Further Development of the Safety and Congestion Relationship for Urban Freeways

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SHRP 2 REPORT S2-L07-RR-3

Further Development of the Safety and Congestion Relationship for Urban Freeways

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The Second Strategic Highway Research Program

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The research reported was performed by MRIGlobal, supported by HDR Engineering Inc. Ingrid B. Potts, MRIGlobal, was the principal investigator. The other authors of this report include Douglas W. Harwood, Chris A. Fees, and Karin M. Bauer of MRIGlobal, and Christopher S. Kinzel of HDR Engineering Inc.

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FOREWORD

Ralph Hessian, P.Eng., FITE, *SHRP 2 Special Consultant, Capacity and Reliability*

To better serve the public and business communities, transportation agencies and professionals have become increasingly interested in reducing nonrecurrent traffic congestion, improving traffic operations, and delivering better travel time reliability performance on the nation's highways. Motor vehicle crashes are one of the primary causes of nonrecurrent congestion and unreliable travel resulting in late arrivals at destinations. This supplementary report confirms a relationship between crash frequency and traffic density developed in the research for SHRP 2 Project L07, Identification and Evaluation of the Cost-Effectiveness of Highway Design Features to Reduce Nonrecurrent Congestion. The report indicates that physical design treatments that have been judged effective in reducing nonrecurrent congestion conditions on urban freeways at higher levels of service should also prove effective in reducing motor vehicle crashes and, thus, in increasing operational and safety benefits.

The continued growth of traffic congestion on the nation's highways is increasing the concerns of transportation agencies, the business community, and the general public. Congestion has recurrent and nonrecurrent components. *Recurrent congestion* reflects routine day-to-day delays during specific time periods when traffic demand exceeds available roadway capacity. Road users come to expect these daily traffic patterns and adjust their travel plans accordingly to achieve timely arrivals. *Nonrecurrent congestion,* which makes up the majority of total congestion, results from random incidents that cause unexpected extra delays, such as crashes, weather, and work zones. Road users are frustrated by unexpected delays, which can lead to unreliable arrival times. The delivery of travel time reliability is an emerging business activity and performance measure for transportation agencies working to meet the increasing expectations of the public and the freight industry.

SHRP 2 Reliability Project L07 provided (1) general guidance on the range of design elements that could be used by transportation agencies to improve travel time reliability and reduce nonrecurrent congestion on urban freeways and (2) the Analysis Tool for measuring operational and safety effectiveness and calculating a life-cycle benefit–cost value. This value can be used to support decision making about the possible use of individual treatments to address actual nonrecurrent traffic conditions. The tool is a Visual Basic for Applications (VBA) interface overlaying a Microsoft-based Excel 2007 spreadsheet. Analysts can input data about a highway such as geometrics, volumes, and crash totals, and the tool computes delay and reliability indicators resulting from various design treatments and translates those results into life-cycle costs and benefits. For the safety-effectiveness analysis, a new relationship between safety and congestion was explored, and a mathematical model was developed to quantify crash frequency at various levels of traffic density.

This supplemental report presents the research findings on the effort to further develop and refine the original safety and congestion relationship model using two additional independent freeway data sets. The results of this additional research confirmed the graphical relationship between crash frequency and traffic density developed in the original research.

The crash rate on urban freeways varies with traffic density in a U-shaped curve. The lowest crash rates occurred at medium traffic densities, with slightly higher crash rates (single-vehicle-dominant) recorded at lower traffic densities and much higher crash rates recorded at higher traffic densities (multiple-vehicle-dominant). Therefore, if a design treatment is effective in reducing nonrecurrent congestion conditions at higher levels of service, it should also be effective in reducing crashes, resulting in a safety benefit.

CONTENTS

Executive Summary

The Reliability area of the second Strategic Highway Research Program (SHRP 2) has focused on the need to improve travel time reliability on freeways and major arterials. SHRP 2 Project L07 has focused specifically on design treatments that can be used to improve travel time reliability. The objectives of Project L07 were to (1) identify the full range of possible roadway design features used by transportation agencies to improve travel time reliability and reduce delays due to key causes of nonrecurrent congestion, (2) assess their costs and operational and safety effectiveness, and (3) provide recommendations for their use and eventual incorporation into appropriate design guides.

Three separate analyses of the design treatments were conducted in Phase 2 of Project L07: operational, safety, and benefit–cost. The traffic operational analysis methodology developed in Phase 2 built on work completed in SHRP 2 Project L03, Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies. As part of the traffic operational analysis, a spreadsheet-based Analysis Tool was developed to allow highway agencies to analyze and compare the effects of a range of design strategies on a given highway segment using the analytical procedures developed in Phase 2 of Project L07. Highway agencies can input data about a highway (e.g., geometrics, volumes, crash totals); the Analysis Tool computes delay and reliability indicators resulting from various design treatments, further translating those results into life-cycle costs and benefits.

In addition to the traffic operational benefits of reducing congestion, the potential safety benefits were explored. The reduction of congestion through application of design treatments or intelligent transportation system (ITS) improvements has been widely thought to have a positive effect on safety, but this relationship had not been well quantified in previous research. Congestion may result in stalled or slowed traffic, and the situation in which high-speed vehicles approach the rear of an unexpected traffic queue clearly presents a substantial risk of collision. The potential for collision within queues of stop-and-go traffic is also clear. Thus, on the one hand, the frequency of these conditions can be ameliorated by treatments that reduce nonrecurrent congestion. On the other hand, since collision severity is clearly a function of speed, the lower speeds on roadways during congested periods may reduce overall collision severity. This trade-off between crash frequency and severity in congested versus uncongested conditions has not been satisfactorily quantified in previous research.

Relationships between safety and congestion were developed in Phase 2 of Project L07 for application in the spreadsheet-based Analysis Tool. Safety-congestion relationships were developed from analyses of traffic operational and crash data for the freeway systems of two metropolitan areas: Seattle, Washington, and Minneapolis–St. Paul, Minnesota. Analysis of these data found that the crash rate on urban freeways varies with traffic density in a U-shaped relationship, with higher crash rates at very low traffic densities (due primarily to single-vehicle crashes), higher crash rates at very high traffic densities (due to multiple-vehicle crashes), and the lowest crash rates at medium traffic densities. This result was found for both fatal-and-injury and property-damage-only crashes. This finding implies that design treatments that are effective in reducing congestion levels on urban freeways should also be effective in reducing crashes.

Since the relationship between congestion and safety was based on only two metropolitan areas, SHRP 2 added a new task to Project L07—designated as Task IV-5—to further explore the relationship between safety and congestion using data from other metropolitan areas. The research in Task IV-5 was conducted to determine whether a similar U-shaped relationship between safety and congestion exists for the freeway systems of other metropolitan areas and how that relationship can be best generalized for broader application in the analysis of design treatments. The research also investigated whether the relationship applies to a full range of nonrecurrent congestion scenarios.

In Task IV-5, relationships between crash rates and level of service (LOS) were developed based on traffic operational and crash data obtained from instrumented directional freeway segments in five metropolitan areas: Seattle, Washington; Minneapolis–St. Paul, Minnesota; Sacramento, California; the Kansas portion of the Kansas City metropolitan area; and the Missouri portion of the Kansas City metropolitan area. The selection of these five metropolitan areas was based on the availability of relevant data. The Kansas and Missouri portions of the Kansas City metropolitan area were analyzed separately because the crash data were obtained from different sources.

The data for Sacramento freeways largely confirm the Seattle and Minneapolis–St. Paul results, showing a U-shaped relationship with minimum crash rates at about LOS C, slightly higher crash rates at lower densities (i.e., better LOS), and substantially higher crash rates at higher densities (i.e., poorer LOS). The data for freeways in both the Kansas and Missouri portions of the Kansas City metropolitan area show little variation in crash rate over the range of traffic density, although crash rates are substantially higher in the lowest traffic density category (LOS A+) and, for the Kansas portion of the metropolitan area, slightly higher in the highest traffic density category (LOS F+). Review of the data shows that the freeways in the Kansas City metropolitan area experienced a substantially lower proportion of LOS F conditions than the other metropolitan areas and, therefore, did not have much opportunity to show higher crash rates at higher traffic densities.

The most appropriate interpretation of these results is that the Seattle, Minneapolis–St. Paul, and Sacramento results show similar shapes for the safety-congestion relationships. The results for the Kansas City metropolitan area are not necessarily inconsistent with the other metropolitan areas but may not include sufficient congestion to show higher crash rates at the highest crash densities.

A combined safety-congestion relationship for the Seattle, Minneapolis–St. Paul, and Sacramento metropolitan areas was developed by translating the curves to the average freeway crash rate for the three metropolitan areas and then averaging the individual data points. With this translation completed, the results are representative of a freeway system with a total crash rate of 1.86 crashes per million vehicle miles of travel (MVMT), a fatal-and-injury (FI) crash rate of 0.42 crashes per MVMT, and a property-damage-only (PDO) crash rate of 0.82 crashes per MVMT. These are the average freeway crash rates for Seattle, Minneapolis–St. Paul, and Sacramento, giving equal weight to each metropolitan area.

Since the focus of Project L07 is on nonrecurrent congestion, a further analysis (using data for Sacramento freeways) was conducted to check whether the U-shaped relationship is specifically applicable to periods of nonrecurrent congestion. Of the more than 5 million site-periods (a 15-min period at a given site), 21% were classified as nonrecurrent congestion and 79% were classified as recurrent congestion or normal uncongested flow. Analysis of the data provided strong evidence that the general relationship between crash rate and traffic density is applicable to both recurrent and nonrecurrent congestion.

Thus, it is recommended that the safety-congestion relationship developed in this research be applied in the L07 Analysis Tool to compare the traffic operational and safety effects of design treatments on a given highway segment.

