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FHWA SIGNALIZED INTERSECTIONS INFO GUIDE – PART II

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Course #:	TRA-111
Course Content:	76 pgs
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TRA-111 EXAM PREVIEW

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Exam Preview:

1. Historically, safety practitioners have identified intersections with the highest number of crashes in a specified time period and focused their efforts and resources at those intersections. This proactive approach can be effective in addressing a small number of high-crash locations.
   a. True
   b. False

2. An RSA audit team consists of a multidisciplinary group of experts who review the intersection from different perspectives, such as safety, design, traffic operations, law enforcement, maintenance, etc. RSA stands for:
   a. Road Stop Authorization
   b. Right Side Alert
   c. Road Safety Authorization
   d. Road Safety Audit

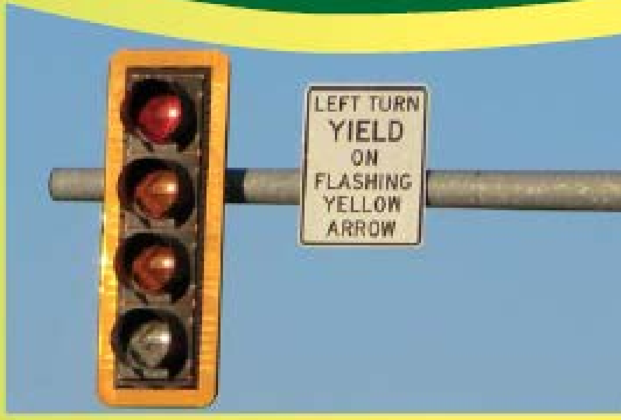
3. In selecting an intersection for a detailed safety analysis, a key question would be what is the safety performance of the location in comparison with other similar locations?
   a. True
   b. False

4. The crash history of a signalized intersection is the key indicator of its safety performance and is the focus of the remainder of this section.
   a. True
   b. False

5. Traditionally, traffic engineers used (and many still use) a frequency-based method of identifying and evaluating the safety of a site. Apart from regression to the mean, there are several other major advantages to using crash frequency as the sole means of evaluating safety at a site. First, a high crash frequency usually means that a site is truly in need of safety improvement.
    a. True
    b. False
6. A _____ can be used to relate the patterns and over-represented characteristics of crashes to a particular approach. A ____ is a two-dimensional plan view representation of the crashes that have occurred at a site within a given time period.
    a. Crash chart
    b. Intersection analysis
    c. Assessment study
    d. Crash diagram
7. _____ identify whether the countermeasures identified in the previous step of the road safety management process have larger benefits than their costs. The _____ quantifies countermeasures' benefits in terms of their safety impacts.
    a. Economic appraisals
    b. Intersection appraisals
    c. Economic countermeasure
    d. Intersection countermeasure
8. Usually, countermeasures will only be effective when applied to a particular target group of crashes.
    a. True
    b. False
9. The potential crash reduction from a countermeasure is determined by dividing the expected number of crashes by the percentage reduction that the countermeasure is expected to have.
    a. True
    b. False
10. Understanding the critical movements and critical volumes of a signalized intersection is a fundamental element of any capacity analysis. A Critical Lane Analysis (CLA) should be performed for all intersections considered for capacity improvement.
    a. True
    b. False

Signalized Intersections Informational Guide

Second Edition



FHWA Safety Program

PART II - ANALYSIS METHODS

U.S. Department of Transportation
Federal Highway Administration

Safe Roads for a Safer Future
Investment in roadway safety saves lives

http://safety.fhwa.dot.gov

Signalized Intersections Informational Guide

Second Edition

Publication No. FHWA-SA-13-027

July 2013

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

This report, now in its Second Edition, complements the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan (SHSP) efforts to develop guidance on enhancing the safety of unsignalized and signalized intersections. The overarching goal is to reduce the number of traffic related deaths that occur on highways and streets in the United States. This guide is an introductory document that contains methods for evaluating the safety and operations of signalized intersections and tools to remedy deficiencies. The treatments in this guide range from low-cost measures such as improvements to signal timing or signing and markings, to high-cost measures such as intersection widening or reconstruction. Topics covered include fundamental principles of user needs and human factors, multimodal accommodations (emphasizing pedestrians and bicyclists), elements of geometric design, and traffic safety design and operation; safety, maintenance and operations practices; and a wide variety of treatments, techniques and strategies to address existing or anticipated problems at multiple levels, including corridor, approach and individual movement treatments. Each recommended treatment includes a discussion of safety performance, operations, multimodal issues, and physical and economic factors that the practitioner should consider. While some treatments may be better suited to high-volume intersections, most of the treatments are applicable for lower volume intersections and would be worthy of systemic implementation. Every attempt has been made to reflect the latest research and documentation on available treatments and best practices in use by jurisdictions across the United States at the time of publication. Since the scope of this guide is necessarily limited, additional resources and references are highlighted for the student, practitioner, researcher, or decision maker who endeavors to learn more about a particular subject.

An electronic version of this document can be downloaded from the Federal Highway Administration, Office of Safety website at http://safety.fhwa.dot.gov/. A hard copy may be requested by contacting the National Highway Institute, 1310 North Courthouse Road, Suite 300, Arlington, VA 22201; telephone (703) 235-0500; fax (703) 235-0593.

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Director
Office of Safety Technologies

NOTICE

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15. Supplementary Notes

Jeffrey Shaw (jeffrey.shaw@dot.gov), Office of Safety Technologies (http://safety.fhwa.dot.gov/), served as the Technical Manager for the Federal Highway Administration (FHWA). The following FHWA staff members contributed as technical working group members, reviewers and/or provided input or feedback to the project at various stages: Timothy Taylor, Bruce Friedman, Tom Elliott, Jim Sturrock, Paul Olson, Mark Doctor, John Broemmelsiek, Joe Bared, James Coylar, Jim McCarthy, Eddie Curtis, Joe Glinski, Ed Rice (retired), Scott Wainwright (retired), Carol Tan, Caroline Trueman and Don Petersen. Additionally, many individual safety partners representing federal, state and local agencies, professional associations, academia and industry, made significant contributions to this project; special thanks to Tom Hicks (retired – Maryland SHA), Mark Hagan (Virginia DOT), Julie Stotlemeyer (Missouri DOT), Jake Kononov (retired – Colorado DOT), Dwight Kingsbury (Florida DOT), Julie Bradley (Pennsylvania DOT), Jim Ellison (retired – Pierce County, WA), Peter Koonce (City of Portland, OR), Dr. Praveen Edara (University of Missouri), Doug Noble (Institute of Transportation Engineers), Melissa Anderson (U.S. Access Board), and Fred Ranck (traffic safety consultant).

16. Abstract

This is the Second Edition of a document that was originally published in 2004. This document serves as an introduction to and guide for evaluating the safety, design, and operations of signalized intersections. It also provides tools to deliver better balanced solutions for all users. It takes a holistic approach to signalized intersections and considers the safety and operational implications of a particular treatment on all system users (e.g., motorists, pedestrians, bicyclists, and transit users). Readers will find the tools and information necessary to make insightful intersection assessments and to understand the impacts of potential improvement measures. The information in this guide is based on the latest research available and includes examples of novel treatments as well as best practices in use by jurisdictions across the United States and other countries.

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SI* (MODERN METRIC) CONVERSION

FACTORS APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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CHAPTER 1

INTRODUCTION

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LIST OF EXHIBITS

References to be used throughout the Guide include:

- TRB *Highway Capacity Manual (*2010)
- FHWA *Manual on Uniform Traffic Control Devices* (2009)
- AASHTO *A Policy on Geometric Design of Highways and Streets* (2011)
- AASHTO Highway Safety Manual (2010)
- TRB NCHRP Report 500 series
- FHWA Alternative Intersections and Interchanges Informational Report (2010)
- U.S. Access Board Draft Public Rights-of-Way Accessibility Guidelines (2011)
- U.S. Access Board ADAAG Requirements for Detectable Warnings (2008)
- U.S. Access Board ADA Standards for Accessible Design (2010)
- FHWA Traffic Signal Timing Manual (2008)
- FHWA Traffic Detector Handbook (2006)
- ITE Traffic Control Devices Handbook (2011)
- IESNA American National Standard Practice for Roadway Lighting (2005)

1.0 INTRODUCTION

This document serves as an introduction to and guide for evaluating the safety, design, and operations of signalized intersections. It also provides tools to deliver better balanced solutions for all users. The treatments in this guide range from low-cost measures such as improvements to signal timing and signing, to high-cost measures such as intersection reconstruction or grade separation. While some treatments apply only to higher volume intersections, much of this guide is applicable to signalized intersections of all volume levels.

The guide takes a holistic approach to signalized intersections and considers the safety and operational implications of a particular treatment on all system users (e.g., motorists, pedestrians, bicyclists, and transit users). When applying operational or safety treatments, it is often necessary to consider the impact one will have on the other. This guide will introduce the user to these trade-offs and their respective considerations.

Practitioners will find the tools and information necessary to make insightful intersection assessments and to understand the impacts of potential improvement measures. The information in this guide is based on the latest research available and includes examples of novel treatments as well as best practices in use by jurisdictions across the United States and other countries. Additional resources and references are mentioned for the practitioner who wishes to learn more about a particular subject.

This guide does not replicate or replace traditional traffic engineering documents such as the *Manual on Uniform Traffic Control Devices* (MUTCD),(1) the *Highway Capacity Manual* (HCM) 2010 (2) or the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets,*(3) nor is it intended to serve as a standard or policy document. Rather, it provides a synthesis of best practices and treatments intended to help practitioners make informed, thoughtful decisions.

1.1 BACKGROUND

Traffic Signal Basics

Traffic signals are electrically operated traffic control devices that provide indication for roadway users to advance their travels by assigning right-of-way to each approach and movement. Traffic signals are a common form of traffic control used by State and local agencies to address roadway operations and safety issues. They allow the shared use of road space by separating conflicting movements in time and allocating delay, and can be used to enhance the mobility and safety of some movements.

Consider the installation of traffic signals when attempting to obtain any of the following:

- Optimization of travel delay
- Reduction of crash frequency and/or severity
- Prioritization of specific roadway user type or movement (such as pedestrians or left turn movements)
- Accommodation of a new intersection approach or increase in traffic volumes (such as the addition of an approach at a new development)

Analysis of traffic volume data, crash history, roadway geometry, and other field conditions are the determining factors when deciding upon the installation of traffic signals. Planners, designers, and traffic engineers work together to determine if conditions are right for installation. Several safety and mobility factors should be considered as new traffic signal installation is being discussed. Chapter 4C of the MUTCD outlines basic warrants for when installation of a traffic signal may be justified. In addition to the considerations presented in the MUTCD, practitioners should give thought to roadway/intersection geometry and sight distance, driver expectancy, and the locations of other nearby traffic signals when considering the installation of new traffic signals.

When weighing the options for traffic control types at an intersection, consider the following important factors:

- The design and operation of traffic signals will require choosing elements that may lead to trade-offs in safety and mobility.
- It is possible to lower the overall crash severity at intersections with traffic signals, but increase the crash frequency. Table 14-7 of the 2010 Highway Safety Manual illustrates the effects of converting a stop controlled intersection to a signalized intersection.
- There will be ongoing operational costs attributed to the maintenance of signal equipment and costs for electrical power.

Once installed, the traffic engineers and field traffic signal technicians who operate and maintain the traffic signals should regularly perform site visits to:

- Ensure that safety and mobility targets for the intersection are being met, and make adjustments to signal timings, if necessary, to meet the targets;
- Inspect corresponding intersection signing and pavement markings to ensure they properly convey the intended instructions to roadway users;
- Log site visit findings for use when making adjustments or recommendations for change; and
- Communicate traffic signal maintenance and repair needs to field technicians.

Ideally, field traffic signal technicians are qualified to perform maintenance inspections at regular intervals. Repairs are made such that the signal operates safely and efficiently at all times. Technicians are also responsible for the general upkeep and operation of signal equipment located at the intersection.

An agency will identify that a traffic signal needs upgrades, replacement or decommission at some point during its life. Degradation of equipment, new technology, or changing conditions at the site, such as lane additions or the need for alternate phasing, may necessitate an upgrade or full replacement. In some instances, the traffic signal may be completely removed if traffic patterns cease to warrant its use.

Traffic Operations: Safety and Mobility

Traffic signals play a prominent role in achieving safer performance at intersections. Research has shown that the proper installation and operation of traffic signals can reduce the severity of crashes. However, unnecessary or inappropriately designed signals can adversely affect traffic, safety, and mobility. Care in their placement, design, and operation is essential.

In some cases, the dual objectives of mobility and safety will conflict. To meet increasing and changing demands, one element may need to be sacrificed to achieve improvements in the other. In all cases, it is important to understand the degree to which traffic signals are providing mobility and safety for all roadway users.

Assuring the efficient operation of the traffic signal is becoming an increasingly important issue as agencies attempt to maximize vehicle roadway capacity to serve the growing demand for travel, while maintaining a high level of safety.

Reducing crashes should always be one of the objectives whenever the design or operational characteristics of a signalized intersection are modified. As described by the Federal Highway Administration (FHWA), the "mission is not simply to improve mobility and productivity, but to ensure that improved mobility and productivity come with improved safety."[(4)]

Exhibit 1-1 shows that in 2009, 21 percent of all crashes and 24 percent of all fatalities and injury collisions occurred at signalized intersections.

Exhibit 1-1. Summary of motor vehicle crashes related to junction and severity in the United States during 2009.

	Total Crashes		**Fatalities/Injuries**	
	Number	*Percent*	*Number*	*Percent*
Non-Intersection Crashes	3.295,000	60	841,027	54
Signalized Intersection Crashes	1,158,000	21	372,299	24
Non-Signalized Intersection Crashes	1,052,000	19	332,471	22
Total	5,505,000	100	1,547,797	100

Source: Adapted from table 29 of Traffic Safety Facts 2009.[(5)]

How a Traffic Signal Works

Traffic signals are designed to allow for the safe and efficient passage of road users when demand exists. Types of traffic signal operation include pre-timed, semi-actuated, fully-actuated, hybrid, adaptive, or traffic responsive. Pre-timed signals give right-of-way to movements based on a predetermined allocation of time. Semi-actuated signals use various detection methods to identify roadway users on the minor approaches, while fully-actuated signals recognize users on all approaches. Chapter 5 discusses each of these methods in further detail.

In addition to the signal heads seen by the road users, signalized intersections may include additional components, such as loop detectors and video detection equipment. The following paragraphs provide information related to each component.

Exhibit 1-2. Vehicle detection by inductive loop (left) and video (right)
(Source: Left: South Carolina DOT / Right: Jeff Shaw, FHWA)

Detection.

Semi- and fully actuated signals use various methods to detect road users. Detection methods for motorists include in-pavement loop detectors or sensors (Exhibit 1-2 (left)) and cameras mounted to signal poles (Exhibit 1-2 (right)). Detection methods for pedestrians and bicyclists include push buttons and weight sensors.

Traffic signal controller.

Each detection method sends vehicle presence information to a traffic signal controller. The controller acts as the “brain” of the traffic signal, changing signal indications based on programmed instructions. The controller will determine when the indication for the approach will change and how much time will be given to each movement. A controller is shown in Exhibit 1-3.

Traffic control algorithms determine the priority and length of time of each approach movement. These algorithms are tailored to the needs of each intersection, based on historical user demand, crash history, and other roadway network considerations.

Signal heads.

Traffic signal heads inform roadway users of when their movement can proceed through the intersection. Signal heads for motorists and bicyclists are usually mounted on mast arms or span wires above the travel lane, and are sometimes repeated on the signal pole. Pedestrian signal heads are often installed on the traffic signal pole, or independently on separate poles depending on the intersection design. Signal heads vary in configuration, shape, and size depending on the movement for which they are used.

Exhibit 1-3. Inside a signal controller cabinet.
Photo Credit: Missouri DOT

Types of Signalized Intersections

In their most common form, signalized intersections have indications for users on each intersection approach. Exhibit 1-4, below, shows a basic signalized intersection with four vehicle approaches and two pedestrian approaches.

In addition to signalizing intersections, it may be necessary to consider the use of pedestrian signals at locations along a corridor with high concentrations of pedestrians. This type of traffic control can be used at signalized intersections with the addition of pedestrian push-buttons and signal heads, or at non-signalized locations that have high volumes of pedestrians crossing. This guide also provides direction on the use of treatments such as the Pedestrian Hybrid Beacon. Pedestrian signals are discussed in more detail in Chapter 5.

1.2 PERFORMANCE MEASUREMENT AND ASSET MANAGEMENT

Agencies face the challenge of providing outstanding customer service with limited resources. Performance measures allow practitioners to assess the effectiveness of a signalized intersection or corridor. These measures can help agencies more effectively allocate resources. Travel performance criteria include: stopped delay, travel speed, arrivals on red, and excessive queuing. Safety performance criteria include crash frequency, crash types, and severity. Traffic signal maintenance data could be categorized according to time of day or types of repair. Over time, practitioners and agencies can refine or adjust these measures.

The practitioner should review this data to assess problem areas to correct. Other information that may be needed includes comments from the practitioner's annual signal timing reviews and annual preventive maintenance program. Examples of questions that may arise from such a review:

- What intersections require monthly visits to fix?
- What types of repetitive repairs are being conducted over a wide number of intersections?
- Are phasing (or other) changes necessary to reduce the number of crashes?

Practitioners should create queries that identify problematic intersections. These queries can also identify global intersection treatments that reduce systematic problems. For example, an agency could choose to install uninterrupted power supply (UPS) units for frequent power outages. The following information can be utilized to monitor performance:

- Detection failures by type of device.
- Outages due to power surges and outages.
- Customer complaints and complements.
- Emergency personnel comments.
- Frequent equipment hits by errant vehicles.
- Damage by weather events.
- Intermittent issues.
- Number of red failures.

Reviews of these measures should involve traffic engineers, technicians, and operations personnel to create a culture of continuous improvement.

1.3 SCOPE OF THE GUIDE

This guide addresses safety and operation for all users of signalized intersections, including motorists, pedestrians, bicyclists, and transit riders. This guide addresses Americans with Disabilities Act (ADA) requirements and provides guidelines for considering older drivers.

Roundabouts and other alternative intersection designs are not addressed directly in this document; for more information, please refer to *Roundabouts: An Informational Guide, Second Edition* [6] and the FHWA *Alternative Intersections/Interchanges Informational Report.*[55]

1.4 AUDIENCE FOR THIS GUIDE

This guide is intended for planners, designers, traffic engineers, operations analysts, and signal technicians who perform or want to perform one or more of the following functions as they pertain to signalized intersections:

- Evaluate substantive safety performance experienced by system users.
- Evaluate operational performance experienced by system users.
- Identify treatments that could address a particular operational or safety deficiency.
- Understand fundamental user needs, geometric design elements, or signal timing and traffic design elements.
- Understand the impacts and tradeoffs of a particular intersection treatment.

It is envisioned that this guide will be used by signal technicians, design and traffic engineers, planners, and decision-makers who:

- Wish to be introduced to basic and intermediate traffic signal concepts.
- Are involved with the planning, design, and operation of signalized intersections, particularly those with high volumes.
- Are involved with the identification of potential treatments.
- Make decisions regarding the implementation of treatments at those intersections.

Exhibit 1-4. Signalized intersection with four approaches.
Source: FHWA

1.5 ORGANIZATION OF THE GUIDE

This guide is arranged in three parts:

- Part I: Fundamentals.
- Part II: Project Process and Analysis Methods.
- Part III: Treatments.

Part I (Chapters 2-5) provides key background information on three topic areas: user needs, data collection, signal warrants, geometric design, and traffic design and illumination. These chapters provide a foundation of knowledge of signalized intersections useful as a learning tool for entry-level engineers and as a refresher for more experienced engineers. Parts II and III reference the information in these chapters.

Part II (Chapters 6-7) describes project process and analysis methods. These chapters outline the steps that should be carried out and the tools to consider for evaluating the safety and operational performance of an intersection and determining geometric and timing needs.

Part III (Chapters 8-11) provides a description of treatments that can be applied to mitigate a known safety or operational deficiency. The treatments are organized by chapter, based on the intersection element. Within each chapter, the treatments are grouped by a particular user type (e.g., pedestrian treatments) or are grouped to reflect a particular condition (e.g., signal head visibility).

Exhibit 1-5 depicts the organization of the guide.

Exhibit 1-5. Organization of the guide.

Part	Chapter	Title
	1	Introduction
Part I: Fundamentals	2	User Needs
	3	Data Collection and Warrants
	4	Geometric Design
	5	Traffic Design and Illumination
Part II: Project Process and Analysis Methods	6	Safety Analysis Methods
	7	Operational Analysis Methods
Part III: Treatments	8	System-Wide Treatments
	9	Intersection-Wide Treatments
	10	Approach Treatments
	11	Individual Movement Treatments

Exhibit 1-6 provides a list of the treatments discussed in Part III. Each treatment includes a description, a photo or diagram where available, and a summary of the treatment's applicability. In addition, these sections identify the following:

- Key design elements;
- Operational and safety impacts;
- Impacts on other modes;
- Socioeconomic and physical impacts; and
- Education, enforcement, and maintenance issues.

