman Station, Alum Rock-Santa Teresa – Baypointe Station to Santa Teresa Station, Ohlone/Chynoweth-Almaden;
- Southeastern Pennsylvania Transportation Authority (Philadelphia, Pennsylvania) – 101 and 102 Trolley Lines; and
- Utah Transit Authority (Salt Lake City, Utah) – Sandy Line.

The Memphis Area Transit Authority (Tennessee) also provided crash data for all of its trolley lines. Only the Main Street Line and the Riverfront Line were in continuous operations during the study period. The crash data were only available from 2004 through 2009 due to records lost with a personnel change. Memphis data were not used in the model development, but were used in the statistical testing.

The Massachusetts Bay Transportation Authority (Boston, Massachusetts) stated a willingness to provide crash data. However, a review of that system showed that the lines in service during the entirety of the 10-year study period consisted of grade-separated crossings only. Consequently, no information was collected for this system.

The Newark Light Rail (New Jersey) from Grove Street to Newark Penn Station has only one at-grade light rail crossing. While crash data was available for this crossing, traffic volume data for the light rail crossing was not available. As a result, no information was collected for this system.

The San Francisco Municipal Railway (California), Sacramento Regional Transit District (California), Portland Tri-County Metropolitan Transportation District of Oregon (Oregon), and the Dallas Area Rapid Transit (Texas) agencies were unable to provide crash data. In an attempt to collect the data, crash data for these four transit agencies were requested from the NTD. The NTD contained crash data from only 2002 through 2009. The crash data for 2002 through 2007 did not contain any information identifying the particular light rail crossing at which the crash occurred. Crash data for 2008 and 2009 did include some light rail crossing identification information, but the information was not specific enough to match every crash with a specific crossing. While NTD data were not used for this study, the data elements that have been gathered since 2008 should make some of the NTD data usable in future light rail grade crossing safety research.

The transit agencies that provided crash data for the study period provided either written copies of the agency internal crash investigation and data reports, or provided the information in a spreadsheet. There is no uniform system used by all of the study transit agencies to collect internal crash investigation data and to report that information within the transit agency. Each transit agency's internal reporting provides information in a format different from the format used by other transit agencies.

In addition, there is no uniform content or level of detail in the reports. Based on the internal crash reports provided by the transit agencies, some transit agencies specifically report whether crashes involve fatalities, injuries, or property damage only while other transit agencies report crashes as either fatal or non-fatal. Some transit agencies provide specific details regarding each crash. These details may or may not include light rail train direction, vehicle direction, whether the crash specifically involved a left-turning or right-turning vehicle, and whether the crash involved a vehicle driver disobeying the traffic control. Some reported crash data had to be interpreted in light of the intersection and track configuration, and traffic control in order to categorize the crash causation.

These transit agency reports provided crash experience and crash severity at the light rail crossing. The crash data provided by the transit agencies were summaries of their specific internal reporting formats and not the data as reported to the NTD. As discussed earlier, NTD data were reviewed for this analysis, but not used due to the lack of specific light rail crossing location information for the earlier years of the data analysis period.

Google Earth™ mapping service and Google Street View™ mapping service through the Google Earth™ software (Google 2013) were used to review and gather data on angle of crossing, crossing warning device, crossing width, crossing surface material, condition of crossing, distance to nearest intersection, number of main tracks, number of other tracks, visibility and sight obstructions, light rail alignment, and light rail operational configuration information for each of the light rail crossings in this study. Crossing widths and distance to the nearest intersection were measured using the Google Earth™ mapping service ruler tool. Angle of crossing was measured using a protractor against the Google Earth™ mapping service aerial image of the crossing.

Crossing warning devices. A visual review of light rail transit systems in this study using Google Earth™ mapping service and Google Street View™ mapping service shows that a number of different types of warning devices are used. For light rail crossings that are adjacent to railroad crossings or that have a more traditional configuration of being located farther from intersections, many of the transit agencies use flashing lights with gates. In many areas, light rail operations occur adjacent to, or within, public roadway rights-of-way. These types of light rail crossings are incorporated into standard traffic signal operations, use passive warning signs, or use no types of warning signs or signals.

Based on the Google Earth™ mapping service and Google Street View™ mapping service review of light systems in the country, more transit systems than common carrier railroads use standard traffic signals as warning devices. As evidence, the specific review of the Denver RTD light rail system discussed earlier determined that approximately 74% of Denver RTD's light rail crossings examined as part of that specific review are controlled by traffic signals. The small number of traffic signal-controlled public railroad crossings is one reason supporting the hypothesis that existing railroad crossing hazard index and crash prediction formulas may not accurately represent light rail operations (Fischhaber and Janson 2012).

Left-turn movement treatments. A visual review of light rail transit systems in this study using Google Earth™ mapping service and Google Street View™ mapping service shows that transit agencies and road authorities use a number of different methods to handle left-turning movements in front of LRVs. Observed left-turn movement treatments include:

- Prohibition of left-turn movements at all times;
- Prohibition of left-turn movements with "No Left Turn" blank-out signs;
- Protected only left-turn movements;
- Protected/Permissive left-turn movements; and

- Permissive left-turn movements.

To the extent it was possible to determine or identify from Google Earth™, information regarding these left-turn treatments was noted as part of the data collection efforts.

Warning signs and striping. A visual review of light rail transit systems in this study using Google Earth™ mapping service and Google Street View™ mapping service shows that use of advance warning signs and other types of passive warning signs (*e.g.*, "No Turn On Red," "Stop On Red") varies by transit agency and road authority. Use of pavement markings also varies by transit agencies and includes use of traditional railroad crossing pavement markings, stop bars, dynamic envelope markings, and markings to indicate the area in which motor vehicles should not stop to avoid being hit by a light rail vehicle.

Specific information on use of warning signs and pavement markings was collected as part of this study in addition to specific information on the crossing warning devices used. It is unknown at this time what effect, if any, each of these data elements has on the safety of light rail crossings and if these data elements will have any influence on predicting the number or severity of crashes at light rail crossings.

Roadway Related Data. Google Earth™ mapping service and Google Street View™ mapping service were used to review and gather data for the number of traffic lanes, pavement markings, road pavement width, and roadway conditions. Road pavement width was measured using the Google Earth™ mapping service ruler tool.

Train Related Data. Light rail train volumes were obtained from the schedules published on each transit agency's website. Maximum timetable speed for each of the crossings will be approximated based on the alignment of the light rail line in which the crossing is located.

Motor Vehicle Related Data. Motor vehicle volumes were the most limited information available for this research. Many road authorities reduced or eliminated jurisdictional traffic counts as part of the economic downturn during the late 2000's. Many other road authorities limit traffic counts to larger roadway facilities and do not count smaller local and collector facilities. To the extent possible, motor vehicle traffic count data were collected as far back as 1999, and local growth rates were applied to these counts to forecast 2009 traffic volumes. Data were collected either through information available on road authority websites or through direct contact with the road authority, either by telephone or email.

Motor vehicle speed was only available at some of the light crossing locations studied. Posted speed limit information was reviewed in the vicinity of each light rail crossing using the Google Street View™ mapping service. Posted speed limits were not found at many of the light crossings reviewed.

Miscellaneous Data. General land use data were collected at each of the study light rail crossings. Location of schools and their distance to each of the study crossings were also collected using the Google Earth™ mapping service ruler tool.

Analysis of Light Rail Crossing Crash Patterns[5]

Crashes at light rail crossings have typically been analyzed based on the total number of crashes that occur at the light rail crossing and have included vehicle,

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[5] Analysis of light rail crossing crash patterns was presented at the Transportation Research Board 93rd Annual Meeting in Washington, D.C. (Fischhaber and Janson 2014).

pedestrian, bicycle, and other possible modes of transportation (Korve et al. 1996; Cleghorn et al. 2009). The TCRP Report 69 (Korve et al. 2001) summarized crashes for motor vehicles and pedestrians for individual systems and, in some cases, included a general discussion of the configuration in which crashes occurred. In some studies, crashes were analyzed based on the alignment type (Korve et al. 1996), and, in other studies, crashes were analyzed and crash ratios were calculated on a system by system basis (Cleghorn et al. 2009).

A review and analysis of the crash data provided in this study of motor vehicle crashes with LRVs was performed for all crash data provided. The crash data were analyzed based on both alignment type and configuration type and were analyzed by combining data from the nine identified study transit light rail systems. The crash data analysis calculated crash rates for alignment type, configuration type, and alignment/configuration type combinations and compares those crash rates to the crash rate for the entire dataset.

Based on a review of the literature, it does not appear that any other studies have analyzed light rail crashes either in relation to configuration type or for an aggregation of light rail systems. This study (i) provides an analysis of crashes for multiple systems based on the alignment types and configuration types of the light rail crossings; (ii) provides a general analysis and comparison of crashes that occur in median running configurations and those that occur in side running configurations; (iii) reviews and analyzed left-turn-related crashes for both median and side running configurations; (iv) reviews left-turn treatments that are currently being used on specific median running configurations; (v) reaches a general conclusion regarding whether a median running, side running, or perpendicular configuration is more effective from a vehicle crash mitigation perspective; and (vi) makes recommendations for further analyses needed on these topics.

Data Used and Data Analysis Results

Using the study period data provided by the nine light rail transit systems, a total of 507 light rail crossings were analyzed. Only motor vehicle crashes were analyzed; all pedestrian, bicycle, pedicab, and horse-drawn carriage crashes were removed from the analysis. In addition, any crash that was confirmed to be a suicide was removed from the data.

Various traffic controls are used at the 507 light rail crossings. The types of traffic control include traffic signals (232), flashing lights with gates (172), stop signs (60), blank-out signs (10), flashing light traffic signals (8), flashing lights with no gates (6), crossbucks (4), and LRV warning signs (4). Thirteen light rail crossings have no traffic or light rail crossing signal or signage control.

In the study period, a total of 898 crashes occurred at 267 of the 507 light rail crossings, and no crashes occurred at 240 of the light rail crossings. Of the total crashes, 88.3% (793) were property damage-only crashes; 10.7% (96) were injury crashes; and 1.0% (9) were fatal crashes.

Of the total crashes, 78.3% (703) occurred at light rail crossings with traffic signal control even though only 45.8% (232) of the light rail crossings are controlled by traffic signals. Of the total crashes, 8.0% (72) occurred at the 60 light rail crossings under stop sign control and 7.8% (70) occurred at the 172 light rail crossings equipped with flashing lights and gates. Of the crashes that occurred at light rail crossings with flashing lights and gates, 38.6% (27) of these crashes involving the driver either driving around or through the light rail crossing gate. Relatively small numbers of crashes occurred at the light rail crossings with the remaining types of traffic control. Table IV.1 shows the number of light rail crossings, the percentage of total crossings, the total number of crashes (including fatal, injury, and property damage only), the percentage of crashes, and the average number of crashes per crossing reported in a 10-year period for each of the crossing warning device types.

Table IV.1 Motor Vehicle Crash Data by Crossing Warning Device Type.

Warning Device Type	Number of Crossings	% of Total Crossings	Number of Crashes	% of Total Crashes	Average Crashes per Crossing
Traffic signal	232	45.8%	703	78.3%	3.03
Flashing lights w/ gates	172	33.9%	70	7.8%	0.41
Flashing lights	14	2.8%	32	3.6%	2.29
Crossbucks	4	0.8%	2	0.2%	0.50
Stop sign	60	11.8%	72	8.0%	1.20
LRV warning signs	4	0.8%	2	0.2%	0.50
Blank-out signs	10	2.0%	11	1.2%	1.10
None	11	2.2%	6	0.7%	0.55
Total	507	100.0%	898	100.0%	1.77

Of the total number of crashes that occurred, drivers running red lights or disobeying the traffic control (including driving around or through gates) accounted for 86.7% (784) of the total crashes. These numbers confirm the findings of Coifman and Bertini (Coifman and Bertini 1996) that many crashes involve drivers disobeying warning signs and systems. The remaining 13.3% (114) of the total crashes included the following: motor vehicles sliding on ice into light rail vehicles; motor vehicles stopped on tracks; motor vehicles encroaching on the trackway; motor vehicles making illegal turns in front of light rail vehicles or being hit by light rail vehicles making turns; general contact with light rail vehicles; and crashes in which alcohol was a contributing factor.

Crash Data by Alignment and Configuration. Reviewing crashes by light rail alignment type, 81.1% of the 507 light rail crossings analyzed were located in either a semiexclusive alignment Type b1 (237) or Type b4 (174). Of the 898 total vehicle crashes, 55.2% (496) occurred at light rail crossings located in semiexclusive alignment Type b4, although this alignment type is only 34.3% of the crossings analyzed. This equates to a higher average number of crashes per crossing than the average number of crashes per crossing for the entire data set. The highest average number of crashes per crossing occurred at crossings located in the semiexclusive Type b2 alignment. While the data show that there are a higher average number of crashes per crossing in nonexclusive alignment Types c2 and c3, the relatively small number of light rail crossings represented by the data for these two alignment types makes it difficult to draw any specific conclusions as to what the data represent. Table IV.2 shows the number of light rail crossings, total number of crashes, and average number of crashes per crossing reported in the 10-year study period for each of the semiexclusive and nonexclusive alignment types.