CHAPTER 1

Introduction

Background

SHRP 2 Reliability Project L07 has focused specifically on the identification and evaluation of design treatments that can be used to reduce delays due to nonrecurrent congestion and improve travel time reliability (*1*). The objectives of Project L07 were to (1) identify the full range of possible design treatments used by transportation agencies to improve travel time reliability and reduce delays due to key causes of nonrecurrent congestion, (2) assess their costs and operational and safety effectiveness, and (3) provide recommendations for their use and eventual incorporation into appropriate design guides.

Three separate analyses of the design treatments were conducted in Phase 2 of Project L07: operational, safety, and benefit–cost. The traffic operational analysis methodology developed in Phase 2 built on work completed in SHRP 2 Project L03. As part of the traffic operational analysis, a spreadsheet-based Analysis Tool was developed to allow highway agencies to analyze and compare the effects of a range of design strategies on a given highway segment using the analytical procedures developed in Phase 2 of Project L07. Highway agencies can input data about a highway (e.g., geometrics, volumes, crash totals), and the Analysis Tool computes delay and reliability indicators resulting from various design treatments, further translating those results into life-cycle costs and benefits.

In addition to the traffic operational benefits of reducing congestion, the potential safety benefits were explored as well. The reduction of congestion through application of design treatments or intelligent transportation system (ITS) improvements has been widely thought to have a positive effect on safety, but this relationship had not been well quantified in previous research. Congestion may result in stalled or slowed traffic, and the situation in which high-speed vehicles approach the rear of an unexpected traffic queue clearly presents a substantial risk of collision. The potential for collision within queues of stop-and-go traffic is also clear. Thus, on the one hand, the frequency of both of these conditions can be ameliorated by treatments to reduce nonrecurrent congestion. On the other hand, collision severity is clearly a function of speed, so the lower speeds on roadways during congested periods may reduce overall collision severity. This trade-off between crash frequency and severity in congested versus uncongested conditions has never been satisfactorily quantified. Previous research on this issue for freeway facilities has been conducted by Zhou and Sisiopiku (*2*) and by Hall and Pendleton (*3*). In particular, Zhou and Sisiopiku suggest that different crash types respond in different ways to volume-to-capacity (v/c) ratios based on hourly volumes. The research results presented below illustrate why a difference between crash types appears reasonable.

Relationships between safety and congestion were developed in Phase 2 of Project L07 for application in the spreadsheet-based Analysis Tool (*1, 4*). The safety-congestion relationship developed in Phase 2, shown in Figure 1.1, is used to quantify the safety benefits associated with the reduction in congestion resulting from implementation of specific design treatments. Figure 1.1 suggests that a reduction in congestion within the range of traffic operational conditions from LOS C to LOS F should result in a corresponding reduction in crashes.

The safety-congestion relationship in Figure 1.1 was developed from analyses of traffic operational and crash data for the freeway systems of two metropolitan areas: Seattle and Minneapolis–St. Paul. Figures 1.2 and 1.3 show the safety-versus-congestion data for freeways in Seattle and in Minneapolis–St. Paul, respectively.

The plot for the Seattle data in Figure 1.2 generally shows a U-shaped relationship, with the lowest crash rates in the middle of the traffic density range at about LOS C. Crash rates at lower densities (i.e., better LOS) are slightly higher than the minimum crash rate, due primarily to single-vehicle crashes. Crash rates at higher densities (i.e., poorer LOS) are substantially higher than the minimum crash rate, due to multiple-vehicle crashes.

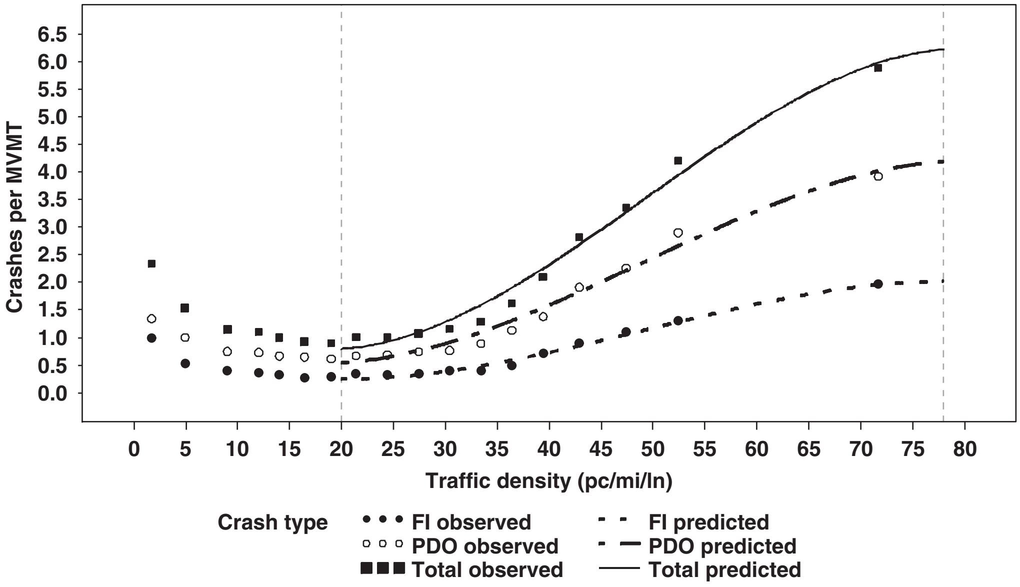

Figure 1.1. Observed and predicted total, FI, and PDO crash rates versus traffic density for Seattle and Minneapolis–St. Paul metropolitan areas combined (1, 4). FI = fatal and injury, PDO = property damage only, and pc/mi/ln = passenger cars per mile per lane.

The relationship implied by Figure 1.2 appears promising to evaluate the safety effects of design treatments intended to reduce nonrecurrent congestion. For example, if a particular treatment shortens the duration of several incidents and results in 5 h per year with traffic operations in LOS C rather than LOS F, the safety-congestion relationships will provide a basis for quantifying that safety benefit as a specific number of crashes reduced.

Figure 1.3 shows a plot of crash rate and traffic density data for the Minneapolis–St. Paul area analogous to that shown for the Seattle area in Figure 1.2. The Minneapolis–St. Paul data show a relationship similar to Seattle, but the U-shaped curve is not as pronounced and is complicated by highly variable data (a secondary peak) in the traffic density range from 30 to 40 passenger cars per mile per lane (pc/mi/ln)—that is, LOS D through E+. However, regression modeling has still confirmed the U-shaped nature of the crash rate–traffic density relationship. There is no obvious explanation for this secondary peak, which is not present in the Seattle data and may be a quirk of the data for Minneapolis–St. Paul.

The U-shaped relationship between crash rate and traffic density has a clear interpretation. At low traffic densities, there are few vehicle-vehicle interactions; and inattentive, fatigued, or impaired drivers are likely to depart from their lane or leave the roadway. As traffic volumes increase, drivers (including even inattentive, fatigued, or impaired drivers) are more likely to collide with another vehicle than run off the road. Furthermore, at high traffic densities, vehicle-vehicle interactions increase to the point that rear-end or sideswipe (e.g., lane changing) crashes become more frequent. Data confirm that single-vehicle crashes predominate at lower traffic densities and multiple-vehicle crashes predominate at higher traffic densities.

Since the relationship between congestion and safety was based on only two metropolitan areas, SHRP 2 added a new task to Project L07—designated as Task IV-5—to further explore the relationship between safety and congestion using data from other metropolitan areas. The research in Task IV-5 was conducted to determine whether a similar U-shaped relationship between safety and congestion exists for the freeway systems of other metropolitan areas and how that relationship can best be generalized for broader application in the analysis of design treatments. The research also investigated whether the relationship applies to a full range of nonrecurrent congestion scenarios.

Objective

The objective of Task IV-5 was to further develop the relationship between safety and congestion that was initially developed in Phase 2 of the research and to test the relationship for various nonrecurrent congestion scenarios.

Task IV-5 was managed in six subtasks as follows:

- Subtask 5A. Identify additional areas for data collection.
- Subtask 5B. Obtain data for selected additional areas.