The treatments in Exhibit 1-6 represent some, but not all, possible treatments.

Exhibit 1-6. List of intersection treatments discussed in this guide.

Treatment Type	Treatments	
System-Wide Treatments (Chapter 8)	• Median treatments • Access management	• Provide signal coordination • Provide signal preemption/priority
Intersection-Wide Treatments (Chapter 9)	• Reduce curb radius • Provide curb extensions • Modify stop line location • Improve pedestrian signal display • Modify pedestrian signal phasing • Grade separate pedestrian movements • High visibility crosswalks	• Provide bicycle box (experimental) • Provide bike lanes • Relocate transit stop • Change signal control from pre-timed to actuated • Modify change and clearance intervals • Modify cycle length • Remove late night/early morning flash • Provide or upgrade illumination • Convert signalized intersection to a roundabout or all-way stop control.
Approach Treatments (Chapter 10)	• Convert to over-the-road signal heads • Add supplemental signal heads • Increase size of signal heads • Increase number of signal heads • Provide backplates	• Provide advance warning • Improve lane use and street name signing • Reduce operating speed • Improve pavement surface • Improve cross section • Remove obstacles from clear zone • Improve sight lines • Provide dilemma zone protection • Provide red light camera enforcement
Individual Movement Treatments (Chapter 11)	• Add single left-turn lane • Add multiple left-turn lane • Add channelizing islands • Add single right-turn lane • Provide double right-turn lanes	• Restrict turns, U-turns • Provide auxiliary through lane • Delineate through path • Provide reversible lane • Provide variable lane use assignments

Part II

Analysis Methods

Part II includes a description of safety analysis methods (chapter 6) and operational analysis methods (chapter 7) that can be used in the evaluation of a signalized intersection. The chapters in part II provide the reader with the tools needed to determine deficiencies of a signalized intersection and areas for improvement and mitigation. The findings from part II should be used to identify applicable treatments in part III.

CHAPTER 6

SAFETY ANALYSIS METHODS

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6.0 SAFETY ANALYSIS METHODS

In addition to operational needs, it is important for signalized intersections to operate safely. Intersections constitute of a small portion of the National Highway System. However, intersection related crashes constitute more than 20 percent of fatal crashes.(71) In some cases a signal is even installed for safety reasons (e.g., severe angle crashes at a stop-controlled intersection). As a result, the safety performance of signalized intersections is as important as the operational performance of these intersections. Signalized intersections must be systematically and continuously monitored throughout their life.

Historically, safety practitioners have identified intersections with the highest number of crashes in a specified time period and focused their efforts and resources at those intersections. This reactive approach can be effective in addressing a small number of high-crash locations.

During the past two decades, road agencies have started to recognize the challenges associated with a highly reactive approach to road safety.(71)

The paradigm shift from a reactive approach to road safety (i.e., only investigate locations with high crash frequency) to also incorporating a proactive approach (i.e., incorporate road safety in all stages of a roadway cycle) occurred in conjunction with the development of analytical tools by researchers and practitioners. These tools can be categorized into qualitative and quantitative tools.

Qualitative approaches are often used when enough historical data is not available or when an intersection is in the planning or design stage. A Road Safety Audit (RSA) is one of the qualitative approaches. The RSA is a formal safety performance examination of an existing or future road or intersection by an independent audit team.

Quantitative approaches have been mostly collected in the Highway Safety Manual (HSM), published by AASHTO in 2010.(11) The HSM presents a systematic approach for a road safety management process. The road safety management process shown in Exhibit 6-1 can be applied to one road entity (e.g., an intersection) or a network (e.g., all signalized intersections in a jurisdiction). This road safety management process starts with network screening in which the main goal is identification of road locations likely to benefit the most from safety improvements. The underlying assumption is that road design attributes often play a significant contributory role in crash occurrence. In network screening, the safety performance of each individual location is compared with the safety performance of similar locations in a jurisdiction to identify whether the safety performance of the subject location is acceptable.

The next step in the road safety management process is diagnosis. This step examines the contributing factors of crashes for locations identified in the network screening process to determine the cause and prepare for the identification of treatments in the next steps.

Countermeasure selection and economic appraisal constitute the next steps in the road safety management process. This involves the selection of treatments potentially able to address the safety issues identified in the diagnosis step. In the course of this selection process, more than one countermeasure with the potential to mitigate the problem is often identified. A subsequent economic appraisal will evaluate all options for all problem locations in order to ensure that the countermeasures are economically viable. In the prioritization of countermeasure projects, the objective is to maximize benefits in terms of crash reductions subject to budget restrictions. Safety effectiveness evaluation involves monitoring implemented improvements to assess their safety effectiveness. The information obtained in this step is extremely valuable for prospective studies so that practitioners can make informed decisions about the effectiveness of each countermeasure.

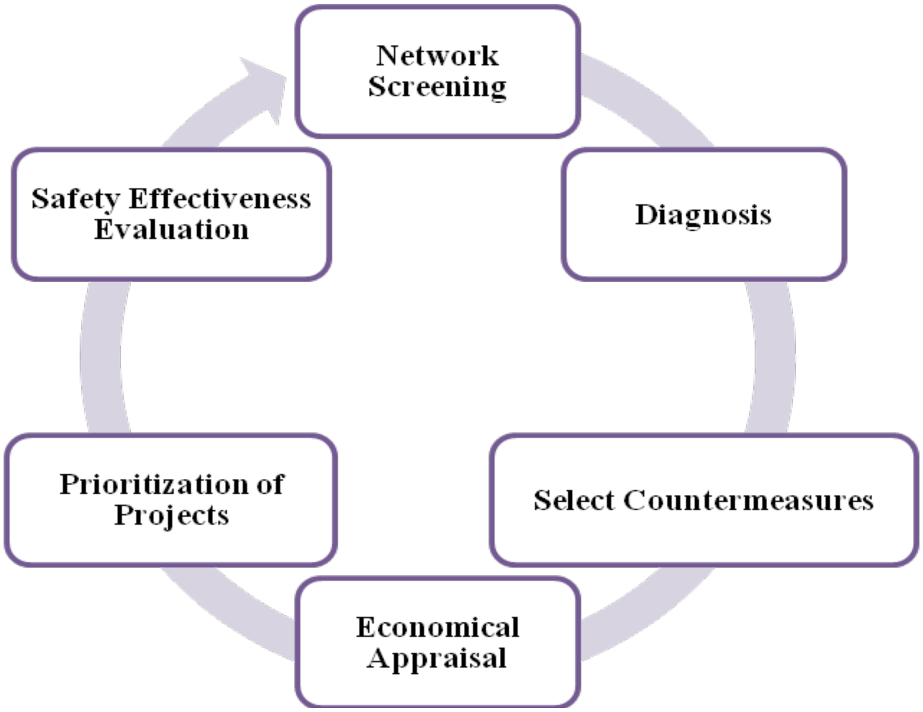

Exhibit 6-1. Road safety management process.[72]

The road safety management process is a continuous process demanding significant resources from road authorities, particularly jurisdictions which constitute large geographic areas (e.g., State agencies). The process requires an extensive amount of data, which should be collected annually. Consequently, road authorities automated the road safety management process as much as possible to increase the efficiency of their road safety programs. In response to this increasing need of road authorities, AASHTO released *SafetyAnalyst* in 2009. *SafetyAnalyst* is a software package that consists of four modules containing six analytical tools, and these analytical tools correspond to the six steps of the road safety management process outlined above.

6.1 QUALITATIVE APPROACH

Qualitative approaches to road safety are important tools that can help a traffic engineer to have a better understanding of the safety issues at signalized intersections. These techniques are especially helpful in circumstances in which the intersection is in the planning or design stage and sufficient operational data (to quantitatively identify the safety problems) or historical data (e.g., collision, volume, etc.) data about the subject intersection is not available. Different qualitative techniques are used by traffic engineers including:

- Positive guidance review.
- Driver behavior observation.
- Human factors review.
- Conflict analysis.
- Surrogate measures such as time to collision using traffic simulation models (e.g., Surrogate Safety Analysis Model (SSAM)).

The above techniques can be used independently or as part of a formal RSA process.

An RSA can be used in any phase of project development, from planning and preliminary engineering to design and construction, regardless of the size of the project. RSAs applied early in the planning and preliminary (functional) design of roads offer the greatest opportunity for benefit. As design progresses into detailed design and construction, changes that may improve safety performance typically become more difficult, costly, and time consuming to implement.

An RSA audit team consists of a multidisciplinary group of experts who review the intersection from different perspectives, such as safety, design, traffic operations, law enforcement, maintenance, etc. The level of success that can be achieved in using the RSA process is highly dependent on the knowledge, skills, experience, and attitudes of the auditors. The team should be able to review project data critically, get the most from the field visits, and engage in the kind of dialogue that leads to the identification of road safety issues. It is important to ensure that a local contact person is included in the audit team.

RSA process includes the following steps:

- **Step 1**: Identify intersection to be audited.
- **Step 2**: Select RSA team.
- **Step 3**: Conduct a pre-audit meeting to review project information.
- **Step 4**: Perform field observations under various conditions.
- **Step 5**: Conduct audit analysis and prepare report of findings.
- **Step 6**: Present audit findings to project owner/design team.
- **Step 7**: Project owner/design team prepares formal response.
- **Step 8**: Incorporate findings into the project when appropriate.

When conducting the field investigation component of an RSA of an existing signalized intersection, the following elements are reviewed:

Conformance, Consistency, and Condition

- Relating to intersection and approach geometrics and geometric characteristics, traffic control devices (traffic signals, signing, pavement markings etc.), illumination and delineation devices, safety devices (guide rail systems, end treatments, crash cushions etc.), and all other roadway features present within the roadway environment on the day of the field investigation, including physical evidence of road user collisions.

Intersection and Approach Geometrics and Geometric Characteristics

- Layout and "readability" (perception) by drivers.
- Horizontal and vertical alignment (visibility all for road users - sight distance review as required).
- Cross-section, lane configuration, and lane continuity.
- Driveway/side street accessibility.
- Access management and corner clearance.
- Active transportation/vulnerable road user facilities (walkability, bicycling, and mobility restricted).
- Alternate mode facilities (e.g. transit).

Traffic Signals

- Visibility and conspicuity of signal displays on approach to and at the intersection (including a sufficient number of indications, recommended one per lane over each lane).

- Placement of signal heads (horizontal and vertical; within the drivers cone of vision).
- Operations (vehicular volumes, level of service, queue lengths, volume/capacity etc.).

Signing

- Advance intersection signing (warning, lane use).
- Advance and turn-off roadway identification signing (lane use, route guidance).
- Signing at the intersection (regulatory and guide).

Pavement Markings

- Proper lane line and edge line markings based on intended lane uses.
- Transverse markings as appropriate (stop lines, horizontal signing, and supplemental legends/symbols).

Illumination and Delineation Devices

- Roadway illumination and luminaire poles.
- Reflective guidance devices (guide posts, post mounted delineators, etc.).

Roadside Features

- Guide rail systems, end treatments, and crash cushions (within the roadway clear zone).
- Potential unprotected roadway and/or roadside hazards.

Site Operations and Road User Interactions

- Road user operations and interactions from the perspective of all users (pedestrians, bicyclists, motorcycles, trucks, buses, automobiles etc.).
- Human factors (positive guidance principles).
- Traffic speed and classification.
- Traffic patterns and behavior from the perspective of all road users.

FHWA published RSA Guidelines in 2006 to help safety professionals conduct a valid and successful RSA. The Guidelines include an intersection-specific prompt list that could prove valuable in reviewing a signalized intersection.(72)

6.2 QUANTITATIVE APPROACH

The road safety management process systematically identifies deficient locations from safety perspectives and addresses safety problems at these locations. The following sections detail the road safety management process.

6.3 NETWORK SCREENING OR SELECTION OF AN INTERSECTION

In selecting an intersection for a detailed safety analysis, the key questions are:

- What is the safety performance of the location in comparison with other similar locations?
- Is the safety performance at the location acceptable or not acceptable?

Selection of an intersection may be the result of a systemic network screening of all signalized intersections in a jurisdiction or a complaint received by the traffic engineer in a jurisdiction. This section briefly describes most commonly used techniques for selecting one or more intersections that may have potential for safety improvements. This section also highlights the advantages and disadvantages of these techniques. It should be noted that the poor safety performance of an intersection (i.e., a sudden spike in frequency of crashes) during a few months or a year should not warrant selection of the intersection for detailed review, because it is likely that crash frequency will decrease in the next few months. This term is referred to as "regression to the mean."

The crash history of a signalized intersection is the key indicator of its safety performance and is the focus of the remainder of this section. The network screening techniques for evaluating crash performance vary from basic to the complex. They may compare the safety performance of a single signalized intersection to another group of similar intersections or serve as a screening tool for sifting through a large group of sites and determining which site has the most promise for improvement.

Many jurisdictions carrying out a review of safety at a signalized intersection will usually have a crash database that provides information on the location, time, severity, and other circumstances surrounding each crash reported by police or the parties involved. Crash data in this form can provide the traffic engineer with a quick assessment of safety at a location. The crash data is critical to the overall road safety management process. As a result, it is important for the traffic engineer to fully understand the crash data processing practices in a jurisdiction. For example, it is important to know what types of crashes are non-reportable. It is also critical to know the methodology for assigning crashes to intersections. In some jurisdictions, intersection-related crashes are assigned to the legs of intersections, and in other jurisdictions these crashes are directly assigned to the intersections.

Once data are available, the most common method of network screening is to compare the crash history of each site to other similar locations. For signalized intersections, similar intersections should have the same number of approaches as the site being examined; sites with different traffic control devices and layouts can be expected to have differing levels of safety. Surrounding land use will also have a significant effect on crash frequency, with intersections in urban areas having a different crash profile than intersections in rural areas. Finally, comparisons with sites that are located in other jurisdictions may be tainted by differing crash reporting thresholds, enforcement, predominant land use, vehicle mix, road users, climatic conditions, or other unknown factors; results of such a comparison should be tempered with caution.

With these in mind, different methods of using crash data to conduct network screening and assess safety performance of a site are discussed in the following sections, highlighting their benefits and drawbacks. The different methods to be discussed are:

- Average annual crash frequency.
- Crash rate.
- Critical rate.
- Equivalent property damage only (EPDO) average crash frequency.
- Excess predicted average crash frequency using safety performance functions (SPFs).
- Excess expected average crash frequency with empirical Bayes adjustment.

Chapter 4 of the HSM provides details of the above methods. Also, the HSM provides additional techniques for network screening. However, the techniques provided in this Guide are the most commonly used techniques in practice.

6.3.1 Average Crash Frequency

Traditionally, traffic engineers used (and many still use) a frequency-based method of identifying and evaluating the safety of a site.[71],[73] Past average annual observed crash frequencies at a site over a certain time period may be used to compare and rank the site against crash frequencies at a reference group (i.e., a group of locations with similar characteristics). Many jurisdictions produce a top 10 list of the intersections producing the highest average crash frequency in their jurisdictions and concentrate all of their efforts at reducing crashes at these sites.

The average crash frequency method may also be used to screen candidate sites for improvements. The average crash frequency at the site may be compared to the average crash frequency for the reference population to calculate a potential for improvement.

The study period is often 3 to 5 years in safety analyses. Relatively short periods of time, such as one year of crash data, are not recommended as the basis for a safety intervention. Because crashes are relatively rare events, a high crash frequency in any given year at a particular intersection may be simply a random fluctuation around a much lower long-term average at the site. In the next year or series of years, the crash frequency may drop without any safety intervention at all. This phenomenon is referred to as regression to the mean. Regression to the mean may be minimized by using data collected over a longer period of time (3 to 5 years) when evaluating the site. Site selection based on multiple years of crash data will provide a truer picture of the crash profile of the intersection and avoid errors that can result from looking at crash history over a short period.

Apart from regression to the mean, there are several other disadvantages to using crash frequency as the sole means of evaluating safety at a site. First, a high crash frequency may not necessarily mean that a site is truly in need of safety improvement. It is known that sites with higher volumes will have a higher crash frequency than sites with lower volumes. Therefore, sites ranked simply by crash frequency will invariably end up with higher volume sites at the top of the list. Second, the method does not address the severity of crashes at the site. Failing to consider severity may result in the identification of sites with high numbers of minor crashes, while ignoring sites with fewer but more severe crashes. The approach results in a failure to identify sites at which the public has greater risk of injury or death.

6.3.2 Crash Rate

The crash rate method improves upon the average crash frequency in that it normalizes the frequency of crashes with the exposure, as measured by traffic. Crash rates are calculated by dividing the total crash frequency for a period of time by the estimated average annual daily traffic (AADT) of vehicles entering from all approaches in that time period. Crash rate provides an improved yardstick for comparison between sites. As with average crash frequency, a crash rate for an intersection undergoing a safety assessment may be compared to similar intersections (signalized, same number of legs, same range in AADT). The intersection may be ranked to produce a top 10 list, or a threshold value may be used above which a detailed safety analysis is warranted. Using a crash rate will account for the effect that volume has on crash frequency.

However, using a simple crash rate to screen locations has several disadvantages. First, using a crash rate to rank sites that have different volumes requires the assumption that crash frequency and volume have a linear relationship, but research suggests that this is not the case. Lower volume sites tend to experience a higher crash rate. Ignoring this fact means that low volume sites may appear less safe than their higher volume counterparts. Second, crash rates, as with crash frequency, do not consider crash severity. Sites with a high crash rate may have relatively few severe (fatal and injury) crashes. Last, as crash rates are calculated from crash frequency, which fluctuates around a long-term average and experiences regression to the mean, a site might be ranked high on a list due to a recent period with an unusually higher number of crashes. If crash rates are being used to screen out candidate sites for safety improvements, it is recommended that a study period between 3 to 5 years be selected.

6.3.3 Critical Rate

The critical crash rate method has been widely used among traffic engineers. In this method, the observed crash rate at a site is compared with a critical crash rate unique to each site. The critical crash rate for a site is a function of the average crash rate of a reference group associated with the site, the traffic volume of the site, and a desired level of confidence. In this method, sites where the crash rates exceed the critical rate require further detailed analysis in the diagnosis step, which is the next step of the road safety management process.

The critical crash rate method is more robust than using average crash frequency or crash rate alone, as it provides a means of statistically testing how different the crash rate is at a site when compared to a reference group. The desired level of confidence may vary depending on the preference of the user.

Disadvantages of using this method are that it still does not consider the severity of the crashes and assumes that traffic volume and crashes have a linear relationship. In addition, this approach does not consider regression to the mean.

6.3.4 Equivalent Property Damage Only (EPDO) Average Crash Frequency

In the above discussion, sites were considered for further analysis if the crash frequency and rate were particularly high. As indicated, a weakness with these methods is not considering the severity of the crashes involved. The crash severity method considers the distribution of crash severity for each site under consideration. A typical approach is through the use of the EPDO score. It attaches greater importance, or weight, to crashes resulting in a serious injury or a fatality, lesser importance to crashes resulting in a moderate or slight injury, and the least importance to property-damage-only crashes.

The HSM suggests using the ratio of the societal cost of crashes over the societal cost of PDO crashes as weighting factors to calculate an EPDO score for each site. Exhibit 6-2 shows the suggested societal crash costs and EPDO weight factors by the HSM.

Severity	**Cost**	**Weight**
Fatal (K)	$4,008,900	542
Injury (A/B/C)	$82,600	11
PDO (O)	$7,400	1

Exhibit 6-2. Societal crash costs and EPDO weights.(71)

Depending on local considerations, the above weighting system may be modified to reflect actual values in terms of cost, such as property damage, lost earnings, lost household production, medical costs, and workplace costs. A comparison with similar intersections (signalized, same number of legs, same range of AADT) may be done by calculating the EPDO score for similar sites to the one being considered. The EPDO score will explicitly consider the severity breakdown of crashes, providing greater weight to fatal and injury crashes over PDO crashes. The traffic engineer should be aware, however, that because the severity of a crash is associated with higher speeds, signalized intersections on roads with a higher operating speed, such as in a rural location, will likely have a higher EPDO score than those in urban areas. This may result in a bias that emphasizes higher speed locations. In addition, as with rankings based on crash frequency and rate, regression to the mean will be an issue if the study period chosen is short.

