

**A Framework and Analytical Methods for Evaluation of
Preferential Treatment for Emergency and
Transit Vehicles at Signalized Intersections**

William C. Louisell

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John Collura, Chair

Antoine Hobeika

Dusan Teodorovic

Eileen Van Aken

Sam Tignor

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(ABSTRACT)

Preferential treatments are employed to provide preemption for emergency vehicles (EV) and conditional priority for transit vehicles at signalized intersections. *EV preemption* employs technologies and signal control strategies seeking to reduce emergency vehicle crash potential and response times. *Transit priority* employs the same technologies with signal control strategies seeking to reduce travel time and travel time variability. Where both preemption and transit technologies are deployed, operational strategies deconflict simultaneous requests. Thus far, researchers have developed separate evaluation frameworks for preemption and priority.

This research addresses the issue of preemption and priority signal control strategies in breadth and depth. In breadth, this research introduces a framework that reveals planning interdependence and operational interaction between preemption and priority from the controlling strategy down to roadway hardware operation under the inclusive title: *preferential treatment*. This fulfills a current gap in evaluation. In depth, this research focuses on evaluation of EV preemption.

There are two major analytical contributions resulting from this research. The first is a method to evaluate the *safety benefits* of preemption based on conflict analysis. The second is an algorithm, suitable for use in future traffic simulation models, that incorporates the impact of auto driver behavior into the determination of *travel time savings* for emergency vehicles operating on signalized arterial roadways. These two analytical methods are a foundation for future research that seeks to overcome the principal weakness of current EV preemption evaluation.

Current methods, which rely on modeling and simulation tools, do not consider the unique auto driver behaviors observed when emergency vehicles are present. This research capitalizes on data collected during a field operational test in Northern Virginia, which included field observations of emergency vehicles traversing signalized intersections under a wide variety of geometric, traffic flow, and signal operating conditions. The methods provide a means to quantify the role of EV preemption in reducing the number and severity of conflict points and the delay experienced at signalized intersections. This forms a critical basis for developing deployment and operational guidelines, and eventually, warrants.

Dedication

I would like to dedicate this work to my late mother, Ann Gaines Louisell. Ann believed strongly in the value of education and she devoted her life to ensuring each of her children received the benefit of every educational opportunity she could afford them.

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Many individuals have assisted me on the way to this goal. Many will go unnamed but that does not diminish the value of the experience that I have had with them.

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Like most accomplishments, this one took a team effort. I would like to thank my research team associates Manoj Mittal and Vinit Deshpande (both of whose work I reference) for their help in this project, their friendship, and the fun we had while discovering our way to our objectives.

Finally, I would like to thank my wife, Lisa, and my daughter, Chandler, who have encouraged me through six years of graduate studies in concert with a full time job and a busy life. Thank you both for your support and for taking me away from the computer to make sure I experienced our life along the way. Your support has allowed me to keep this goal in sight allowing me to define a platform for a new pursuit and lifestyle for us all.

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CHAPTER 1: INTRODUCTION

This chapter provides a discussion and review of preferential treatment systems designed to provide traffic signal preemption for emergency vehicles (EVs) and traffic signal priority for transit vehicles. The need for an evaluation framework examining the benefits and impacts of joint deployments for both preemption and priority is introduced as the breadth component of this research. Additionally, the need for improved analytical methods to assess the safety impacts for EV preemption is introduced as the depth component. Also provided in this chapter is an outline of the remaining chapters for this dissertation.

1.1 PREFERENTIAL TREATMENT AT TRAFFIC SIGNALS

Preferential treatments are deployed to provide preemption for emergency vehicles and conditional priority for transit vehicles at signalized intersections. EV preemption employs technologies and traffic signal control strategies seeking to reduce emergency vehicle crash potential and response times. Transit vehicle priority employs the same technologies with traffic signal control strategies seeking to reduce total route travel time and the variation in travel times. In cases where both are deployed, traffic signal control strategies deconflict simultaneous requests according to vehicle class hierarchy and conditional strategies established by the operating agency.

Preferential treatment systems generally involve a vehicle request for a green phase extension or for an early green recall to facilitate safe and efficient intersection passage at the highest practical speed. The preferential treatment process begins with a request from the vehicle. The request is sent via an emitter using a coded infrared beam. A detector on the signal arm receives the request and transmits it via cable to a signal phase selector, which identifies the request type (EV preemption or transit priority); polls the signal controller for the current signal status; and then determines if the predetermined qualifying conditions are met. Once this validation process is complete, the signal phase selector instructs the signal controller to grant the request and follows preprogrammed phase transition sequences consistent with the Manual on Uniform Traffic Control Devices (MUTCD) and local procedures. A schematic diagram of the preferential treatment process and physical architecture is shown in Figure 1.1.