Reviewing crashes by light rail configuration type, most of the light rail crossings are located in two-way motor vehicle travel/two-way light rail vehicle travel configuration Types 2A (194) and 2C (185), and 67.7% (608) of the total crashes occurring in these two configurations. No light rail crossings in the dataset were constructed in configuration Types 1C, 2D, and 2E. The highest average number of crashes per crossing occurred in configuration Type 1D. However, there is only one light rail crossing from the entire dataset located in this type of configuration, so it is difficult to draw any specific conclusions as to what the data represents.

Table IV.2 Motor Vehicle Crash Data by Light Rail Alignment Type.

ROW	Type	Number of Crossings	Number of Crashes	Average Number of Crashes/Crossing
Semiexclusive	b1	237	206	0.87
Semiexclusive	b2	18	89	4.94
Semiexclusive	b3	44	71	1.61
Semiexclusive	b4	174	496	2.85
Semiexclusive	b5	18	20	1.11
Nonexclusive	c1	12	1	0.08
Nonexclusive	c2	1	3	3.00
Nonexclusive	c3	3	12	4.00
	Total	507	898	1.77

Excluding the Type 1D alignment, perpendicular running configurations have, on average, fewer crashes per crossing than median running or side running configurations. This lower crash rate is likely because perpendicular running configurations have only one or two directions of through moving motor vehicles crossing the light rail tracks at a right-angle and no turning movements are being made across the light rail tracks.

Table IV.3 shows the number of crossings, total number of crashes, and the number of crashes per crossing reported in a 10-year period for each of the configuration types. Again, excluding the single Type 1D alignment, configuration Types 1B, 2B, 2C, and 2G show the highest numbers of crashes per crossing.

The data were next examined on the basis of light rail alignment type and configuration type combinations. The data were first reviewed looking at general combinations of alignment and configuration types as shown in Table IV.4. The crash rates at perpendicular running configurations in semiexclusive rights-of-way are substantially lower than the crash rates at median running or side running configurations in semiexclusive rights-of-way. For nonexclusive rights-of-way, there were no light rail crossings in the dataset that were constructed in a side running configuration. For nonexclusive alignment types, the number of light rail crossings constructed in a perpendicular or median running configuration is minimal compared to the entire dataset. As a result, it is difficult to draw any conclusions from the data.

Table IV.3 Motor Vehicle Crash Data by Light Rail Running Configuration Type.

Configuration Type	Running Configuration	Number of Crossings	Number of Crashes	Average Number of Crashes/Crossing
1A	Perpendicular	29	51	1.76
1B	Side	19	86	4.53
1D	Perpendicular	1	5	5.00
1E	Side	17	20	1.18
1F	Side	21	9	0.43
2A	Perpendicular	194	163	0.84
2B	Side	22	73	3.32
2C	Median	185	445	2.41
2F	Side	1	0	0.00
2G	Median	18	46	2.56
	Total	507	898	1.77

Table IV.4 Motor Vehicle Crash Data by General Light Rail Alignment and Running Configuration Type.

ROW	Running Configuration	Number of Crossings	Number of Crashes	Average Number of Crashes/Crossing
Semiexclusive	Perpendicular	222	207	0.93
Semiexclusive	Side	80	188	2.35
Semiexclusive	Median	189	487	2.58
Nonexclusive	Perpendicular	3	12	4.00
Nonexclusive	Median	13	4	0.31
	Total	507	898	1.77

An analysis of variance (ANOVA) was then performed. That analysis showed that the crash rates for the three running configurations in Table IV.4 were significantly different at the 95% confidence level. However, a post-ANOVA pairwise comparison of these rates using Tukey's q-test showed that the median and side running configurations did not have significantly different crash rates given that zero lies within the confidence interval. Table IV.5 contains the t-test and Tukey q-test statistics.

Table IV.5 Running Configuration Statistics.

Running Configuration	Number of Crossings	Number of Crashes	Average Number of Crashes/Crossing
Perpendicular	225	219	0.97
Side	80	188	2.35
Median	202	491	2.43
		Sample Average	1.92
		Sample Std Dev	0.82
		t_{stat} =	4.06
		p-value =	0.03
		t_{crit} =	2.92
		$q_{0.05,2,895}$=	2.77
		Lower confidence interval	Upper confidence interval
Median/Side Running Pairwise Comparison		-0.06	0.22

The results of the statistical analysis of this data suggest that neither a median running nor a side running configuration is more effective from a crash mitigation standpoint, which appears to be a different from the conclusion reached in TCRP Report 17 (Korve et al. 1996) where median running configurations are recommended as preferable to side running configurations. Further comparison of the data used to develop the recommendations in TCRP Report 17 to current data should be performed because there are a larger number of systems and more data are available to study crash patterns with the various running configurations.

The two alignment/configuration type combinations in which the most light rail crossings are located are semiexclusive Type b1 with configuration Type 2A (182) and semiexclusive Type b4 with Type 2C (135). From a crash analysis perspective, as shown in Table IV.6, the Type b1/Type 2A crossing locations showed a lower than average number of crashes per crossing (0.69) while the Type b4/Type 2C light rail crossing locations showed a higher than average number of crashes per crossing (2.77).

There were fewer light rail crossings (190) represented by the remaining 23 alignment/configuration combinations; this results in a greater variation in crashes per crossing for those combinations of light rail crossing types. As a result of the small sample sizes for each of these 23 alignment/configuration combinations, no specific trends can be clearly defined by inspection of the data and no conclusions can be specifically drawn from the data.

Table IV.6 shows the number of light rail crossings, total number of crashes, and average number of crashes per crossing reported in the 10-year study period for each combination of alignment and configuration type. The two prominent alignment/configuration type combinations for which trends are analyzed are in italics in this table while the remaining 23 alignment/configuration type combinations are in standard text.

The crashes that occurred in median running configuration Types 2C and 2G, and the crashes that occurred in perpendicular configuration Types 1A, 1D, and 2A were analyzed. There were a total of 491 crashes at 202 light rail crossings, an average of 2.43 crashes per crossing, at median running configurations. Red light running/disobedience to the traffic control by the motor vehicle driver accounted for 446 (90.8%) of these 491 crashes, and 305 (62.1%) of these 491 crashes involved left-turning vehicles at these median running configurations.

There were a total of 188 crashes at 80 light rail crossings, an average of 2.35 crashes per crossing, at side running configurations. Red light running/disobedience to the traffic control by the motor vehicle driver accounted for 101 (53.7%) of these 188 crashes, and 59 (31.4%) of these 188 crashes involved left-turning motor vehicles at these side running configurations.

There were a total of 219 crashes at 225 light rail crossings, an average of 0.97 crashes per crossing, at perpendicular running configurations. Red light running/disobedience to the traffic control by the motor vehicle driver accounted for 141 (64.4%) of these 219 crashes. Because of the nature of these crossings, no left-turning or right-turning crashes occurred at these perpendicular running configurations.

Crash Data by Left-Turning and Right-Turning Motor Vehicles. Crashes involving left-turning and right-turning motor vehicles were examined more closely in the analysis. A crash was categorized as a left-turn or right-turn crash only where the data specifically stated that a left-turning or right-turning motor vehicle was involved. A total of 385 left-turn related crashes for all alignment/configuration types were reported, and 16 right-turn related crashes were reported.

Median running alignment/configuration Type b4/Type 2C (135 light rail crossings) showed the highest number of left-turn crashes. Left-turn crashes accounted for 235 of the 374 crashes that occurred at these crossings. These numbers also confirm the findings of Coifman and Bertini (1996) that left-turning crashes are the most prevalent type of crashes.

Table IV.6 Crash Data by Light Rail Alignment and Running Configuration Type.

ROW	Type	Configuration Type	Running Configuration	Number of Crossings	Number of Crashes	Average Number of Crashes/Crossing
Semiexclusive	b1	1A	Perpendicular	13	5	0.38
Semiexclusive	*b1*	*2A*	*Perpendicular*	*182*	*125*	*0.69*
Semiexclusive	b1	2B	Side	5	6	1.20
Semiexclusive	b1	2C	Median	37	70	1.89
Semiexclusive	b2	1B	Side	2	15	7.50
Semiexclusive	b2	2A	Perpendicular	1	7	7.00
Semiexclusive	b2	2B	Side	15	67	4.47
Semiexclusive	b3	1A	Perpendicular	3	2	0.67
Semiexclusive	b3	1B	Side	13	44	3.38
Semiexclusive	b3	1D	Perpendicular	1	5	5.00
Semiexclusive	b3	1F	Side	21	9	0.43
Semiexclusive	b3	2A	Perpendicular	4	11	2.75
Semiexclusive	b3	2B	Side	2	0	0.00
Semiexclusive	b4	1A	Perpendicular	13	44	3.38
Semiexclusive	b4	1B	Side	4	27	6.75
Semiexclusive	b4	1E	Side	1	0	0.00
Semiexclusive	b4	2A	Perpendicular	4	8	2.00
Semiexclusive	*b4*	*2C*	*Median*	*135*	*374*	*2.77*
Semiexclusive	b4	2G	Median	17	43	2.53
Semiexclusive	b5	1E	Side	16	20	1.25
Semiexclusive	b5	2C	Median	1	0	0.00
Semiexclusive	b5	2F	Side	1	0	0.00
Nonexclusive	c1	2C	Median	12	1	0.08
Nonexclusive	c2	2G	Median	1	3	3.00
Nonexclusive	c3	2A	Perpendicular	3	12	4.00
			Total	507	898	1.77

Traffic controls for the alignment/configuration Type b4/Type 2C light rail crossings were analyzed. Of the 135 light rail crossings of this alignment/configuration type, 107 of the crossings have one of the following: (i) permanent no left-turn restrictions, (ii) left-turn restrictions that are imposed with blank-out signs during the time a train is in the area, (iii) protected left-turn movements across the tracks, or (iv) a combination of protected left-turn movements enhanced with no left-turn blank-out signs during the time a train is in the area. Farrán (2000) discusses some of these methods for controlling motor vehicles that make turns in front of light rail vehicles, describes five different turning violation situations, and provides candidate solutions for each of these situations. Transit agencies have implemented many of the solutions described by Farrán at many of the light rail crossings in this study. However, the specific traffic signal operations (*e.g.*, leading versus lagging left turns) are unknown. It is therefore unknown if any of the traffic signal phasing solutions have been implemented at any of the subject light rail crossings.

One possible reason for the higher percentage of left-turn crashes at median running configurations (62.1%) as compared to side running configurations (31.4%) is the number of left-turn movements that cross the tracks in each of these configurations. With a median running configuration in a typical four-leg intersection, left turns from all four legs will cross the tracks whereas only two of the left-turn movements will cross the tracks with a side running configuration. Further data collection and analysis is needed to determine if this theory is correct as to why the percentages of left-turn crashes at median running configurations are almost double the percentages of left-turn crashes at side running configurations.

When the data shown in Table IV.5 are analyzed, the average number of crashes per crossing for median running configurations (2.43) and the average number of crashes per crossing for side running configurations (2.35) are fairly close. The similarity in this statistic leads to the suggestion that neither a median running configuration nor a side running configuration can be considered more effective than the other as a mitigation measure for crashes. Whether a transit agency constructs a median running configuration or side running configuration does not appear to provide mitigation for the primary cause of crashes experienced at light rail crossings: motor vehicle driver disobedience of traffic control at light rail crossings.

Although construction of light rail crossings in a perpendicular running configuration reduces the crash rate at light rail crossings, motor vehicle driver disobedience of traffic control remains the primary cause of crashes at these light rail crossing types.

All 16 of the right-turn crashes occurred in the side running alignment/configuration Type b5/Type 1E (16 light rail crossings). This configuration involves motor vehicles traveling on a one-way roadway that are moving in the same direction as one-way moving light rail vehicles. The crashes were reported as motor vehicle drivers disobeying the traffic control in place for the light rail crossing. With this light rail crossing configuration, it is likely that the motor vehicle drivers failed to look over their right shoulders prior to making the right-turn to see if a train was approaching the light rail crossing.

Consideration was given to possible mitigation measures to address crashes involving this alignment/configuration. One possible mitigation measure for these types of crashes is to use LRV activated LED blank-out signs. These types of blank-out signs were recently installed on a segment of the Denver RTD Central Corridor. The blank-out sign installed shows the LRV approaching symbol alternating with the no right-turn symbol. These LED blank-out signs are providing promising results on the Denver RTD

Central Corridor. A figure showing examples of LED blank-out signs can be found in Figure 2 of Farrán's (2000) paper.