6.3.5 Relative Severity Index

Monetary crash costs are assigned to each crash type and the total cost of all crashes is calculated for each site. An average crash cost per site is then compared to an overall average crash cost for the site's reference population. The overall average crash cost is an average of the total costs at all sites in the reference population. The resulting Relative Severity Index (RSI) performance measure shows whether a site experiences higher crash costs than the average for other sites with similar characteristics. Strengths of this method include the simplicity of the analysis and the consideration of collision type and crash severity. Weaknesses include lack of Regression-to-the-Mean bias or traffic volume considerations. This type of analysis can also overemphasize locations with a small number of severe crashes depending on weighting factors, and it can prioritize low-volume, low-collision sites.

6.3.6 Excess Predicted Average Crash Frequency Using Safety Performance Functions

In this technique for network screening, average crash frequency at a site is compared with a predicted average crash frequency, obtained from an SPF. If the observed average crash frequency exceeds the predicted average crash frequency at a site, the site is flagged for further analysis. The SPF equation presents the mathematical relationship between crash frequency and volume for a reference group (e.g., 4-leg signalized intersections in a jurisdiction). When crash frequency and volume are plotted, an equation can be developed that is represented by a curve that is the best fit possible through the various points. Generally, SPFs demonstrate that the expected number of crashes increases as traffic volume increases.

The advantages of this method are more accurately calculating the potential for safety improvement and acknowledging the complex, non-linear relationship between crash frequency and volume. Disadvantages are that this method is relatively complex and still does not acknowledge the random variation of crashes.

As part of the HSM, SPFs for intersections have been developed based on data obtained from a number of states in the U.S. Chapter 10, 11, and 12 of the HSM include these SPFs. The SPFs in the HSM were classified based on the surrounding area land-use (i.e., rural, suburban, and urban), geometric configuration of intersections (i.e., 3-leg and 4-leg), traffic control device of intersections (i.e., traffic signal and stop control), and functional classification of the main roadway.

It is advisable to develop SPFs for intersections in each jurisdiction based on the local intersection characteristic (e.g., number of approaches, traffic control device, and adjacent land-use). Road agencies require intersection characteristic data, traffic volume in the form of entering AADT volumes, and crash data. The traffic volume data and crash data need to be available for 3 to 5 years for each location. It should be noted that SPFs can be borrowed from similar jurisdictions (jurisdictions with the same network characteristics, traffic characteristics, weather conditions, driver population, and driving behavior).

6.3.7 Excess Expected Average Crash Frequency with Empirical Bayes Adjustment

Each of the above methods only considers past crash history, either by ranking and selecting a candidate site for further crash analysis or by determining whether a particular intersection under study has a crash problem. Using crash history alone is flawed because the frequency of crashes from year to year will randomly fluctuate about a long-term average (regression to the mean). Improved methods have evolved that identify high-risk sites that may benefit from remedial treatment(s), particularly the empirical Bayes (EB) method. Many jurisdictions are already employing the EB method.

The EB method calculates expected crash frequencies through a combination of observed and predicted crash frequencies. The predicted crash frequencies are derived through the development of an SPF.

The pivotal concept upon which contemporary methods for conducting proper road safety evaluations depend is the EB method. It is superior to traditional methods because it:

- Considers regression to the mean.
- Produces more stable and precise estimates of safety.
- Allows for estimates over time of expected crashes.

In case of a network screening for the entire jurisdiction, excess expected average crash frequency is calculated for all intersections in the study area. Expected crash frequency is the difference between the expected collision frequency and the predicted collision frequency, which is obtained from the SPF. The predicted collision frequency represents the overall safety performance of similar intersections. If a site has positive excess, it shows that the site has a potential for safety improvement and merits further detailed investigation. In a network screening exercise, sites are ranked based on their excess crash frequency. The same approach can be used to identify whether further analysis is warranted for a specific intersection.

6.3.8 Summary

The above section detailed various methods of assessing the safety of a location through consideration of its crash history and comparison with other similar sites. Care must be taken to ensure that the site is being compared with sites that should have a similar level of safety (i.e., sites with a traffic signal and the same number of legs). Methods such as crash frequency and crash rate may provide a simple and quick way of diagnosing a potential safety problem, but should be used with caution. The traffic engineer may consider using the critical rate method or the EPDO average crash frequency method as these provide a more balanced assessment of safety. Developing an SPF, either on its own or for use in applying to the EB method, is a much more sophisticated method of evaluating safety at a site. Given the availability of SPFs in many jurisdictions in the U.S. and Canada, as well as through the HSM, road agencies are encouraged to use the excess expected average crash frequency with EB adjustment methodology for network screening. Exhibit 6-3 presents a summary of the relative merits and drawbacks of each method.

Method	Advantages	Disadvantages
Average crash frequency	Simple to use Easy for the public to understand	Biased toward high-volume sites Does not consider exposure Severity not considered Regression to the mean not addressed
Crash rates	Simple to use Considers exposure	Biased toward low-volume sites Requires volume data Assumes crashes and volume have linear relationship Severity not considered Regression to the mean not addressed
Critical rate	Relatively simple Considers exposure Applies a recognized statistical method	Requires volume data Assumes crashes and volume have linear relationship Severity not considered Regression to the mean not addressed
Equivalent property damage only average crash frequency	Relatively simple Considers crash severity	Does not account for exposure May overemphasize sites with a low frequency of severe crashes depending on weighting factors used Regression to the mean not addressed
Excess predicted average crash frequency using safety performance	More accurate Considers exposure Acknowledges that crashes and volume have a nonlinear relationship	Requires volume data Regression to the mean not addressed Labor intensive Difficult for public to conceptualize
Excess expected average crash frequency with empirical Bayes adjustment	Most accurate Considers exposure Acknowledges that crashes and volume have a nonlinear relationship Addresses regression to the mean	Requires volume data Difficult for public to conceptualize

Exhibit 6-3. Common methods of assessing safety at a location.

6.3.9 Case Study

The purpose of this case study is to show the application of the network screening step of the road safety management process. This case study will be completed throughout this chapter as other steps of the road safety management process are described.

A County has conducted network screening using the excess expected average crash frequency with EB adjustment methodology for all signalized intersections within the county. Exhibit 6-4 shows the results of the network screening for the top 10 intersections that have been ranked based on Potential for Safety Improvement (PSI). The PSI is the difference between expected crashes (obtained from the EB method) and predicted crashes (obtained from SPFs).

This table is a typical output of a network screening exercise. The county then chooses to further analyze these intersections to address potential safety issues. As a case study, the first intersection presented in this exhibit STREET A @ ROAD B will be further analyzed and referred to throughout this chapter.

Rank	Description	Average AADT Major	Average AADT Minor	Intersection Type	Traffic Control	Study Period (Years)	Total Observed Crashes	Total Predicted Crashes	Total Expected Crashes	Potential for Safety Improvement (PSI)
1	STREET A @ ROAD B	27299	11341	4-legged	Signalized	5	90	52.337	87.610	35.273
2	STREET G @ ROAD H	30584	2935	4-legged	Signalized	5	42	19.599	38.568	18.969
3	STREET P @ ROAD Q	27154	3258	4-legged	Signalized	5	38	19.672	35.201	15.529
4	STREET R @ ROAD S	36966	5045	4-legged	Signalized	5	47	33.884	45.757	11.873
5	STREET A @ ROAD D	8132	4711	4-legged	Signalized	5	26	11.920	22.772	10.852
6	STREET E @ ROAD F	39732	8639	4-legged	Signalized	5	64	54.090	63.390	9.300
7	STREET G @ ROAD Q	52765	18028	4-legged	Signalized	5	122	115.747	121.814	6.067
8	STREET R @ ROAD H	27815	3773	4-legged	Signalized	5	28	22.414	27.237	4.823
9	STREET C @ ROAD D	38180	4506	4-legged	Signalized	5	37	31.683	36.465	4.782
10	STREET C @ ROAD F	32025	25576	4-legged	Signalized	5	113	109.720	112.897	3.177

Exhibit 6-4. Top 10 ranked signalized intersections in a county.

6.4 DIAGNOSIS

The previous section discussed different tools used to select a candidate intersection for a safety evaluation. At a certain point, the traffic engineer will conclude, based on past crash history, that there is a safety concern and a significant potential for safety improvement at the location in question. It should be noted that some traffic engineers may have completely bypassed the entire first step of this process (in determining a candidate intersection for safety improvements) because they have been asked to carry out a safety analysis of an intersection due to:

1. Safety complaints or concerns raised by others (other departments, local politicians, the public).
2. Planned reconstruction that would make it worthwhile to carry out a safety evaluation and improvements.
3. Identified operational deficiencies.

This section will discuss how the traffic engineer may correctly diagnose what types of safety problems/issue may be present at an intersection. Diagnosis of a particular safety concern can then lead to appropriate countermeasures.

The following four-step process can be used to diagnose safety problems at a site:

- Step 1 – Conduct Safety Data Review.
- Step 2 – Assess Supporting Documentation.
- Step 3 – Assess Field Conditions.
- Step 4 – Define Problem Statement(s).

The above process is consistent with the recommendations of Chapter 5 of the HSM.

6.4.1 Step 1 – Conduct Safety Data Review

In conducting a safety diagnosis at a signalized intersection, the traffic engineer seeks to understand any patterns in the crash data and identify contributing factors of crashes within the functional boundary of the intersection.

The safety data review can be conducted in three stages:

1. Assemble crash data.
2. Describe crash statistics.
3. Summarize crashes by location.

Assemble Crash Data

Crash data used for diagnosing safety at a signalized intersection should represent 3 to 5 years of crash data. It should include all crashes reported as occurring at or related to the intersection's influence zone. The relationship of crashes to intersections is often expressed in the Model Minimum Uniform Crash Criteria (MMUCC) Guideline [74] in "Relation to Junction."

Most agencies have electronic databases from which the following characteristics of crashes associated with the subject intersection can be extracted:

- Crash identifiers such as date, time of day, and time.
- Severity: which is often represented in the KABCO scale, defined as follows:
    - K-Fatal injury: an injury that results in death.
    - A-Incapacitating injury: any injury, other than a fatal injury, that prevents the injured person from walking, driving, or normally conducting the activities the person was capable of performing before the injury occurred.

    - B-Non-incapacitating evident injury: any injury, other than a fatal injury or an incapacitating injury, that is evident to observers at the scene of the crash in which the injury occurred.
    - C-Possible injury: any injury reported or claimed that is not a fatal injury, incapacitating injury, or non-incapacitating evident injury and includes claim of injuries not evident.
    - O-No Injury/Property Damage Only (PDO).
- Crash Type.
    - Rear-end.
    - Sideswipe.
    - Angle.
    - Turning.
    - Head-on.
    - Fixed object.
- Direction of travel before crash.
- Sequence of events.
- Contributing circumstances:
    - Parties involved – vehicle only, pedestrian and vehicle, bicycle and vehicle.
    - Road condition at the time of the crash – dry, wet, snow, ice.
    - Lighting condition at the time of the crash – dawn, daylight, dusk, dark-lighted, dark-not lighted.
    - Weather condition at the time of the crash – clear, cloudy, fog, rain, snow, ice.
    - Impairments of parties involved – alcohol, drugs, fatigue.

If available, the original police reports should be used to gather anecdotal comments written by police officers at the crash scene and firsthand accounts of the crashes from involved parties and eyewitnesses.

Describe Crash Statistics

Once crash data for the intersection has been extracted from the database, it is important to identify patterns and potential contributing factors from the historical crash data. Three techniques are often used by practitioners to identify crash patterns and contributing factors of crashes in a safety diagnosis exercise:

1. Develop visualization tools – graphs and charts can assist the traffic engineer in visualizing crash frequencies in terms of various crash attributes.
2. Conduct a crash cluster analysis – the crash cluster analysis process involves a manual screening of crash attributes. In this type of analysis, the object is to identify crash clusters for each crash attribute, such as crash impact type, road surface condition, lighting condition, etc.
3. Conduct over-representation analysis – over-representation analysis is used to determine whether the proportion of a characteristic found at a specific intersection is the same as that found in a group of similar sites. Identification of abnormal trends can lead toward possible solutions. To ensure that the determination of overrepresentation is valid, appropriate statistical techniques should be employed. The chi-square method is one of the methods for identifying over-representation at a site. The HSM refers to this analysis as "Specific Crash Types Exceeding Threshold Proportion," and details of this technique can be found in Chapter 4 of the HSM.

The crash characteristics should be reviewed for over-representation through comparison with crash characteristic information representing the typical experience of a signalized intersection. Examples of questions that can be answered by the above three techniques to identify over-representations or patterns in the crash attributes are highlighted below.

An examination of crash pattern by season, day of week, or time of day may be helpful in finding patterns that relate to the general travel patterns of road users passing through the intersection. Seasonal patterns, indicating a higher-than-expected proportion of crashes occurring during a particular time of year, may coincide with an influx of unfamiliar drivers to an area—as may be the case in resort areas and/or areas with a significant number of tourist attractions. Day of week and time of day patterns should be examined. Morning/afternoon weekday over-representation may suggest crash patterns related to commuting traffic (coinciding with the morning and afternoon rush hours). A late night/early morning/weekend overrepresentation may suggest problems with drunk drivers.

Over-representation in crash severity will highlight a location that has an unusually high proportion of fatal and/or injury crashes. A higher proportion of fatal and/or injury crashes may suggest a problem with higher operating speeds.

Summarize Crashes by Location

The end product of the descriptive crash statistics will be a set of characteristics identified as being over-represented. The next step is to relate the patterns and over-represented characteristics of crashes to a particular approach. A crash diagram can be used to create such relationship. A crash diagram is a two-dimensional plan view representation of the crashes that have occurred at a site within a given time period. In a crash diagram, each crash type is represented by combinations of arrows and symbols. Exhibit 6-6 shows proposed symbols for classification of various crash types.

6.4.2 Step 2 – Assess Supporting Documentation

The main goal of this step is to gather and review documented information or personal opinion about the site. This information can be gathered from previous studies relevant to the subject intersection, complaints filed with the road agency by residents, or consultation with the authorities who have local knowledge about the study area. This is an important step in which the crash patterns can be studied in the context of the past changes in the study area. For example, an increase in pedestrian crashes in the past 3 years can be correlated with the opening of a new school in the vicinity of the subject intersection 3 years ago.

The HSM suggests that the following types of information may be useful as supporting documentation to the diagnosis of safety problems at a site:

- Current traffic volumes for all travel modes.
- As-built construction plans.
- Relevant design criteria and pertinent guidelines.
- Inventory of field conditions (e.g. traffic signs, traffic control devices, number of travel lanes, posted speed limits, etc.).
- Relevant photos.
- Maintenance logs.
- Recent traffic operations or transportation studies conducted in the vicinity of the site.
- Land use mapping and traffic access control characteristics.
- Historic patterns of adverse weather.
- Records of public comments or complaints on transportation issues.
- Roadway improvement plans in the site vicinity.
- Anecdotal information about travel through the site.

Appendix 5B of the HSM provides a list of questions and data to consider when reviewing past site documentations.

6.4.3 Step 3 – Assess Field Conditions

To supplement the analysis and diagnosis using crash data, a site visit or series of site visits should be undertaken. Before initiating site visit(s), the study team should be aware of:

- Whether certain crash characteristics were over-represented based on the analysis of crash over-representation.
- Which areas within the intersection's sphere of influence are showing unusual clusters of crashes.
- If available, what operational problems have been identified as part of the operational analysis.

The purpose of the site visit is to gather additional information that can aid in pinpointing potential underlying cause or causes of the abnormal crash patterns (Exhibit 6-6). The site visit should be undertaken to:

- Observe driver/road user behavior during the following conditions:
  - Peak and off-peak periods.
  - Evening/night (as necessary).
  - Wet weather (as necessary).
  - Weekend and special events (as necessary).
- Photograph relevant features. Consideration may be given to using video recording to capture each intersection approach from the driver's perspective.
- Review the site from the perspective of all users, including motorists, pedestrians, and bicyclists. This includes observing motorist, bicyclist, and pedestrian circulation and identifying origins and destinations in the vicinity.
- Check for physical evidence of crashes or near-crashes, such as vehicle damage to street furniture, signs and other objects near the roadway, skid marks on the intersection approaches, and tire marks on the shoulder or ground adjacent to the roadway.
- Conduct a conformance/consistency check: an assessment of signs and traffic control, markings, delineation, geometry and street furniture to ensure standard application and consistency and that all traffic control devices are in conformance with local, State, and Federal standards.

One of the key tasks the study team will wish to conduct during the site visit is a positive guidance review.(9) A positive guidance review uses an in-depth knowledge of human factors and the driving task to screen roadways for:

- Information deficiencies.
- Expectancy violations.
- Workload issues.

Each of the above may contribute to the occurrence of driver error and crashes.

Information deficiencies occur when information that the driver needs to carry out the driving task safely is missing. An example may be inadequate signing/pavement marking for a designated right-turn lane that traps drivers intending to proceed straight. Attempts to move over to the through lane can cause queuing and possible rear-end and sideswipe conflicts.

Expectancy violations occur when a driver encounters a traffic control or roadway design that conflicts with his or her expectations. The traffic engineer should structure expectancies about treatments at similar locations.(75) The key to effective expectancy structuring is uniformity and standardization.

Standard devices that are inconsistently applied can create expectancy problems for drivers. A prime example of this is the use of a left-hand exit amidst a series of right-hand exits. Positive guidance seeks to address this expectancy violation through clearly communicating to the driver that a left-hand exit is ahead.

Workload issues occur when the driver is bombarded with too much information, increasing the likelihood of error. This may occur at an intersection with an abundance of signing, pavement markings, traffic signals, and pedestrian and bicycle activity. All of the above may be further complicated if the operating speed on the approaches is high, giving the driver even less time to sort through and comprehend what to do to get safely through the intersection and on to the intended destination. The traffic engineer should seek to reduce the complexity of the information the driver receives at the intersection or to spread information by using advance signs.

Although positive guidance techniques are generally applied to the driving task, these concepts and tools can easily be considered from the perspective of all road users. Positive guidance is a holistic approach treating the roadway, the vehicle, and the driver as a single, integrated system. It recognizes drivers as the information gatherers and decision-makers within the system and focuses attention on assuring that they get the information they need, when they need it, in a form they can understand, in time to make rapid, error-free decisions and take appropriate actions. Creating and sustaining a supportive information environment on the roadway is the goal of positive guidance.

In conducting a positive guidance review, the analyst attempts to view the roadway through the eyes of an average driver, postulating what the driver's perceptions, interpretations, expectations, and actions might be. This is done to formulate theories and possible explanations regarding the cause or causes of previous or potential conflicts and/or crashes.

Positive guidance normally focuses on low-cost, information-oriented improvements that can be implemented quickly, either as solutions in and of themselves or as interim improvements until a more definitive solution can be achieved. It may also identify the need for additional investigation, in the form of conventional engineering analysis, to support theories regarding the contributory causes of crashes, and to justify mitigation measures.

Appendix 5C of the HSM provides a process required for preparation for a field assessment undertaking, and Appendix 5D of the HSM provides a field review checklist for signalized intersections.

It should be noted that an RSA, which was described in the qualitative approach for safety review of signalized intersections, always includes a field review for existing intersections (obviously a field review is not possible for intersections in planning and design stages). The process for conducting an RSA field review described in this section can be followed.

6.4.4 Define Problem Statement(s)

A set of one or more clear problem statements should be developed. The problem statement(s) are developed on the basis of the crash analysis (i.e., evidence of over-representation among a crash subgrouping) and should be supported through the site visit and any further analysis. The problem statement should correlate crash patterns observed with potential contributing factors.

The problem statement helps clearly define safety concerns at the location. Circumstances associated with these safety concerns may be mentioned along with possible causal factors. The problem statement may be multifaceted and encompass the physical and/or operational attributes of the intersection, road user behavior and/or actions, environment and/or temporal conditions, as well as transitory or peripheral events. In many instances, the study team will identify several problems or issues.

Example problem statements are given in Exhibit 6-5.

Problem Statement #1 Rear-end crashes and crashes occurring between 3 and 6 p.m. are over-represented. The crash diagram shows that almost all of these occur on the westbound approach. Based on the site visit, the initial problem statement is that these are occurring due to: • Lack of traffic signal visibility for westbound drivers. • Movement into and out of a commercial driveway on the near side of the intersection. • A polished pavement surface on this approach. • Glare from the afternoon sun.
Problem Statement #2 Fatal and injury crashes were over-represented, and four fatal or injury crashes involved pedestrians. The crash diagram indicates that all occurred on the southwest corner of the intersection and are related to the right-turn lane channelization. Based on the site visit and subsequent further analysis, the initial problem statement is that these are occurring due to: • The design of the right-turn channelization operating under YIELD control, which contributes to excessive driver speed. • Drivers failing to yield to pedestrians. • The presence of a bus shelter that partially blocks the view of the crosswalk.

Exhibit 6-5. Example problem statements.