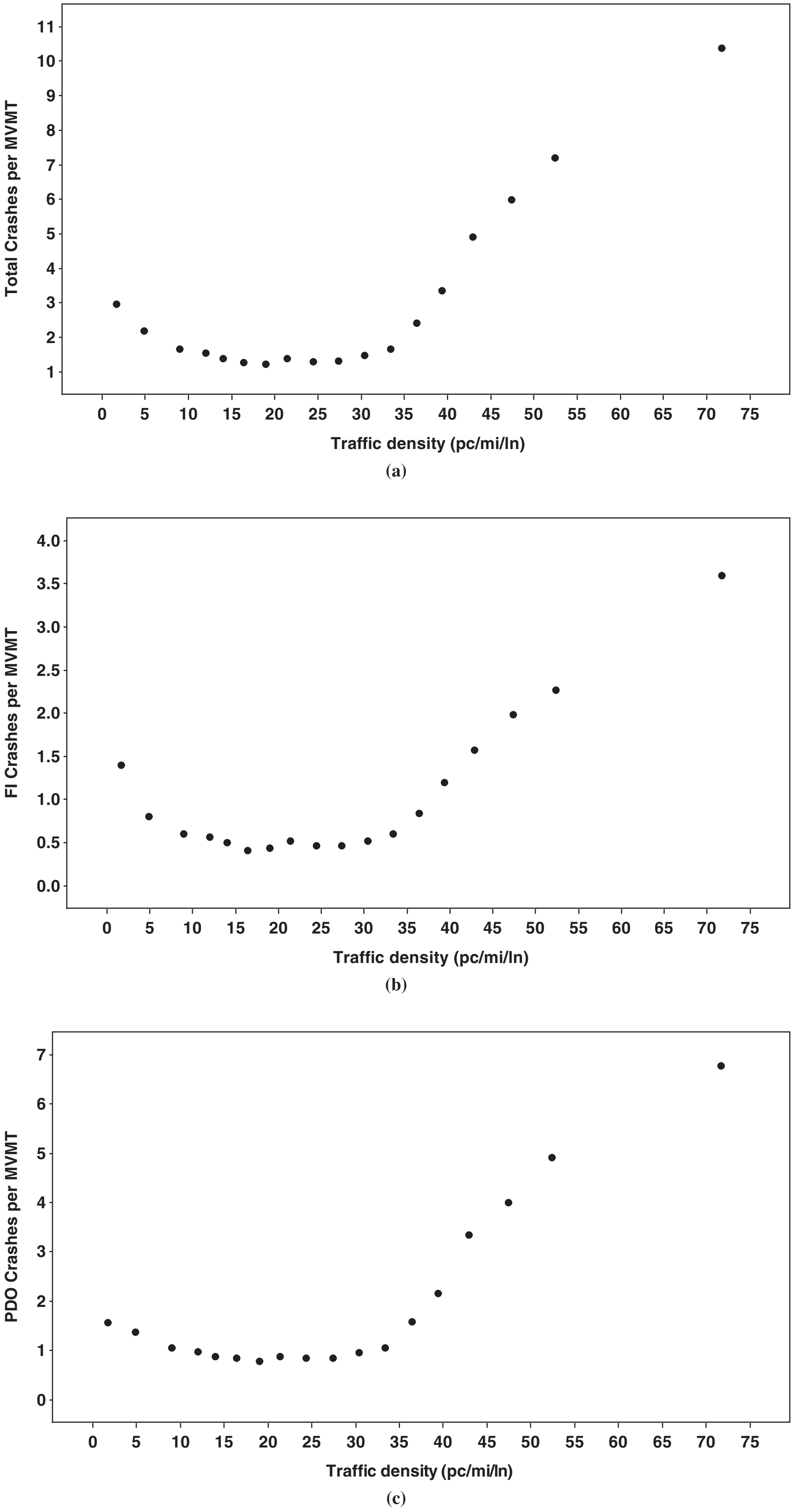

Figure 1.2. Observed (a) total, (b) FI, and (c) PDO crash rates versus traffic density for freeways in the Seattle area.

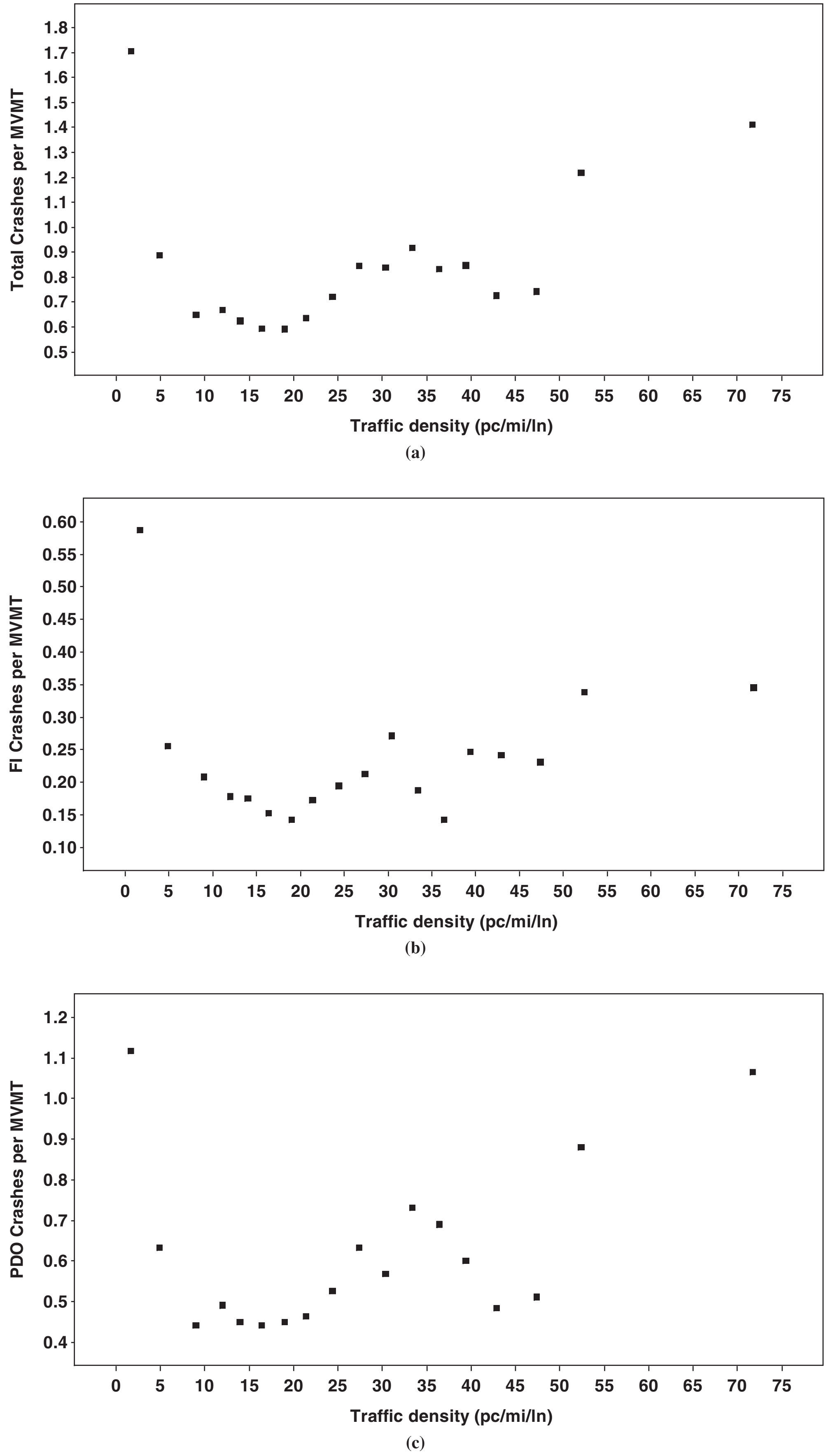

Figure 1.3. Observed (a) total, (b) FI, and (c) PDO crash rates versus traffic density for freeways in the Minneapolis–St. Paul area.

- Subtask 5C. Develop safety-congestion relationships for each selected area.
- Subtask 5D. Compare and combine the safety-congestion relationships.
- Subtask 5E. Test the safety-congestion relationships for specific nonrecurrent congestion scenarios.
- Subtask 5F. Revise the Project L07 Analysis Tool to the extent needed to implement the Task 5 results.

The background for this work and the research plan for each subtask are presented in Chapter 2.

Organization of the Report

This report presents the results of the research to further develop a safety-congestion relationship for urban freeways. The remainder of this report is organized as follows. Chapter 2 describes the technical approach to the research and presents a summary of the database and results by state. Chapter 3 compares the safety-congestion relationships developed in each metropolitan area, presents a combined safety-congestion relationship, and explores the application of this relationship to recurrent and nonrecurrent congestion. Chapter 4 presents the conclusions and recommendations of the research.

CHAPTER 2

Research Approach and State-by-State Results

To determine a relationship between safety and congestion for use in evaluating design treatments, relationships between crash rates and level of service (LOS) were developed based on traffic operational and crash data obtained from instrumented directional freeway segments in five metropolitan areas: Seattle, Washington; Minneapolis–St. Paul, Minnesota; Sacramento, California; the Kansas portion of the Kansas City metropolitan area; and the Missouri portion of the Kansas City metropolitan area. The selection of these five metropolitan areas was based on the availability of relevant data. The Kansas and Missouri portions of the Kansas City metropolitan area were analyzed separately because the crash data were obtained from different sources.

Technical Approach

For analysis purposes, the freeway system in each metropolitan area was divided into directional segments, usually extending from one interchange to the next. The sections were selected so that a given detector station would be representative of the traffic conditions for all crashes within that section. All of the detector stations used in the study were located on the mainline freeway, rather than on ramps; and each detector station provided coverage for all through lanes on the directional freeway segment, including any high-occupancy vehicle (HOV) lanes that were present adjacent to the mainline freeway lanes. (Separate HOV roadways in the freeway median were excluded from the analysis.) The most appropriate detector station was selected for each directional segment; whenever possible, a detector station near the center of a segment was selected. In some cases, a detector station on the mainline freeway within the limits of either the upstream or downstream interchange was used. In a few cases, a detector station located in the immediately upstream or downstream freeway segment was used; this was done only in limited cases where the intervening interchange was relatively minor in nature.

The traffic operational data collected at each detector station on the directional freeway segments consisted of 5-min volume and average speed data for each travel lane. Speed or volume was missing for some 5-min intervals on one or more lanes. Most missing data were attributed to detector malfunctions. No set of loop detectors will function across all freeway lanes all of the time; therefore, some missing volume and speed data are inevitable. A detector that malfunctions is usually out of service for a substantial time period; however, there is no reason to believe that missing data due to a malfunctioning detector lead to a bias in the remaining data set.

Data for each detector station were obtained for a specified study period—either 3 or 5 years. Some detector stations were either first installed or taken out of service during the study period. When this occurred, data from the detector station could only be obtained for time periods when the detector station was actually in service. For such detector stations, the term *missing data* simply represents time periods when the detector station did not exist.

Flow rates in vehicles per hour per lane were computed from the data for each station, both for each lane and for all lanes combined based on the available 5-min volume data. These 5-min flow rates showed some large fluctuations. The speed and volume data were aggregated into 15-min intervals, which provided much more stable data. Once processed, the volume and speed data were used to determine the level of service for each 15-min interval.

Crash data for each directional freeway segment were compiled for the same 15-min periods as the traffic volume and speed detector data on the basis of the reported crash date and time. The crash data included all mainline freeway crashes that occurred within the limits of each roadway section of interest during the study period. Crash severity levels considered in the evaluation are

- Total crashes (i.e., all crash severity levels combined);
- Fatal-and-injury (FI) crashes; and
- Property-damage-only (PDO) crashes.