A preferential treatment request that is granted results in a green light on the requesting intersection approach. Because preferential treatment temporarily interrupts the normal signal phasing sequence and timing plans (including offsets in coordinated signal systems), the signal controller executes a recovery strategy selected by the signal-operating agency. The recovery strategy reestablishes all aspects of the signal-timing plan over a series of signal cycles. Normally, the number of cycles used in the recovery process is three or six using factory encoded transition algorithms; however, signal-operating agencies may develop custom recovery plans consistent with local needs.

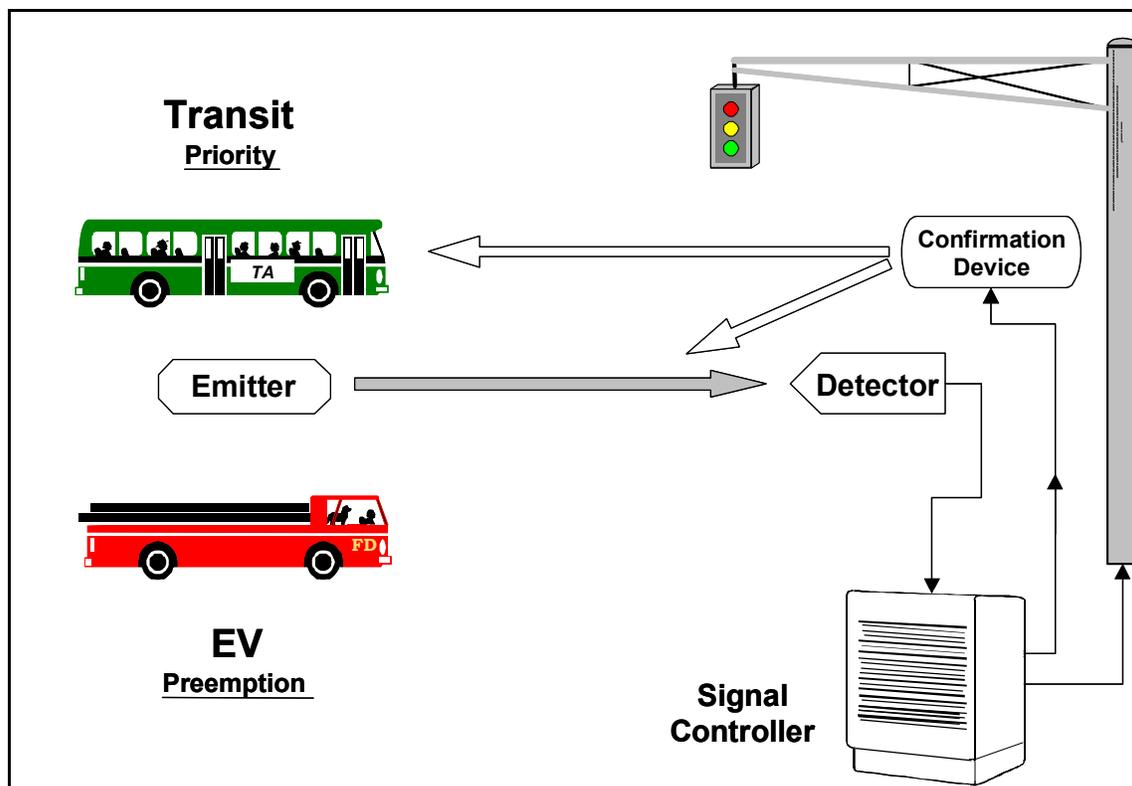


Figure 1.1. Physical Architecture of Preferential Treatment Systems

1.2 PREFERENTIAL TREATMENT SYSTEMS EVALUATION

Preferential treatments are not new to the traffic operations community; yet, these systems have recently received increased attention as part of the community's interest in using Intelligent Transportation Systems (ITS) to offset the negative impact of ever increasing congestion on signalized arterials. Emergency vehicles and transit vehicles are not unaffected by the higher congestion levels. For emergency vehicles, the potential for crashes increases as emergency vehicles traverse signalized intersections operating at higher volumes, and the time to respond to calls is increased as emergency vehicles must often penetrate static queues stopped at red signals. For transit vehicles, in many jurisdictions under normal conditions, signal systems operate with extended cycle times designed to promote progression of high automobile traffic volumes. Under these conditions, route run times for transit vehicles are increased due to extended control delays, which significantly reduce average operating speeds. In addition, the extended control delays introduce wide variation in the time required to serve a specific route at a specific time of day.

In the past 10 years, the United States Department of Transportation (USDOT) has taken significant interest in measuring ITS deployment impacts and in establishing methods to determine the costs and benefits associated with specific technologies and concepts. With the Intermodal Surface Transportation Efficiency Act and the Transportation Equity Act for the 21st Century, there is an accelerated interest in assessing the benefits associated with all ITS projects. The Federal Highway Administration (FHWA) created the ITS Joint Program Office (JPO),

whose charge is to promote the study and documentation of associated costs and benefits of ITS. Preferential treatments at signalized intersections are included in this charge.