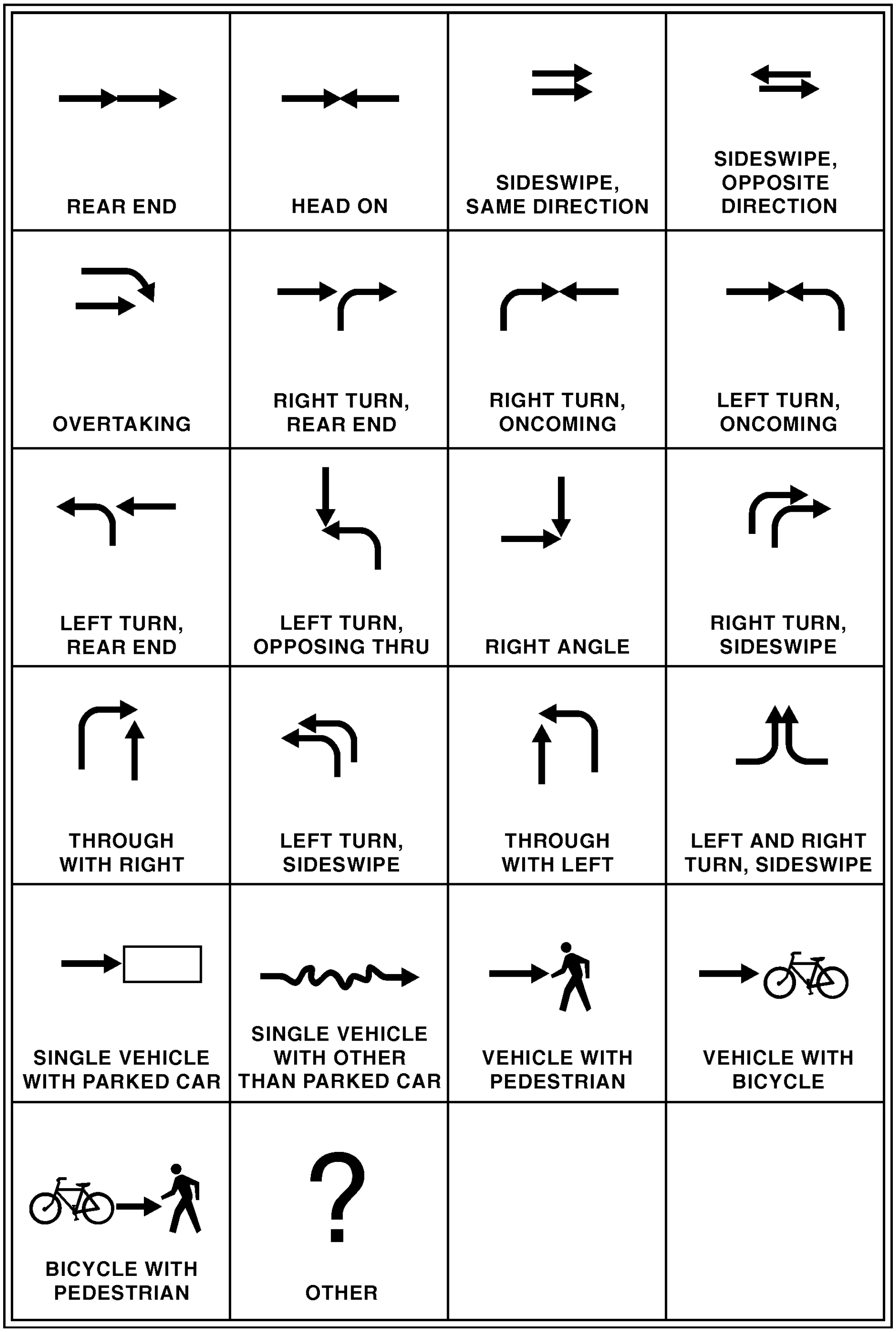

Exhibit 6-6. Possible taxonomy for crash type classification.

6.4.5 Case Study

The purpose of this case study is to show the application of the diagnosis step of the road safety management process.

The intersection of Street A and Road B (shown in Exhibit 6-7) was ranked first in the network screening exercise of all 4-leg signalized intersection in the county, as shown in the previous section. It was identified that the potential for safety improvement is 35.3 crashes per a 5 year period. The intersection characteristics include:

Geometric Characteristics

Street A (a major east-west arterial roadway), immediately east of Road B, is essentially flat and straight vertically and horizontally; to the west of Road B, Street A contains a horizontal curve and vertical curve. The vertical curve exists immediately west and in advance of the intersection, resulting in a vertical crest for eastbound approaching road users. Road B (a minor north-south arterial roadway) is essentially flat and straight on the approach to Street A.

Traffic Control

The intersection contains two mast arm-mounted primary signal displays for the through movements and a secondary signal display for the left-turning movements on all approaches. The signals are both horizontally and vertically located within the required mounting field of view, as per the FHWA MUTCD. The signal displays contain three-section, vertically arranged signal bulbs comprised of circular red, yellow, and green indications and are positioned over the appropriate lanes based on FHWA MUTCD 2009 guidance.[1]

Signing

Regulatory speed limit signs are present on all approaches to the intersection. Street name signs both for Street A and Road B are present on the primary signal pole for all approaches (far right quadrant of the intersection). Advance street name signing is present on both northbound and southbound approaches to the intersection Signal ahead warning signs are present on the northbound and southbound approaches to the intersection. The signs are all located appropriate distances upstream of the intersection.

Exhibit 6-7. Study intersection.
Source: Google, 2012

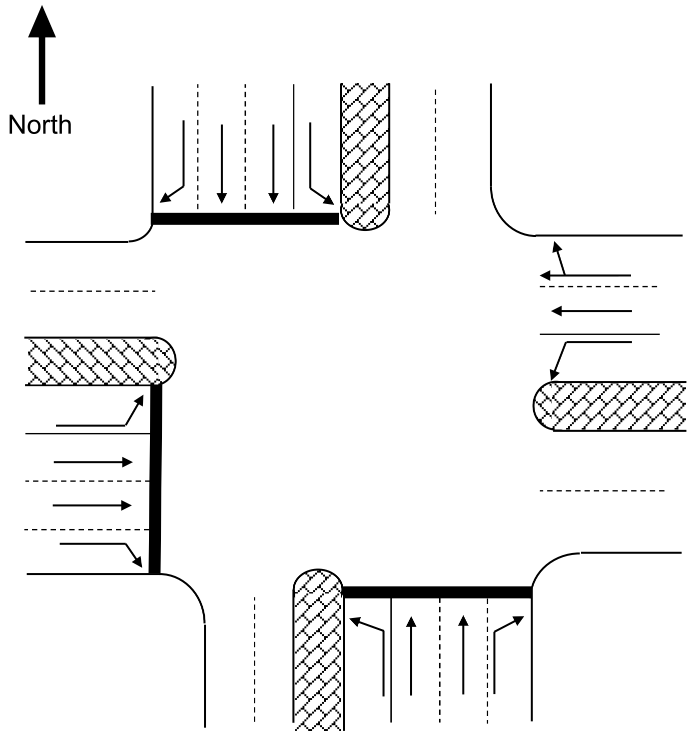

Exhibit 6-8. Lane configuration of the study intersection.

Step 1 – Safety Data Review

Assemble Crash Data

The County has provided crashes for the period of 2006 to 2010 to the traffic engineer. Exhibit 6-9 provides a summary of crashes in terms of severity, and Exhibit 6-10 shows the same crashes in terms of their impact type.

Crash Severity	Year					
	2006	2007	2008	2009	2010	Total
Fatal/Injury	3	10	8	1	3	25
PDO	10	15	18	14	8	65
Total	**13**	**25**	**26**	**15**	**11**	**90**

Exhibit 6-9. Crashes in the study intersection from 2006 to 2010, by severity.

Row Labels	2006	2007	2008	2009	2010	Grand Total
Angle	2	2	3	2	1	10
Rear End	6	14	14	8	5	47
Sideswipe	1	3	3	1	2	10
Turning	4	6	6	4	3	23
Grand Total	**13**	**25**	**26**	**15**	**11**	**90**

Exhibit 6-10. Crashes at the study intersection from 2006 to 2010, by impact type.

Descriptive crash statistics

Exhibit 6-11 shows crash frequencies in terms of crash types and road surface condition. Based on this exhibit, a significant number of rear-end and turning movement crashes have been identified at this intersection. There is also potential concern regarding the number of crashes during wet and slippery road surface conditions. However, to confirm whether such a problem exists, the proportions of road surface condition crashes at this intersection should be compared to similar intersections (over-representation analysis).

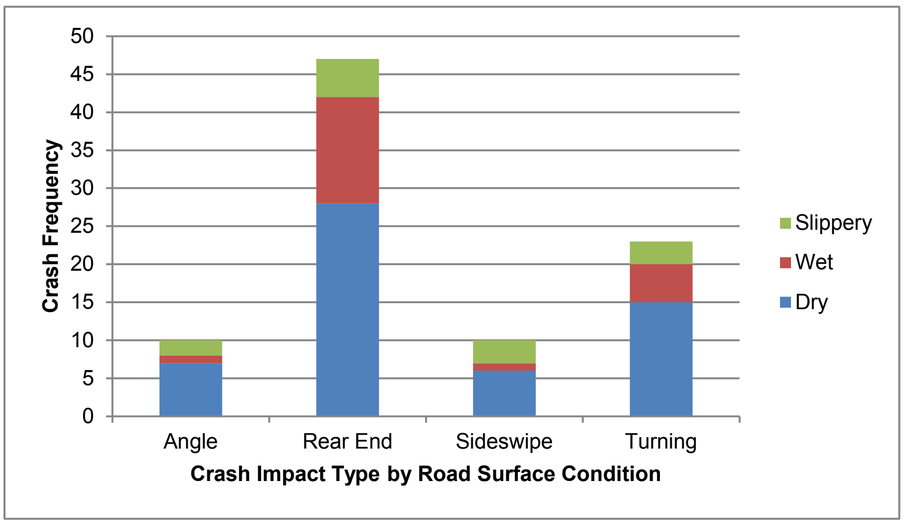

Exhibit 6-11. Crash frequencies in terms of crash impact types and road surface conditions.

Exhibit 6-12 shows crash frequencies in terms of crash impact types and light condition. This exhibit shows that most crashes occur during daylight. There might be some concerns related to turning movement crashes during dark hours of days. To be confident about these findings, an over-representation analysis should be conducted.

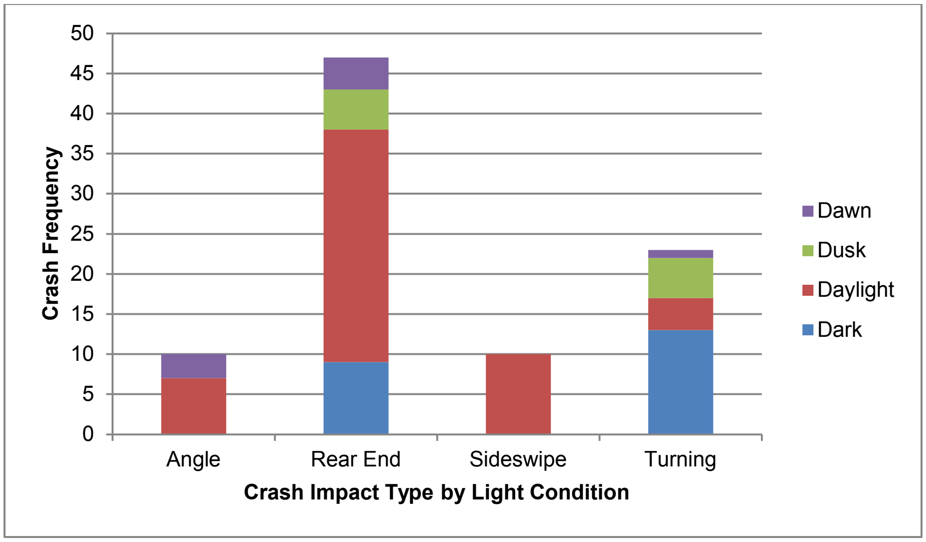

Exhibit 6-12. Crash frequencies in terms of crash impact types and light conditions.

The results of the proportional analysis (over-representation analysis) showed that the following crash attributes are over-represented at the study intersection:

- Angle crashes.
- Rear-end crashes.
- Turning movement crashes.
- Wet road surface condition.

Summarizing Crashes by Location

Exhibit 6-13 illustrates the crash diagram associated with the study area. In this diagram the crashes reviewed in the previous stage are related to each approach of the intersection. Different crash impact types are shown with different symbols. The number shown beside each crash cluster shows the number of crashes per each cluster. Red arrows in this diagram represent the at-fault vehicles. The crash diagram shows that most turning movements have occurred between eastbound left-turning vehicles and westbound through vehicles. Rear-end crash clusters dominantly exist on east and west approaches of the intersection. Angle crashes have occurred between southbound through vehicles and westbound through vehicles.

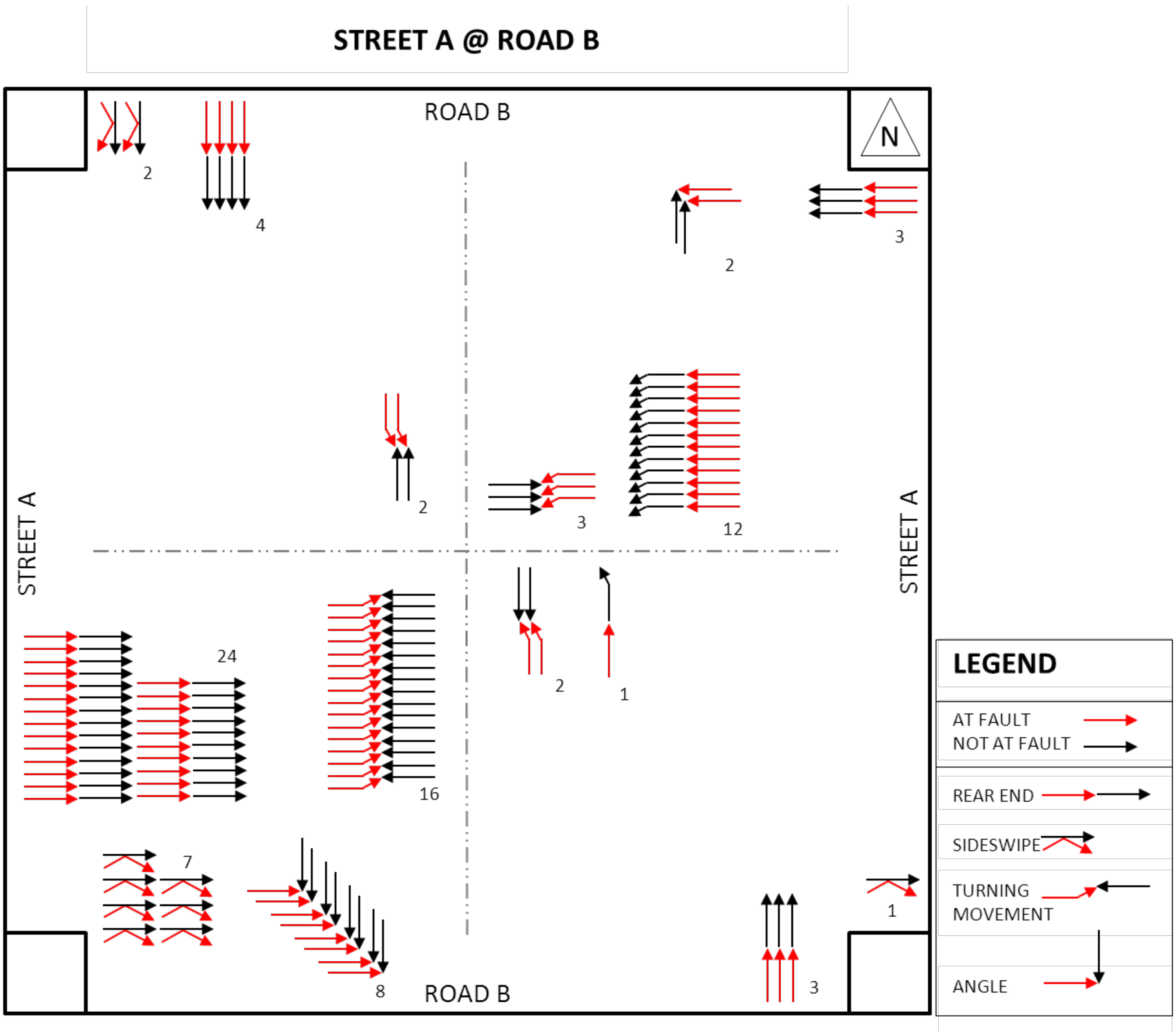

Exhibit 6-13. Crash diagram for the intersection of Street A and Road B.

Step 2 – Assess Supporting Documentation

- Speed limit on all approaches to the intersection is 35 mph.
- Entering AADT of the intersection is 53,866.
- The County has indicated that the following guidelines and manuals are relevant in this study:
    - The geometric design guideline pertinent to the study is the AASHTO Green Book – A Policy on Geometric Design of Highways and Streets.
    - All signing and other traffic control devices must conform to the latest edition of the MUTCD.
- Consultation with the County's traffic engineer revealed that the westbound left-turning vehicles have capacity challenges.

Step 3 – Assess Field Conditions

Exhibit 6-14 presents the findings of the field investigation. The field visit consisted of peak and off-peak visits as well as visits during day light and dark lighted.

Location	Findings
Street A, just west of and on approach to Road B	• Signal displays are inconspicuous on approach (signal bulbs are dull, and back plates are inconspicuous at night). • Vertical crest curve in advance of intersection – stopping sight distance measured and is inadequate. • Exclusive eastbound right-turn exit lane exists; however, no exclusive turn lane signs exist. Due to vertical crest curve, it is difficult to determine the lane configuration on intersection approach for drivers. • Polished and worn pavement surface on intersection approach. • The street name sign at the intersection is being obscured by auxiliary signal pole for opposing direction. • No advance street name signs exist on intersection approach. • No advance intersection ahead warning signs exist on intersection approach • Road user interactions (eastbound): red light running; high travel speeds (well in excess of posted speed limit); uncertain maneuvers made by road users, potentially due to non-present advance notice (signage); conflicts (near-misses) between eastbound road users, potentially leading to rear-end type as well as eastbound left-turning with westbound through-turning movement type crashes.
Street A @ Road B	• Road user interactions (westbound): conflicts (near-misses) between westbound left-turning and through-bound road users (potentially leading to rear-end type crashes).

Exhibit 6-14. Field investigation findings.

Step 4: Define Problem Statement

Exhibit 6-15 summarizes problem statements associated with the intersection of Street A and Road B. The crash patterns and over-represented crashes identified in Step 1 of the diagnosis process are correlated with potential contributing factors identified through assessment of supporting documents and assessment of field conditions.

Crash Attributes	Problem Statement
Angle: Eastbound through at fault, with southbound through movements. **Rear-end**: Westbound through at fault, with westbound left-turn movements. **Turning movement**: Eastbound left-turn at fault, with westbound through movements. **Rear-end**: Westbound through at fault, with westbound left-turn movements. **Wet Road Surface Conditions:** Westbound through vehicles contributing to rear-end crashes.	**Street A just west of, and on approach to, Road B** • Signal displays are inconspicuous on approach (signal bulbs are dull, and back plates are inconspicuous at night). • Vertical crest curve in advance of intersection – stopping sight distance measured and is inadequate. • Exclusive eastbound right-turn exit lane exists, however, no exclusive turn lane signs exist. Due to vertical crest curve, it is difficult to determine the lane configuration on intersection approach. • Polished and worn pavement surface on intersection approach. • The street name sign at the intersection is being obscured by auxiliary signal pole for opposing direction. • No advance street name signs exist on intersection approach. • No advance intersection ahead warning signs exist on intersection approach. • Road user interactions (eastbound): red light running; high travel speeds (well in excess of posted speed limit); uncertain maneuvers made by road users, potentially due to non-present advance notice (signing); conflicts (near-misses) between eastbound road users, potentially leading to rear-end type as well as eastbound left-turning with westbound through-turning movement type crashes, **Street A @ Road B** • Road user interactions (westbound): conflicts (near-misses) between westbound left-turning and through-bound road users (potentially leading to rear-end type crashes).

Exhibit 6-15. Problem statements.

6.5 SELECTING COUNTERMEASURES

After diagnosis, the next step in the road safety management process is countermeasure selection. The end product of the diagnosis process is one or more problem statements in which a crash pattern is related to a number of potential contributing factors. The objective of the countermeasure selection step is to develop countermeasures to address the contributing factors identified as part of the diagnosis step.

Countermeasures include all measures likely to decrease the frequency or severity of crashes identified as exhibiting an abnormal pattern (over-representation).

In Part III of this guide, the reader will find countermeasures (treatments) organized into five broad groups:

- System-wide treatments (Chapter 8).
- Intersection-wide treatments (Chapter 9).
- Approach treatments (Chapter 10).
- Individual movement treatments (Chapter 11).