Level of service was computed for each 15-min record using the operational analysis procedure presented in the 1994 *Highway Capacity Manual* (HCM) Chapter 23 (*2*). Components in the LOS calculations included directional volume, directional speed, flow rate, traffic mix adjustment factor to determine flow rates in passenger cars per hour per lane (i.e., heavy-vehicle adjustment factor), and traffic density. Truck percentages for each roadway section were obtained from maps and other data published by the state department of transportation (DOT) or the relevant metropolitan planning organization (MPO). Truck percentages were typically available for the day as a whole (i.e., a typical 24-h period), but were not available for specific peak-hour or off-peak periods.

The study periods for the five metropolitan areas ranged from 3 to 5 years. For each 15-min period during the study period, the available data included the following:

- 15-min traffic volume (number of vehicles counted) summed across all lanes of the directional freeway segment;
- Average spot speed of vehicles across all lanes (weighted by lane volumes) (mi/h); and
- Number of crashes that occurred on the directional freeway segment during the 15-min period (generally either zero or one) by crash severity level.

Data were used for all 15-min periods during the study period, unless some of the needed data values were missing. Data were used for all available periods, including peak and off-peak periods, daytime and nighttime, weekdays, weekends, and holidays, as the data for each of the periods represent a valid observation of crash rate. Thus, in a 3-year study period, the number of 15-min periods for which data were available at any given site was calculated as follows (Equation 2.1):

$$\frac{4\ \text{15-min periods}}{\text{h}} \times \frac{24\ \text{h}}{\text{day}} \times \frac{365\ \text{days}}{\text{year}} \times 3\ \text{years} = 105{,}120\ \text{15-min periods} \qquad (2.1)$$

For a 5-year study period, the number of 15-min periods for which data were available at any given site was calculated as follows (Equation 2.2):

$$\frac{4\ \text{15-min periods}}{\text{h}} \times \frac{24\ \text{h}}{\text{day}} \times \frac{365\ \text{days}}{\text{year}} \times 5\ \text{years} = 175{,}200\ \text{15-min periods} \qquad (2.2)$$

Appropriate adjustments were made for leap year, as needed.

Site characteristics data available to compute traffic density and vehicle miles of exposure and to determine LOS included the following:

- Directional segment length;
- Number of lanes; and
- Average truck percentage.

The operational measure used to define LOS for freeways is the traffic density in passenger cars per mile per hour. The traffic density for a 15-min period was computed from the available speed and volume data as follows (Equation 2.3):

$$D_{15} = \frac{4V_{15} f_{HV}}{nS_{15}} \qquad (2.3)$$

where

D_{15} = traffic density for a 15-min period (passenger cars per mile per lane);

V_{15} = traffic volume for the 15-min period (vehicle) summed across all lanes of the directional freeway segment;

f_{HV} = heavy-vehicle adjustment factor from HCM Equation 23-3 (assuming site-specific truck percentage, but zero recreational vehicles);

S_{15} = average spot speed across all lanes (weighted by lane volumes) (mi/h); and

n = number of lanes on directional freeway segment.

It should be noted that Equation 2.3 does not include the peak-hour factor, so D_{15} is based on the actual 15-min volume and not the highest 15-min volume during a particular hour, as is commonly used in HCM procedures.

As specified in the HCM, six LOS categories are assigned by density ranges as shown in Table 2.1 (*2*):

Since the LOS categories are quite broad, a more refined LOS categorization was used to better capture the relationship

Table 2.1. LOS Categories by Density Range

LOS	Traffic Density Range (pc/mi/ln)
A	0 to 11
B	11 to 18
C	18 to 26
D	26 to 35
E	35 to 45
F	45+

between density and crash rates. The 18 LOS categories selected are shown in Table 2.2.

Based on the 15-min crash rate and traffic density data, average crash rates (expressed in crashes/MVMT) were calculated within each of the 18 LOS categories, separately for each severity level and each metropolitan area. Specifically, the crash rate for a given LOS category was determined using Equation 2.4 for all 15-min periods in that LOS category combined.

$$\text{Crash rate} = \frac{\sum \text{number of crashes}}{\sum \text{veh-mi of travel}} \tag{2.4}$$

The median traffic density was simply the median traffic density for all 15-min periods in that LOS category combined, with equal weight given to each 15-min period. Similarly, median traffic densities were calculated within each of the 18 LOS categories in each metropolitan area. The results of the analysis of these data for individual metropolitan areas are presented in the next section, Database and Results by State. The results across all metropolitan areas are subsequently reviewed in Summary of Full Data Set.

Table 2.2. LOS Categories Used in Study

LOS	Traffic Density Range (pc/mi/ln)
A+	0 to 3
A	3 to 7
A–	7 to 11
B+	11 to 13
B	13 to 15
B–	15 to 18
C+	18 to 20
C	20 to 23
C–	23 to 26
D+	26 to 29
D	29 to 32
D–	32 to 35
E+	35 to 38
E	38 to 41
E–	41 to 45
F+	45 to 50
F	50 to 55
F–	55+

Database and Results by State

Seattle, Washington

For the Seattle metropolitan area, data were obtained in the original Phase 2 research in Project L07 for 139 freeway sites representing 194 mi of directional freeway segments. The study period for Seattle was 3 years from 2005 to 2007, inclusive. Traffic operational data were provided by the Washington State DOT traffic management center to SHRP 2 Project L03. Project L03 organized and formatted the data and provided them to Project L07 for analysis. Crash data for the study period were drawn from Washington State DOT records provided by the Federal Highway Administration (FHWA) Highway Safety Information System (HSIS).

Table 2.3 presents a summary of the site characteristics in the Seattle metropolitan area and the number of 15-min records available for analysis.

Figure 2.1 presents a plot of crash rate versus traffic density by LOS level for the Seattle metropolitan area for each crash severity level.

Minneapolis–St. Paul, Minnesota

For the Minneapolis–St. Paul metropolitan area, data were obtained in the original Phase 2 research in Project L07 for 423 freeway sites representing 411 mi of directional freeway segments. The study period for Minneapolis–St. Paul was from 2005 to 2007, inclusive. Because of the unusual flow conditions, a decision was reached to exclude from the study all data in the Minneapolis–St. Paul area after the I-35W bridge collapse on August 1, 2007. While this period might have been interesting (because volumes changed dramatically on many freeway segments), the changed driving conditions were new to many drivers and the Minnesota DOT made many modifications to specific roadways to increase base

Table 2.3. Site Distribution Characteristics for Directional Freeway Segments in the Seattle Metropolitan Area

Number of Directional Lanes[a]	Number of Sites	Length (mi)	Number of 15-Min Records[b]
2	62	89.1	5,834,492
3	53	71.6	5,781,601
4	24	33.4	2,522,880
All lanes	139	194.1	14,138,973

[a] Not including HOV lanes.

[b] Includes records with missing volume or speed.

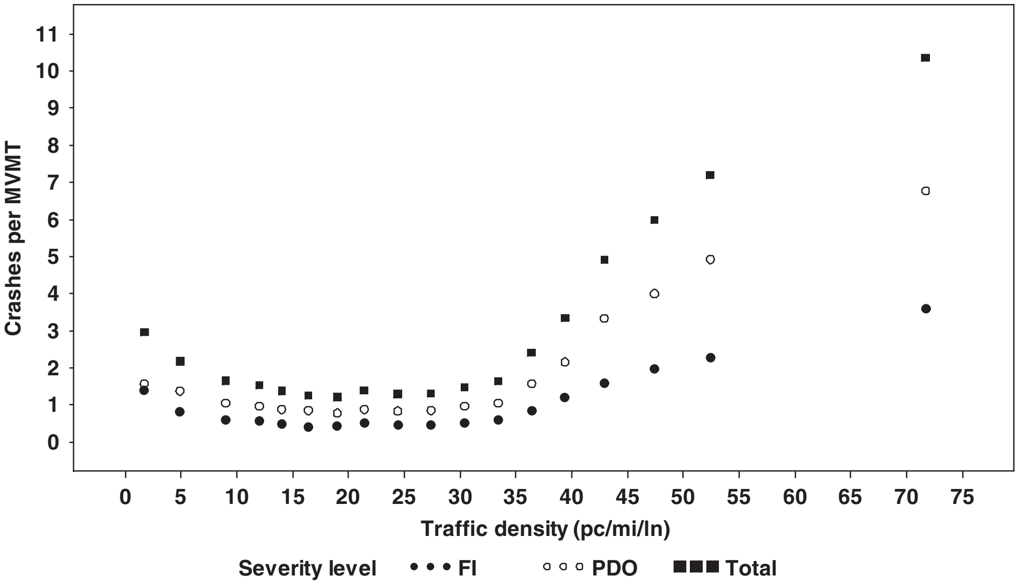

Figure 2.1. FI, PDO, and total crash rates versus traffic density for directional freeway segments in the Seattle metropolitan area. FI = fatal and injury, PDO = property damage only, and pc/mi/ln = passenger cars per mile per lane.

capacity. Thus, the study period for Minneapolis–St. Paul was 2.6 years.

Traffic operational data were provided by the Minnesota DOT traffic management center to SHRP 2 Project L03. Project L03 organized and formatted the data and provided them to Project L07 for analysis. Crash data for the study period were drawn from Minnesota DOT records provided by the FHWA HSIS.

Table 2.4 presents a summary of the site characteristics in the Minneapolis–St. Paul metropolitan area and the number of 15-min records available for analysis.

Figure 2.2 presents a plot of crash rate versus traffic density by LOS level for the Minneapolis–St. Paul metropolitan area for each crash severity level.

Table 2.4. Site Distribution Characteristics for Directional Freeway Segments in the Minneapolis–St. Paul Metropolitan Area

Number of Directional Lanes[a]	Number of Sites	Length (mi)	Number of 15-Min Records[b]
2	153	147.3	13,742,976
3	185	183.3	16,695,168
4	73	65.3	660,536
5	12	15.0	1,085,184
All lanes	423	410.9	38,124,864

[a] Not including HOV lanes.

[b] Includes records with missing volume or speed.