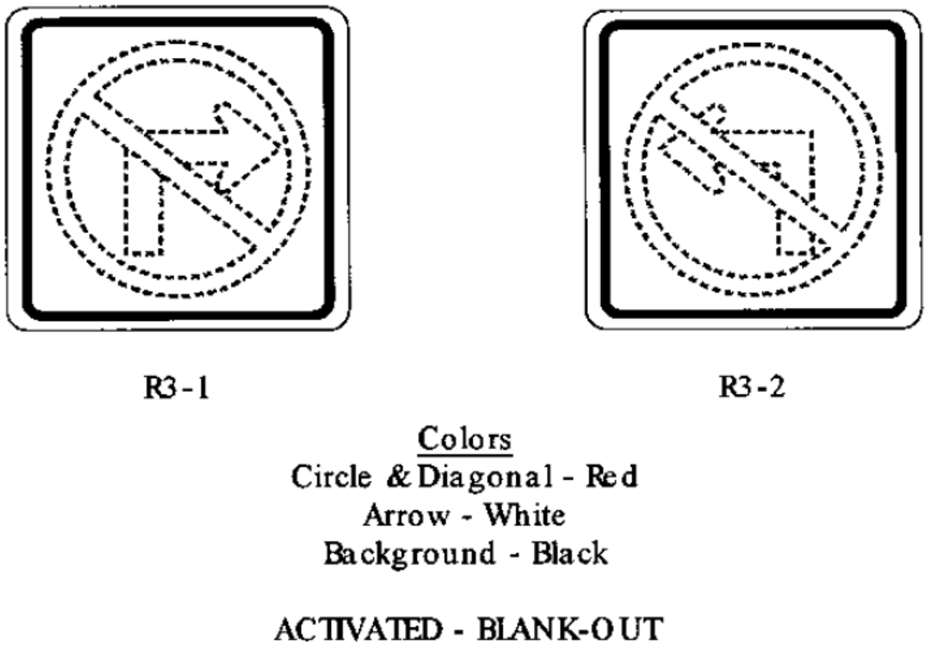

Figure IV.1 Farrán (2000) Figure 2 – LRT-activated Turn Prohibition Signs, 600 x 600 mm or 900 x 900 mm.

Findings Based on Analysis of Light Rail Crossing Crash Patterns

The analysis is on data collected from portions of nine light rail systems throughout the United States that were in continuous operation for the 10-year analysis period of the study. The analysis provides some initial insight into vehicle crash patterns at light rail crossings in relation to the alignment type and the configuration in which the light rail crossing is constructed.

This study found that semiexclusive light rail alignment Types b1 and b4 are the most prevalent alignments of light rail crossings.

This study calculated the average number of crashes per crossing for each light rail alignment type and compared those averages to the number of crashes per crossing for the entire data set. This study found that crashes occurred at a lower than average rate at semiexclusive alignment Types b1, b3, and b5 and nonexclusive Type c1 as shown in Table IV.2. Crashes occurred at a higher than average rate at semiexclusive alignment Types b2 and b4, and nonexclusive Types c2 and c3 as shown in Table IV.2. This study found that it is difficult to draw any conclusions regarding nonexclusive Types c2 and c3 due to the low number of light crossings for these alignment types in the data set reviewed.

A review of the same data for different configuration types revealed, as shown in Table IV.3, that configuration Types 2A and 2C are the most prevalent light rail configurations. This study calculated the average number of crashes per crossing for each light rail configuration type and compared those averaged to the number of crashes per crossing for the entire data set. This study found that, as shown in Table IV.3, configuration Types 1A, 1E, 1F, 2A, and 2F had lower than average crashes per crossing and that configuration Types 1B, 1D, 2B, 2C and 2G had higher than average crashes per crossing. This study also found that both median running and side running configurations had similar rates of crashes per crossing. This study found that it is difficult to draw any conclusions regarding configuration Types 1D and 2F given the low number of light rail crossings for these configuration types in the data set reviewed.

Looking at the primary cause of crashes for median running and side running configurations, this study found that the percentage of crashes that occur because of motor vehicle drivers running red lights or disobeying traffic control is very high for median running configurations (90.8%) and high for side running configurations (53.7%). This study found that the highest number of left-turn crashes occurred at the alignment/configuration Type b4/Type 2C light rail crossings despite the fact that 107 of the 135 light rail crossings in this category have left-turn restrictions or protected left-turn movements across the tracks.

While these numbers may raise a question about the efficacy of these types of left-turning treatments, the number of total crashes that occur at light rail crossings ultimately has to be viewed in light of the total number of LRVs and motor vehicles that use light rail crossings and in light of the low percentage of fatal crashes compared to the total number of crashes that occur at light rail crossings. Additionally, the crash rates shown in Tables IV.2, IV.3, IV.4, and IV.6 are the average number of reported crashes that have occurred at light rail crossings over the 10-year study period. When the rates are divided by the 10-year period, the crashes average to less than one crash per year per crossing.

Turning to the examination of perpendicular running configurations, this study found that, as shown in Table IV.5 the crash rates at these types of light rail crossings are lower than the crash rates at median running or side running configurations. Construction of a light rail crossing in a perpendicular running configuration appears to mitigate the crash rate at light rail crossings. However, even though the average crash rate at perpendicular running light rail crossings is lower than the crash rate for median or side running configurations, motor vehicle driver disobedience of the traffic control at perpendicular running light rail crossings (64.4%) is still the primary cause of crashes.

Finally, considering combinations of alignment and configuration types, this study found that semiexclusive Type b1/configuration Type 2A and semiexclusive Type b4/configuration Type 2C are the prevalent types of light rail crossings. This study found that it is difficult to identify any trends or draw any conclusions regarding crash patterns for most of the alignment/configuration combinations because there are a relatively small number of light rail crossings constructed in any single combination. From a review of the various alignment/configuration combinations in which light rail crossings have been constructed, this study found that there does not appear to be a single alignment/combination type that mitigates crashes for all configuration types or vice versa.

Conclusions Based on the Analysis of Light Rail Crossing Crash Patterns

Based on an analysis of light rail crossing crash patterns from the study data, a general suggestion can be made that from a crash mitigation perspective, neither a median running nor a side running configuration can be shown to be the more effective configuration type as a method to reduce crash rates, whereas a perpendicular running configuration does appear to mitigate crash rates at light rail crossings. This analysis should be performed again in the future with data from more transit systems and with data that is more uniform in information collection in order to get a more complete picture of crash patterns that occur at light rail crossings based on alignment type and configuration. Future analyses should also include analysis of crash patterns, including review of motor vehicle volumes and LRV train volumes.

This study also indicates that the available data set is limited because few light rail crossings have been constructed in many of the different configuration types. As a result of this limitation, the equations developed may be need to be limited to general categories of light rail crossing configurations (median, side, perpendicular) as opposed to a more granular configuration breakdown into the different configuration types.

Development of Light Rail Crossing Specific Equations

The light rail specific equations were developed through a series of steps. Each data element was initially analyzed to determine if it should move forward in the model development process. Those elements that were moved forward in the process were used in the development of the light rail specific equations through nonlinear regression techniques followed by an EB Method adjustment to the initial predicted numbers to account for the actual crash history at each crossing. Finally, statistical tests were performed to assess the statistical validity of the model and to determine whether any model parameters had a significant effect on the predicted value of the number of crashes expected to occur at a light rail crossing.

Data Available for Equation Development

There were a total of 560 at-grade light rail vehicle crossings available for study on the systems of the 10 transit agencies that provided crash data for this research. Availability of AADT count data was the limiting factor for this research because AADT count data were available for only 234 of the 560 crossings. Nine of the transit systems had crash data available for the full 10-year study period, while one system had only six years of crash history available.

The 213 crossings for which 10 years of crash data were available were used to develop the model equations. The model equations were developed using 2000 through

2004 crash data. The 21 crossings from the tenth transit system were added to the 213 crossings to test the statistical validity of the developed models using 2005 through 2009 crash data.

The use of five years of crash data to develop the models and five years of crash data to include in the crash history analysis equation is consistent with the methodology used by the US DOT to develop the US DOT Crash Prediction Equations. Farr (1987, 7) discuses using five years of crash data to develop the US DOT Initial Crash Prediction Equation shown in Equation II.5 and using no more than the most recent five years of crash data in the US DOT Second Crash Prediction Equation shown in Equation II.6 as the extent of improvement is minimal for any data more than five years old (Farr 1987, 13). This methodology appears to be successful as the US DOT has not modified the basic equations since 1987 and has only recalculated the normalizing constants used in the US DOT Final Crash Prediction Equation shown in Equation II.7 on a periodic basis as discussed by Farr (1987, 23).

To be consistent with the methodology used by the US DOT in developing the light rail specific equations, five years of crash data was used to develop the models. To test the statistical validity of the models, a different five years of data was used consistent with the US DOT methodology recommending the use of no more than five years of crash data. It would not be appropriate to use the same data to develop the models and test the model validity, so the available crash data was segmented into five years of development data and five years of statistical test data.

Data Elements to Use in Equation Development

Each category of data gathered for this study was graphed against a 5-year crash history from 2000-2004 for all of the crossings. These graphs were used as a preliminary method to determine whether the data element showed any likelihood of contributing to the number of crashes that occurred at the crossings or if the patterns for the data element were in line with the number of crossings containing that specific data element. A brief discussion of each data element reviewed is presented below and includes whether (and if so, why) a data element was eliminated from further consideration or moved forward in the model development process.

The crash data graphed against light rail alignments showed no specific patterns. Only nine of the model development crossings were located in nonexclusive categories, and the bulk of the remaining model development crossings were located in semiexclusive types b1, b3, and b4. There was little to no representation of the remaining semiexclusive and nonexclusive alignment types. Consequently, direct use of alignment types were removed from the model development parameters.

Specific light rail configuration types were not carried forward as a model development parameter because there were not enough data for each specific type to see a discernible crash pattern. However, the data were regrouped into the three general configuration types of median running, side running, and perpendicular running for use in developing the light rail specific models.

The crossing data available in the US DOT database group crossings according to the crossing angle and puts the crossing in one of these ranges: 0-20 degrees, 21-59 degrees, and 60-90 degrees. When looking at the light rail specific crossing angle data, the majority of the crossings in the dataset fall in the 60-90 degree range with most crossings in this range being 90 degree crossings. There was not a large number of crashes associated with the more skewed angle crossings in the dataset. Angle of crossing does not appear to be a contributing factor to light rail crashes and was removed from the model development parameters.

Crossing surface material also did not appear to be a contributing factor in light rail crossing crashes. The number of crashes that occurred on each crossing material type appeared to match the trend of the number of crossings with that material, so this element was removed from further consideration.

The number of tracks, either main tracks or other tracks, did not appear to have an influence on the number of crashes as there was no identifiable trend in the data related to the number of tracks at the crossing. Since the majority of the crossings in the data set had either one or two tracks and there was no pattern of more crashes occurring at one or the other, this parameter was removed from further consideration.

The graph for parallel road characteristics showed no crash pattern based on the number of parallel road lanes. This parameter appeared to have no influence on the number of crashes and was removed from consideration.

The presence or absence of pavement markings and advance warning signs at the light rail crossings appeared to have no trend for the number of crashes that occurred at the crossings. With this lack of trend and apparent lack of influence, these two parameters were removed from further consideration.

Sixty-five of the 231 crossings in the dataset were crossings where light rail tracks and railroad tracks shared the crossing. The number of crashes that occurred at shared crossings appeared to be similar to the number of crashes that occurred at non-shared crossings, so this parameter was removed from further consideration.

Distance of the crossing to the nearest intersection appeared to have some effect on the number of crashes at passive crossings, but not much influence on other warning types. This input was kept as a parameter to move forward for further consideration.

Sight obstructions appeared to show some trending of crossings with higher numbers of crashes having sight obstructions at the crossing. This input was kept as a parameter to move forward for further consideration.

Specific maximum timetable speeds were not available for each crossing, so a proxy for the maximum timetable speed was used based on the alignment type of the crossing. The preliminary graphs of the proxy maximum timetable speed appeared to have some effect on the number of crashes, so this parameter was moved forward for further consideration.

Land uses in general did not appear to have any specific trend. When considered as the separate groupings of residential, commercial, and other, residential appeared to have some effect of reducing the number of crashes that occurred at crossings adjacent to residential areas. This parameter was moved forward for further consideration.

Distance of the crossing to schools was included for 33 of the crossings used in the model development. There appeared to be a possible trend, so this parameter was moved forward for further consideration.

Train volume, AADT volume, and exposure factor were each graphed against the number of crashes. The graphs appeared to show a stronger relationship between the exposure factor and the number of crashes than either the train volume alone or the

AADT volume alone, so the exposure factor parameter was moved forward for further consideration.

The parameters of crossing width, number of traffic lanes, and road pavement width each appeared to have some effect on the number of crashes. All three parameters were moved forward with an expectation that one of these three parameters will represent the general width of the crossing in the final equation.

Initial Crash Number Equation Development

There were 560 at-grade crossings available on the ten transit systems used in this study. Only 234 of these crossings were used as the model development data because AADT data was only available for these 234 crossings. Crash data for the full 10-year study was available for 213 of these crossings. The available model development data were divided into groups based on crossing warning devices. The four crossing warning device categories were traffic signals, flashing lights, flashing lights with gates, and passive warning devices including all crossbucks and stop signs.

Of the 560 at-grade crossings available on the ten transit systems, there were only five crossings with flashing light warning devices. This provided insufficient data to develop an equation. More data for crossings with flashing lights will be needed in the future to develop a light rail specific equation for flashing light warning devices.