For each treatment, there are references to possible crash groups that are likely to be positively affected through a treatment's implementation. At signalized intersections, the following crash patterns are most commonly identified:

- Rear-end crashes.
- Angle crashes.
- Left-turn or right-turn movement crashes.
- Nighttime crashes.
- Wet pavement crashes.
- Crashes involving pedestrians and bicyclists.

Exhibit 6-16 presents possible contributing factors and countermeasures for each of these types, along with the appropriate chapter.

The material presented in this section provides a range of options that could be selected, but is not fully comprehensive. It is not possible to develop a complete list of all potential crash treatments, because new tools and techniques for improving traffic safety are constantly being developed and adopted. It is important that the study team not limit itself to existing lists or tables of treatments. The team should consider a wide range of treatments (including those based on local practice) that may be beneficial, particularly when the crash pattern identified represents a unique situation.

Over the course of the above crash diagnostic analysis, site visits, and field analysis, the traffic engineer may have identified treatments that are of little cost and undoubtedly beneficial to improving safety at the intersection. Such treatments may relate to repairing sidewalks, removing sight obstructions, reapplying faded pavement markings, and relocating or adding new signs. These may be implemented without going through the process described below.

Crash Type	Possible Contributing Factors	Possible Treatment Group (Chapter)
Rear-end crashes	• Sudden and unexpected slowing or stopping when motorists make left turns in and out of driveways along corridor.	• Median treatments (Chapter 8)
	• Sudden and unexpected slowing or stopping when motorists make right turns in and out of driveways along corridor.	• Access management (Chapter 8)
	• Too much slowing and stopping along corridor due to turbulent traffic flow.	• Change signal control from pre-timed to actuated (Chapter 9)
	• Too much slowing and stopping along intersection approaches due to traffic-control issues. • Drivers caught in intersection during red phase due to inadequate traffic control or inadequate change and clearance interval. • Traffic signal not conspicuous or visible to approaching drivers, causing sudden and unexpected slowing or stopping movements.	• Change signal control from pre-timed to actuated (Chapter 9) • Red light camera enforcement (Chapter 10)
	• Sudden and unexpected slowing or stopping due to inadequate intersection capacity.	• Change signal control from pre-timed to actuated (Chapter 9) • Individual movement treatments (Chapter 11)
Angle crashes	• Drivers caught in intersection during red phase due to inadequate traffic control or inadequate change and clearance interval. • Traffic signal not conspicuous or visible to approaching drivers, causing drivers to get caught in intersection during red phase. • Drivers caught in intersection during red phase due to inadequate warning/inability to stop.	• Modify change and clearance intervals (Chapter 9) • Increase size of signal; Add supplemental signal heads; Provide backplates (Chapter 10)
Left-turn crashes	• Intersection cannot accommodate left-turn movements safely.	• Add single or multiple left-turn lane (Chapter 11) • Restrict turns (Chapter 11)
Nighttime related Crashes	• Poor nighttime visibility or light. • Poor sign visibility. • Inadequate channelization or delineation. • Inadequate maintenance. • Excessive speed. • Inadequate sight distance.	• Provide or upgrade illumination (Chapter 9) • Add channelizing islands (Chapter 10)
Wet pavement related crashes	• Slippery pavement • Inadequate pavement markings • Inadequate maintenance • Excessive speed	• High visibility crosswalks. (chapter 9) • Improve pavement surface. (chapter 10)
Crashes or conflicts involving bicyclists and pedestrians	• Either the intersection cannot safely accommodate the pedestrians and/or bicyclists, or motorists are failing to see or yield to their movements.	• Pedestrian, bicycle, and/or transit improvements (Chapter 9)

Exhibit 6-16. Crash types commonly identified, possible causes, and associated treatments.

The practitioner should generate a list of countermeasures (some of which may have been identified in this guide) that are based on local practice or are representative of a unique situation identified at the intersection through the diagnosis step. Before conducting the economic appraisal of each countermeasure, it is advisable to screen the countermeasures to narrow the options for the economic appraisal step.

The practitioner should generate a list of countermeasures (some of which may have been identified in this guide) that are based on local practice or are representative of a unique situation identified at the

intersection through the diagnosis step. Before conducting the economic appraisal of each countermeasure, it is advisable to screen the countermeasures to narrow the options for the economic appraisal step.

One method of screening proposed countermeasure is to develop a matrix where each treatment is given a score within different categories based on the consensus among study team members. The individual score categories may be as follows:

- **Overall Feasibility:** How feasible would it be to implement the countermeasure? Would it involve a significant amount of work, time and/or coordination with police, maintenance staff, transportation planners, or the public? Straightforward treatments get positive scores. Difficult-to-implement countermeasures get negative scores.
- **Impact on Traffic Operations:** Is the countermeasure expected to improve the flow of traffic within the intersection influence area? Countermeasures that would improve traffic operations score positive. Countermeasures that would degrade traffic operations score negative.
- **Consistency with Local Practice:** Is the countermeasure consistent with local practice? Countermeasures that are familiar to the public and have known benefits score positive. Countermeasures that are unfamiliar and are largely untested score negative.

Scoring each countermeasure allows the study team to quickly determine which treatments are expected to have a positive or negative effect on the intersection. The long list of potential countermeasures then can be reduced to a short list of viable countermeasures. Based on a threshold score decided upon among the study team, the countermeasures may then be screened and those scoring poorly may be discarded.

6.5.1 Case Study

For the case study presented in the diagnosis step, Exhibit 6-17 shows a list of countermeasures proposed for the study intersection that can potentially address safety problems identified in the problem statements.

Countermeasure	Description
Heighten conspicuity of the signal displays for eastbound intersection-approaching road users.	This countermeasure involves installation of devices to heighten the conspicuity of the signal displays for road users approaching the intersection along Road B. The following treatments are recommended: • Install new signal bulbs and ensure they are conspicuous to intersection-approaching road users. • Install the recommended one signal per lane over each lane. • Install yellow retroreflective sheeting border on the eastbound traffic signal display back plates.[76]
Address stopping sight distance issues on eastbound approach to the intersection.	Low-Cost Solution: This countermeasure involves installation of warning signage to heighten awareness of the sight distance issue on the intersection approach. The following treatments are recommended: • Install either a “SIGNAL AHEAD” warning sign or a “BE PREPARED TO STOP” warning sign to heighten awareness of the presence of the

Countermeasure	Description
	intersection on approach. High-Cost Solution: This countermeasure involves re-design and reconstruction of the vertical curvature of the roadway to ensure the stopping sight distance on approach to the intersection is met.
Enhance presence of lane designation on eastbound approach to the intersection.	This countermeasure involves the installation of lane designation signs and markings for exclusive eastbound right-turn lane to ensure lane designation is evident to intersection-approaching road users.
Pavement friction test and potential follow-on construction work.	This countermeasure involves conducting a friction test of the existing pavement surface. An empirical test of the friction properties of the pavement could determine if additional friction should be added to the pavement surface. Increasing pavement friction may assist road users' ability to maneuver during events leading up to a potential collision, particularly eastbound rear-end collisions.
Installation/Relocation of street name signs	This countermeasure involves enhancing the conspicuity of the standard street regulatory name sign for Road B by increasing the size of the sign and relocating it to a position over the curb-through lane on the signal mast arm.
Further enhance the presence of Road B on approach along Street A.	This countermeasure involves installation of signage to better inform approaching road users of the downstream condition and the subject signalized intersection so that they can make appropriate decisions about lanes, etc., and can enter with caution due to the existing issue with vertical geometry. Advance street name sign for Road B on eastbound approach.(77) Conspicuity enhancement of the standard street regulatory name sign for Road B through increasing the size of the sign and relocating it to a position over the curb-through lane on the signal mast arm.
Install INTERSECTION AHEAD warning sign.	This countermeasure involves the installation of an INTERSECTION AHEAD warning sign to provide appropriate advance notice of the downstream condition to eastbound intersection-approaching road users.
Install a westbound left-turn lane.	This countermeasure involves the installation of a westbound left-turn lane at the intersection to remove westbound left-turning road users from the stream of through traffic.

Exhibit 6-17. Proposed long list of countermeasures.

6.6 ECONOMIC APPRAISAL

Economic appraisals identify whether the countermeasures identified in the previous step of the road safety management process have larger benefits than their costs. The economic appraisal quantifies countermeasures' benefits in terms of their safety impacts. The ability to evaluate the safety impacts of a countermeasure is paramount to implementing an intersection improvement plan. Information is needed on whether the treatment under consideration is effective in reducing crashes. Most treatments proposed in Part III of this guide have some published material that provides a quantitative estimate of effectiveness. For other treatments in Part III, no research was found that provided any quantifiable estimate of safety benefits. Before any further consideration as to be applicability of a treatment can occur, the study team will need to decide whether they have a quantifiable estimate of the expected results of a treatment available. If they do, they can proceed with the steps described below. If not, they should carefully consider whether the treatment should be implemented.

The economic appraisals include three steps:

- Step 1: Estimate benefits of countermeasures.
- Step 2: Estimate costs of countermeasures.
- Step 3: Evaluate cost effectiveness of countermeasures.

6.6.1 Step 1 – Estimate Benefits of Countermeasures

To estimate the benefits of safety improvement projects (countermeasures), crash modification factors (CMF) are utilized. CMF is a term that is widely used in road safety engineering. A CMF is the ratio of expected crash frequency at a location with a countermeasure divided by the expected crash frequency at the location without the countermeasure. If the expected crash frequency with a treatment is 9 and the expected crash frequency without the treatment is 12, then the CMF is 9/12 = 0.75.

Some jurisdictions have developed reference lists of CMFs to help them choose an appropriate treatment for an intersection improvement plan. In some cases, very little or no documentation exists showing how these CMFs were derived. Some State authorities are currently using CMFs developed from in-house projects; others use CMFs developed by other transportation authorities or based on published research. FHWA has developed the CMF Clearinghouse,[78] which houses a Web-based database of CMFs along with supporting documentation to help traffic engineers identify the most appropriate countermeasure for their safety needs. It is a live database in which new CMFs are added as they become available through research. The CMF clearinghouse has adopted a star rating to represent the quality of each CMF. A 5-star CMF represents a CMF that has been developed using a valid statistical methodology.

Part III of this guide reports study findings from a variety of sources. These findings reported a change in crash frequency or crash rate as part of a cross-sectional study, a before-after study, or by more sophisticated methods. Each study finding was reviewed in terms of:

- The reasonableness of the values presented.
- The year of the study.
- The general integrity of the study in terms of crash data used, methodology, and sample size.
- The country of origin.

In general, findings that appeared unreasonable, outdated, used overly simplistic methods, or were based on research carried out outside of North America (unless no other finding was available for the treatment in question) were discarded. The results are presented as the expected change in crash frequency, expressed as a percentage. A study finding of 50 percent means that there is expected to be a reduction of 50 percent in the number of crashes occurring after the application of the treatment the study finding describes. Each CMF or study finding in Part III of this guide is referenced. In applying a CMF or in finding ways to determine the expected outcome of implementing a treatment, the user is urged to review the source material from which the CMF or study finding was derived in order to determine its applicability to his or her specific project. Readers may wish to use their own CMFs or the results of another study finding known to them should they believe that it is more accurate or better reflects conditions occurring at the location in question.

The target benefit of any countermeasure is a reduction in the frequency or severity of crashes. Assumptions regarding the potential benefit(s) of a countermeasure must be realistic. The crash frequency (or crash frequency of a specific group of crashes) cannot be driven below zero. To quantify the safety benefit of implementing a countermeasure, the estimated crash reduction that will be connected with the implementation of the countermeasure must be determined. If a countermeasure is successful in eliminating or reducing the severity of crashes that would have been expected without the countermeasure, then the benefits can be attributed to the countermeasure.

When two countermeasures are considered and each has a quantifiable safety benefit, a common way to express the combined safety benefit is to multiply both values. For example, countermeasure A might have a CMF of 0.90, and countermeasure B might have a CMF of 0.80. Combined, the two countermeasures should have an expected benefit of 0.72 (CMF A (0.90) x CMF B (0.80)).

Usually, countermeasures will only be effective when applied to a particular target group of crashes. For example, the installation of protected left-turn phasing on one approach should substantially reduce left-turn crashes involving that particular approach, but cannot be expected to affect left-turn crashes on any other approach.

Countermeasures can also have undesirable effects worth considering in evaluating their overall benefit. For example, the installation of right-turn channelization may reduce crashes involving right-turning vehicles and possibly rear-end crashes on a particular approach, but may increase crashes involving pedestrians. If the countermeasure is to be applied, both positive and negative consequences need to be considered.

The potential crash reduction from a countermeasure is determined by multiplying the expected number of crashes by the percentage reduction that the countermeasure is expected to have. The expected number of crashes (total or by severity) may be assumed to be the same as in the period before the countermeasure, but a much more refined method would be to develop an estimate of the expected number of crashes based on SPF curves or the EB method.

Placing an economic value on crashes by severity is a common practice in quantifying the safety benefits of a countermeasure. There are several ways of arriving at societal cost (such figures are available from FHWA and various State transportation agencies).

Calculating the safety benefit of a countermeasure means multiplying the expected crash reduction by severity (property damage, injury, and fatal) by applicable society cost figures. A means of expressing the calculation of the safety benefit of the countermeasure is as follows:

$$\text{Safety Benefit (\$)} = \Delta n_{PDO} \times C_{PDO} + \Delta n_I \times C_I + \Delta n_F \times C_F \qquad (5)$$

Where: Δn_{PDO} = Expected reduction in property-damage-only crashes
C_{PDO} = Societal costs of property-damage-only crashes
Δn_I = Expected reduction in injury crashes
C_I = Societal costs of injury crashes
Δn_F = Expected reduction in fatal crashes
C_F = Societal costs of fatal crashes.

Collision Type	Societal Crash Costs
Fatal (K)	$4,008,900
Disabling Injury (A)	$216,000
Evident Injury (B)	$79,000
Fatal/Injury (K/A/B)	$158,200
Possible Injury (C)	$44,900
PDO (0)	$7,400

Exhibit 6-18. Societal crash cost estimates by crash severity
Source: Table 7-1 of the Highway Safety Manual

As an example: a multilane signalized intersection has been diagnosed as having a safety problem associated with a particular approach. Adding a right-turn lane is being considered as a possible countermeasure. Calculation of the safety benefit involves determining the product of the yearly average number of crashes, the societal benefit, and the estimated reduction in crashes grouped by crash type (Exhibit 6-19). The total societal benefit is calculated to be $104,948.

Crash Type	5-Year Total Before Treatment	Yearly Average Before Treatment	Estimated Reduction Due to Treatment	Estimated Yearly Average After Treatment	Unit Societal Benefit	Estimated Yearly Benefit of Treatment
Fatal/ Injury	8	1.6	40%	0.64	$158,200	$101,248
PDO	25	5.00	10%	0.50	$7,4, 00	$3,700
Total						**$104,948**

Exhibit 6-19. Example calculation of safety benefit of adding a right-turn lane.

6.6.2 Step 2 – Estimate Costs of Countermeasures

The next step of economic appraisal is the estimation of implementation costs of projects (countermeasures). Similar to other roadway improvement projects, implementation costs of projects may include right-of-way acquisition, construction cost, utility relocation, environmental impacts, operation costs, maintenance costs, and the cost associated with planning and engineering.

The most important source for the implementation costs of projects is the local past experience of the road agency. The *SafetyAnalyst* software also has costs associated with a number of countermeasures built-in.

6.6.3 Step 3 – Evaluate Cost Effectiveness of Countermeasures

Once benefits and costs of road safety improvement projects are calculated, various methods for benefit-cost analysis practiced in engineering economy can be utilized to evaluate whether the projects are economically viable. In practice, net present worth and benefit-cost ratio are the most commonly used methods.

The benefits and costs estimated before are likely to occur in the future in different time spans. As a result, the present worth of benefits and costs are calculated using an average interest rate (discount rate). Then, the difference between the discounted costs and discounted benefits at the present year (net present worth) is calculated. A project with a net present worth greater than zero indicates a projects with benefits more than costs. These types of projects are economically viable.

In the benefit-cost ratio (BCR) method, first the present worth of benefits and costs are calculated. Then the ratio of present worth of benefits over present worth of costs is calculated. If the ratio is greater than 1.0, the project is economically justified.

The countermeasures which are found economically justified can be implemented to address the safety problems identified in the diagnosis step. However, the main challenge is that resources to implement all countermeasures are not available. As a result, the road agency needs to make a decision to identify which countermeasures should be implemented considering the scarce resources.

6.6.4 Case Study

Exhibit 6-20 summarizes the result of benefit-cost analysis. In this table, the countermeasures proposed in the countermeasure selection step are listed. CMFs associated with each countermeasure have been obtained from the CMF Clearinghouse. The original studies through which the CMFs were developed are cited as footnotes. No CMF was found for two of the countermeasures in Exhibit 6-20. Using the CMFs, crash reduction over a 5-year period was calculated. The crash reduction was converted to benefits using the societal cost of crashes shown in exhibit 6-20. Net present worth of benefits was calculated using a discount rate of 2%. Net present worth of total costs of projects was calculated. A life cycle of 20 years was assumed for countermeasures. The BCR for countermeasures shows that all proposed countermeasures are economically justified.

The two countermeasures for which no CMF was found are recommended because both are low cost countermeasures and potentially have positive operational impacts.

Countermeasure	CMF	5-Year Total Crash Reduction After Countermeasure	Benefits ($)	Total Cost ($)	BCR
Heighten conspicuity of the signal displays for eastbound intersection-approaching road-users	0.85 for all crashes (all severities)	13.5	627,267	6,000	104.5
Address stopping sight distance issues on eastbound approach to the intersection	0.65 for angle crashes (all severities)	3.5	162,625	2,000	81.3
Pavement friction test and potential follow-on construction work	0.76 for all crashes (all severities)	21.6	1,003,627	60,000	16.7
Further enhance the presence of Road B, on approach along Street A	0.984 for all crashes (all severities)	1.44	66,909	2,000	33.5
Install "Intersection Ahead" warning sign	0.65 for all crashes (all severities)	3.5	162,625	2,000	81.3
Install a westbound left-turn lane	0.9 for all crashes (all severities)	9	418,178	280,000	1.5

CMF values developed from a variety of sources, including the Highway Safety Manual and the CMF Clearinghouse

Exhibit 6-20. Summary of benefit-cost analysis.

6.7 PROJECT PRIORITIZATION

In the previous steps of the road safety management process, one or more countermeasures for one or more intersections might be selected. One countermeasure or a combination of countermeasures can be referred to as one project. Now the traffic engineer and the road agency face the important decision of which project should be implemented first and which projects should be implemented at all, considering the limited available resources to maximize benefits to the public (i.e., have most safety improvements).

The following two simple methods can help prioritize projects [71]:

- Ranking by economic effectiveness measures.
- Incremental benefit-cost analysis ranking.

The ranking by economic effectiveness methods is the simplest method for prioritization of projects. In this method, economically justified projects are ranking from high to low by any of the following measures:

- Net present worth.
- Projects costs.
- Monetary value of project benefits.

- Total number of crashes reduced.

Next, the agency may start the projects from the top of the list to the bottom. The main challenge associated with this method is that it ignores resource constraints and potential competing priorities.

In the incremental benefit-cost analysis ranking, the following steps are to be taken [71]:

1. Calculate the BCR for each project.
2. Arrange projects with a BCR greater than 1.0 in increasing order based on their estimated cost. The project with the smallest cost is listed first.
3. Calculate the BCR for the incremental investment by dividing the difference between benefits of the first two ranked projects by the difference between costs of the first two ranked projects.
4. If the BCR for the incremental investment is greater than 1.0, the project with the higher cost is compared to the next project in the list. If the BCR for the incremental investment is less than 1.0, the project with the lower cost is compared to the next project in the list.
5. Repeat this process. The project selected in the last pairing is considered the best economic investment.

To produce a ranking of projects, the entire evaluation is repeated without the projects previously determined to be the best economic investment until the ranking of every project is determined.

6.7.1 Case Study

Exhibit 6-21 shows the priority ranking of countermeasures, which were selected as part of the countermeasure selection step shown in Exhibit 6-20. In this case study, ranking was performed based on the monetary value of project benefits. It should be noted that the road agency has to consider their budget constraints to identify all or some of the projects that can be implemented. Also, if the criteria for ranking changes based on the road agency strategic directions, the priority ranking will change. For example, if the ranking is performed based on total cost of the project, another ranked list is obtained.