Sacramento, California

For the Sacramento metropolitan area, data were obtained in the new Task IV-5 research in Project L07 for 319 freeway sites representing 437.7 mi of directional freeway segments. The study period for Sacramento was 3 years from 2009 to 2011, inclusive. Traffic operational data were obtained from the California DOT (Caltrans) Performance Measurement System (PeMS). Crash data for the study period were drawn from Caltrans records provided by the FHWA HSIS.

Table 2.5 presents a summary of the site characteristics in the Sacramento metropolitan area and the number of 15-min records available for analysis.

Figure 2.3 presents a plot of crash rate versus traffic density by LOS level for the Sacramento metropolitan area for each crash severity level.

Kansas City, Kansas

For the Kansas portion of the Kansas City metropolitan area, data were obtained in the new Task IV-5 research in Project L07 for 144 freeway sites representing 139.7 mi of directional freeway segments. The study period for Kansas City was 5 years from 2008 to 2012, inclusive. Traffic operational data were obtained from the Kansas City Scout traffic management center, which is jointly operated by the Kansas and Missouri DOTs. Crash data for the study period were provided by the Kansas DOT.

Table 2.6 presents a summary of the site characteristics in the Kansas portion of the Kansas City metropolitan area and the number of 15-min records available for analysis.

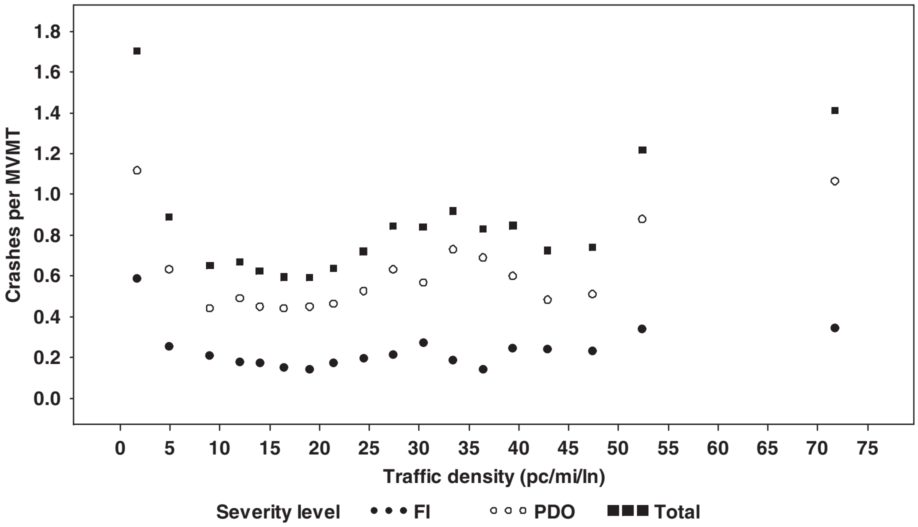

Figure 2.2. FI, PDO, and total crash rates versus traffic density for directional freeway segments in the Minneapolis–St. Paul metropolitan area.

Table 2.5. Site Distribution Characteristics for Directional Freeway Segments in the Sacramento Metropolitan Area

Number of Directional Lanes[a]	Number of Sites	Length (mi)	Number of 15-Min Records[b]
2	96	146.5	8,382,244
3	99	141.0	8,660,719
4	78	92.9	6,343,977
5	43	52.6	3,381,762
6	1	2.0	105,108
7	2	2.7	210,220
All lanes	319	437.7	27,084,030

[a] Not including HOV lanes.

[b] Includes records with missing volume or speed.

Table 2.6. Site Distribution Characteristics for Directional Freeway Segments in the Kansas Portion of Kansas City Metropolitan Area

Number of Directional Lanes	Number of Sites	Length (mi)	Number of 15-Min Records[a]
2	22	26.8	864,552
3	79	68.8	7,448,853
4	32	28.4	3,720,877
5	10	14.7	759,396
6	1	1.0	171,219
All lanes	144	139.7	12,964,897

[a] Includes records with missing volume or speed.

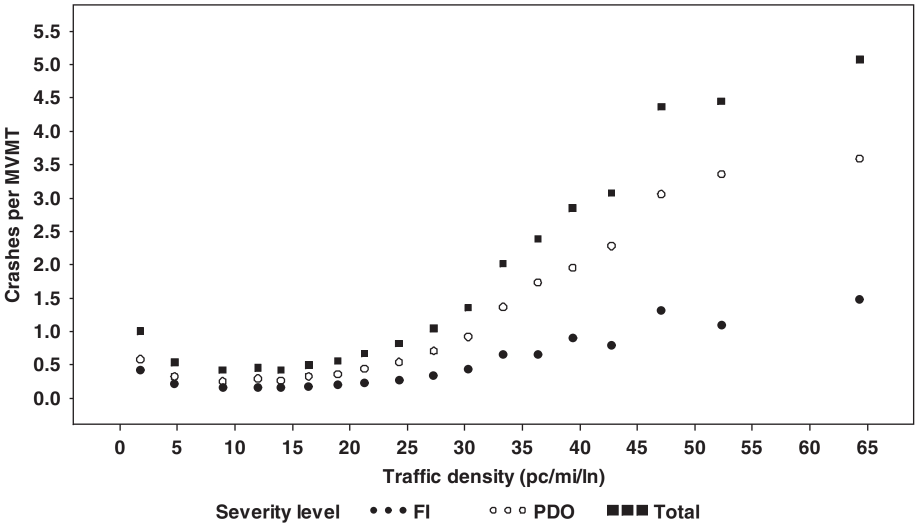

Figure 2.3. FI, PDO, and total crash rates versus traffic density for directional freeway segments in the Sacramento metropolitan area.

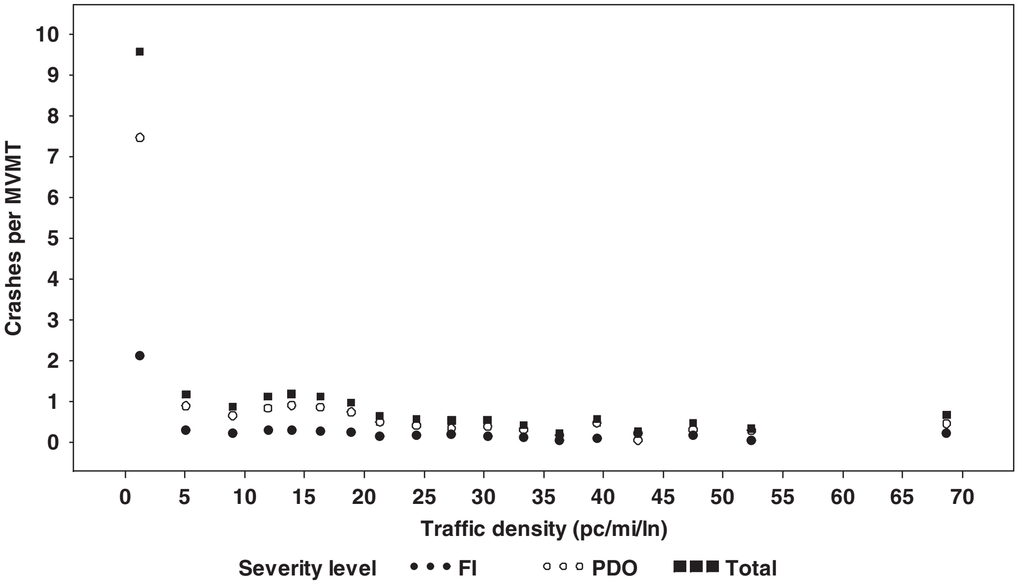

Figure 2.4. FI, PDO, and total crash rates versus traffic density for directional freeway segments in the Kansas portion of Kansas City metropolitan area.

Figure 2.4 presents a plot of crash rate versus traffic density by LOS level for the Kansas portion of the Kansas City metropolitan area for each crash severity level.

Kansas City, Missouri

For the Missouri portion of the Kansas City metropolitan area, data were obtained in the new Task IV-5 research in Project L07 for 201 freeway sites representing 184.2 mi of directional freeway segments. The study period for Kansas City was 5 years from 2008 to 2012, inclusive. Traffic operational data were obtained from the Kansas City Scout traffic management center, which is jointly operated by the Kansas and Missouri DOTs. Crash data for the study period were provided by the Missouri DOT.

Table 2.7 presents a summary of the site characteristics in the Missouri portion of the Kansas City metropolitan area and the number of 15-min records available for analysis.

Figure 2.5 presents a plot of crash rate versus traffic density by LOS level for the Missouri portion of the Kansas City metropolitan area for each crash severity level.

Summary of Full Data Set

Table 2.8 presents a summary of the sample sizes in the full data set for all five metropolitan areas/states. The table shows that 1,226 sites were studied for a potential total of 4,191 site-years of data. Table 2.9 summarizes the crash and exposure data during the periods for which volume and speed data were available.

Table 2.7. Site Distribution Characteristics for Directional Freeway Segments in Missouri Portion of Kansas City Metropolitan Area

Number of Directional Lanes	Number of Sites	Length (mi)	Number of 15-Min Records[a]
2	57	48.7	4,374,666
3	115	110.2	11,106,428
4	26	21.7	3,209,361
5	1	0.9	97,716
6	2	2.7	65,896
All lanes	201	184.2	18,854,067

[a] Includes records with missing volume or speed.