The available model development data were also divided into a group of 213 crossings for which the 2000-2004 crash data were used to develop the light rail specific models and a group of 234 crossings for which the 2005-2009 crash data were used to test the statistical validity of the developed models.

Once the data were divided by warning device, each group of data was set-up to perform a non-linear regression analysis using techniques published by Brown (2001) to use the Microsoft Excel SOLVER function. Brown's formulas seemed to provide inconsistent results, so the technique was modified to calculate standard error and coefficient of determination (R^2) by calculating each of these parameters by line and summing the columns to include in the final calculation instead of programming the formula directly into the final equation.

The SOLVER function was used separately for each warning device type. The formulas for each warning device type were adjusted to include the cell ranges representing the data for each warning type. The initial equation tested was established as a non-linear equation where configuration type, sight obstructions, and residential areas were set-up as a coefficient to the exponential function. These equation parameters were established using a one if the parameter existed and zero if the parameter did not exist. Using these as coefficients to the exponential function guarantees that if the parameter does not exist, the specific parameter will not be included in the equation for that specific crossing.

Using a modified version of the Brown technique, cells were named for each of the parameter coefficients included in the initial model. The SOLVER function was then run to maximize the R^2 for the tested equation. Each proposed parameter was tested for each warning device type. Each equation was also tested using the separate parameters of crossing width, number of lanes, and roadway width. The number of lanes parameter provided the highest R^2 value for each of the three warning device types.

To test the sensitivity of the developed models, the SOLVER function was run numerous times with different starting values for each model coefficient parameter. If the coefficient parameter did not change from the initial value once the SOLVER function was run, that model parameter was removed from the initial test equation, the SOLVER function was rerun, and the sensitivity of the new model was again tested for sensitivity by changing the initial values for the parameters. The equation and coefficients were recorded once the SOLVER equation maximized the R^2 value.

The developed equations for each of the three warning control devices are:

$$a = 0.0615 * e^{(-1.1489*Median)} * (0.0615*MaxTTSpeed) * (0.0615*NumTrafLanes) * (AADT*Train\ Volume)^{0.1406}$$

Equation IV.1 The Fischhaber Traffic Signal Equation.

$$a = 0.0372 * e^{(-1.1489*Median)} * e^{(1.2757*Side)} * e^{(0.9187*Perpendicular)} * (0.0372*MaxTTSpeed) * e^{(-0.8193*SightObstruction)} * e^{(-0.6002*ResArea)} * (0.0372*NumTrafLanes) * (AADT*Train\ Volume)^{0.0943}$$

Equation IV.2 The Fischhaber Gates Equation.

$$a = 0.0285 * e^{(0.3998*Side)} * (0.0285*MaxTTSpeed) * e^{(0.2993*SightObstruction)} * e^{(-0.7886*ResArea)} * (0.0285*NumTrafLanes) * (AADT*Train\ Volume)^{0.3595}$$

Equation IV.3 The Fischhaber Signs Equation.

where:

a	= initial crash number in crashes per year
Median	= median configuration (yes=1, no=0)
Side	= side configuration (yes=1, no=0)
Perpendicular	= perpendicular configuration (yes=1, no=0)
MaxTTSpeed	= proxy maximum timetable speed 65 MPH for alignments b1 and b2 35 MPH for alignments b3, b4, c1, and c2

15 MPH for alignments b5 and c3

SightObstruction = sight obstruction at the crossing (yes=1, no=0)

ResArea = crossing adjacent to a residential area (yes=1, no=0)

NumTrafLanes = number of lanes across the crossing

AADT = annual average daily traffic volume using the crossing

Train Volume = number of trains per day using the crossing

EB Method Equation Development

Once the initial crash number equations were developed, the EB Method was developed and applied to the initial crash number to adjust the initial crash number based on the actual crash experience at the crossing. The EB Method is a technique that increases the precision of estimation of a model and corrects for regression-to-mean and was calculated in this study as shown in the paper by Hauer et al. (2002). The EB Method implements a weighted average of the expected crash frequency at similar crossings and the count of crashes at the specific crossing. Use of the EB Method recognizes that the safety of a crossing is not solely determined by the number of crashes that occur at the specific crossing, but also by looking at what is known about safety at similar crossings (Hauer et. al. 2002, 126). The EB Method estimates an expected value of the dependent variable to equal a weighted combination of the predicted and observed values. The EB Method equation is:

$$N_{expected} = w*N_{predicted} + (1-w)*N_{observed}$$

Equation IV.4 The EB Method Equation.

where:

$N_{expected}$ = expected number of crashes at a specific crossing

$N_{predicted}$ = predicted number of crashes at similar crossings

$N_{observed}$ = observed number of crashes at this specific crossing during the time period of data used to calibrate the prediction equation

w = weighting factor

$$w = 1/(1+((\mu * Y)/\varphi))$$

Equation IV.5 The EB Weighting Factor Equation.

where:

w = weighting factor

μ = number of crashes/year expected for similar crossings

Y = number of years of crash counts used

φ = overdispersion parameter

Overdispersion parameters have been estimated for the developed Safety Performance Functions for different roadway facility types as discussed in the Highway Safety Manual. Crash modification factors have been developed for different intersection treatment types in the Highway Safety Manual. In addition, a few crash modification factors have been developed for treatments (*e.g.*, flashing lights with gates) related to highway-rail grade crossing traffic control and operational elements in the Highway Safety Manual. However, the Highway Safety Manual currently has no information regarding either treatments related to highway-light rail grade crossing traffic control and operational elements or traffic signal control treatments at any type of crossing. Due to the current lack of development of overdispersion parameters related to any type of crossing, the light rail crash data were used to estimate overdispersion parameters.

The overdispersion parameters were estimated using Methods-of-Moments Estimate (MME) discussed in a paper by Zhang, Ye, and Lord (2007). While Zhang, Ye, and Lord do not specifically recommend the use of the MME, the remaining estimators in the paper would require a mathematic or statistical software package to adequately perform the calculations. The overdispersion parameter can be easily calculated in a Microsoft Excel spreadsheet from the available model development data using the equation

$$\varphi = \bar{x}^2/(s^2 - \bar{x})$$

Equation IV.6 The MME Overdispersion Parameter Equation.

where:

φ = overdispersion parameter

$\bar{x}$ = first unbiased sample moment (sample average)

s^2 = second unbiased sample moment (sample standard deviation)

Overdispersion parameters were estimated for each combination of warning type device and track running configuration represented by the model development data using the same five years of crash data used to develop Equations IV.1-IV.3. Table IV.7 contains the overdispersion parameters estimated using Equation IV.6.

Table IV.7 Estimated Overdispersion Parameters by Warning Device and General Light Rail Running Configuration Type.

Estimated Overdispersion Parameters			
	Median	Side	Perpendicular
Traffic Signal	0.394	0.199	0.160
Gates	0.033	0.098	0.065
Passive	N/A	0.146	N/A

The estimated overdispersion parameters and the average number of crashes/year expected for similar crossings using a five-year crash history were used in Equation IV.5 to calculate the EB weighting factor. The EB weighting factor, the predicted number of crashes, and the observed number of crashes per year were used in Equation IV.4 to calculate the expected number of crashes at each specific crossing.

Statistical Testing of Light Rail Specific Models

Once the initial crash number equations and EB Method overdispersion parameters were developed, these equations were applied to the 234 crossings using 2005-2009 crash data. Predicted numbers of crashes were calculated for each crossing using the Fischhaber equations with EB Method adjustments and using the US DOT equations. For traffic signal controlled crossings, both the US DOT Flashing Lights and US DOT Gates equations were used because the US DOT formula does not have an output parameter for traffic signal control. The five years of crash data were used to determine the average number of crashes per year at each of the crossings.

F-statistics, R, and R^2 values were calculated for each model in each traffic control type using the average number of crashes per year at the crossing for calendar years 2005-2009. These statistics were calculated for the predicted number of crashes using the Fischhaber equations and the predicted number of crashes using the US DOT equations. Table IV.8 shows the results of these calculations for the 112 traffic signal controlled crossings, Table IV.9 shows the results of these calculations for the 103 flashing light and gate controlled crossings, and Table IV.10 shows these results for the 19 sign controlled crossings.

The F-statistic for the traffic signal control crossing models shows that, at a 99% confidence interval, the null hypothesis that all equation coefficients are equal to zero is rejected for all three models. This means that the predicted number of crashes is related to at least one of the input variables. Each of the three models has a p-value less than 0.01 confirming the validity of the F-statistic outcome. When comparing the p-values of the three traffic signal models, the Fischhaber model has the smallest p-value (8.93×10^{-32}) and the two US DOT models have p-values in the 10^{-4} to 10^{-5} range. This indicates that the Fischhaber model is the better fitting model. When comparing the R^2 values of the three traffic signal equations, the Fischhaber model has an R^2 value that is more than twice as great as either of the two US DOT models. This confirms that the Fischhaber model is the better fitting model for traffic signals.

Table IV.8 F-Statistic Analysis of Fischhaber Equations and US DOT Formula Predicted Crashes for Traffic Signal Control at a 99% Confidence Interval.

		Calculated Crashes Per Year			Fischhaber Traffic Signal Equation			US DOT Flashing Lights Equation			US DOT Gates Equation		
		Fischhaber	US DOT										
Crossing	2005-2009 Avg. Crashes	Traffic Signals	Flashing Lights	Gates	SST	SSR	SSE	SST	SSR	SSE	SST	SSR	SSE
1	2.75	2.77	1.31	1.44	5.13	5.22	0.00	5.13	0.68	2.08	5.13	0.91	1.72
2	0.00	0.18	0.15	0.14	0.23	0.09	0.03	0.23	0.11	0.02	0.23	0.12	0.02
3	1.75	1.56	0.79	0.88	1.60	1.17	0.03	1.60	0.09	0.92	1.60	0.16	0.75
4	4.50	2.76	1.33	1.51	16.13	5.19	3.02	16.13	0.72	10.02	16.13	1.05	8.94
5	0.00	0.09	0.08	0.08	0.23	0.16	0.01	0.23	0.16	0.01	0.23	0.17	0.01
6	0.75	0.57	0.31	0.31	0.07	0.01	0.03	0.07	0.03	0.19	0.07	0.03	0.19
7	2.50	2.16	1.06	1.18	4.06	2.82	0.11	4.06	0.33	2.08	4.06	0.48	1.75
8	0.00	0.04	0.07	0.06	0.23	0.20	0.00	0.23	0.17	0.00	0.23	0.18	0.00
9	0.50	0.17	0.16	0.15	0.00	0.10	0.11	0.00	0.10	0.11	0.00	0.11	0.12
10	0.00	0.05	0.08	0.07	0.23	0.19	0.00	0.23	0.17	0.01	0.23	0.17	0.00
11	1.25	0.54	0.32	0.30	0.59	0.00	0.50	0.59	0.03	0.87	0.59	0.03	0.91
12	0.00	0.05	0.07	0.06	0.23	0.19	0.00	0.23	0.17	0.01	0.23	0.18	0.00
13	1.00	0.77	0.43	0.45	0.27	0.08	0.05	0.27	0.00	0.33	0.27	0.00	0.31
14	0.75	0.57	0.33	0.34	0.07	0.01	0.03	0.07	0.02	0.17	0.07	0.02	0.17
15	2.25	1.56	0.76	0.80	3.12	1.16	0.47	3.12	0.08	2.21	3.12	0.10	2.12
16	1.25	0.77	0.43	0.44	0.59	0.08	0.23	0.59	0.00	0.68	0.59	0.00	0.65
17	0.25	0.18	0.14	0.13	0.05	0.10	0.01	0.05	0.12	0.01	0.05	0.13	0.01
18	0.25	0.18	0.17	0.17	0.05	0.09	0.00	0.05	0.10	0.01	0.05	0.10	0.01
19	0.50	0.17	0.12	0.11	0.00	0.10	0.11	0.00	0.14	0.15	0.00	0.14	0.16
20	0.00	0.02	0.06	0.05	0.23	0.22	0.00	0.23	0.18	0.00	0.23	0.19	0.00
21	1.50	1.36	0.66	0.67	1.03	0.77	0.02	1.03	0.03	0.70	1.03	0.03	0.70
22	0.00	0.02	0.07	0.06	0.23	0.21	0.00	0.23	0.17	0.01	0.23	0.18	0.00
23	0.25	0.18	0.17	0.17	0.05	0.09	0.01	0.05	0.10	0.01	0.05	0.10	0.01
24	0.00	0.08	0.09	0.10	0.23	0.17	0.01	0.23	0.16	0.01	0.23	0.15	0.01
25	1.00	0.96	0.51	0.54	0.27	0.23	0.00	0.27	0.00	0.24	0.27	0.00	0.21
26	0.00	0.04	0.08	0.08	0.23	0.19	0.00	0.23	0.16	0.01	0.23	0.16	0.01
27	0.00	0.06	0.08	0.08	0.23	0.18	0.00	0.23	0.16	0.01	0.23	0.16	0.01
28	0.00	0.02	0.07	0.06	0.23	0.21	0.00	0.23	0.18	0.00	0.23	0.18	0.00
29	0.00	0.06	0.08	0.08	0.23	0.18	0.00	0.23	0.16	0.01	0.23	0.16	0.01
30	0.00	0.04	0.09	0.09	0.23	0.20	0.00	0.23	0.16	0.01	0.23	0.16	0.01
31	0.00	0.02	0.07	0.07	0.23	0.21	0.00	0.23	0.17	0.01	0.23	0.18	0.00
32	0.00	0.06	0.08	0.08	0.23	0.18	0.00	0.23	0.16	0.01	0.23	0.16	0.01
33	0.00	0.02	0.07	0.06	0.23	0.21	0.00	0.23	0.18	0.00	0.23	0.18	0.00
34	0.50	0.37	0.25	0.27	0.00	0.01	0.02	0.00	0.05	0.06	0.00	0.05	0.05