Rank	Countermeasure	CMF	5-Year Total Crash Reduction After Countermeasure	Benefits ($)	Total Cost ($)	BCR
1	Pavement friction test and potential follow-on construction work	0.76 for all crashes (all severities)	13.5	627,267	6,000	104.5
2	Heighten conspicuity of the signal displays for eastbound intersection-approaching road-users	0.85 for all crashes (all severities)	3.5	162,625	2,000	81.3
3	Install a westbound left-turn lane	0.9 for all crashes (all severities)	21.6	1,003,627	60,000	16.7
4	Address stopping sight distance issues on eastbound approach to the intersection	0.65 for all crashes (all severities)	1.44	66,909	2,000	33.5
5	Install “Intersection Ahead” warning sign	0.65 for all crashes (all severities)	3.5	162,625	2,000	81.3
6	Further enhance the presence of Road B, on approach along Street A	0.984 for all crashes (all severities)	9	418,178	280,000	1.5

Exhibit 6-21. Priority ranking of selected countermeasures.

6.8 SAFETY EFFECTIVENESS EVALUATION

Safety effectiveness evaluation is the process of developing quantitative estimates of how a countermeasure, project, or a group of projects has affected crash frequencies or severities. The effectiveness estimate for a project or treatment is a valuable piece of information for future safety decision making and policy development.

Safety effectiveness evaluation may include:

- Evaluating a single project at a specific site to document the safety effectiveness of that specific project.
- Evaluating a group of similar projects to document the safety effectiveness of those projects.
- Evaluating a group of similar projects for the specific purpose of quantifying a CMF for a countermeasure.
- Assessing the overall safety effectiveness of specific types of projects or countermeasures in comparison to their costs.

Practitioners should conduct a before-after study to evaluate the safety effectiveness of any project. A before-after study compares crash frequencies at a site are before and after implementation of a treatment. The main challenge associated with conducting a before-after study is that a number of factors change at the subject site from the before to after period, in addition to the treatment. These factors may include a change in traffic volume, a change in weather conditions, and other unknown factors. As a result, it is critical to separate the safety changes associated with the treatment from the other factors that have changed from the before period to the after period through a valid before-after study.

In a before-after study, the collision frequencies at the treated sites in the after period are compared with collision frequencies at the same sites had the treatment not been implemented in the after period. Obviously, the collision frequencies had the treatment not been applied are not known. As a result, there are a number of techniques in the literature to predict the collision frequencies in the after period had the treatment not been applied. The following section identifies the commonly used techniques in road safety:

6.8.1 Before-After Study with Comparison Group

In this type of before-after study, a comparison group is selected comprising sites that have similar geometric and operational characteristics as the treatment sites. The number of sites in the comparison group is more than the treatment group. The rationale behind this technique is that all contributing factors that affect safety (i.e., traffic volume, weather, etc.) from the before period to the after period impact both the treatment group and the comparison group in the same way, and the only difference between the treatment sites and comparison sites is the treatment itself. In this method, collision frequency of the treatment group had the treatment not been applied is predicted by multiplying crash frequency of the treatment sites in the after period by the ratio of crash frequency of the comparison sites in the after period to the crash ratio of the comparison sites in the before period.

This method has been widely used in road safety. The only challenge associated with this method is that it does not consider the regression-to-the-mean phenomenon.

6.8.2 Before-After Study with Empirical Bayes

In this technique, instead of using a comparison group, the SPF developed for the reference group associated with the treatment sites is used to predict crash frequency at the treatment sites in the after period had the treatment not been applied. This technique is the preferred technique because it considers the regression-to-the-mean phenomenon.

The HSM provides more details on study design and methods for evaluation of safety effectiveness of countermeasures, and Ezra Hauer provides details on various methods for conducting a valid before-after study in road safety in his seminal book.[79]

CHAPTER 7

OPERATIONAL ANALYSIS METHODS

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LIST OF EXHIBITS

7.0 OPERATIONAL ANALYSIS METHODS

Chapter 6 described tools that can be used to assess safety performance at a signalized intersection. Evaluating a candidate treatment also usually requires assessing its performance from the perspective of traffic operations. This chapter will focus on measures for assessing operational performance and computational procedures used to determine specific values for those measures.

The relationships between safety performance and operational performance are difficult to define in general terms. Some intersection treatments that would improve safety might also improve operational performance, but others might diminish operational performance. Furthermore, the nature of safety and operational measures makes them difficult to combine in a way that would represent both perspectives.

Operational performance measures tend to be fewer in number and more easily related to site-specific conditions than are safety performance measures. The computations themselves are more amenable to deterministic models, and a wide variety of such models, mostly software-based, are available. Selection of a model for a specific purpose is generally based on the tradeoff between the difficulty of applying the model and the required degree of accuracy and confidence in the results. The degree of application difficulty is reflected in the required amount of site-specific data as well as the level of personnel time and training needed to apply the model and to interpret the results.

Recent user interface enhancements in the more advanced traffic model software products have made the products much easier to apply. Most can generate animated graphics displays depicting the movement of individual vehicles and pedestrians in an intersection (see Exhibit 7-1) and some allow for three-dimensional rendering. These enhancements have caused an increasing trend toward the use and acceptance of advanced traffic modeling techniques.

While the range of operational performance models is more or less continuous, it will be categorized into the following analysis levels for purposes of this discussion:

- Rules of thumb for intersection sizing.
- Critical lane analysis.
- The *HCM 2010* operational analysis procedure.[2]
- Arterial signal timing design and evaluation models.
- Microscopic simulation models.

These levels are listed in order of complexity and application difficulty, from least to greatest. Each analysis level will be discussed separately.

The process for evaluating the operational performance of an intersection remains unchanged regardless of the analysis level and the issues at hand. The analysis should begin at the highest level and should continue to the next level of detail until the key operations-related issues and concerns have been addressed in sufficient detail. Additional guidance for each level above can be found in the FHWA Traffic Analysis Tools Program website at http://ops.fhwa.dot.gov/trafficanalysistools/.

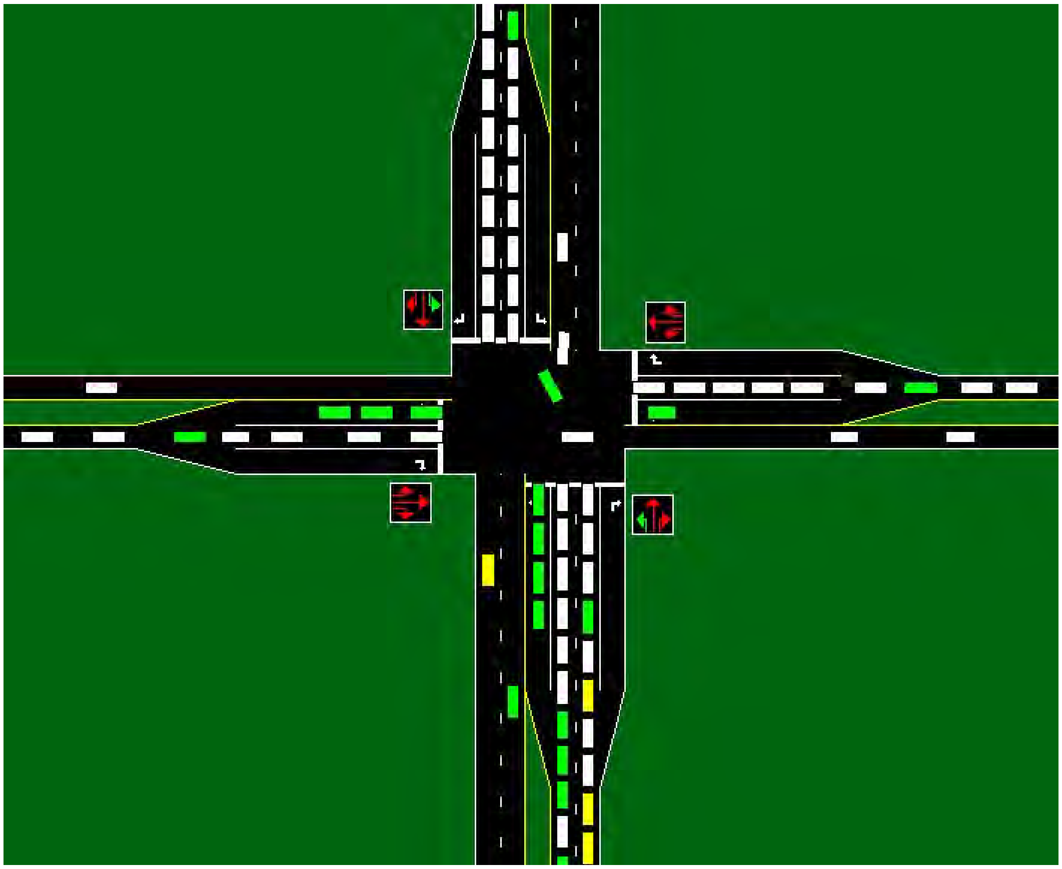


Exhibit 7-1. Still reproduction of a graphic from an animated traffic operations model.

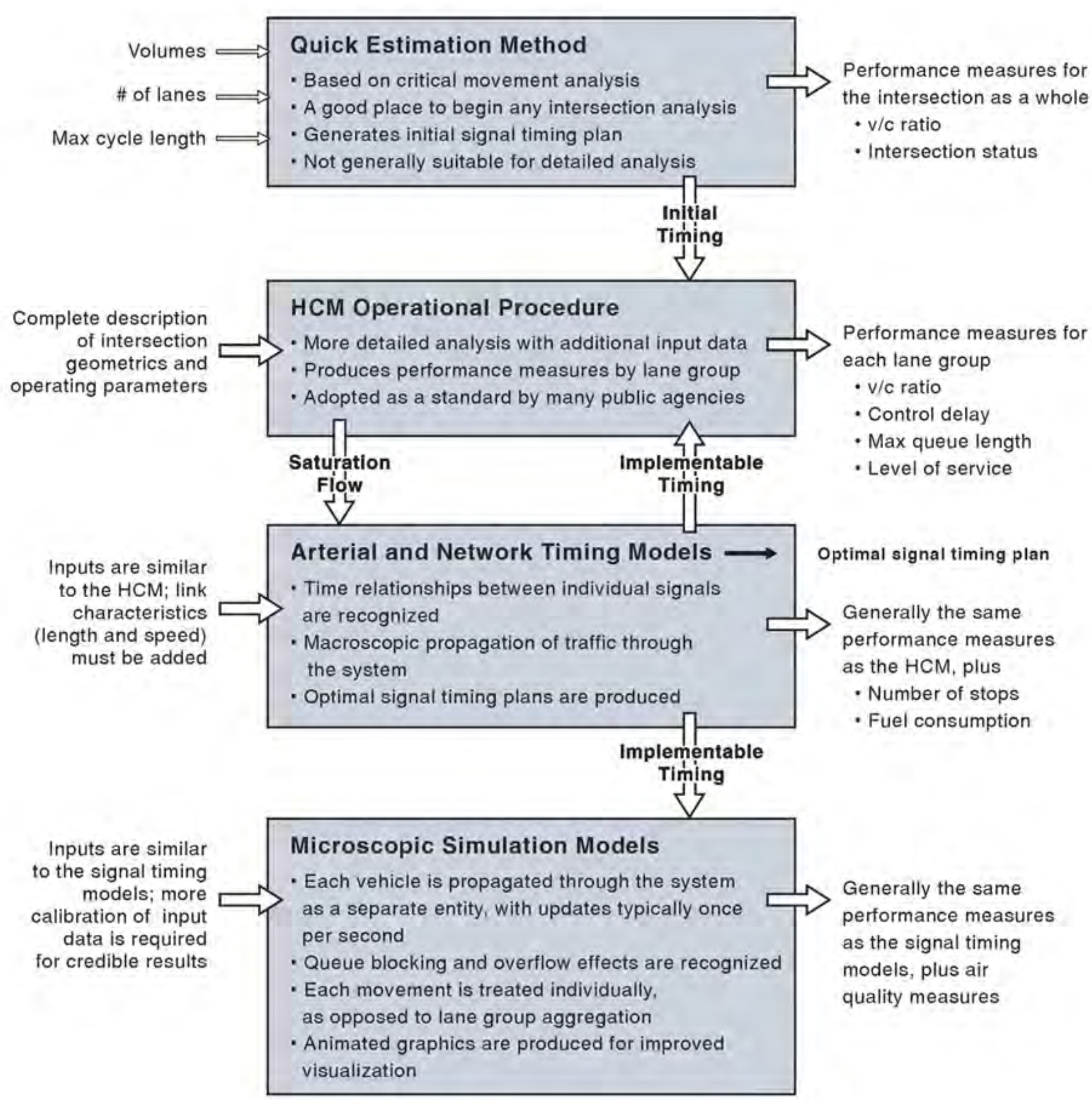


Exhibit 7-2. Overview of intersection traffic analysis models.

The ability to measure, evaluate, and forecast traffic operations is a fundamental element of effectively diagnosing problems and selecting appropriate treatments for signalized intersections. A traffic operations analysis should describe how well an intersection accommodates demand for all user groups. Traffic operations analysis can be used at a high level to size a facility and at a refined level to develop signal timing plans. This section describes key elements of signalized intersection operations and provides guidance for evaluating results.

In all analysis methods, especially those that involve modeling, it is important that any tools used are calibrated and validated for real-life field conditions to ensure credible analysis results. Data collected include entering traffic volume, turning movements, queue lengths, vehicle speed, and lane capacity. Modifications to the software tools may be necessary to accurately reflect field conditions. It is necessary to document all calibration adjustments to support credibility.

7.1 OPERATIONAL PERFORMANCE MEASURES

A signalized intersection's performance is described by the use of one or more quantitative measures that characterize some aspects of the service provided to specific road user groups. The *HCM 2010* introduces four road user groups: automobile, pedestrian, bicycle, and transit. In order to encourage users to consider all travelers on a facility when they perform analyses and make decisions, the *HCM 2010* integrates material on automobile and non-automobile modes.

Generally, three methodologies are used to evaluate the performance measures of signalized intersection operations. They are referred to as the automobile methodology, the pedestrian methodology, and the bicycle methodology. Each methodology addresses one possible travel mode through the intersection. A complete evaluation of intersection operation includes the separate examination of performance for all relevant travel modes. The performance measures associated with each travel mode are as follows:

a) Automobile mode

- Capacity and volume-to-capacity ratio.
- Delay and Level of Service (LOS).
- The back-of-queue and queue storage ratio.
- Probability of phase termination by max out or force-off.

b) Pedestrian mode

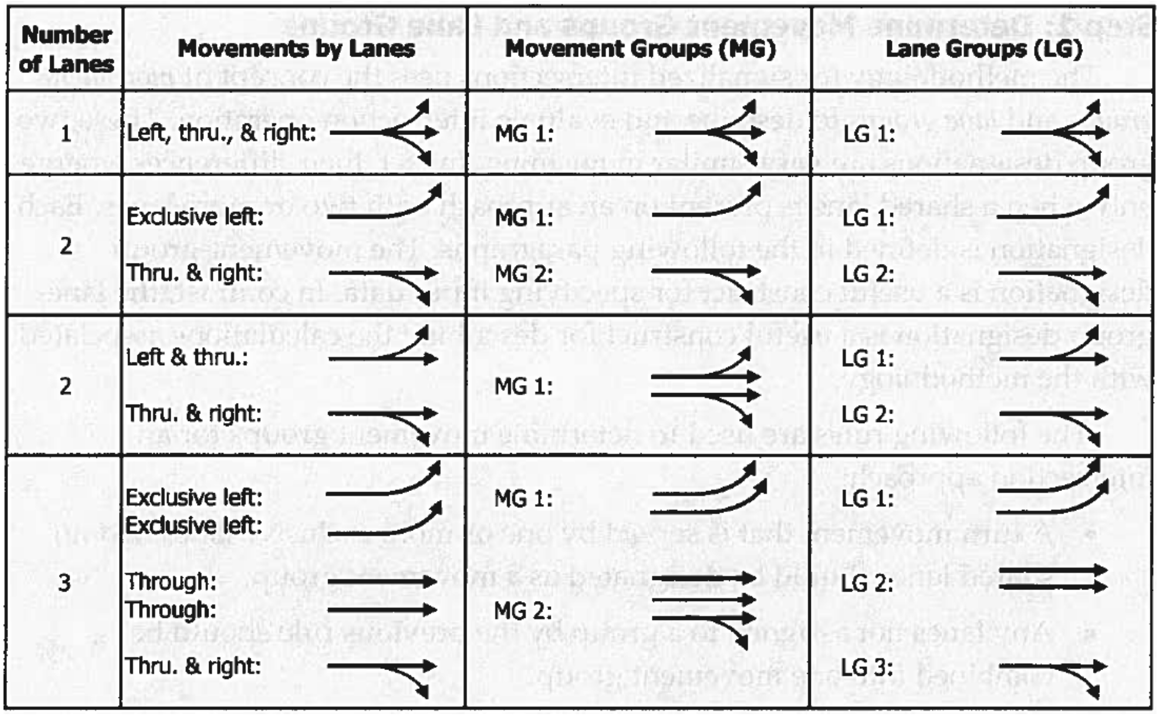
- Corner and crosswalk circulation area.
- Pedestrian delay.
- Pedestrian LOS score.

c) Bicycle mode

- Bicycle delay.
- Bicycle LOS score.

The *HCM 2010* evaluates the intersection operation by the concept of movement groups and lane groups.(2) A separate movement group is established for (a) each turn movement with one or more exclusive turn lanes with no shared movements, and (b) the through movement inclusive of any turn movements that share a lane.

The movement group and lane group designations are very similar in meaning. In fact, their differences emerge only when a shared lane (such as a through lane that is also serving right turns) is present on an approach with two or more lanes. (2) Thus, any shared lane is considered as a separate lane group, while an exclusive turn lane or lanes should be designated as another separate lane group. Similar to movement group definition, any lanes that are not exclusive turn lanes or shared lanes are combined into one lane group. These rules for movement group and lane group result in designation of different group possibilities for an intersection approach. Exhibit 7-3 presents some common movement groups and lane groups.(2)



Number of Lanes	Movements by Lanes	Movement Groups (MG)	Lane Groups (LG)
1	Left, thru., & right:	MG 1:	LG 1:
2	Exclusive left: Thru. & right:	MG 1: MG 2:	LG 1: LG 2:
2	Left & thru.: Thru. & right:	MG 1:	LG 1: LG 2:
3	Exclusive left: Exclusive left: Through: Through: Thru. & right:	MG 1: MG 2:	LG 1: LG 2: LG 3:

Exhibit 7-3. Typical lane groups for analysis.[2]

7.1.1 Automobile Methodology

The automobile methodology described in the *HCM 2010* is originally based on the results of NCHRP Project 3-28(2) study that formulized (a) the critical movement analysis procedure developed in the United States, Australia, Great Britain, and Sweden, and (b) the automobile delay estimation procedure, developed in Great Britain, Australia, and the United States. The updated procedures described in the *HCM 2010* are used to evaluate the associated automobile performance measures for signalized intersection.

7.1.1.1 Capacity and volume-to-capacity ratio

Capacity is defined as the maximum sustainable flow rate at which vehicles can pass through a given point in an hour under prevailing conditions; it is often estimated based on assumed values for saturation flow, and width of lanes, grades, and lane use allocations, as well as signalization conditions. Under the *HCM 2010* procedure, intersection capacity is measured for critical lane groups (those lane groups that have the highest volume-to-capacity ratios). Critical intersection volume-to-capacity ratios are based on flow ratio for the critical phase. A critical phase is one phase of a set of phases that occur in sequence and whose combined flow ratio is the largest for the signal cycle. Rules for determining critical flow ratio and critical path are further explained in *HCM 2010*.

Research conducted as part of the 1985 HCM showed that the capacity for the critical lanes at a signalized intersection was approximately 1,400 vehicles per hour.[80] This capacity is a planning-level estimate that incorporates the effects of loss time and typical saturation flow rates. Studies conducted in the State of Maryland have shown that signalized intersections in urbanized areas have critical lane volumes upwards of 1,800 vehicles per hour. [81]

The volume-to-capacity (v/c) ratio, also referred to as degree of saturation, represents the sufficiency of an intersection to accommodate the vehicular demand. A v/c ratio less than 0.85 generally indicates that adequate capacity is available and vehicles are not expected to experience significant queues and delays. As the v/c ratio approaches 1.0, traffic flow may become unstable, and delay and queuing conditions may occur. Once the demand exceeds the capacity (a v/c ratio greater than 1.0), traffic flow is unstable and excessive delay and queuing is expected. Aside from the excessive demand, there are other factors that may contribute to cycle failure as well (e.g., influence of pedestrians, poor signal timing, incidents, etc.). Under these conditions, vehicles may require more than one signal cycle to pass through the intersection (known as a cycle failure). For design purposes, a v/c ratio between 0.85 and 0.95 generally is used for the peak hour of the horizon year (generally 20 years out). Over-designing an intersection should be avoided due to negative impacts to all users associated with wider street crossings, the potential for speeding, land use impacts, and cost.