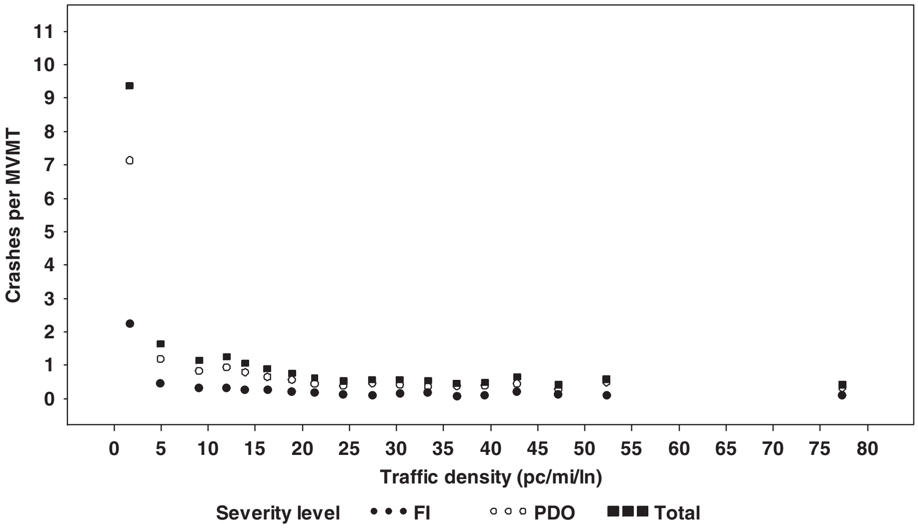

Figure 2.5. FI, PDO, and total crash rates versus traffic density for directional freeway segments in the Missouri portion of Kansas City metropolitan area.

Table 2.8. Summary of the Sample Sizes in the Full Data Set by State

Metropolitan Area	State	Number of Sites	Total Length (mi)	Number of Years	Potential Number of Site-Years	Maximum Potential Number of 15-Min Records	Actual Number of 15-Min Records with Detector Present	Actual Number of 15-Min Records with Nonmissing Volume and Speed Data	Missing Volume and Speed Data (%)
Seattle	Washington	139	194.1	3	417	14,611,680	14,138,973	11,526,511	18.5
Minneapolis–St. Paul	Minnesota	423	410.9	2.6[a]	1,092[a]	38,252,736	38,124,864	31,986,802	16.1
Sacramento	California	319	437.7	3	957	33,533,280	27,001,960	26,720,533	1.0
Kansas City	Kansas	144	139.7	5	720	25,242,624	12,964,850	11,858,383	8.5
Kansas City	Missouri	201	184.2	5	1,005	35,234,496	18,845,109	15,742,204	16.5
Total		1,226	1,366.6	na	4,191	146,874,816	111,075,756	97,834,433	11.9

Note: na = not applicable.

[a] After excluding the period from August 1, 2007, to December 31, 2007, when traffic conditions were changed due to the I-35W bridge collapse.

Table 2.9. Crash, Exposure, and Crash Rate Data by State

Metropolitan Area	State	Reported Crashes During Period with Volume and Speed Data Available			MVMT During Period with Volume and Speed Data Available	Crash Rate per MVMT During Period with Volume and Speed Data Available		
		FI	PDO	Total		FI	PDO	Total
Seattle	Washington	3,863	7,131	10,994	4,793.9	0.81	1.49	2.29
Minneapolis–St. Paul	Minnesota	1,289	3,360	4,649	6,298.0	0.20	0.53	0.74
Sacramento	California	4,598	8,653	13,251	19,452.0	0.24	0.44	0.68
Kansas City	Kansas	1,566	4,885	6,451	5,035.6	0.31	0.97	1.28
Kansas City	Missouri	1,914	5,481	7,395	5,565.9	0.34	0.98	1.33
Total		13,230	29,510	42,740	41,145.4	0.32	0.72	1.04

CHAPTER 3

Interpretation of Results

This chapter addresses interpreting the state-by-state results presented in Chapter 2.

Comparison of the Safety-Congestion Relationships Between States

Chapter 2 presented the safety-congestion relationships developed in both the original Phase 2 research and in the new Task IV-5 research. As noted in the background discussion in Chapter 1, the original safety-congestion relationships developed in Phase 2 for Seattle and Minneapolis–St. Paul freeways both showed a U-shaped curve with the lowest crash rates in the middle of the traffic density range, at about LOS C. Crash rates at lower densities (i.e., better LOS) are slightly higher than the minimum crash rate, due primarily to single-vehicle crashes. Crash rates at higher densities (i.e., poorer LOS) are substantially higher than the minimum crash rate, due to multiple-vehicle crashes. This U-shaped relationship is quite pronounced for the Seattle data in Figure 2.1 and is clearly present in Minneapolis–St. Paul, though confounded by a secondary peak in the middle traffic density range (approximately LOS D), as shown in Figure 2.2.

The data for Sacramento freeways, shown in Figure 2.3, largely confirm the Seattle and Minneapolis–St. Paul results, showing a U-shaped relationship with minimum crash rates at about LOS C, slightly higher crash rates at lower densities (i.e., better LOS), and substantially higher crash rates at higher densities (i.e., poorer LOS).

The data for freeways in the Kansas portion of the Kansas City metropolitan area (see Figure 2.4) show little variation in crash rate over the range of traffic density, although crash rates were substantially higher in the lowest traffic density category (LOS A+) and slightly higher in the highest traffic density category (LOS F+). Review of the data shows that the Kansas freeways experienced a substantially lower portion of LOS F conditions than the other metropolitan areas and, therefore, did not have much opportunity to show higher crash rates at higher traffic densities.

The data for freeways in the Missouri portion of the Kansas City metropolitan area (see Figure 2.5) show very similar results to those in the Kansas portion, although the crash rate for the highest traffic density category (LOS F+) was not any higher than the crash rates at medium crash densities (LOS C and D).

The most appropriate interpretation of these results is that the Seattle, Minneapolis–St. Paul, and Sacramento results show similar shapes for the safety-congestion relationships. The results for the Kansas City metropolitan area are not necessarily inconsistent with the other metropolitan areas but may not include sufficient congestion to show higher crash rates at the highest crash densities.

Combined Safety-Congestion Relationship

The research team's assessment was that the most appropriate method to obtain an overall safety-congestion relationship was to combine the Seattle, Minneapolis–St. Paul, and Sacramento results into a single relationship. Graphs of the data from these three metropolitan areas all show relationships between safety and congestion with similar shapes. The Kansas City data were not included because they did not show higher crash rates at higher traffic densities. It should be recognized that the available data for the Kansas City area are not necessarily inconsistent with the relationships found for Seattle, Minneapolis–St. Paul, and Sacramento; especially for the Kansas portion of the Kansas City metropolitan area, the lack of definitive results for sites with high traffic densities was due primarily to the sparsity of data for high congestion levels and does not necessarily represent any fundamental difference in the safety-congestion relationship from the other areas. It should also be noted that the shape of the overall safety-congestion relationship would not have been very different even if the Kansas City data were included, because the average crash rate for Kansas City freeways was very close to the average crash rate for the other three metropolitan areas; the lack of data for higher traffic densities in Kansas City means that inclusion of the Kansas City data would have had only a small influence on that end of the curve.

Table 2.7 shows that volume and/or speed data are missing for 18.5% of the 15-min periods in the Seattle metropolitan area and 16.1% of the 15-min periods in the Minneapolis–St. Paul metropolitan area. These missing data were due primarily to random events such as detector outages and should not represent any systematic bias in the data. Therefore, the presence of these missing data does not raise a concern about using the remaining data for the Seattle and Minneapolis–St. Paul metropolitan areas in modeling the safety-congestion relationship.

The Sacramento metropolitan area had the least missing data among the metropolitan areas studied (only about 1% of the available 15-min periods) because the Caltrans PeMS includes estimates for speed and volume when actual data are not available. The research team reviewed the data, and most of the estimated values appeared to be during nighttime periods when the traffic operational conditions were unquestionably at LOS A. Since the analysis conducted focused on the level of service range from LOS C to LOS F, the inclusion of some estimated speed and volume data for low-volume conditions at LOS A did not appear to bias the study results in any way.

A combined safety-congestion relationship for the Seattle, Minneapolis–St. Paul, and Sacramento metropolitan areas was developed by translating the curves to the average freeway crash rate for the three metropolitan areas and then averaging the individual data points. With this translation completed, the results are representative of a freeway system with a total crash rate of 1.86 crashes per MVMT, a fatal-and-injury crash rate of 0.42 crashes per MVMT, and a property-damage-only crash rate of 0.82 crashes per MVMT, which represents the average freeway crash rate for Seattle, Minneapolis–St. Paul, and Sacramento, giving equal weight to each metropolitan area.

The portion of the safety-congestion relationship that is most relevant to the objectives of Project L07 is the range from LOS C to LOS F, which shows that freeway crash rates can be reduced by decreasing congestion. As in the original Phase 2 research, the best fit to the safety-congestion relationship in this range was found to be a cubic functional form. Figure 3.1 illustrates the combined safety-congestion relationship by crash severity levels. The coefficients of these cubic relationships are presented in Table 3.1.

The curves shown in Figure 3.1 can be represented mathematically as follows in Equations 3.1–3.3:

$$\text{Total crashes per MVMT} = 2.190 - 0.1979 \times D + 0.00728 \times D^2 - 5.34 \times 10^{-5} \times D^3 \quad (3.1)$$

$$\text{FI crashes per MVMT} = 0.831 - 0.0718 \times D + 0.00246 \times D^2 - 1.76 \times 10^{-5} \times D^3 \quad (3.2)$$

$$\text{PDO crashes per MVMT} = 1.359 - 0.1261 \times D + 0.00482 \times D^2 - 3.58 \times 10^{-5} \times D^3 \quad (3.3)$$

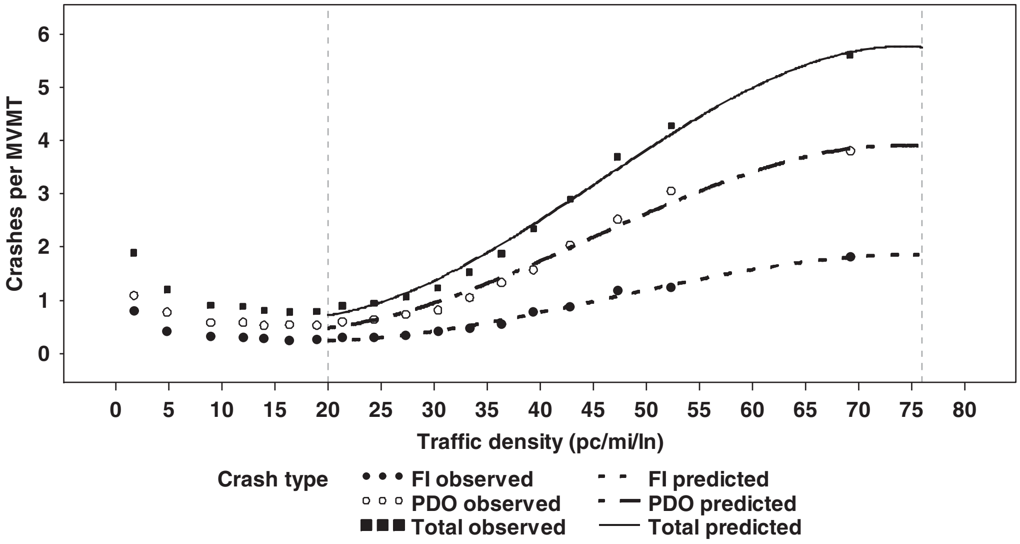

Figure 3.1. Observed and predicted FI, PDO, and total crash rates versus traffic density (Seattle, Minneapolis–St. Paul, and Sacramento areas combined).