Within the ITS community, many stakeholder groups have devoted significant efforts in determining the associated costs and benefits of ITS solutions. These ITS solutions seek to leverage the performance of traditional transportation infrastructure components by integrating technologies that detect specific conditions and activate specific response strategies. For the fire and rescue community, EV preemption offers the capability to reduce both the potential for crashes at signalized intersections and the time required to travel to the scene of a traffic incident, medical emergency, house or business fire, major industrial accident, or even a terrorist attack. For the transit community, transit vehicle priority offers the potential to reduce route run times and variation in route run times improving on-time performance.

1.3 REVIEW OF CURRENT ASSESSMENT METHODS

Thus far, researchers have followed distinctly separate evaluation pathways and employed unique data collection methods to evaluate EV preemption and transit priority. These data collection methods have included interviews with stakeholders, field data collection, computer simulation and modeling, or combinations of some or all of the individual methods.

1.3.1 EV Preemption

Some of the earliest evaluations focused on EV preemption as a safety enhancement. However, over the last three decades, there has been increased emphasis on the reduction of emergency vehicle travel time. In 1977, the St. Paul, Minnesota Department of Fire and Safety Services conducted an analysis of emergency vehicle crash frequency (Letter from the Fire Chief, 1977), and, in 1978, the City of Denver, Colorado Department of Public Safety evaluated *before* and *after* emergency vehicle crash histories and travel times as the basis for deployment recommendation (City of Denver, Department of Safety, 1978). In a 1991 study for the Houston Metropolitan Transit Authority, a private engineering company conducted a field test for the City of Houston, Texas, to examine the *before* and *after* emergency vehicle response time improvement based on the installation of preemption systems on 22 intersections (11 intersections in two different districts). This evaluation indicated a 16% improvement in one district, and a 23 % improvement in the other (Traffic Engineers, Inc., 1991).

In recent years, while the safety aspect of EV preemption has received little attention, the time-savings potential is being heavily researched using computer simulation (McHale and Collura, 2003) (Bullock, Morales, and Sanderson, 2003) (Nelson and Bullock, 2000). Computer simulation overcomes the high cost of field data collection and allows researchers to examine various operational strategies under a range of operating conditions designed to expose sensitivities and generate control parameter values that correspond to optimum system performance.

A key element to using more sophisticated and matured analysis methods is to incorporate the potential policy parameters needed to meet the various stakeholder needs. Gifford, Pelletiere, and Collura (2001) conducted an extensive effort to establish the prevailing knowledge level of, requirements of, and biases of stakeholders as an initial step in developing a Washington D. C.

regional study of EV preemption and transit priority (Gifford et al., 2001). These efforts resulted in the design and execution of a Field Operational Test (FOT), which produced the bulk of the data used for the research effort documented in this dissertation.

1.3.2 Transit Priority

Transit priority evaluations have also received significant attention in the past 3 years. Localities desiring to meet clean air standards and transit operators desiring to increase ridership have partnered to fund significant research efforts aimed at proving the benefit as part of their applications for federal funding. Most of this research has made use of computer simulation using INTEGRATION, CORSIM, and most recently, VISSIM.

INTEGRATION (Chang, 2002) and CORSIM (City of Bremerton, 1997) were successfully used to gain insights into schedule reliability improvements and route run time reduction, as well as the impact to autos on the side streets. In addition to these familiar models, a new model, VISSIM, was recently used in evaluating transit operations based on its ability to include stochastic passenger demand at bus stops and variations in operations policies and bus stop design (Wadjas and Furth, 2003). VISSIM combines the ability to model transit operating characteristics with the ability to program conditional transit priority strategies into traffic signal performance within the simulation. This program offers the potential to gain very granular data relative to the performance of transit priority systems. VISSIM also provides a means to assess fundamental signal system performance elements such as green phase extension and green phase recall strategies along with variation in splits, cycle length, and offsets before, during, and after a priority request (Ivanovic, et al., 2002).

1.4 PROBLEM STATEMENT

There is a need for an evaluation framework to examine both preemption and priority under the title of *preferential treatment*. This broader framework should extend the scope of evaluation to a system level that considers the major components and interactions. Such a tool will be useful to stakeholders (policy makers, transportation planners, traffic engineers, fire and rescue planners, fire and rescue system operators, transit vehicle system planners, and transit vehicle system operators) across the entire preferential treatment deployment process. The current tools adequately address specific elements of this process; however, there is no end-to-end, holistic process by which preemption and priority deployment sites are identified, prioritized, selected, designed, and operated. A holistic process is needed to provide the highest overall benefit, with the lowest level of interference between targeted beneficiaries at an acceptable level of impact to other user groups.