		Calculated Crashes Per Year			Fischhaber Traffic Signal Equation			US DOT Flashing Lights Equation			US DOT Gates Equation		
		Fischhaber	US DOT										
Crossing	2005-2009 Avg. Crashes	Traffic Signals	Flashing Lights	Gates	SST	SSR	SSE	SST	SSR	SSE	SST	SSR	SSE
35	0.00	0.06	0.08	0.08	0.23	0.18	0.00	0.23	0.16	0.01	0.23	0.16	0.01
36	0.00	0.04	0.08	0.09	0.23	0.20	0.00	0.23	0.16	0.01	0.23	0.16	0.01
37	0.25	0.18	0.17	0.17	0.05	0.09	0.01	0.05	0.10	0.01	0.05	0.10	0.01
38	0.50	0.37	0.25	0.25	0.00	0.01	0.02	0.00	0.06	0.06	0.00	0.05	0.06
39	0.00	0.04	0.08	0.07	0.23	0.20	0.00	0.23	0.17	0.01	0.23	0.17	0.01
40	1.50	0.96	0.45	0.44	1.03	0.23	0.29	1.03	0.00	1.10	1.03	0.00	1.13
41	0.75	0.37	0.25	0.26	0.07	0.01	0.15	0.07	0.05	0.25	0.07	0.05	0.24
42	0.50	0.37	0.24	0.23	0.00	0.01	0.02	0.00	0.06	0.07	0.00	0.07	0.07
43	0.00	0.06	0.08	0.08	0.23	0.18	0.00	0.23	0.16	0.01	0.23	0.16	0.01
44	1.00	0.18	0.17	0.18	0.27	0.09	0.68	0.27	0.10	0.69	0.27	0.09	0.68
45	0.00	0.04	0.08	0.07	0.23	0.19	0.00	0.23	0.17	0.01	0.23	0.17	0.01
46	0.25	0.18	0.17	0.16	0.05	0.09	0.01	0.05	0.10	0.01	0.05	0.10	0.01
47	0.00	0.04	0.08	0.08	0.23	0.20	0.00	0.23	0.16	0.01	0.23	0.17	0.01
48	0.75	0.56	0.34	0.35	0.07	0.01	0.03	0.07	0.02	0.17	0.07	0.02	0.16
49	0.25	0.18	0.15	0.15	0.05	0.10	0.01	0.05	0.11	0.01	0.05	0.11	0.01
50	1.75	1.76	0.84	0.89	1.60	1.63	0.00	1.60	0.13	0.82	1.60	0.16	0.75
51	0.50	0.57	0.33	0.34	0.00	0.01	0.00	0.00	0.02	0.03	0.00	0.02	0.02
52	0.00	0.02	0.07	0.05	0.23	0.21	0.00	0.23	0.18	0.00	0.23	0.19	0.00
53	0.00	0.03	0.07	0.06	0.23	0.21	0.00	0.23	0.17	0.01	0.23	0.18	0.00
54	0.25	0.03	0.08	0.07	0.05	0.21	0.05	0.05	0.17	0.03	0.05	0.18	0.03
55	0.00	0.15	0.14	0.12	0.23	0.11	0.02	0.23	0.12	0.02	0.23	0.13	0.01
56	0.00	0.02	0.07	0.06	0.23	0.21	0.00	0.23	0.17	0.00	0.23	0.18	0.00
57	0.75	0.34	0.25	0.24	0.07	0.02	0.17	0.07	0.06	0.26	0.07	0.06	0.26
58	0.00	0.10	0.09	0.09	0.23	0.15	0.01	0.23	0.16	0.01	0.23	0.16	0.01
59	1.00	0.74	0.44	0.49	0.27	0.06	0.07	0.27	0.00	0.31	0.27	0.00	0.26
60	0.25	0.15	0.15	0.15	0.05	0.11	0.01	0.05	0.11	0.01	0.05	0.11	0.01
61	0.00	0.12	0.09	0.09	0.23	0.14	0.01	0.23	0.16	0.01	0.23	0.15	0.01
62	0.25	0.35	0.26	0.27	0.05	0.02	0.01	0.05	0.05	0.00	0.05	0.05	0.00
63	0.75	0.74	0.44	0.48	0.07	0.06	0.00	0.07	0.00	0.10	0.07	0.00	0.07
64	0.50	0.17	0.17	0.18	0.00	0.10	0.11	0.00	0.10	0.11	0.00	0.09	0.10
65	0.50	0.16	0.17	0.18	0.00	0.10	0.11	0.00	0.10	0.11	0.00	0.09	0.10
66	0.25	0.06	0.08	0.08	0.05	0.18	0.04	0.05	0.16	0.03	0.05	0.16	0.03
67	0.50	0.34	0.26	0.26	0.00	0.02	0.02	0.00	0.05	0.06	0.00	0.05	0.06
68	0.25	0.16	0.16	0.16	0.05	0.11	0.01	0.05	0.10	0.01	0.05	0.11	0.01
69	0.25	0.16	0.16	0.16	0.05	0.11	0.01	0.05	0.10	0.01	0.05	0.11	0.01
70	0.00	0.04	0.07	0.05	0.23	0.20	0.00	0.23	0.17	0.00	0.23	0.19	0.00
71	0.00	0.03	0.07	0.06	0.23	0.21	0.00	0.23	0.17	0.01	0.23	0.18	0.00

		Calculated Crashes Per Year			Fischhaber Traffic Signal Equation			US DOT Flashing Lights Equation			US DOT Gates Equation		
		Fischhaber	US DOT										
Crossing	2005-2009 Avg. Crashes	Traffic Signals	Flashing Lights	Gates	SST	SSR	SSE	SST	SSR	SSE	SST	SSR	SSE
72	0.50	0.19	0.18	0.19	0.00	0.09	0.10	0.00	0.09	0.10	0.00	0.09	0.10
73	1.00	0.55	0.36	0.40	0.27	0.00	0.20	0.27	0.02	0.41	0.27	0.01	0.36
74	1.00	0.54	0.35	0.38	0.27	0.00	0.21	0.27	0.02	0.42	0.27	0.01	0.39
75	0.75	0.35	0.26	0.28	0.07	0.02	0.16	0.07	0.05	0.24	0.07	0.04	0.23
76	1.50	1.33	0.68	0.72	1.03	0.71	0.03	1.03	0.04	0.67	1.03	0.05	0.61
77	0.75	0.35	0.26	0.27	0.07	0.02	0.16	0.07	0.05	0.24	0.07	0.05	0.23
78	1.00	0.54	0.35	0.38	0.27	0.00	0.21	0.27	0.02	0.42	0.27	0.01	0.39
79	0.75	0.53	0.29	0.27	0.07	0.00	0.05	0.07	0.04	0.21	0.07	0.04	0.23
80	0.00	0.09	0.26	0.27	0.23	0.16	0.01	0.23	0.05	0.07	0.23	0.04	0.08
81	0.50	0.54	0.35	0.38	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.01	0.02
82	0.00	0.09	0.09	0.09	0.23	0.16	0.01	0.23	0.16	0.01	0.23	0.15	0.01
83	0.00	0.09	0.09	0.09	0.23	0.16	0.01	0.23	0.16	0.01	0.23	0.15	0.01
84	0.75	0.55	0.36	0.40	0.07	0.00	0.04	0.07	0.02	0.15	0.07	0.01	0.12
85	0.00	0.02	0.06	0.05	0.23	0.21	0.00	0.23	0.18	0.00	0.23	0.19	0.00
86	0.00	0.04	0.07	0.06	0.23	0.20	0.00	0.23	0.17	0.00	0.23	0.18	0.00
87	0.00	0.04	0.07	0.06	0.23	0.20	0.00	0.23	0.17	0.01	0.23	0.18	0.00
88	0.00	0.18	0.17	0.17	0.23	0.09	0.03	0.23	0.10	0.03	0.23	0.10	0.03
89	0.00	0.01	0.07	0.06	0.23	0.23	0.00	0.23	0.17	0.00	0.23	0.18	0.00
90	0.00	0.01	0.07	0.06	0.23	0.23	0.00	0.23	0.17	0.01	0.23	0.18	0.00
91	0.75	0.37	0.25	0.25	0.07	0.01	0.14	0.07	0.06	0.25	0.07	0.06	0.25
92	0.00	0.15	0.09	0.09	0.23	0.11	0.02	0.23	0.16	0.01	0.23	0.16	0.01
93	0.00	0.19	0.08	0.08	0.23	0.09	0.04	0.23	0.16	0.01	0.23	0.16	0.01
94	0.25	0.18	0.15	0.13	0.05	0.09	0.01	0.05	0.11	0.01	0.05	0.12	0.01
95	0.25	0.18	0.14	0.13	0.05	0.10	0.01	0.05	0.12	0.01	0.05	0.13	0.01
96	0.25	0.37	0.22	0.20	0.05	0.01	0.01	0.05	0.07	0.00	0.05	0.08	0.00
97	0.75	0.57	0.34	0.35	0.07	0.01	0.03	0.07	0.02	0.17	0.07	0.02	0.16
98	0.00	0.02	0.07	0.06	0.23	0.22	0.00	0.23	0.17	0.00	0.23	0.18	0.00
99	0.00	0.04	0.07	0.06	0.23	0.19	0.00	0.23	0.17	0.00	0.23	0.18	0.00
100	0.50	0.18	0.17	0.16	0.00	0.09	0.10	0.00	0.10	0.11	0.00	0.10	0.11
101	0.25	0.16	0.15	0.14	0.05	0.10	0.01	0.05	0.11	0.01	0.05	0.12	0.01
102	1.00	0.73	0.38	0.37	0.27	0.06	0.07	0.27	0.01	0.39	0.27	0.01	0.40
103	0.25	0.34	0.24	0.24	0.05	0.02	0.01	0.05	0.06	0.00	0.05	0.06	0.00
104	0.75	0.53	0.32	0.31	0.07	0.00	0.05	0.07	0.03	0.19	0.07	0.03	0.19
105	0.25	0.34	0.25	0.24	0.05	0.02	0.01	0.05	0.06	0.00	0.05	0.06	0.00
106	0.00	0.04	0.07	0.06	0.23	0.20	0.00	0.23	0.17	0.00	0.23	0.18	0.00
107	0.75	0.57	0.32	0.31	0.07	0.01	0.03	0.07	0.03	0.19	0.07	0.03	0.19
108	0.00	0.01	0.07	0.06	0.23	0.23	0.00	0.23	0.17	0.01	0.23	0.18	0.00

		Calculated Crashes Per Year			Fischhaber Traffic Signal Equation			US DOT Flashing Lights Equation			US DOT Gates Equation		
		Fischhaber	US DOT										
Crossing	2005-2009 Avg. Crashes	Traffic Signals	Flashing Lights	Gates	SST	SSR	SSE	SST	SSR	SSE	SST	SSR	SSE
109	1.75	1.37	0.66	0.69	1.60	0.78	0.15	1.60	0.03	1.18	1.60	0.04	1.12
110	0.25	0.17	0.14	0.13	0.05	0.10	0.01	0.05	0.12	0.01	0.05	0.13	0.02
111	0.25	0.17	0.15	0.14	0.05	0.10	0.01	0.05	0.11	0.01	0.05	0.12	0.01
112	0.50	0.57	0.34	0.35	0.00	0.01	0.01	0.00	0.02	0.03	0.00	0.02	0.02
Average	0.484			Sum	52.29	31.25	8.62	52.29	13.05	30.90	52.29	14.11	28.39
				R^2=	0.60			0.25			0.27		
				R =	0.77			0.50			0.52		
				n=	112			112			112		
				k=	7			12			12		
				F_{stat} =	53.88			3.48			4.10		
				p-value =	8.9E-32			2.6E-04			3.5E-05		
				F_{crit} =	2.98			2.43			2.43		
				$H_0 : \beta_1=\beta_2=...\beta_k=0$	Reject			Reject			Reject		

Table IV.9 F-Statistic Analysis of Fischhaber Equations and US DOT Formula Predicted Crashes for Gates Control at a 99% Confidence Interval.