Table 3.1. Regression Results for Total, FI, and PDO Crash Rates Versus Traffic Density (Seattle, Minneapolis–St. Paul, and Sacramento Areas Combined)

Severity Level	Regression Coefficients				Model Fit		Crash Rate (Crashes per MVMT) at Specified Density	
	a_0	a_1	a_2	a_3	RMSE[a]	R^2 (%)	20 pc/mi/ln	76 pc/mi/ln
Total	2.190	–0.1979	0.00728	-5.34×10^{-5}	0.145	99.1	0.72	5.77
FI	0.831	–0.0718	0.00246	-1.76×10^{-5}	0.060	98.4	0.24	1.86
PDO[b]	1.359	–0.1261	0.00482	-3.58×10^{-5}	NA	NA	0.48	3.91

[a] Root mean square error.

[b] Regression coefficients and crash rates for 20 and 76 pc/mi/ln obtained by subtraction (Total – FI).

Over the entire traffic density range, crash rates are expressed as follows in Equations 3.4 through 3.6, based on Table 3.1:

Total crashes per MVMT =

$$\begin{cases} 0.72 \quad \text{if Density} < 20 \text{ pc/mi/ln} \\ 2.190 - 0.1979 \times D + 0.00728 \times D^2 - 5.34 \times 10^{-5} \times D^3 \\ 5.77 \quad \text{if Density} > 76 \text{ pc/mi/ln} \end{cases} \qquad (3.4)$$

FI crashes per MVMT =

$$\begin{cases} 0.24 \quad \text{if Density} < 20 \text{ pc/mi/ln} \\ 0.831 - 0.0718 \times D + 0.00246 \times D^2 - 1.76 \times 10^{-5} \times D^3 \\ 1.86 \quad \text{if Density} > 76 \text{ pc/mi/ln} \end{cases} \qquad (3.5)$$

PDO crashes per MVMT =

$$\begin{cases} 0.48 \quad \text{if Density} < 20 \text{ pc/mi/ln} \\ 1.359 - 0.1261 \times D + 0.00482 \times D^2 - 3.58 \times 10^{-5} \times D^3 \\ 3.91 \quad \text{if Density} > 76 \text{ pc/mi/ln} \end{cases} \qquad (3.6)$$

Figure 3.2 compares the curves developed from the Seattle, Minneapolis–St. Paul, and Sacramento data (black lines) to the original curves developed from the Seattle and Minneapolis–St. Paul data only (gray lines). The figure shows that the revised relationships differ only slightly from the original relationships.

The safety-congestion relationships shown in Figure 3.1 and Equations 3.4 through 3.6 are appropriate for use in the Project L07 Analysis Tool in place of the original relationships shown in Figure 1.1, and the tool will be updated accordingly.

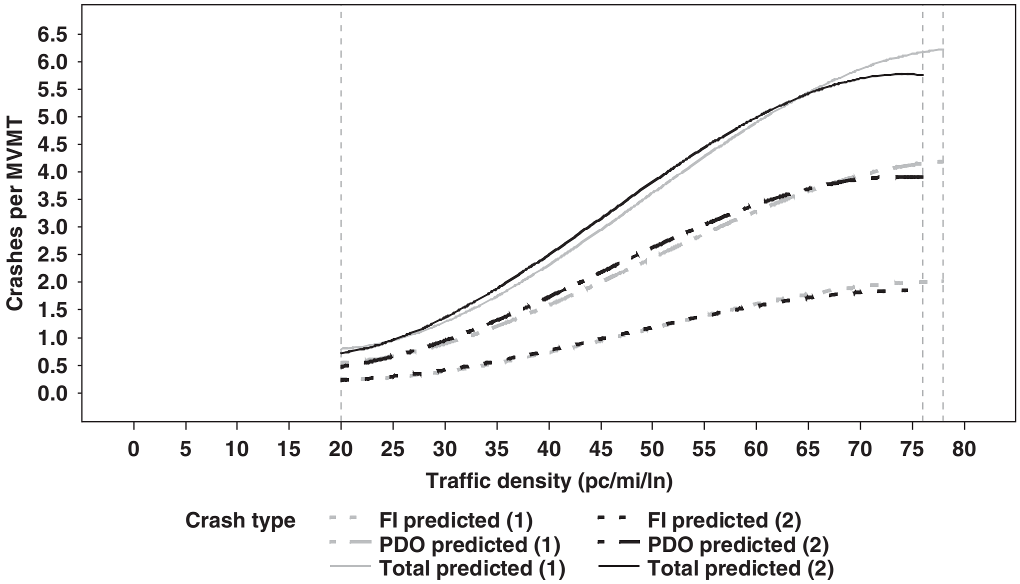

Figure 3.2. Predicted FI, PDO, and total crash rates versus traffic density (1 = Seattle and Minneapolis–St. Paul areas combined; 2 = Seattle, Minneapolis–St. Paul, and Sacramento, areas combined).

Safety-Congestion Relationships for Specific Nonrecurrent Congestion Scenarios

The results shown in Figures 3.1 and 3.2 incorporate the effects of both recurrent and nonrecurrent congestion as well as many periods of uncongested flow. Since the focus of Project L07 is on nonrecurrent congestion, a further analysis was conducted to check whether the results shown in Figures 3.1 and 3.2 are representative of nonrecurrent congestion. This investigation was conducted with the data for Sacramento freeways.

The investigation of nonrecurrent congestion required the development of criteria to distinguish recurrent and nonrecurrent congestion. This was accomplished as follows:

- First, periods when medium- or long-term work zones were present on the study sites were identified. This was accomplished by plotting the time sequence of mean 15-min traffic speeds for off-peak periods (separately for daytime and nighttime periods). Periods with medium- or long-term work zones that constitute nonrecurrent congestion were easily identified by noting periods of reduced traffic speeds that lasted for a defined time period (often weeks or months) and then returned to normal levels. Some work zones were daytime-only work zones, some were nighttime-only work zones, and some were under way during both daytime and nighttime hours. Work-zone periods with reduced speeds were classified as nonrecurrent congestion regardless of the actual traffic flow levels in the work zone (i.e., a work zone in place with reduced speeds 24 h per day was classified as nonrecurrent congestion for 24 h per day).
- Second, other periods of nonrecurrent congestion (not in work zones) were identified by application of a set of rules. These rules were based on experience in other projects and a review of a sample of the Sacramento data. For each 15-min time slice, for each day of the week at each site (e.g., 1:00 p.m. to 1:15 p.m. for all Mondays during the 3-year study period), the mean and standard deviation of the daily 15-min speeds were determined based on data for all periods when medium- to long-term work zones were not present (see above). The rules for identifying nonrecurrent congestion periods other than work-zone periods were as follows:
  - ○ If the standard deviation of speed for a site, day of week, and time of day (15-min period) time slice is greater than or equal to 6 mph, then the 15-min periods for every day in that time slice are not classified as nonrecurrent congestion (i.e., they represent either recurrent congestion or normal uncongested flow).
  - ○ If the speed for an individual 15-min period is less than the mean speed for the time slice minus 1.5 times the standard deviation of speed for the time slice and the speed for that individual 15-min period is more than 8 mph less than the mean speed for the time slice, then that individual 15-min period is classified as nonrecurrent congestion.

Application of the preceding criteria to 26,960,918 individual site-periods (a 15-min period at a given site) for which volume and speed data are available for Sacramento freeways resulted in 5,636,666 site-periods (21%) classified as nonrecurrent congestion and 21,324,252 site-periods (79%) classified as recurrent congestion or normal uncongested flow.

Figure 3.3 presents crash rate versus traffic density for the nonrecurrent congestion periods, and Figure 3.4 presents comparable data for the recurrent congestion and normal uncongested flow. Both plots show the same U-shaped relationship between crash rate and traffic density found for the

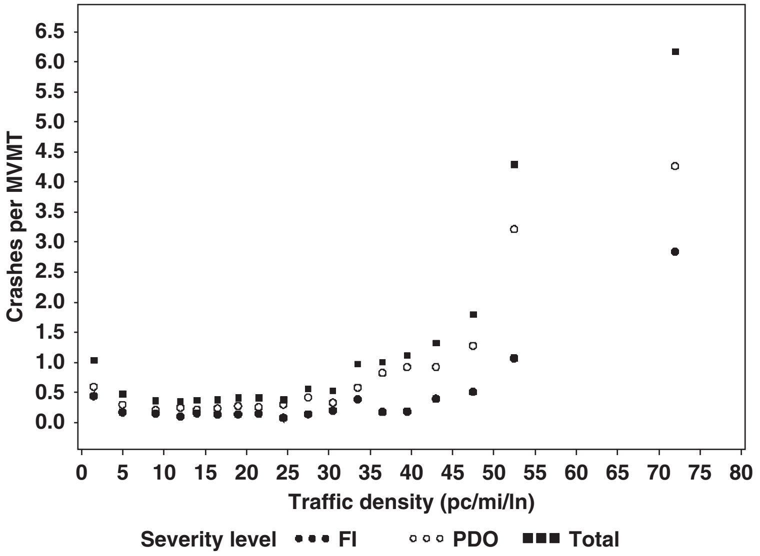

Figure 3.3. Crash rate versus traffic density for nonrecurrent congestion periods in Sacramento.