Within the EV preemption component, there is a need for analytical methods, applicable in the field, to evaluate the entire range of EV preemption benefits and impacts. These methodologies must function with the type and quantity of data available to the decision makers in the design and deployment of EV preemption systems. The methodologies must address emergency vehicle safety benefits and travel time savings, as well as the potential negative impact to other roadway users in the form of increased control delay. Quantifiable measurements will benefit the profession and industry providing the understanding required to support EV preemption deployment decisions.

1.5 RESEARCH GOALS

There is a two-fold goal involved with the research contained in this dissertation. The first is to formulate an evaluation framework for preferential treatment of emergency and transit vehicles at signalized intersections that satisfies the spectrum of need from the planning level down to the operational level. The second is to develop the analytical methods required to evaluate the safety and travel time benefits for emergency vehicles.

In terms of breadth, this research seeks to develop a framework that reveals planning interdependence and operational interaction from the controlling strategy level down to the roadway and hardware level. This will fulfill the need for an evaluation framework that examines both preemption and priority under the inclusive title of *preferential treatment*. In depth, this research will focus on EV preemption in terms of benefits to the emergency vehicles in the form of reduced crash potential and reduced delay at signalized intersections.

The major analytical contribution of this research includes developing methods to evaluate emergency vehicle safety benefits and travel time benefits associated with EV preemption. Current evaluation methods rely on modeling and simulation to measure EV preemption benefits. Because none of the current traffic simulation approaches include driver behavior parameters or crash modeling, the simulation approaches are unable to provide insight into the potential safety benefits. Further, limitations within the simulation algorithms prevent accurate assessment of the potential travel time benefits. This research intends to capitalize on observations and data collected during a FOT in Northern Virginia. The research introduces several concepts, definitions, and measurement techniques required to support the analytical methods that will increase the qualitative and quantitative understanding of the benefits associated with EV preemption.

1.6 CENTRAL PREMISE AND HYPOTHESIS

The overall research approach centers on the premise stated as follows:

Emergency and transit vehicles will benefit from *preferential treatment strategies* with minimum negative impact on other users. Further, the degree of benefit and impact is directly dependent on the operational environment, which is defined as the interaction of the geometric properties of the roadway, the signal strategies, and the characteristics and flow of the primary user classes (emergency vehicles, transit vehicles, other traffic, and pedestrians).

The following hypotheses, derived from the previously stated premise, form the basis for evaluation to be conducted in this research:

- For *EV preemption*, benefits accrue in the reduction of crash potential when emergency vehicles cross a signalized intersection, and in the reduction in delay caused when emergency vehicles approach and pass through signalized intersections during a red signal phase.
- For *transit vehicle priority*, the benefits accrue in the reduction of travel time over a measured route segment, and in the reduction in the variation in travel time.

- For *other users*, the impact is increased control delay on the mainline and the side streets.

1.7 DOCUMENT ORGANIZATION

This dissertation document provides a report on the research conducted over the period January 2002 to May 2003. The remaining chapters contained in this document are organized in the following manner, with Chapter 3, 4, and 5 also reporting on the research objectives:

- Chapter 2—Literature Review: This chapter details pertinent empirical and secondary research sources that are cited via excerpts and synopses to support this dissertation.
- Chapter 3—A Framework for Evaluation of Preferential Treatment Systems: This chapter introduces an overarching evaluation framework, which establishes a holistic understanding regarding the evaluation issues associated with preferential treatment, and suggests a framework that may guide future research and evaluation.
- Chapter 4—An Analytical Method to Evaluate Safety Benefits: This chapter presents the analytical methods developed to fill critical gaps in the ability for researchers to evaluate the safety benefits of emergency preemption.
- Chapter 5—An Analytical Method to Evaluate Travel Time Benefits: This chapter presents the analytical methods developed to fill critical gaps in the ability for researchers to evaluate the travel time benefits of emergency preemption.
- Chapter 6—Conclusions and Recommendations: This chapter offers conclusions and recommendations for future research.
- Appendix A— Use of the CART Algorithm: This appendix reports on the data analysis, which supports the analytical method presented in Chapter 4.
- Appendix B— Emergency Vehicle Crash Analysis: This appendix reports on a study of emergency vehicle crash analysis. The findings of this study support development of the analytical method presented in Chapter 4.
- Appendix C— Fire and Rescue Response Time Goals: This appendix reports on a study of emergency vehicle response time goals across the four counties that make up the Northern Virginia region. The findings of this study support development of the analytical method presented in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

This chapter identifies the purpose and structure of the literature review that supports this research effort. The following elements are identified and outlined: key literature categories; the connection between research for this dissertation with previously conducted research at the Virginia Polytechnic Institute and State University; and key supporting works and industry concepts.