		Calculated Crashes Per Year		Fischhaber Gates Equation			US DOT Gates Equation		
Crossing	2005-2009 Avg. Crashes	Fischhaber Gates	US DOT Gates	SST	SSR	SSE	SST	SSR	SSE
113	0.00	0.007	0.078	0.002	0.002	0.000	0.002	0.001	0.006
114	0.25	0.188	0.162	0.041	0.019	0.004	0.041	0.013	0.008
115	0.00	0.005	0.054	0.002	0.002	0.000	0.002	0.000	0.003
116	0.00	0.002	0.032	0.002	0.002	0.000	0.002	0.000	0.001
117	0.00	0.009	0.032	0.002	0.002	0.000	0.002	0.000	0.001
118	0.00	0.003	0.068	0.002	0.002	0.000	0.002	0.000	0.005
119	0.00	0.189	0.164	0.002	0.020	0.036	0.002	0.013	0.027
120	0.00	0.019	0.083	0.002	0.001	0.000	0.002	0.001	0.007
121	0.00	0.015	0.08	0.002	0.001	0.000	0.002	0.001	0.006
122	0.00	0.016	0.084	0.002	0.001	0.000	0.002	0.001	0.007
123	0.00	0.030	0.086	0.002	0.000	0.001	0.002	0.001	0.007
124	0.25	0.006	0.066	0.041	0.002	0.060	0.041	0.000	0.034
125	0.00	0.026	0.075	0.002	0.000	0.001	0.002	0.001	0.006

		Calculated Crashes Per Year		Fischhaber Gates Equation			US DOT Gates Equation		
Crossing	2005-2009 Avg. Crashes	Fischhaber Gates	US DOT Gates	SST	SSR	SSE	SST	SSR	SSE
126	0.00	0.043	0.087	0.002	0.000	0.002	0.002	0.001	0.008
127	0.00	0.190	0.172	0.002	0.020	0.036	0.002	0.015	0.030
128	0.00	0.006	0.08	0.002	0.002	0.000	0.002	0.001	0.006
129	0.00	0.015	0.076	0.002	0.001	0.000	0.002	0.001	0.006
130	0.00	0.006	0.058	0.002	0.002	0.000	0.002	0.000	0.003
131	0.00	0.007	0.087	0.002	0.002	0.000	0.002	0.001	0.008
132	0.00	0.013	0.068	0.002	0.001	0.000	0.002	0.000	0.005
133	0.00	0.030	0.088	0.002	0.000	0.001	0.002	0.002	0.008
134	0.00	0.028	0.081	0.002	0.000	0.001	0.002	0.001	0.007
135	0.00	0.029	0.085	0.002	0.000	0.001	0.002	0.001	0.007
136	0.00	0.027	0.078	0.002	0.000	0.001	0.002	0.001	0.006
137	0.00	0.046	0.095	0.002	0.000	0.002	0.002	0.002	0.009
138	0.25	0.190	0.181	0.041	0.020	0.004	0.041	0.018	0.005
139	0.00	0.007	0.064	0.002	0.002	0.000	0.002	0.000	0.004
140	0.00	0.023	0.086	0.002	0.001	0.001	0.002	0.001	0.007
141	0.00	0.015	0.076	0.002	0.001	0.000	0.002	0.001	0.006
142	0.00	0.019	0.072	0.002	0.001	0.000	0.002	0.001	0.005
143	0.00	0.004	0.064	0.002	0.002	0.000	0.002	0.000	0.004
144	0.00	0.017	0.062	0.002	0.001	0.000	0.002	0.000	0.004
145	0.00	0.039	0.082	0.002	0.000	0.002	0.002	0.001	0.007
146	0.00	0.009	0.055	0.002	0.002	0.000	0.002	0.000	0.003
147	0.00	0.004	0.057	0.002	0.002	0.000	0.002	0.000	0.003
148	0.00	0.017	0.058	0.002	0.001	0.000	0.002	0.000	0.003
149	0.25	0.004	0.057	0.041	0.002	0.061	0.041	0.000	0.037
150	0.00	0.003	0.046	0.002	0.002	0.000	0.002	0.000	0.002
151	0.00	0.009	0.078	0.002	0.002	0.000	0.002	0.001	0.006
152	0.00	0.004	0.051	0.002	0.002	0.000	0.002	0.000	0.003
153	0.00	0.004	0.051	0.002	0.002	0.000	0.002	0.000	0.003
154	0.00	0.010	0.065	0.002	0.002	0.000	0.002	0.000	0.004
155	0.00	0.183	0.171	0.002	0.018	0.034	0.002	0.015	0.029
156	0.00	0.015	0.149	0.002	0.001	0.000	0.002	0.010	0.022
157	0.00	0.015	0.068	0.002	0.001	0.000	0.002	0.000	0.005
158	0.00	0.000	0.069	0.002	0.002	0.000	0.002	0.000	0.005
159	0.00	0.000	0.057	0.002	0.002	0.000	0.002	0.000	0.003
160	0.00	0.003	0.08	0.002	0.002	0.000	0.002	0.001	0.006
161	0.50	0.393	0.227	0.204	0.119	0.011	0.204	0.032	0.075
162	0.00	0.001	0.07	0.002	0.002	0.000	0.002	0.000	0.005

		Calculated Crashes Per Year		Fischhaber Gates Equation			US DOT Gates Equation		
Crossing	2005-2009 Avg. Crashes	Fischhaber Gates	US DOT Gates	SST	SSR	SSE	SST	SSR	SSE
163	0.00	0.001	0.06	0.002	0.002	0.000	0.002	0.000	0.004
164	0.00	0.004	0.051	0.002	0.002	0.000	0.002	0.000	0.003
165	0.00	0.004	0.059	0.002	0.002	0.000	0.002	0.000	0.003
166	0.00	0.010	0.085	0.002	0.001	0.000	0.002	0.001	0.007
167	0.00	0.009	0.072	0.002	0.002	0.000	0.002	0.001	0.005
168	0.00	0.007	0.074	0.002	0.002	0.000	0.002	0.001	0.005
169	0.00	0.009	0.057	0.002	0.002	0.000	0.002	0.000	0.003
170	0.00	0.023	0.082	0.002	0.001	0.001	0.002	0.001	0.007
171	0.00	0.020	0.075	0.002	0.001	0.000	0.002	0.001	0.006
172	0.25	0.188	0.137	0.041	0.020	0.004	0.041	0.008	0.013
173	0.00	0.018	0.062	0.002	0.001	0.000	0.002	0.000	0.004
174	0.00	0.015	0.076	0.002	0.001	0.000	0.002	0.001	0.006
175	0.00	0.006	0.07	0.002	0.002	0.000	0.002	0.000	0.005
176	0.00	0.003	0.055	0.002	0.002	0.000	0.002	0.000	0.003
177	0.00	0.003	0.055	0.002	0.002	0.000	0.002	0.000	0.003
178	0.00	0.012	0.076	0.002	0.001	0.000	0.002	0.001	0.006
179	0.25	0.188	0.128	0.041	0.019	0.004	0.041	0.006	0.015
180	0.00	0.018	0.069	0.002	0.001	0.000	0.002	0.000	0.005
181	0.00	0.006	0.068	0.002	0.002	0.000	0.002	0.000	0.005
182	0.00	0.014	0.068	0.002	0.001	0.000	0.002	0.000	0.005
183	0.00	0.017	0.072	0.002	0.001	0.000	0.002	0.001	0.005
184	0.00	0.004	0.059	0.002	0.002	0.000	0.002	0.000	0.003
185	0.00	0.184	0.165	0.002	0.018	0.034	0.002	0.014	0.027
186	0.25	0.184	0.19	0.041	0.018	0.004	0.041	0.020	0.004
187	0.00	0.009	0.075	0.002	0.002	0.000	0.002	0.001	0.006
188	0.00	0.006	0.061	0.002	0.002	0.000	0.002	0.000	0.004
189	0.00	0.049	0.081	0.002	0.000	0.002	0.002	0.001	0.007
190	0.00	0.022	0.081	0.002	0.001	0.000	0.002	0.001	0.007
191	0.00	0.004	0.064	0.002	0.002	0.000	0.002	0.000	0.004
192	0.00	0.024	0.069	0.002	0.001	0.001	0.002	0.000	0.005
193	0.00	0.036	0.082	0.002	0.000	0.001	0.002	0.001	0.007
194	0.50	0.383	0.204	0.204	0.112	0.014	0.204	0.024	0.088
195	0.00	0.021	0.078	0.002	0.001	0.000	0.002	0.001	0.006
196	0.00	0.025	0.071	0.002	0.001	0.001	0.002	0.001	0.005
197	0.00	0.008	0.046	0.002	0.002	0.000	0.002	0.000	0.002
198	0.00	0.041	0.073	0.002	0.000	0.002	0.002	0.001	0.005
199	0.00	0.027	0.079	0.002	0.000	0.001	0.002	0.001	0.006

		Calculated Crashes Per Year		Fischhaber Gates Equation			US DOT Gates Equation		
Crossing	2005-2009 Avg. Crashes	Fischhaber Gates	US DOT Gates	SST	SSR	SSE	SST	SSR	SSE
200	0.50	0.188	0.134	0.204	0.020	0.097	0.204	0.007	0.134
201	0.00	0.188	0.15	0.002	0.020	0.035	0.002	0.010	0.023
202	0.75	0.388	0.205	0.492	0.115	0.131	0.492	0.024	0.297
203	0.00	0.013	0.06	0.002	0.001	0.000	0.002	0.000	0.004
204	0.00	0.006	0.051	0.002	0.002	0.000	0.002	0.000	0.003
205	0.50	0.183	0.163	0.204	0.018	0.100	0.204	0.013	0.114
206	0.00	0.019	0.086	0.002	0.001	0.000	0.002	0.001	0.007
207	0.00	0.040	0.093	0.002	0.000	0.002	0.002	0.002	0.009
208	0.00	0.007	0.068	0.002	0.002	0.000	0.002	0.000	0.005
209	0.00	0.021	0.075	0.002	0.001	0.000	0.002	0.001	0.006
210	0.00	0.007	0.042	0.002	0.002	0.000	0.002	0.000	0.002
211	0.00	0.014	0.052	0.002	0.001	0.000	0.002	0.000	0.003
212	0.00	0.007	0.038	0.002	0.002	0.000	0.002	0.000	0.001
213	0.00	0.007	0.039	0.002	0.002	0.000	0.002	0.000	0.002
214	0.00	0.014	0.052	0.002	0.001	0.000	0.002	0.000	0.003
215	0.50	0.388	0.212	0.204	0.115	0.013	0.204	0.027	0.083
Average	0.049		Sum	2.007	0.804	0.710	2.007	0.319	1.469
			R^2=	0.401			0.159		
			R =	0.633			0.399		
			n=	104			104		
			k=	11			12		
			F_{stat} =	9.481			1.646		
			p-value =	0.000			0.093		
			F_{crit} =	2.518			2.447		
			H0 : β1=β2=...βk =0	Reject			Accept		

Table IV.10 F-Statistic Analysis of Fischhaber Equations and US DOT Formula Predicted Crashes for Passive Sign Control at a 95% Confidence Interval.

		Calculated Crashes Per Year		Fischhaber Passive Signs Equation			US DOT Passive Signs Equation		
Crossing	2005-2009 Avg. Crashes	Fischhaber Signs	US DOT Signs	SST	SSR	SSE	SST	SSR	SSE
216	0.00	0.024	0.085	0.177	0.158	0.001	0.177	0.113	0.007
217	0.75	0.573	0.379	0.108	0.023	0.031	0.108	0.002	0.138
218	1.00	0.573	0.379	0.335	0.023	0.182	0.335	0.002	0.386
219	0.25	0.177	0.185	0.029	0.059	0.005	0.029	0.056	0.004
220	0.75	0.573	0.379	0.108	0.023	0.031	0.108	0.002	0.138
221	0.75	0.573	0.379	0.108	0.023	0.031	0.108	0.002	0.138
222	0.25	0.177	0.185	0.029	0.059	0.005	0.029	0.056	0.004
223	1.50	1.372	0.768	1.164	0.905	0.016	1.164	0.120	0.536
224	1.00	0.973	0.574	0.335	0.304	0.001	0.335	0.023	0.181
225	0.00	0.033	0.095	0.177	0.150	0.001	0.177	0.106	0.009
226	0.00	0.025	0.086	0.177	0.157	0.001	0.177	0.112	0.007
227	0.00	0.017	0.085	0.177	0.164	0.000	0.177	0.113	0.007
228	0.75	0.378	0.344	0.108	0.002	0.139	0.108	0.006	0.165
229	0.75	0.775	0.583	0.108	0.125	0.001	0.108	0.026	0.028
230	0.00	0.020	0.079	0.177	0.161	0.000	0.177	0.117	0.006
231	0.00	0.176	0.152	0.177	0.060	0.031	0.177	0.072	0.023
232	0.00	0.051	0.092	0.177	0.137	0.003	0.177	0.108	0.008
233	0.00	0.022	0.084	0.177	0.159	0.000	0.177	0.114	0.007
234	0.25	0.177	0.175	0.029	0.059	0.005	0.029	0.061	0.006
Average	0.421		Sum	3.882	2.752	0.485	3.882	1.211	1.798
			R^2=	0.709			0.312		
			R =	0.842			0.558		
			n=	19			19		
			k=	11			12		
			F_{stat} =	3.609			0.337		
			p-value =	0.050			0.949		
			F_{crit} =	3.347			3.603		
			H0 : β1=β2=...βk =0	Reject			Accept		

The F-statistic for the gates control crossing models shows that, at a 99% confidence interval, the null hypothesis for the US DOT model for gates is accepted while the Fischhaber equation for gates is rejected. This means that the Fischhaber model is statistically valid and the US DOT model is not. The Fischhaber model has a p-value less than 0.01, confirming the validity of the F-statistic outcome.