Delay

Delay is defined in the *HCM 2010* as “the additional travel time experienced by a driver, passenger, bicyclist, or pedestrian beyond that is required to travel at the desired speed.”(2) The signalized intersection chapter (Chapter 18) of the *HCM 2010* provides equations for calculating control delay, the delay a motorist experiences that is attributable to the presence of the traffic signal and conflicting traffic. This includes time spent decelerating, in the queue, and accelerating. Expectation of delay at a signalized intersection is different than at an unsignalized intersection.

The control delay equation comprises three elements: uniform delay, incremental delay, and initial queue delay. The primary factors that affect uniform delay are lane group volume, lane group capacity, cycle length, and effective green time. Two factors that account for incremental delay are (a) the effect of random and cycle-by-cycle fluctuations in demand that occasionally exceed capacity, and (b) a sustained oversaturation during the analysis period, when the aggregate demand exceeds the aggregate capacity. The third component of the control delay illustrates the delay due to an initial queue, as a result of unmet demand in the previous time period.

The Back-of-queue and Queue Storage Ratio

Practitioners should evaluate vehicle queuing, an important performance measure, as part of all signalized intersections analyses. Vehicle queue estimates help determine the amount of storage required for turn lanes and whether spillover occurs at upstream facilities (driveways, unsignalized intersections, signalized intersections, etc.). Queues that extend upstream from an intersection can spill back into and block upstream intersections, causing side streets to begin to queue back. The back-of-queue is the maximum backward extent of queued vehicles during a typical cycle. This back-of-queue length depends on the arrival pattern of vehicles and the number of vehicles that do not clear the intersection during the previous cycle.(2) Approaches that experience extensive queues also may experience an over-representation of rear-end collisions. Vehicle queues for design purposes are typically estimated based on the 95th percentile queue that is expected during the design period. This is the length at which 95 percent of lane queues are less than in a given study period.

The queue storage ratio represents the proportion of the available queue storage distance that is occupied at the point in the cycle when the back-of-queue position is reached.(2) If this ratio exceeds 1.0, then the storage space will overflow and queued vehicles may block other vehicles from moving forward.

Volume 3 of the *HCM 2010* provides procedures for calculating back-of-queue length and the queue storage ratio. In addition, all known simulation models provide ways of obtaining queue estimates.

Level of Service (LOS)

Level of Service (LOS) is a grading-scale based descriptor that attempts to relate relative operational quality (based on certain measures of effectiveness) to that of driver perception in a simple fashion. Control delay is used as the basis for determining LOS for an intersection or a single approach. Delay thresholds for the various LOS are given in Exhibit 7-4.

Typically LOS is reported on an A through F scale, with Level A being the best LOS and Level F being the worst. While the A through F scale seems fairly straightforward, the quantifiable measures of effectiveness (MOEs) used to derive the “grading scale” are derived from empirical data.

For signalized intersections, control delay (in seconds) is the MOE for the LOS scale (note that the grade thresholds for signalized intersections are different than for stop-controlled intersections). However, there are other MOEs that are important in characterizing the operations of signalized intersections, including v/c ratio and intersection utilization. Furthermore, while it is common for weighted averages to be used in describing overall intersection operation, it is often the case where one or more specific movements, lane groups, or approaches may be operating poorly, but be masked by the overall average. Also, when intersections are operating at capacity (i.e., LOS F) and beyond, only close analysis of the various MOEs will allow for distinctions to be made among different alternatives. Finally, it should be noted that safety is not reflected or implied in LOS.

Exhibit 7-4. Automobile LOS thresholds at signalized intersections.[2]

Control Delay per Vehicle (seconds per vehicle)	LOS by V/C Ratio	
	≤1	>1
≤ 10	A	F
> 10-20	B	F
> 20-35	C	F
> 35-55	D	F
> 55-80	E	F
> 80	F	F

LOS has historically been given high emphasis by practitioners due to its relative ease of explanation, but it is a crude measure at best. The language of LOS (A-F scale) is easily understood, regardless of the background MOEs used or their accuracy in actually determining the operation of the intersection.

Probability of Phase Termination by Max-out or Force-off

For actuated and semi-actuated operation, the maximum green time is the maximum limit to which the green time can be extended for a phase in the presence of a call from a conflicting phase. The maximum green time begins when a call is placed on a conflicting phase. The phase is allowed to "max-out" if the maximum green time is reached even if actuations have been received that would typically extend the phase. However, the safety benefit of green extension can be negated if the phase is extended to its maximum duration (i.e., maximum-green setting). The probability of termination by “max-out” is dependent on flow rate in the subject phase and the “maximum allowable headway.” Exhibit 7-5 illustrates the relationship between max-out probability, maximum allowable headway, maximum green, and flow rate for actuated and semi-actuated operation. For coordinated operation, the main street phase will receive its entire split time (effectively a force-off) regardless of calls on conflicting phases.

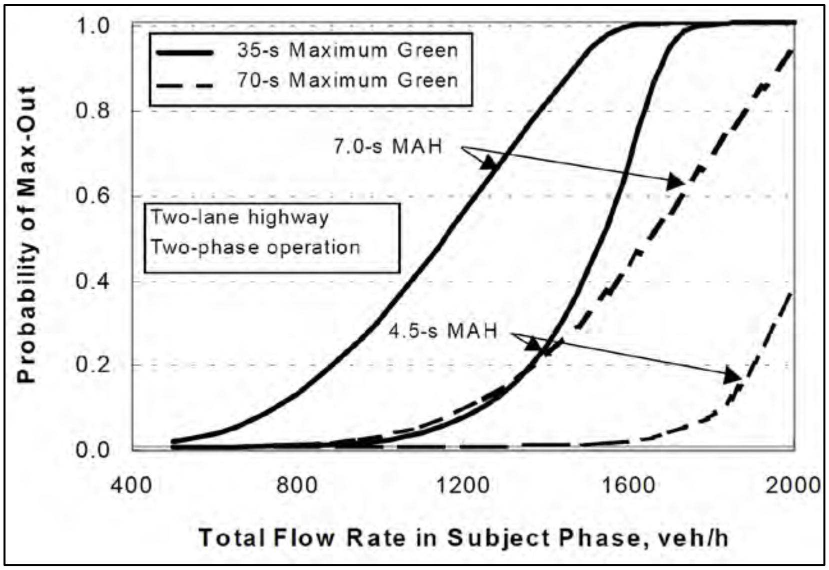


Exhibit 7-5. Effect of flow rate and detection design on max-out probability.
Source: Bonneson, J. et al, *Intelligent Detection-Control System for Rural Signalized Intersections*, FHWA/TX-03/4022-2, 2002.

7.1.2 Pedestrian Methodology

This section describes the methodology for evaluating the performance of a signalized intersection in terms of its service to pedestrians.

Corner and Crosswalk Circulation Area

The corner and crosswalk circulation area are used to evaluate the circulation area provided to pedestrians while they are waiting at the corner or crossing the crosswalk, respectively. Exhibit 7-6 can be used to evaluate intersection performance from a circulation-area prospective in terms of space available to the average pedestrian.(2)

Exhibit 7-6. Evaluation of circulation area based on pedestrian space.(2)

Pedestrian Space (ft^2 per pedestrian)	Description
>60	Ability to move in desired path, no need to alter movements
> 40-60	Occasional need to adjust path to avoid conflicts
> 24-40	Frequent need to adjust path to avoid conflicts
> 15-24	Speed and ability to pass slower pedestrian restricted
> 8-15	Speed restricted, very limited ability to pass slower pedestrian
≤ 8	Speed severely restricted, frequent contact with other users

The critical parameter for the analysis of circulation area at the street corner and crosswalk is the product of available time and space with pedestrian demand, which combines the physical design constrains (i.e., available space) and signal operation (i.e., available time). This parameter is referred to as the “time-space” available for pedestrian circulation.(2) Circulation time-space and pedestrian circulation area are estimated based on intersection and pedestrian signal phasing settings, pedestrian flow rates in different directions, and physical characteristics of the sidewalks. Chapter 18 of the *HCM 2010* provides the detailed procedure for calculating street corner and crosswalk circulation area.

Pedestrian Delay

In the *HCM 2010* (Chapter 18), pedestrian delay at a signalized intersection while crossing the major street is determined based on effective walk time and cycle length. The delay computed in this step can be used to make judgments about pedestrian compliance. Research indicates that pedestrians become impatient when they experienced delay in excess of 30 seconds per pedestrian. In contrast, it is reported that pedestrians are very likely to comply with signal indicators if their expected delay is less than 10 seconds per pedestrian.(2)

Pedestrian LOS Score

Historically, the HCM has used a single performance measure as the basis for defining LOS. However, in the *HCM 2010*, the LOS is separated for automobile and non-automobile modes. Based on traveler perception research for pedestrians and bicyclists, it was found that a wide variety of factors should be considered in assessing the quality of service for non-automobile road users. Therefore, a methodology for evaluating each mode was developed to mathematically combine various factors into a score. Exhibit 7-7 presents the range of scores associated with each LOS for pedestrian and bicycle travel modes.

Exhibit 7-7. LOS criteria for pedestrian and bicycle modes.(2)

LOS Score	LOS
≤ 2.00	A
> 2.00 – 2.75	B
> 2.75 – 3.50	C
> 3.50 – 4.25	D
> 4.25 – 5.00	E
> 5.00	F

The pedestrian LOS score for the intersection is calculated based on a number of factors, such as traffic counts during a 15-min period, 85th percentile speed on the major street, pedestrian delay when traversing, and number of right-turn channelizing islands along crosswalk. The detailed calculations of pedestrian LOS score are presented in the *HCM 2010* (Chapter 18). Finally, the pedestrian LOS is determined from Exhibit 7-7 by using the calculated pedestrian LOS score. As discussed above, LOS is a crude measure of pedestrian operational efficiency and is often overused by designers.

7.1.3 Bicycle Methodology

This section describes the methodology for evaluating the performance of a signalized intersection in terms of its service to bicyclists. This section replicates the procedure from Chapter 18 of the *HCM 2010*.

Bicycle Delay

The *HCM 2010* provides an analysis procedure for assessing the delay for bicycles at signalized intersections where there is a designated on-street bicycle lane on at least one approach or a shoulder that can be used by bicyclists as a bicycle lane.

Many countries have reported a wide range of capacities and saturation flow rates for bicycle lanes at signalized intersections. The *HCM 2010* recommends the use of a saturation flow rate of 2,000 bicycles per hour as an average value achievable at most intersections. This rate assumes that right-turning motor vehicles yield the right-of-way to through bicyclists. Where aggressive right-turning traffic exists, this rate may not be achievable and local observations are recommended to determine an appropriate saturation flow rate.

Using the default saturation flow rate of 2,000 bicycles per hour, the capacity of the bicycle lane and control delay at a signalized intersection can be computed, based on effective green time for the bicycle lane, and cycle length.

At most signalized intersections, the only delay to bicycles is caused by the signal itself because bicycles have right-of-way over turning motor vehicles. Where bicycles are forced to weave with motor vehicle traffic or where bicycle right-of-way is disrupted due to turning traffic, additional delay may be incurred. Bicyclists tend to have about the same tolerance for delay as pedestrians.

Bicycle LOS Score

Following the same methodology as pedestrian mode, bicycle LOS score is first calculated based on physical characteristics of the intersection, traffic flow rate, and the proportion of on-street occupied parking. The detailed calculations of bicycle LOS score are presented in the *HCM 2010* (Chapter 18). Finally, the bicycle LOS is determined from Exhibit 7-7 by using the calculated bicycle LOS score. As discussed above, LOS is a crude measure of pedestrian operational efficiency and is often overused by designers.

7.1.4 Multimodal Approach

In the *HCM 2010*, there are no stand-alone analyses for pedestrians, bicyclists, and transit users. Instead, the HCM encourages performing multimodal analysis of non-automobile modes on a specific facility of urban streets, such as a signalized intersection, in addition to automobile analysis. The *Transit Capacity and Quality of Service Manual (TCQSM),* recognized as the companion of *HCM 2010*, extensively covers the analysis of the transit mode. Therefore, the *HCM 2010* now addresses the transit mode only with respect to multimodal analysis of urban streets.[2]

7.2 TRAFFIC OPERATIONS ELEMENTS

The following sections will describe signalized intersection operations as a function of the following three elements and discuss their effects on operations.

1. Traffic volume characteristics.
2. Roadway geometry.
3. Signal timing and hardware capabilities.

7.2.1 Traffic Volume Characteristics

The traffic characteristics used in an analysis can play a critical role in determining intersection treatments. Over-conservative judgment may result in economic inefficiencies due to the construction of unnecessary treatments or an oversized intersection, while the failure to account for certain conditions (such as a peak recreational season) may result in facilities that are inadequate and experience failing conditions during certain periods of the year.

An important element of developing an appropriate traffic profile is distinguishing between traffic demand and traffic volume. For an intersection, traffic demand represents the arrival pattern of vehicles, while traffic volume is generally measured as the number of vehicles that pass through the intersection over a specific period of time. In the case of overcapacity or constrained situations, the traffic volume typically does not reflect the true demand on an intersection because vehicles are queued upstream. In these cases, the user should develop a demand profile by measuring vehicle arrivals upstream of the overcapacity or constrained approach. The difference between arrivals and departures represents the vehicle demand that does not get served by the traffic signal. This volume should be accounted for in the traffic operations analysis.

Traffic volume at an intersection may also be less than the traffic demand due to an overcapacity condition at an upstream or downstream signal. If the constraint is upstream, traffic volumes would be metered at that location and "starve" the demand at the subject intersection; if the constraint is downstream, traffic could spill back to the subject intersection and impede traffic flow. These effects are often best accounted for using a microsimulation analysis tool.

7.2.2 Intersection Geometry

The geometric features of an intersection influence the service volume or amount of traffic an intersection can process. A key measure used to establish the supply of an intersection is saturation flow, which is similar to capacity in that it represents the number of vehicles that traverse a point per hour. However, saturation flow is reported assuming the traffic signal is green the entire hour. By knowing the saturation flow and signal timing for an intersection, one can calculate the capacity (capacity = saturation flow times the ratio of green time to cycle length). Saturation headway is determined by measuring the average time headway between vehicles that discharge from a standing queue at the start of green, beginning with the fourth vehicle.(2) Saturation headway is expressed in time (seconds) per vehicle.

Saturation flow rate is simply determined by dividing the average saturation headway into the number of seconds in an hour (3,600) to yield units of vehicles per hour. The *HCM 2010* uses a default ideal saturation flow rate of 1,900 vehicles per hour. Ideal saturation flow assumes the following:

- 12-ft wide travel lanes.
- Through movements only.
- Even lane utilization,
- Level grades.
- No curbside impedances
- No pedestrians/bicyclists.
- No central business district influences.

The *HCM 2010* provides adjustment factors for non-ideal conditions to estimate the prevailing saturation flow rate. Saturation flow rate can vary in time and location and has been observed to range between 1,500 and 2,000 passenger cars per hour per lane.(2) Given the variation that exists in saturation flow rates, local data should be collected where possible to improve the accuracy of the analysis.

Practitioners should evaluate existing or planned intersection geometry to determine features that may impact operations and that require special consideration.

7.2.3 Signal Timing and Hardware Capabilities

The signal timing of an intersection also plays an important role in its operational performance. Key factors include:

- **Effective green time.** Effective green time represents the amount of usable time available to serve vehicular movements during a phase of a cycle. It is equal to the displayed green time minus startup lost time. The effective green time for each phase is generally determined based on the proportion of volume in the critical lane for that phase relative to the total critical volume of the intersection. If not enough green time is provided, vehicle queues will not be able to clear the intersection, and cycle failures will occur. If too much green time is provided, portions of the cycle will be unused, resulting in inefficient operations and frustration for drivers on the adjacent approaches.

- **Change and clearance interval.** The change and clearance interval represents the amount of time needed for vehicles to safely clear the intersection. It includes the yellow change and red clearance intervals and is primarily set based on the speed of approaching vehicles and the width of the intersection. The effect of the change and clearance interval on capacity is dependent upon the lost time.
- **Lost time.** Lost time represents the unused portion of a vehicle phase. Lost time occurs twice during a phase: at the beginning when vehicles are accelerating from a stopped position, and at the end when vehicles decelerate in anticipation of the red indication. Longer lost times reduce the amount of effective green time available and thus reduce the capacity of the intersection. Wide intersections and intersections with skewed approaches or unusual geometrics typically experience greater lost times than conventional intersections.
- **Cycle length.** Cycle length determines how frequently during the hour each movement is served. It is a direct input, in the case of pre-timed or coordinated signal systems running on a common cycle length, or an output of vehicle actuations, minimum and maximum green settings, and clearance intervals. Cycle lengths that are too short do not provide adequate green time for all phases and result in cycle failures. Longer cycle lengths can result in increased delay and queues for all users, and may result in disobedience of the traffic signal and other aggressive driving behavior.
- **Phasing.** The phasing plan is based on the treatment of each left turn (protected, permitted, or protected-permitted). The number of phases at a signalized intersection, which is directly correlated with its treatment of left turns, impacts the operating capacity of the intersection as it affects effective green time for each movement.
- **Signal Technology.** Technology can play a significant role in the operating capacity of a signalized intersection. A pre-timed signal, which provides a fixed amount of green time to each intersection approach independent of actual traffic demand, is the simplest form of operation. Actuated signals rely on vehicle detection technology and generally operate more efficiently by extending signal phases when continuous demand is present and skipping phases that would not be servicing any vehicles. The most advanced signal technology, called adaptive signal control, uses sensors to read current traffic conditions and modify signal timings based on real-time information.
- **Progression.** Progression is the movement of vehicle platoons from one signalized intersection to the next. A well-progressed or well-coordinated system moves platoons of vehicles so that they arrive during the green phase of the downstream intersection. When this occurs, fewer vehicles arrive on red, and vehicle delays, queues, and stops are minimized. A poorly coordinated system moves platoons such that vehicles arrive on red, which increases the delay and queues for those movements beyond what would be experienced if random arrivals occurred.
- **Detector Technology.** Use of detector features and settings can impact operations positively or negatively. Employing features such as delay, lock, or switch can improve service to waiting or approaching vehicles and streamline intersection operations. Factors such as volumes, phasing, geometry, and driver characteristics (aggressive or passive) will help influence if and how detector settings are used, and how the controller receives those inputs.

7.3 GENERAL CONSIDERATIONS FOR SIZING AN INTERSECTION

This first level of analysis does not use formal models or procedures; instead, it relies on past experience and rules of thumb to offer a very coarse approximation. In spite of its obvious limitations, this approach can be used to size an intersection and determine appropriate lane configurations. Guidelines for determining intersection geometry at the planning level are shown in Exhibit 7-8.

Exhibit 7-8. Planning-level guidelines for sizing an intersection.

Geometric Property	Comment
Number of lanes[2]	As a general suggestion, enough roadway lanes should be provided to prevent a lane from exceeding 450 vehicles per hour. Mainline facilities that are allocated the majority of green time may accommodate higher volumes. Other elements that should be considered in the sizing of a facility include the number of upstream/downstream lanes, lane balance, signal design elements, pedestrian/bicycle effects, right-of-way constraints, and safety implications.
Exclusive left-turn lanes[2]	The decision to provide an exclusive left-turn lane should generally be based on the volume of left-turning and opposing traffic, intersection design, and safety implications. Exclusive left-turn lanes should be investigated when a left-turn volume exceeds 100 vehicles per hour. Dual left-turn lanes could be considered when the left-turn volume exceeds 300 vehicles per hour. On some facilities, left-turn lanes may be desirable at all locations regardless of volume.
Exclusive right-turn lanes[2]	The provision of right-turn lanes reduces impedances between lower speed right-turning vehicles and higher speed left-turning or through vehicles. Separating right turns also reduces the green time required for a through lane. Safety implications associated with pedestrians and bicyclists should be considered. In general, a right-turn lane at a signalized intersection should be considered when the right-turn volume and adjacent through lane volume each exceeds 300 vehicles per hour.
Left-turn storage bay length[3]	Storage bays should accommodate one and one-half to two times the average number of left-turn arrivals during a cycle.

7.4 CRITICAL LANE ANALYSIS

Critical lane analysis (CLA) is usually applied at the planning stage and represents the highest of the four levels of operational performance models.

The Quick Estimation Method (QEM) can be carried out by hand, although software implementation is much more productive. The computations themselves are somewhat complex, but the minimal requirement for site-specific field data (traffic volumes and number of lanes) allows the QEM to remain a simple procedure. While the level of output detail is simplified in comparison to more data-intensive analysis procedures, the QEM provides a useful description of the operational performance by answering the following questions:

- What are the critical movements at the intersection?
- Is the intersection operating below, near, at, or above capacity?
- Where are the capacity improvements needed?