2.1 PURPOSE

The purpose of the literature review is to identify and synthesize appropriate references to establish a baseline understanding and to identify knowledge gaps that may be addressed in this research. References include journal articles, conference papers, published reports, and other readily available sources of information, such as selected Web pages from the Internet. The literature review also presents evidence that supports or rejects the theories and supporting hypotheses presented in this dissertation

2.2 LITERATURE CATEGORIES

Literature used to support this research spans across several individual domains of transportation and traffic engineering reflecting the cross-cutting research objective and the integrative nature of the work. Five distinct areas are searched: EV preemption; transit vehicle priority; traditional traffic and transportation engineering principles; simulation tools for evaluating traffic flow; and national, state, and local codes and ordinances.

- *EV preemption* was reviewed to determine the state of the art in terms of operational evaluation, planning considerations, and methods for evaluation derived from simulation and field studies.
- *Transit vehicle priority* was reviewed to determine the state of the art in terms of operational evaluation, planning considerations, and methods for evaluation derived from simulation and field studies.
- *Traditional traffic and transportation engineering principles* were reviewed to find linkages to accepted methodologies and to establish the theoretical basis for evaluating preemption and priority systems and strategies.
- *Simulation tools* were reviewed to determine which tools possess the intrinsic capabilities to model the preemption and priority phenomena.

2.3 EV PREEMPTION

2.3.1 *EV Preemption Overview*

Traveling with Success, (Public Technology, Inc., sponsored by USDOT, 1995).

This pamphlet summarizes how local governments use ITS to improve safety and efficiency in transportation and traffic operations. The document states that the main objective of traffic signal

preemption is to improve response times for fire and medical emergencies and enhance public safety by eliminating conflicts between emergency vehicles and cross-street traffic. This statement supports the overall goal of this research, and it provides measurable statements of desired outcomes upon which evaluation concepts are built.

Stakeholder Requirements for Traffic Signal Preemption and Priority in the Washington D.C. Region, (Gifford, Pelletiere, and Collura, J., 2001).

In this study, the authors conduct a stakeholder requirements review in the Washington D.C. area. Researchers include interviews with stakeholders in Northern Virginia, Washington D.C., and Maryland in an effort to determine attitudes, issues, and barriers. The study identifies three major stakeholder communities: fire and rescue; transit operations; and traffic operations. The authors found that the relationship between the traffic operations and fire and rescue communities was more developed than the relationship between the traffic operations and transit operating communities. Further, the fire and rescue community express concern that integrated deployment of preemption and priority may reduce the effectiveness of preemption systems.

The traffic operations community, while concerned over disruption to signal-timing plans and traffic flow by preemption, was more willing to allow preemption in the interest of public safety than it was to put signal-timing plans and traffic flow at risk for priority.

Traffic Signal Preemption and Priority: Technologies, Past Deployments, and System Requirements, (Collura, Chang, and Wilhaus, 2001).

This study reviews technologies employed in EV preemption and transit priority systems across the United States. The study identifies the general logical and physical architectures employing technologies that consist of an emitter on the vehicle, a detector on the traffic signal arm, a preemption/priority control module, and an interface with the traffic signal controller. Technologies include light, infrared, and sound-based systems that possess various performance characteristics, and various levels of interoperability and utility in joint preemption/priority system deployments. The study was conducted to support a regional study in the Washington, D.C. area.

Traffic Signal Preemption Study, (Asmussen, et al., for the Virginia Department of Transportation [VDOT], September 1997).

This study, conducted in 1997, by VDOT includes a survey of all 50 states to determine both the extent of EV preemption system deployment and the maturity of deployment guidelines and operational procedures. Survey results indicated that 94% of the responding 50 agencies had deployed traffic signal preemption systems; however, in the jurisdictions with EV preemption, the systems were implemented on only a small percentage of their traffic signals.

2.3.2 EV Preemption Performance Measurement

An Assessment Methodology for Emergency Vehicle Traffic Signal Priority Systems (McHale, 2002).

McHale's dissertation examines the ITS Deployment Analysis Software (IDAS) (developed by the FHWA to aid policymakers in ITS deployment decisions) regarding traffic signal preemption for emergency vehicles. Through the use of CORSIM, McHale sought to enhance the benefit estimates (reduced travel time by the emergency vehicle) and impact estimates (increased delay to cross-street traffic) used in IDAS. The results are determined using CORSIM to emulate the provision of preemption at a signal located within a seven-signal series along an arterial roadway. Benefits are quantified in terms of reduced travel time and increased travel speed. Impact to cross-street traffic and the time period to restore the network to equilibrium flows is also quantified. Travel time reductions of 30% are indicated with minor increases in delay to cross-street traffic. Due to CORSIM limitations in being able to manage the dynamics associated with driver behavior in the presence of emergency vehicles, this research needs to be validated in field tests along arterials employing preemption at successive intersections along a corridor segment of interest.