The F-statistic for the signs control models shows that, at a 99% confidence interval, the null hypothesis is accepted for both models. At a 95% confidence interval, the null hypothesis for the US DOT signs model is accepted while the Fischhaber signs model is rejected. This means that the Fischhaber model is statistically valid at a 95% confidence interval and the US DOT model is not. The p-value for the Fischhaber model is right at 0.05, which confirms the validity of the F-statistic. The R^2 value is substantial at 0.709 meaning the Fischhaber model is a good fitting model.

Conclusions Based on the Analysis of Fischhaber Light Rail Specific Crash Prediction Equations

Based on the statistical analysis, the Fischhaber equations produce statistically significant results at a 99% confidence interval for the traffic signal and gates equations and at a 95% confidence interval for the signs model because the null hypothesis is rejected. Rejection of the null hypothesis means that at least one of the equation input variables relates significantly to the calculated number of crashes.

Research Question Answered by Model Development and Statistical Analysis

Based on the statistical analysis of the Fischhaber light rail specific crash prediction models, the answer to research question four is that there is a significant statistical difference between the number of crashes predicted by the Fischhaber equations developed to predict crash number specifically at light rail crossings controlled with flashing lights and gates and controlled with signs and the number of crashes predicted by railroad crossing crash prediction equations. The Fischhaber equations developed to predict the number of crashes at light rail crossings controlled with traffic signals is a much better fitting model than either of the US DOT crash prediction equations used as a proxy for predicting the number of crashes at light rail crossings controlled with traffic signals.

CHAPTER V

GIS MODEL FLOW CHRAT DEVELOPMENT

GIS is a powerful tool that can be used to perform spatial analysis and display spatially related information. A specific calculation and analysis model was not developed as part of this study due to much of the necessary model input information currently not being in formats that are favorable to input into a GIS model. A generic GIS model flow chart is developed as part of this research to be used as a tool for how the various input data should be stored in the future to make the data usable in a GIS model.

Use of GIS

GIS was used in this study to develop Figure III.2, a map showing the Denver RTD light rail crossing locations of the Central Corridor and Central Platte Valley Corridor in the Downtown Denver area. This map contains a legend that shows the locations of at-grade crossings, driveway crossings, grade-separated crossings, light rail lines and light rail station locations. GIS was also used in this study to develop Figure III.6, a map showing the number of crashes on the Denver RTD system Central Corridor from 1999 through 2009. This figure used thematic mapping to show relative differences in the number of crashes that occurred at each crossing. Figure III.6 shows that there are concentrations of crashes at the crossings of 7th Street, 9th Street, Kalamath Street, Speer Boulevard SB and Spear Boulevard NB. This figure also shows that there are more crashes that occur at crossings adjacent to the Welton Street corridor than generally occur in the Downtown Denver area, with the exception of some crossings along Stout Street from 15th Street south and along 14th Street between Stout Street and California Street. This type of thematic mapping is used for the entire Denver RTD system to provide a visual analysis of where there are crash problem locations on the entire system. This type of thematic mapping can be used with existing systems to demonstrate where problem areas on a system may occur, or could be used by transit agencies looking to expand systems to see where potential future crash issues may exist on planned or proposed alignments. This type of mapping can also be used to assist in determining the types of warning devices that should be considered at proposed crossings.

GIS, used in conjunction with safety analysis equations, can provide useful information in monitoring safety at light rail crossings. Panchanathan and Faghri (1995) developed such a tool for the State of Delaware that could provide a knowledge-based system that used GIS in analyzing safety at railroad crossings. Panchanathan and Faghri developed a program that used site-specific qualitative factors in conjunction with US DOT railroad crash index and inventory database information to assign indicators of danger levels at railroad crossings in Delaware. The knowledge-based system was able to suggest remedial action for safety improvements at these crossings, and provided 15 possible safety improvement alternatives. The knowledge-based model also established cost and effectiveness factors for each of the possible safety improvement alternatives. The developed model used a phase-by-phase evaluation process and presented a set of possible actions for safety improvements for each crossing.

The studies performed by Miller (1999, 2000) found that GIS provided a number of benefits for various types of crash data analysis at a macroscopic level. Miller concluded that GIS has the ability to manipulate data in a creative manner; that GIS can be used at a corridor level to identify potential problem sites; that GIS can be used as an analytic tool for crash analysis instead of just as a display tool; and that GIS can be integrated with multiple computer-based methods of obtaining crash locations. Miller's studies were specific to the state of Virginia.

Based on the work by Panchanathan and Faghri (1995) and Miller (1999, 2000) he GIS model developed for light rail crossings could incorporate similar functions to provide for crash analysis, determination of possible mitigation measures, and ability to analyze information at a corridor level to provide predictive information regarding proposed new alignments or system upgrades.

GIS Model Flow Chart Development

This study has identified a lack of uniformity of storing information regarding light rail crossing alignment, configuration, and crash history information. A desired outcome of this research is to identify what specific information is necessary to determine safety at light rail crossings. With this identification, hopefully a more uniform system of data collection and storage can occur either at the transit agencies, or can be developed or included in existing national databases. Because the specific means and methods of storing this identified information is in its infancy, a specific GIS model flow chart cannot be developed. However, knowing the specific type of information that is needed for the safety calculations, a general GIS model flow chart can be developed outlining the necessary information and types of calculation processes that will be necessary.

The general model will involve inputs of vector data with associated attributes for the light rail crossing configuration data and table data of the light rail crossing crashes. These two inputs will be used to calculate the predicted number of crashes at each crossing in the dataset. The output of this calculation process will be a geodatabase table of predicted crashes by crossing. This calculated data will need to be registered to create a relation between the crossing vector point data and the predicted crashes by crossing through a primary key to create a derived relation to display with the crossings. The primary key will be a unique light rail crossing identifier. Once the derived relationship is created, a relational database can be created of the crossing crash information to the crossing location and this information can be used to determine crossing warning device options based on specific input factors and predicted crashes. This process will generate a second derived relationship of the crossing warning device options to the crossings. This derived relationship can also be displayed thematically and a relational database can be created of the crossing warning device options to the crossing location.

Model development can be accomplished in a GIS software such as ArcGIS® Desktop software (ESRI 2011). ArcGIS® Desktop software has a ModelBuilder™ function that is part of the software. Techniques to use the ModelBuilder™ function to construct GIS models have been developed by Allen (Allen 2011), and this resource is a step-by-step tutorial on how to use the ArcGIS® ModelBuilder™ function. Figure V.1 shows a proposed general GIS model flow chart that can be used to develop the light rail crossing calculation model in the future.

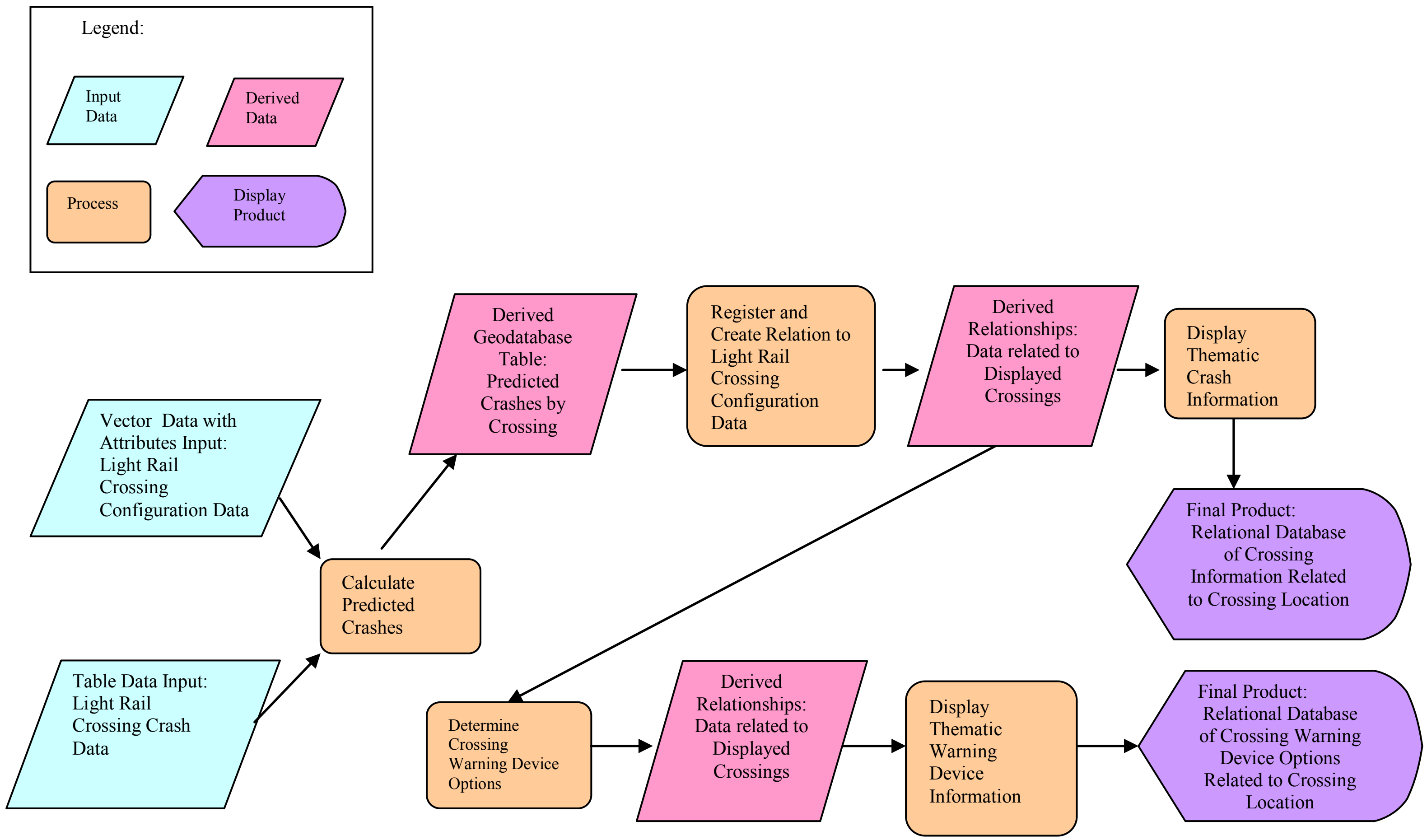

Figure V.1 Proposed GIS Model Flow Chart.

Conclusions Based on the GIS Model Flow Chart Development

Review of the literature and development of a preliminary GIS model flow chart show that a GIS model should be developed to allow for prediction of crashes at light rail crossings with the ability to use the GIS to display results for trend analysis. Further research is necessary to determine how the specific model inputs need to be configured and to develop the logic to determine crossing control options that would be available for each type of crossing alignment and configuration. Future research is also necessary to determine how to develop a model flexible enough to allow for the addition of crash severity predictions in the future, and calculation of predicted crash rates for additional crossing warning device types.

Research Question Answered by GIS Model Flow Chart Development

Based on the preliminary GIS model flow chart development, the answer to research question five is that GIS models can be used in the application of crash number prediction equations. The research also shows that such a GIS model can be used to perform analyses along light rail corridors for trend analysis, light rail crossing safety upgrade determination, and for planning of future light rail line extensions or developments.

CHAPTER VI

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This study analyzed the safety at light rail crossings to determine whether existing crash prediction and/or hazard index formulas developed to predict safety at railroad crossings could be used to predict safety at light rail crossings. Below is a discussion of the findings of this research, the conclusions that can be drawn from this research, and the recommendations for future research.

Discussion

The purpose of this study was to determine whether separate equations are necessary to predict crash number or to predict relative hazards for light rail crossings. The research shows that the answer to this question is a resounding yes. The initial models developed to predict safety at light rail crossings show that light rail operational configuration through crossings and intersections contributes to the predictive aspect of the models.

Light Rail Operational Configuration

One of the initial hypotheses of this research was that specific light rail operational configurations contribute to safety at light rail crossings. The data used in this research shows that the transit agencies that provided crash data for this study construct two configuration types more often than all other configuration types. These are configuration types 2A (a perpendicular running configuration where two-way light rail vehicle operations with light rail operating in semiexclusive right-of-way perpendicular to the roadway with no adjacent intersections) and type 2C (a median running configuration where two-way light rail vehicle operations with light rail operating parallel in-between the motor vehicle operations). The general configuration types of median running, side running, and perpendicular running were found to contribute to determining the level of safety at light rail crossings as these configurations are inputs to the developed light rail specific crash prediction models.

Further research on all transit agencies in the country should be performed to determine whether this configuration trend carries through all transit agencies or whether different configuration patterns exist at other transit agencies in the country. Additional data would also allow the original hypothesis to be better tested to determine if specific light rail operational configurations contribute to safety at light rail crossings or if the general light rail operational configuration categories of median running, side running, and perpendicular running are sufficient.