The requirement for site-specific data is minimized through the use of assumed values for most of the operating parameters and by a set of steps that synthesizes a “reasonable and effective” operating plan for the signal. Exhibit 7-9 illustrates the various steps involved in conducting a QEM analysis, and Exhibit 7-10 identifies the various thresholds for the v/c ratio.

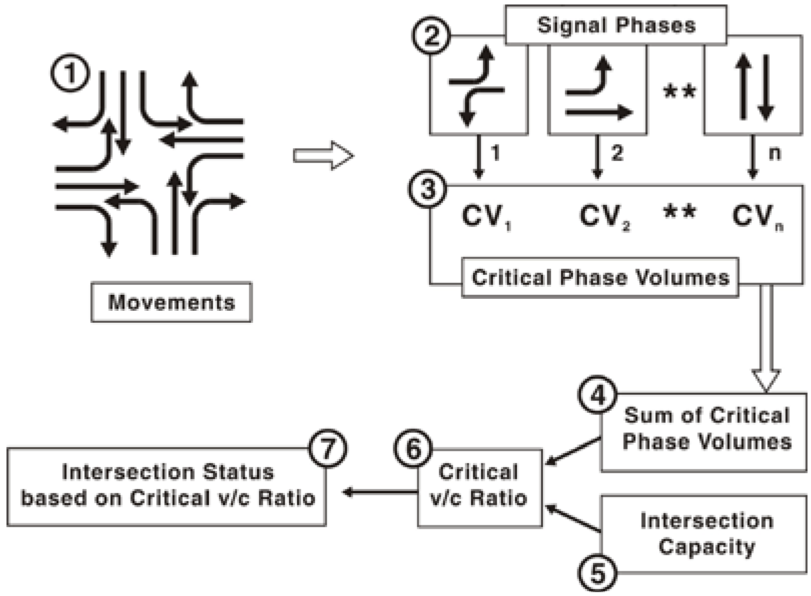


Exhibit 7-9. Graphical summary of the quick estimation method.

Step 1 – Identify movements to be served and assign hourly traffic volumes per lane. This is the only site-specific data that must be provided. The hourly traffic volumes are usually adjusted to represent the peak 15-minute period. The number of lanes must be known to compute the hourly volumes per lane.

Step 2 – Arrange the movements into the desired signal phasing plan. The phasing plan is based on the treatment of each left turn (protected, permitted, etc.). The actual left-turn treatment may be used, if known. Otherwise, the likelihood of needing left-turn protection on each approach will be established from the left-turn volume and the opposing through traffic volume.

Step 3 – Determine the critical volume per lane that must be accommodated on each phase. Each phase typically accommodates two non-conflicting movements. This step determines which movements are critical. The critical lane volume determines the amount of time that must be assigned to the phase on each signal cycle.

Step 4 – Sum the critical phase volumes to determine the overall critical volume that must be accommodated by the intersection. This is a simple mathematical step that produces an estimate of how much traffic the intersection needs to accommodate.

Step 5 – Determine the maximum critical volume that the intersection can accommodate. This represents the overall intersection capacity.

Step 6 – Determine the critical v/c ratio, which is computed by dividing the overall critical volume by the overall intersection capacity, after adjusting the intersection capacity to account for time lost due to starting and stopping traffic on each cycle. The lost time will be a function of the cycle length and the number of protected left turns.

Step 7 – Determine the intersection status from the critical volume-to-capacity ratio. The status thresholds are given in Exhibit 7-10.

Exhibit 7-10. V/C ratio threshold descriptions for the quick estimation method.[2]

Critical Volume-to-Capacity Ratio	Assessment
< 0.85	Intersection is operating under capacity. Excessive delays are not experienced.
0.85-0.95	Intersection is operating near its capacity. Higher delays may be expected, but continuously increasing queues should not occur.
0.95-1.0	Unstable flow results in a wide range of delay. Intersection improvements will be required soon to avoid excessive delays.
> 1.0	The demand exceeds the available capacity of the intersection. Excessive delays and queuing are anticipated.

Understanding the critical movements and critical volumes of a signalized intersection is a fundamental element of any capacity analysis. A CLA should be performed for all intersections considered for capacity improvement. The usefulness and effectiveness of this step should not be overlooked, even for cases where more detailed levels of analysis are required. The CLA procedure gives a quick assessment of the overall sufficiency of an intersection. For this reason, it is useful as a screening tool for quickly evaluating the feasibility of a capacity improvement and discarding those that are clearly not viable.

Some limitations of CLA procedures in general, and the QEM in particular:

- No provision exists for the situation in which the timing requirements for a concurrent pedestrian phase (such as for crossing a wide street) exceed the timing requirements for the parallel vehicular phase. As a result, the CLA procedure may underestimate the green time requirements for a particular phase.
- A fixed value is assumed for the overall intersection capacity per lane. Adjustment factors are not provided to account for differing conditions among various sites, and there is no provision for the use of field data to override the fixed assumption.
- Complex phasing schemes such as lagging left-turn phases, right-turn overlap with a left-turn movement, exclusive pedestrian phases, leading/lagging pedestrian intervals, etc., are not considered. Significant operational and/or safety benefits can sometimes be achieved by the use of complex phasing.
- Lost time is not directly accounted for in the CLA procedures. Therefore, the effect of longer change and clearance intervals cannot be directly accommodated with this procedure.
- The synthesized operating plan for the signal does not take minimum green times into account, and therefore may not be readily implemented as a part of an intersection design. The HCM specifically warns against the use of the QEM for signal timing design.
- Performance measures (e.g., control delay, LOS, and back of queue) are not provided.

For these reasons, it will be often necessary to examine the intersection using a more detailed level of operational performance modeling.

7.5 HCM OPERATIONAL PROCEDURE FOR SIGNALIZED INTERSECTIONS

For many applications, performance measures such as vehicle delay, LOS, and queues are desired. These measures are not reported by the CLA procedures, but are provided by macroscopic-level procedures such as the HCM operational analysis methodology for signalized intersections. This procedure is represented as the second analysis level in Exhibit 7-2 Macroscopic-level analyses provide results over multiple cycle lengths based on hourly vehicle demand and service rates. HCM analyses are commonly performed for 15-minute periods to accommodate the heaviest part of the peak hour.

The HCM analysis procedures provide estimates of saturation flow, capacity, delay, LOS, and back of queue by lane group for each approach. Exclusive turn lanes are considered as separate lane groups. Lanes with shared movements are considered a single lane group. Lane group results can be aggregated to estimate average control delay per vehicle at the intersection level.

The increased output detail compared to the CLA procedure is obtained at the expense of additional input data requirements. A complete description of intersection geometrics and operating parameters must be provided. Several factors that influence the saturation flow rates (e.g., lane width, grade, parking, pedestrians) must be specified. A complete signal operating plan, including phasing, cycle length, and green times, must be developed externally. As indicated in Exhibit 7-2, an initial signal operating plan may be obtained from the QEM, or a more detailed and implementable plan may be established using a signal timing model that represents the next level of analysis. Existing signal timing may also be obtained from the field.

In addition to the signalized intersection procedure, the HCM also includes procedures to estimate the LOS for bicyclists, pedestrians, and transit users at signalized intersections. These have been discussed previously in this chapter.

The *HCM 2010* provides a more detailed analysis procedure than previous editions as it now has improved methods for calculating delays and queues as well as for analyzing intersections with actuated signals.

Known limitations of the HCM analysis procedures for signalized intersections exist under the following conditions:

- Available software products that perform HCM analyses generally do not accommodate intersections with more than four approaches.
- The analysis may not be appropriate for alternative intersection designs.
- The effect of queues that exceed the available storage bay length is not treated in sufficient detail, nor is the backup of queues that block a stop line during a portion of the green time.
- Driveways located within the influence area of signalized intersections are not recognized.
- The analysis does not explicitly account for travel lanes added just upstream or dropped just downstream of the intersection.
- The effect of arterial progression in coordinated systems is recognized, but only in terms of a coarse approximation.
- Heterogeneous effects on individual lanes within multilane lane groups (e.g., downstream taper, freeway on-ramp, driveways) are not recognized.

If any of these conditions exist, it may be necessary to proceed to the next level of analysis.

7.6 ARTERIAL AND NETWORK SIGNAL TIMING MODELS

7.6.1 Introduction

Arterial and network signal timing models are also macroscopic in nature. They do, however, deal with a higher level of detail and are more oriented to operational design than the HCM. Most of the macroscopic simulation models for signalized intersections are designed to develop optimum signal timing along an arterial. These models are usually used to improve progression between intersections. The effect of traffic progression between intersections is treated explicitly, either as a simple time-space diagram or a more complex platoon propagation phenomenon. In addition, these models can explicitly account for pedestrian actuations at intersections and their effect on green time for affected phases.

These models attempt to optimize some aspect of the system performance as a part of the design process. The two most common optimization criteria are quality of progression as perceived by the driver, and overall system performance, using measures such as stops, delay, and fuel consumption. As indicated in Exhibit 7-2, the optimized signal timing plan may be passed back to the HCM analysis or forward to the next level of analysis, which involves microscopic simulation.

While the signal timing models are more detailed than the HCM procedures in most respects, they are less detailed when it comes to determining the saturation flow rates. The HCM provides the computational structure for determining saturation flow rates as a function of geometric and operational parameters. On the other hand, saturation flow rates are generally treated as input data by signal timing models. The transfer of saturation flow rate data between the HCM and the signal timing models is therefore indicated in Exhibit 7-2 as a part of the data flow between the various analysis levels.

7.6.2 Developing a Macroscopic Simulation Model

Arterial and network models represent traffic flow by considering traffic stream characteristics like speed, flow and density and their relationship to each other. These macroscopic models do not track individual vehicles and their interactions, but rather employ equations of known traffic flow behavior on the roadway facility being analyzed. Versions of these models have been designed for specific types of facilities, but their application is usually limited to those unique applications (such as unconventional or alternate design configurations). Macroscopic analysis models are also limited by the inability of the embedded models to accurately model oversaturated conditions. Specifically, signalized intersection models have some limitations in estimating the delay experienced, number of stops, and queue length in oversaturated conditions. Some arterial and network model developers have attempted to overcome these issues by varying flow levels and performing input/output flow checks at intersections. However, the typical practice is to apply microscopic simulation models if the effects and extent of arterial or network congestion need to be analyzed.

Macroscopic models require the following four types of data to be collected.

- Traffic data comprising traffic volumes and turning movement counts are typically collected in 15-minute increments and usually the peak one hour count and the peak 15-minute count within that one hour will be identified as input data into the model. These counts are made for periods of interest within a day, which typically includes the AM peak, PM peak, and off-peak periods.
- Geometric data such as the number of lanes and lane assignment at the intersection, as well as turn bay presence and length.
- Phasing data that can be implemented will depend on existing geometry, signal head locations and configurations, and the signal controller's capabilities.
- Requirements of pedestrians and other intersection users like rail and transit will have a significant impact on signal timing.

The additional detail present in the signal timing models overcomes many of the limitations of the HCM for purposes of operational analysis of signalized intersections. It will not generally be necessary to proceed to the final analysis level, which involves microscopic simulation, unless complex interactions take place between movements or additional outputs, such as animated graphics, are considered desirable.

7.7 MICROSCOPIC SIMULATION MODELS

7.7.1 Introduction

For cases where individual cycle operations and/or individual vehicle operations are desired, a microscopic-level analysis should be considered to supplement the aggregate results provided by the less detailed analysis levels. Microscopic analyses are performed using one or more of an increasing range of available microsimulation software products. Microsimulation analysis tools are based on a set of rules used to propagate the position of vehicles from one time step (usually each second) to the next. Rules such as car following, lane changing, yielding, response to signals, etc., are an intrinsic part of each simulation software package. The rules are generally stochastic in nature; in other words, there is a random variability associated with multiple aspects of driver decision-making in the simulated environment. Some simulation models can explicitly model pedestrians, enabling the analyst to study the impedance effects of vehicles on pedestrians and vice versa.

Microscopic models produce similar measures of effectiveness as their macroscopic counterparts, although minor differences exist in the definition of some measures. Microscopic model results typically include pollutant discharge measures. Interestingly, one of the most important measures, capacity, is notably absent from simulation results because the nature of simulation models does not lend itself to capacity computations. Rather than being a model input, capacity is an outcome produced by the driver behavior rules intrinsic to the model and the modeler's calibration adjustments to realistically replicate field conditions.

Microscopic simulation models also can be used to identify a condition's duration, and can account for the capacity and delay effects associated with known system-wide travel patterns. Because microscopic models track the behavior of individual vehicles within a given roadway environment, they are often more realistic in representing traffic flow and queuing propagation under congested conditions than macroscopic tools. As a result, output measures of effectiveness for congested networks from microsimulation models are often more representative than those produced by macroscopic methods or tools.

Microscopic simulation tools can be particularly effective for cases where intersections are located within the influence area of adjacent signalized intersections and are affected by upstream and/or downstream operations. In addition, graphical simulation output may be desired to verify field observations and/or provide a visual description of traffic operations for an audience. Several modern simulation tools allow analysts to render their roadway network simulation in two or three dimensions, allowing the model to serve not only its analytical purpose but also as a demonstration and public involvement tool.

7.7.2 Developing a Microsimulation Model

In the past, the level of effort involved with developing a microscopic simulation network was greater than that of a macroscopic analysis, and significantly greater than a CLA. However, recently there have been significant strides in modeling tool integration and user interface development. Some macroscopic intersection analysis tools currently feature conversion utilities to generate a draft input file for a microsimulation model, or even feature the developer's own microsimulation model as part of an integrated traffic analysis and modeling suite. Like the HCM operational procedure, microscopic simulation tools require a fully specified signal-timing plan that must be generated externally; however, in the case of an integrated signal optimization and microsimulation modeling suite of tools, alternative timing plans can be developed and modeled at the microscopic level with the literal "press of a button." Unlike the HCM, calibration effort using field data is essential to the production of credible results. For this reason, the decision of whether to use a microscopic simulation tool should be made on a case-by-case basis, considering the resources available for acquisition of the software and for collecting the necessary data for calibrating the model to the intersection being studied. The typical steps in a successful microsimulation modeling effort include:

Step 1—Identify the scope of the model. For signalized intersections or arterials, this will include the subject intersection or roadway corridor and adequate length of roadway segments at the model boundaries to permit lane changing and full queue storage for signalized and unsignalized intersections (including driveways, etc.) in the model.

Step 2—Collect and organize field data. Data requirements include traffic volume data (either roadway directional counts and intersection turning movements counts, or roadway counts and origin-destination routing data, depending on model type), geometric data (road segment lengths and number of lanes, length and number of turn bays, etc.) and traffic control data (lane markings, signing, signals and their timing plans). Field performance measures such as arterial average speed or average queue lengths should also be collected, as these measures are commonly used for model calibration and validation.

Step 3—Develop the current condition, or base, model in the microsimulation tool. Note that almost all modern microsimulation models allow analysts to create their networks by “drawing” them over scaled background aerial photography, greatly reducing model development time.

Step 4—Verify that the model performs as observed in the field, correcting any logical or coding errors where present and re-running the model. Calibration adjustments to aspects of the driver behavior model(s) may be necessary to accurately reflect field conditions; all such adjustments must be documented.

Step 5—Validate the model. Microsimulation model validation is an essential step in producing credible results. Validation typically takes the form of statistical tests comparing average output from multiple runs of the microsimulation model and the same output measures collected in the field (see Step 2).

Step 6—Perform final current condition model runs and summarize output. The number of runs to perform in generating the final performance measures are affected by network size and performance variability, with larger networks and congested networks requiring more modeling runs to ensure statistically valid results. At least five (5) microsimulation modeling runs should be performed as a general rule, and the results averaged for presentation.

Step 7—Develop alternatives. Using the current/base model as a departure point, create a new version of the network for each set of alternative conditions requiring analysis. Ensure that the same calibration settings used in the validated, current condition model are used for all alternatives.

Step 8—Perform final runs of alternative model(s) and summarize output. As in Step 6, the number of final runs for each alternative is dependent on network size and performance variability. Typical practice is to perform the same number of runs of each alternative model as were conducted for the base model.

Step 9—Presentation and reporting. As with any analysis process, the final step in using microsimulation models is the presentation of output measures of performance and the assessment of alternatives based on those measures. The two- or three-dimensional renderings of the modeled network possible with modern microsimulation tools can be a valuable method for familiarizing professionals and the public with the modeling process and increasing audience confidence in both the tool and its results.

7.8 OPERATIONAL PERFORMANCE MODEL SELECTION

Situations vary widely based on a multitude of factors. Practitioners should strive to choose the right tool for their intersection needs. Often models can be combined in some way by practitioners to address their particular situation.

The first step is identification of the analytical context for the task: planning, design, or operations/construction. Seven additional criteria are necessary to help identify the analytical tools that are most appropriate for a particular project. Depending on the analytical context and the project's goals and objectives, the relevance of each criterion may differ. The criteria include:

1. Ability to analyze the appropriate **geographic scope** or study area for the analysis, including isolated intersection, single roadway, corridor, or network.
2. Capability of modeling various **facility types**, such as freeways, high-occupancy vehicle (HOV) lanes, ramps, arterials, toll plazas, etc.
3. Ability to analyze various **travel modes**, such as single-occupancy vehicle (SOV), HOV, bus, train, truck, bicycle, and pedestrian traffic.
4. Ability to analyze various **traffic management strategies and applications**, such as ramp metering, signal coordination, incident management, etc.
5. Capability of estimating **traveler responses** to traffic management strategies, including route diversion, departure time choice, mode shift, destination choice, and induced/foregone demand.
6. Ability to directly produce and output **performance measures**, such as safety measures (crashes, fatalities), efficiency (throughput, volumes, vehicle-miles of travel (VMT)), mobility (travel time, speed, vehicle-hours of travel (VHT)), productivity (cost savings), and environmental measures (emissions, fuel consumption, noise).
7. **Tool/cost-effectiveness** for the task, mainly from a management or operational perspective. Parameters that influence cost-effectiveness include tool capital cost, level of effort required, ease of use, hardware requirements, data requirements, animation, etc.

Exhibit 7-11 summarizes the criteria that may be considered for the selection of a tool category.

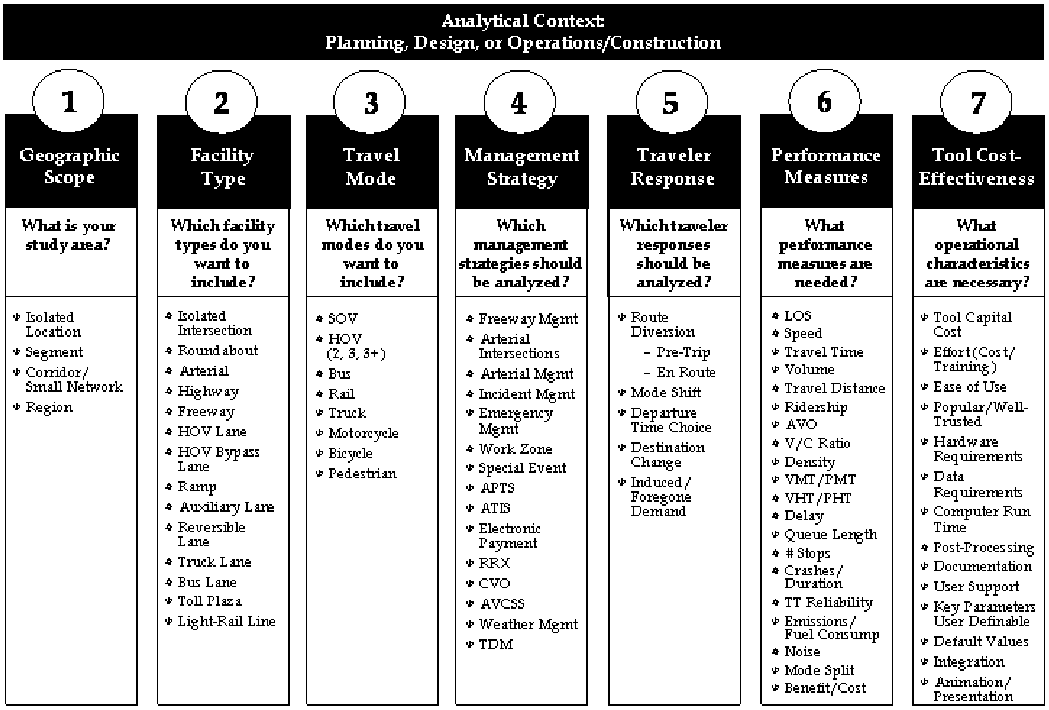


Exhibit 7-11. Criteria for selecting a traffic analysis tool category.
Source: FHWA *Traffic Analysis Tools, Volume 2,* 2004.

Situations vary widely based on a multitude of factors. Practitioners should strive to choose the right tool for their intersection needs. Additional guidance is available from the *FHWA Traffic Analysis Tools* website at http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol2/index.htm.