A Macroscopic Model for Evaluating the Impact of Emergency Vehicle Signal Preemption on Traffic, (Casturi, Lin, and Collura, 2000).

This study proposes that the current microscopic simulation methods are unable to model EV preemption due to their inability to emulate the nonstandard driver behaviors that occur in the presence of emergency vehicles. As a result, most prior evaluation depended on expensive field studies that are difficult to execute in an environment in which the frequency of observations is low. The authors state that none of the currently available simulation models have the capability to model the presence of emergency vehicles and simulate the traffic dynamics of the vehicles surrounding them.

This study presents a macroscopic traffic model for examining the effect of signal preemption for emergency vehicles on traffic control measures, roadway capacity, and delays incurred by the vehicles on the side streets. The model is based on the cell transmission model, which is consistent with the hydrodynamic theory of traffic flow. The authors develop an analogy in which an emergency vehicle represents a moving bottleneck as overtaken cars pull out of the emergency vehicle's path. Analysis results were generated under various base traffic conditions and emergency vehicle arrival points within the signal cycle. Performance measures were obtained for such elements as average vehicle delay, maximum delay, and standard deviation of delay to traffic on all approaches. The model examined a single intersection working in isolation indicating a need for further application of the model to a more complex network.

Evaluation of Emergency Vehicle Signal Preemption on the Route 7, Virginia, Corridor, (Bullock, Morales, Sanderson, 1999).

This study analyzes the impact of emergency vehicle traffic signal preemption across three coordinated intersections on Route 7 near Landsdowne, Virginia. FHWA's Traffic Software Integrated System (TSIS) package (which includes the CORSIM microscopic traffic simulation) was used to perform the analysis. Hardware-in-the-loop analysis was performed using a controller interface device, which allowed CORSIM to directly interface with Type 170 traffic signal controllers supplied by VDOT. Results showed that the impact on other traffic is statistically significant; however, it is minimal with a 2.4% increase in average travel time when

priority is requested. While the authors were able to employ a “hardware-in-the-loop” method to overcome signal control simulation issues associated with CORSIM, the lack of CORSIM’s consideration of realistic driver behavior in the presence of emergency vehicles may skew the results.

Impact Evaluation of Emergency Vehicle Preemption on Signalized Corridor Operation, (Nelson and Bullock, 2000).

In this paper, Nelson and Bullock report on the results of a microsimulation analysis of traffic signal preemption for emergency vehicles. The paper examines the impact of various transition algorithms used to control entry and exit from preemption control. Three common transition algorithms are examined: smooth; add only; and dwell. The purpose of the transition algorithms is to bring the signal back into the cycle length, phase splits, and offsets associated with the specific signal-timing plan in effect.

For the “smooth” transition algorithm, the signal controller selects a shortened or extended cycle length over a preset number of cycles to bring the signal back into coordination. The traffic signal controller determines whether it or not it is quicker to add or subtract this time from the timing cycle.

An “add only” transition algorithm employs the same method, but will only execute an option that extends the cycle length by a percentage commensurate with the number of recovery cycles selected by the traffic engineer. The advantage of the “add only” method is that no truncated cycles are executed. The disadvantage is that it may take more cycles to reset coordination parameters unless the traffic engineer allows an excessive (up to 33%) addition to take place.

The “dwell” transition method inserts a pause in the current signal phase until a point in time when coordination is regained. This method is the quickest; however, the adverse impact to side-street traffic is maximum.

The authors use CORSIM on a diamond interchange with hardware-in-the-loop to simulate real-world traffic signal controllers. The authors identify the following factors as affecting the impact of EV preemption: intersection spacing; transitioning algorithm; intersection saturation; duration of the preemption; and the amount of slack time available in each intersection’s cycle.

Emergency Vehicle Accident Study (Year 1977) (Fire Chief, Department of Fire and Safety Services, St. Paul, Minnesota, 1977).

This study is the only report about the safety benefit of EV preemption contained in the ITS Benefits Database maintained by the FHWA. The report is a pre-and post-EV preemption safety impact analysis produced in 1977 by the Fire Chief from the City of St. Paul, Minnesota, in response to a question from city officials. The Fire Chief studied the emergency vehicle crash history before and after the EV preemption system deployment. The Fire Chief’s response was based on the data presented in Table 2.1.

While the data is limited and the study was not extensive in terms of root cause determination or statistical rigor, it provides a baseline on the performance in a jurisdiction-wide deployment, which covered an incremental emergency vehicle deployment over a 7-year period of time:

- During the period from 1970 through 1976, the City of St. Paul deployed 285 Opticom systems over 308 intersections, while the number of emergency alarms grew from 8,300 to 20,668.
- During this period, the number of EV crashes decreased from the 1967 high of 8 to an average of 3.3 per year.