Light Rail Alignment Type

A second hypothesis of this research was that light rail alignment type contributes to safety at light rail crossings. The data used in this research show that the transit agencies that provided crash data for this study construct two specific alignment types more often than all other types. These are semiexclusive b1 (an alignment similar to an exclusive alignment type, but that has at-grade automobile, bicycle, and/or pedestrian crossing openings between fencing or other barriers at appropriate locations) and semiexclusive b4 (light rail tracks are located within a street right-of-way, but are separated by mountable curbs, striping, and/or lane designation, and motor vehicles, bicycles, and pedestrians should only cross the alignment at designated locations). Light rail alignment was included as a model parameter input through use of the maximum timetable speed proxy factor where the maximum timetable operating speed for the alignment type was used as a proxy for actual operating timetable speeds at the light rail crossing and was found to contribute to determining the level of safety at light rail crossings as an input to the developed light rail specific crash prediction models.

Further research on all transit agencies in the country should be performed to determine whether this alignment type trend carries through all transit agencies or whether different alignment patterns exist at other transit agencies. Additional data regarding light rail alignment would also allow the original hypotheses to be tested more thoroughly to determine if specific light rail alignment types contribute to safety at light rail crossings.

Traffic Count Data

The road authorities through which the transit agencies ran were very helpful in providing whatever data they had for the crossings being studied. Many of these road authorities also make public their traffic count data on their websites. Nonetheless, AADT data turned out to be the most difficult data to acquire in this research. AADT data was found to contribute to determining the level of safety at light rail crossings as AADT is an input to the developed light rail specific crash prediction models.

The principle issues with obtaining traffic volume data were the roadway types over which the light rail lines crossed and the economic downturn which occurred in 2008. Regarding the roadway types, road authorities tend to concentrate their traffic count data budgets on larger arterial and collector roadways as opposed to the smaller collector and local roadways. The economic downturn which occurred starting in 2008 reduced available budgets for road authorities, and data collection suffered as a result of these budget cuts.

One way to address this limited traffic data problem would be to require that traffic volumes at all light rail crossings be counted on a minimum specified basis. There is existing federal legislation that, if made applicable to light rail crossings, might provide data. In 2008, Congress enacted the Rail Safety Improvement Act, which requires that all rail crossings be assigned a crossing identification number and that data for the crossing be included in the national inventory database. The Rail Safety Improvement Act of 2008 also requires that traffic count data at each crossing be updated at least every three-years. It is unclear if light rail crossings were intended by Congress to be included in this required data collection. Inclusion of light rail crossings in this national database would ensure that all light rail crossings have traffic count data associated with the crossing and that this traffic count data would be updated with sufficient frequency to allow the data to be used for safety calculations, trend analysis, and research purposes. If transit agencies are not required to provide their information to the FRA national database, hopefully another federal agency such as the Federal Transit Administration (FTA) will move to enhance its data collection efforts in the area of light rail grade crossings to require the collection and reporting of this information.

Light Rail Crossing Crash Data

Crash data were also somewhat difficult to obtain as part of this research. The ten transit agencies that provided data were very forthcoming and very helpful with providing their crash data. For other agencies that were asked to share data, while there was a willingness to provide the data, the demands of ongoing construction and limited staffs in the safety departments at these properties hampered the ability of the properties to provide their data.   In addition, the lack of uniformity of available data limited the research that could be performed. It was hoped that, as part of this research, crash severity prediction equations could be developed. The available data prevented this because some crashes were reported as fatal or non-fatal and others were reported as fatal, injury, or property damage only. These severity reporting differences did not allow for the development of crash severity prediction equations.

Currently, transit agencies are required to report any light rail grade crossing crashes to their State Safety Oversight Agency as well as to the NTD. The information reported to each of these entities, unfortunately, is different and incomplete.

The NTD only recently started collecting information about the location of the grade crossing crash in its database. However, the information provided by many of the transit agencies regarding location only refers to the light rail line on which the crash occurred as opposed to the actual location of the crash.

Information provided to some State Safety Oversight Agencies includes crash location information. However, when the State Safety Oversight Agencies are required to report all crash and incident information to the FTA as part of an annual report, FTA fails to collect crash location information for the grade crossing crashes.

There are two initial ideas of how these information issues could be solved. First, if all transit agencies were required to obtain a national crossing inventory number, this crossing number could easily be included in the crash information reports to the NTD, to the FTA through the State Safety Oversight Agency annual report, or to both. Second, if crossing inventory numbers are not required for transit agencies, then data collection efforts by the NTD and FTA need to be increased to include specific location information for all grade crossing crashes reported. Collection of this information will allow numerous agencies to look at crash trends, and severity trends and to better determine exiting safety needs at these light rail crossings.

Fischhaber Equations

Data limitations prevented a full set of crash prediction equations from being developed in this research. For example, there were only five crossings in the entire dataset that used flashing lights as the warning device type, so flashing light warning type equations could not be developed.

This research developed statistically valid equations for determining the number of crashes that occur at light rail crossings controlled through passive warning signs, active warning flashing lights with gates, and traffic signals through an initial crash number that is updated through the EB Method to account for the specific crash history at the crossing.

The research shows that additional work needs to be done regarding modeling crashes at light rail crossings, and that, although not considered as part of this research due to data limitations, there may be additional inputs for light rail crossings controlled by traffic signals. The outcome of the statistical analysis shows that, while the initial model contains some inputs that are related to the calculated crash value, there are other model inputs that are needed to model crash prediction at light rail crossings controlled by traffic signals. Based on some of the findings through this research, some other model inputs to be researched in the future including (1) turning movement counts across the light rail tracks, (2) use of static and dynamic signs limiting and/or prohibiting specific turning movements, and (3) traffic signal operations (*e.g.* leading left-turn operations, lagging left-turn operations, or lead-lag left-turn operations). Additionally, there are new traffic signal operations, such as flashing yellow arrow left-turn operations, that may be used to mitigate certain types of crashes and that should be investigated.

GIS Models

This research determined that a GIS model should be developed to allow for prediction of crashes at light rail crossings with the ability to use the GIS to display results for trend analysis. This research also determined that the GIS model can be used to assist in determining what crossing warning devices would be available to use at a crossing based on the specific crossing configuration and the number of predicted crashes at the light rail crossing. Further research is necessary to determine how the specific model inputs need to be configured and to develop the logic to determine crossing control options that would be available for each type of crossing alignment and configuration.

Research Contribution

As stated in the introduction to this study, common carrier railroad operations began in the 1820's. The first railroad crossing hazard index model for railroads was developed approximately 120 years later in 1941 (Peabody and Dimmick 1941) and the first railroad crash prediction equations were developed approximately 155 years later in 1976 (Coleman and Stewart 1976). The literature review for this research contains 19 different crash prediction formulas that have been developed since 1976 to predict railroad crossing crashes using a variety of statistical methods to develop those formulas. Thus, there has been much research in the area of crash predictions at railroad crossings.

The mode of light rail transit developed as early as 1834 and modern light rail systems began appearing in 1981. This research showed that the hazard index and crash prediction formulas used for railroads do not adequately represent crash histories specifically at light rail crossings. To date no hazard index formulas specific to light rail operations have been developed. With this research, the first crash prediction formulas have been developed specific to light rail crossings some 33 years after modern light rail systems began appearing in the United States and 180 years after light rail transit developed as a mode of transportation. A review of the literature for this study shows that while much research has occurred regarding light rail, that research has been limited to the general areas of planning, potential crossing crash mitigation measures, and light rail operations. Until this study, the research to develop crash prediction tools that is prevalent for railroad crossings has been non-existent for light rail crossings.

This study has taken the ideas and concepts used in railroad crossing safety research and applied them to light rail crossing safety research for the first time. Additionally, this research provides the first empirically-based estimation procedure to predict crash numbers at light rail crossings that takes into account the use of traffic signals as a crossing warning device.

One possible reason that railroad crossing crash prediction research has moved forward while light rail crossing crash prediction research is only beginning is data availability. The US DOT developed a database of railroad crossing information that contains information about every railroad crossing in the country. This inventory information includes number of trains that use the crossing per day, AADT, maximum train timetable speeds, roadway classification and usage information, and crossing warning devices at the crossing. Additionally, the US DOT developed a database that contains information regarding all crashes that have occurred at all railroad crossings in the country. This crash database includes date, time, location, train speed, weather, and crash severity. Similar databases of information do not exist for light rail crossings. For this research, crash information had to be obtained from each separate transit agency, and inventory information for each light rail crossing studied had to be obtained through a combination of data from Google Earth™, contacting road authorities through websites, email, or by phone, or collecting train volume information from transit agency websites. If inventory and crash information were more readily available, a major roadblock for light rail crossing crash prediction research would be removed including both the development and refinement of crash frequency and severity prediction equations.

Research Use

The results of this research can be used by light rail transit agencies, road authorities that interact with light rail systems, and State safety and regulatory agencies charged with regulating and overseeing crossing safety. The crash prediction equations can be used in the planning and design of new systems and system extensions as a risk analysis tool to estimate the likely number of crashes at crossings based on proposed alignments and crossing controls.

The Manual on Uniform Traffic Control Devices provides no guidance or thresholds on when certain types of crossing controls should be considered for use at crossings. Hence, the use of these equations as a risk analysis tool provides information to transit agencies, road authorities, and regulatory bodies that can be used as part of the crossing safety diagnostic process to determine if and when crossing control mitigation is necessary. The crash prediction equations can be used to assess the safety of existing crossing controls to determine if other crossing warning devices may potentially reduce or eliminate crashes, which can provide input to transit agencies for a benefit/cost analysis of the proposed changes.

While general risk levels for each of the signage types reviewed in this study can be inferred from Table IV.1, the crash prediction equations can also be used to assess what the different risk levels are for the different types of signage for each variation of alignment and/or configuration type holding all other inputs the same.

Future Research Needs

Socioeconomic data was not utilized to develop any of the crash prediction equations reviewed or developed as part of this study. While this information is typically reviewed and analyzed to prepare an environmental impact statement, it does not appear that socioeconomic data has ever been used as an input to crash prediction equations for rail crossings. Future research needs to review and determine if and what socioeconomic data can contribute to crash frequency and severity prediction at light rail crossings.

One modeling methodology that has not been used to develop crash prediction equations at crossings and not considered as part of this research was the zero-inflated negative binomial regression model. One issue that arises with the use of the standard negative binomial regression model is the likelihood of a low sample mean due to the potential number of crossings with zero crashes in the dataset. A zero-inflated model adjusts for frequent zero-valued observations within the data. Future research should be done to develop light rail crash prediction equations using the zero-inflated negative binomial distribution to see if this modeling technique adequately addresses the low sample mean and overdispersion issues that were found in this research data set.

Conclusions

The objectives of this study were to determine whether existing railroad crossing crash prediction and hazard index equations adequately predict crashes and hazards at light rail crossings and, if they did not, to develop crash prediction equations specifically to model operations at light rail crossings. This study accomplished the following:

- This study determined that existing railroad crossing crash prediction and hazard index equations do not adequately predict crashes and hazards at light rail crossings;
- This study determined that a nonlinear modeling technique is preferable for determining initial crash prediction equations and that the EB Method should be used to adjust the initial crash prediction to account for the crash history at the specific crossing;
- This study developed light rail specific crash prediction equations for light rail crossings controlled by traffic signals, gates, and passive warning devices;
- This study determined that the equations developed for all warning device types are statistically valid equations;
- This study determined that a GIS model should be developed to allow for prediction of crashes at light-rail crossings with the ability to use the GIS to display results for trend analysis.

Recommendations

This study was the first study to examine crash prediction specifically at light rail crossings. Future work should be conducted to find all relevant model inputs to accurately predict crashes at light rail crossings controlled with traffic signals. A complete set of data should be used that is representative of all light rail crossings in all transit systems. Additionally, newer crossing warning devices are being installed at light rail crossings (for example, four-quadrant gate systems) for which little to no data currently exist. Future research should include such changes. Also, descriptive data are needed regarding crash severity so that crash severity prediction equations specific to light rail crossings can be developed in the future.

This study focused solely on motor vehicle crashes at crossings. Pedestrian and bicycle crashes also occur at light rail crossings. Specific data need to be gathered regarding pedestrian and bicycle collisions at light rail grade crossings. Further research should also be conducted on pedestrian incidents at light rail grade crossings stations with a goal of developing predictive equations for the number of pedestrian-related incidents expected to occur at light rail transit stations.

Data available for light rail crossing research are currently limited. Efforts should be made by federal agencies to require transit agencies to provide specific and descriptive data of location, severity, and motor vehicle movement with respect to crashes that occur at light rail crossings. Additionally, efforts need to be made to require motor vehicle traffic counts to be taken at all light rail crossings.

Further research needs to be performed to look at the feasibility of developing safety performance functions and/or crash modification factors specific to light rail crossings and light rail facilities. Sufficient before and after data will need to be gathered for light rail facilities and light rail crossings for determination of feasibility and calculation of such factors.

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