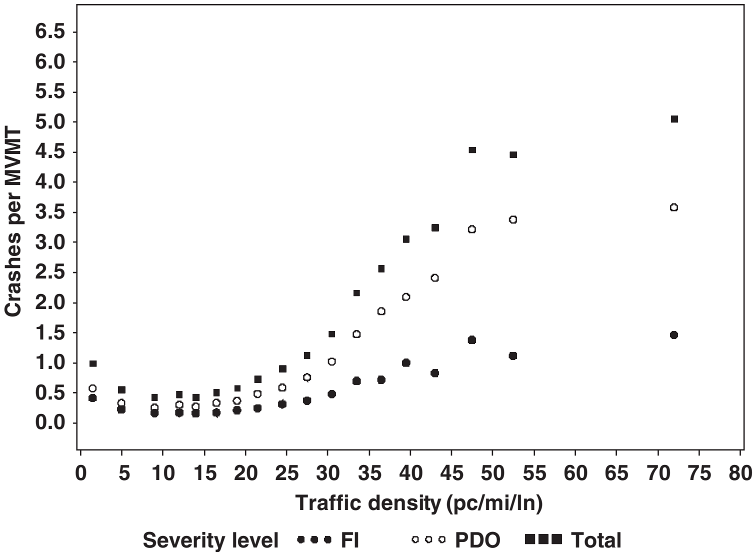

Figure 3.4. Crash rate versus traffic density for recurrent congestion and normal uncongested flow (non-work-zone periods) in Sacramento.

overall data set (see Figure 2.3). This provides strong evidence that the general relationship between crash rate and traffic density shown in Figure 3.1 is applicable to both recurrent and nonrecurrent congestion.

A further investigation was undertaken to examine the role of various sources of nonrecurrent congestion. The 5,636,666 site-periods of nonrecurrent congestion on Sacramento freeways were broken down as follows:

- 5,631,097 site-periods related to work zones;
- 59 site-periods related to crashes; and
- 5,510 site-periods related to other sources of nonrecurrent congestion.

The work-zone periods were identified as previously described. These periods constituted the vast majority of the periods identified as nonrecurrent congestion. Figure 3.5 illustrates the relationship between crash rate and traffic density for work-zone periods. This plot is virtually identical to the plot in Figure 3.3 and displays the same U-shaped relationship shown previously. Figure 3.5 includes congestion related to crashes that occurred in work zones.

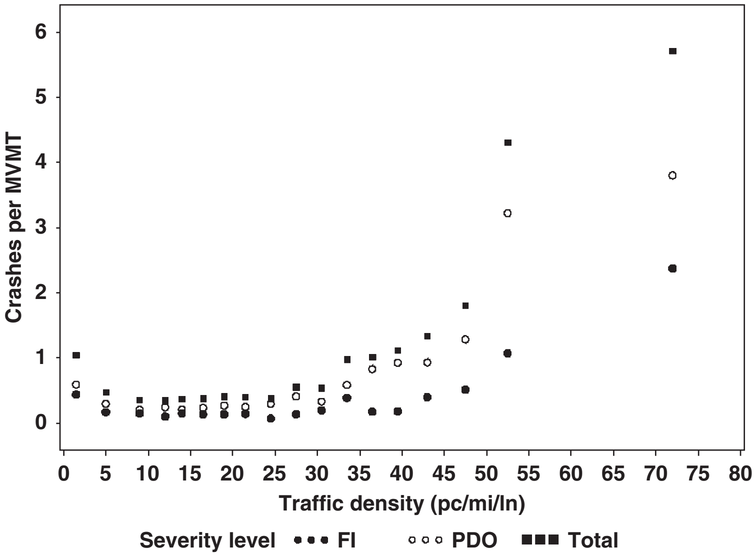

Figure 3.5. Crash rate versus traffic density for work-zone periods in Sacramento.

Nonrecurrent congestion related to crashes was identified by matching all periods of nonrecurrent congestion identified according to the rules presented above with the locations and times of crashes. Any nonrecurrent congestion was identified as crash-influenced if it occurred

- In the same 15-min period as a crash or in one of the three subsequent 15-min periods; and
- In the same freeway section as a crash or in any freeway section within 2 mi upstream of the freeway section where the crash occurred.

This process identified only 59 site-periods with nonrecurrent congestion related to crashes (not including crashes in the work zones). There were so few crash-related periods of nonrecurrent congestion that it was not meaningful to plot them. However, all of the crash-related periods of nonrecurrent congestion resulted in traffic densities in the range from LOS C to LOS D. There were no periods of extremely high traffic density (i.e., LOS E or F) related to crashes.

The other 5,510 site-periods of nonrecurrent congestion relate to other congestion sources; these include vehicle breakdowns, short-term work zones, and weather events. There were no crashes during these 5,510 site-periods because, by definition, all periods with crashes (or influenced by crashes) were included in one of the other nonrecurrent congestion categories. Therefore, it is not feasible to plot crash rate versus traffic density for these periods.

Interpretation of Results

Figure 3.1 presents the best overall illustration of the relationship between safety and congestion found in the research. The relationships shown in Figure 3.1 are represented analytically in Table 3.1 and Equations 3.1 through 3.6.

Variation of Crash Severity with Increasing Congestion Levels

The authors' original expectation was that, while crash frequency might increase at higher congestion levels, crash severity might not increase, or might even decrease, because traffic speeds would be lower at high congestion levels. The research results, as illustrated in Figure 3.1, contradict this original expectation. The research results in Figure 3.1 show that both fatal-and-injury and property-damage-only crashes increase as the traffic density increases. The increase in fatal-and-injury crashes is not as large as the increase in property-damage-only crashes, but the frequency of more severe crashes does increase as congestion increases.

Using the Safety-Versus-Congestion Results to Estimate Crash Reduction due to Congestion Reduction Resulting from Design Treatments

The full algorithm developed in Reliability Project L07 for assessing the cost-effectiveness of design treatments for reducing nonrecurrent congestion is presented in the Project L07 final report (*1*). This section discusses how the results presented in this chapter's Combined Safety-Congestion Relationship section are used in that algorithm to estimate the safety effect of congestion reduction. To understand the full context of this procedure, as applied in the Project L07 Analysis Tool, refer to the Project L07 final report (*1*).

As an example, suppose that a design treatment was under consideration for implementation on an urban freeway and application of the procedures in the Project L07 final report indicated that, for the traffic conditions present in one particular hour of a typical day, implementation of the design treatment would reduce congestion such that the traffic density would be reduced by that treatment from 65 to 55 pc/mi/ln. Computations with Equation 3.5 indicate that such a change in density would, on average, reduce fatal-and-injury crashes by 19% (from 1.72 to 1.40 crashes per MVMT). Similarly, computations with Equation 3.6 indicate that the change in density would, on average, reduce property-damage-only crashes by 18% (from 3.70 to 3.05 crashes per MVMT). It is therefore reasonable to expect that the expected crash frequency on the candidate treatment site during the hour in question (or during a 1-h time slice representing that particular hour over course of the entire year) would be reduced by 19% for fatal-and-injury crashes and 18% for property-damage-only crashes. To determine the overall annual crash reduction, this calculation would need to be repeated for each of the 24 h of the day. The Analysis Tool developed in Project L07 (*1*) automates this computation to eliminate the need for repetitive manual calculations.

CHAPTER 4

Conclusions and Recommendations

This chapter presents conclusions of the research and recommendations for the implementation of the research results.

Conclusions

1. The results of the research considering relationships between crash rate and traffic density for additional metropolitan areas (Sacramento and Kansas City) confirmed the findings of the original research for the Seattle and Minneapolis–St. Paul metropolitan areas (*1, 4*).
2. Crash rate on urban freeways varies with traffic density in a U-shaped relationship with higher crash rates at very low traffic densities (due primarily to single-vehicle crashes), higher crash rates at very high traffic densities (due to multiple-vehicle crashes), and the lowest crash rates at medium traffic densities. This result was found for both fatal-and-injury and property-damage-only crashes.
3. This finding implies that design treatments that are effective in reducing congestion levels on urban freeways (between approximately LOS C and LOS F) should also be effective in reducing crashes. Figure 3.1 and Equations 3.4 through 3.6 present relationships based on the combined data for three metropolitan areas (Seattle, Minneapolis–St. Paul, and Sacramento) that can be used to quantify the effect on crash rate of reducing congestion within the range from LOS C to LOS F.
4. Further analyses of data for Sacramento freeways demonstrated that the relationships shown in Figure 3.1 and Equations 3.4 through 3.6 are applicable to both recurrent and nonrecurrent congestion.

Recommendations

It is recommended that the relationship between crash rate and traffic density shown in Figure 3.1 and Equations 3.4 through 3.6 be used to represent the safety-congestion relationship in the spreadsheet Analysis Tool developed in Project L07 in place of the original relationships based on only two metropolitan areas (*1, 4*).

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Related SHRP 2 Research

Establishing Monitoring Programs for Travel Time Reliability (L02)
Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (L03)
Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes (L05)
Identification and Evaluation of the Cost-Effectiveness of Highway Design Features to Reduce Nonrecurrent Congestion (L07)
Incorporating Travel Time Reliability into the *Highway Capacity Manual* (L08)
Evaluating Alternative Operations Strategies to Improve Travel Time Reliability (L11)
Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Portland, Oregon, Metro (L35A)
Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Maryland (L35B)
Development of Tools for Assessing Wider Economic Benefits of Transportation (C11)