**Table 2.1. St. Paul Emergency Vehicle Crash History
With / Without EV Preemption**

Year	Number of Emergency Vehicle Accidents	Total Emergency Alarms	Number of Signalized Intersections	Number of Intersections With Opticom
1976	3	20,668	308	285
1975	5	20,061	308	-
1974	2	19,564	306	-
1973	2	13,109	306	252
1972	3	9,152	306	-
1971	4	8,989	297	211
1970	4	8,363	290	190
1969	6	8,300	274	28
1968	7	7,594	274	N/A
1967	8	7,495	267	N/A
1966	6	6,669	-	N/A
1965	2	5,321	-	N/A
1964	4	5,226	243	N/A
1963	1	5,096	227	N/A
1962	5	4,434	223	N/A

Although the no statistical analysis was accomplished in this study, the Fire Chief offered a measure of effectiveness, which may be useful in assessing *before* and *after* field tests of EV preemption. The measure proposed was the emergency vehicle crash rate per alarm. In the St. Paul study, the rate decreases from 1 crash per 2,091 alarms in 1970 to 1 crash per 6,889 alarms in 1976. In the report, the Fire Chief notes that the improvement in crash rates occurred in spite of an increase in the number of alarm responses and the volume of traffic encountered on the St. Paul roadways. The Chief infers that the decrease in the number of emergency vehicle crashes was due to the dramatic reduction in conflicts emergency vehicles are exposed to at signalized intersections.

Time Study of the Effectiveness of the Opticom Traffic Control System (Year 1978),
(City of Denver Department of Safety, 1978).

This study evaluates changes in emergency vehicle response times as a result of signal preemption in the City of Denver, Colorado, between 1977 and 1978. Conducted over a 90-day period, the study includes three fire stations and 75 signalized intersections. Firefighters recorded

travel times necessary to traverse typical routes before and after the Opticom installation. The collected data showed emergency vehicle response times decreased by 14 - 23% and saved approximately 70 seconds per response on a typical route with three to six signalized intersections.

Emergency Response Management System Study, (Traffic Engineers, Inc., 1991).

This report evaluates the Opticom EV preemption system deployed in the City of Houston, Texas, between 1991 and 1992. The system is designed to recall a green phase or extend a green phase for emergency vehicles as they approach signalized intersections. Emitters were installed on emergency vehicles and calibrated to activate signals within a quarter mile of emergency vehicle presence. The preemption system allows cross-street traffic to stop and clear each intersection normally. Traffic queues in approach lanes could then pull through and make way for emergency vehicles. Field tests were run to measure travel time for emergency vehicles (without sirens activated) before and after installation at 22 intersections within two fire districts (11 per district). After a year of operations, the average emergency vehicle travel time decreased 16% in one district, and 23% in the other.

2.4 TRANSIT PRIORITY

2.4.1 Transit Priority Overview

An Introductory Guide to Transit Signal Priority, (Advanced Traffic Management and Advanced Public Transportation Systems Committees, ITS America, 2002).

This introductory guide regarding transit signal priority was published by ITS America in 2002 as a reference aid to a broad spectrum of stakeholders involved in implementing traffic signal priority strategies. The guide provides terminology definitions, outlines benefit and cost measures, indicates deployment planning process elements, illustrates system architectures, and identifies public policy issues related to deployment and implementation. Benefits are primarily stated in terms of reduction in delay at traffic signals, which further translate into reduced travel time and better schedule reliability. Impact to other users is quantified as delay to cross-street traffic. Costs are identified as inconsistently reported making it difficult to compare projects. Cost per intersection is suggested as the preferred measure, though the guide acknowledges this can vary greatly depending on existing signal system infrastructure and the degree of complexity in the execution strategy.

Transit Signal Priority Along an Arterial Using Advanced Detection, (Wadjas, and Furth, 2003).

This research promotes the concept of advanced detection and cycle length adaptation as a strategy for providing priority for transit vehicles. In a departure from control strategies that rely on detection only a few seconds in advance stop lines, the proposed advanced detection control algorithm determines the bus location on the corridor and estimates arrival times at down stream intersections. This method provides a larger window in which to make cycle length, phase split, and offset adjustments to provide a green phase at the time of bus arrival. This advanced detection method uses historical data on delay elements and progression speeds to make estimates. The method employs the traditional green extension and early green recall strategies

within an overall strategy that extends or compresses phase lengths to shift a green period to cover the arrival window. Using VISSIM to model an actual light rail transit route in Boston, Massachusetts, the algorithm demonstrated positive results with 82 percent of trains arriving during a green phase. The authors state that the control strategy results in substantial improvements to transit travel time and regularity, resulting in negligible impacts to private traffic and pedestrians. Overall, this method is found to be more effective than simple priority methods, which rely on local detection.

Control Strategies For Transit Priority, (Skabardonis, 2000).

The author developed a methodology to estimate the potential benefit of transit signal priority systems, and to identify the most important factors that influence the effectiveness of transit signal priority. He identifies the following three broad classes of factors that could be elements of a transit priority specific corridor study:

- Network Configuration: Traffic signal spacing; the number of lanes; bus stop placement and design; pedestrian activity; and the type and operation of traffic signal control system.
- Network Traffic Flow Characteristics: Traffic volumes; turning movements; variability in volumes; the level of congestion; and operational characteristics that create interference with bus operations.
- Transit Flow Characteristics: The bus volume; type of bus service; transit route design; the number of bus stops; the dwell time characteristics; passenger demand at stops; and the availability of communication and monitoring equipment for transit vehicles.

The author uses these factors to optimize the signal-timing plan based on bus arrival patterns at critical intersections along the corridor. Optimization plans were developed using the TRANSYT-7F simulation model program. Optimized plans were then evaluated using CORSIM on the network. Key transit vehicle priority measures of effectiveness include travel time, travel time variation, and control delay.

Review of Transit Priority Projects and Practice, (Dion, 1999).

In this paper, Dion provides a cross-cutting review of then-currently deployed transit vehicle priority systems. Dion catalogues the number of intersections equipped, the number of vehicles equipped, the technology employed, and the benefits reported.

2.4.2 Transit Priority Performance Measurement

Evaluation of Service Reliability Impacts of Traffic Signal Priority Strategies for Bus Transit, (Chang, 2002).

Chang's dissertation examines the evaluation of transit vehicle priority strategies. This research puts forward an evaluation framework and plan that provides a systematic method to assess potential benefits and impacts of transit vehicle priority. Results include specific performance measures corresponding to particular objectives of the project under evaluation. The framework is applied using an actual transit corridor on Columbia Pike in Arlington, Virginia. Chang evaluates the corridor using the INTEGRATION microsimulation tool. Using the measures

developed in the research, statistically significant improvements of 3.2% were found for bus service reliability and 0.9% for bus efficiency, while negative other traffic-related impacts were found in the form of increases in overall delay to the corridor of 1.0% on a vehicle basis or 0.6% on a person basis.

Assessment of Transit Priority Impacts and Benefits, (City of Bremerton, 1997).

This study examines the impact of a transit vehicle priority system in Bremerton, Washington by evaluating the effect on bus travel time and the delay to automobiles at cross streets. The objective is to produce a cost-benefit analysis for the system. Cost is based on the cost of equipment and the delay to cross-street traffic. Benefits are assessed in terms of travel time savings to riders and increased efficiency in transit operations. Ultimately, the city wanted to determine if bus schedules could be modified to provide the same level of service with revised headways. Results indicated a 10% reduction in bus travel time along a 45-minute route. The study findings indicate that the determination of benefits is highly contextual based on the operational environment, including the base traffic, the transit service schedule, pedestrian volumes, roadway geometry, and the base signal-timing plan.

Advanced Public Transportation Systems: Evaluation Guidelines, (Casey and Collura, 1993).

This USDOT published set of guidelines was developed to guide early ITS deployment in the public transportation area. These guidelines offer extensive suggestions as to the type of measurements that may be important in establishing the benefits and impacts associated with ITS in public transportation systems. Of particular value is an approach that maps measures to data needs. The pamphlet points to one of the key issues in transportation and traffic measurement, which is the difficulty in getting a large amount of meaningful data at minimum cost. The key point is that data collection is expensive and time consuming. This implies that the strategy for getting the data is nearly as important as determining the measures themselves. Suggestions for strategies include planning data collection to ensure a “fair” test. The pamphlet defines two categories of data: collected and derived. Collected data is captured directly, but by itself, may be not be as meaningful as data that is derived from collected data using the empirical relationships accepted in the field, statistical methods, mathematical techniques, and engineering principles borrowed from other fields.

2.5 TRAFFIC AND TRANSPORTATION ENGINEERING PRINCIPLES

2.5.1 Principles of Traffic Flow Theory

Traffic and Highway Engineering, (Garber and Hoel, 1999).

Garber and Hoel open the chapter on Traffic Control Devices by stating that a primary objective in designing a traffic control system at an intersection is to reduce the number of significant conflict points. They propose that engineers analyze the turning movements at intersections to determine the significant conflict points. They further suggest that crossing conflicts are the most severe and should be minimized. Additionally, they state that the severity of a conflict point is a function of the type of conflict (diverging, merging, or crossing), the number of vehicles

involved, and vehicular speed in the traffic stream. The authors infer that crash potential is related to the number and severity of conflict points that exist at an intersection.

Traffic Flow Theory and Control, (Drew, 1968).

Drew's traffic flow theory was based on studying the actions of drivers in highway driving conditions. He determines that for any given section of roadway, the manner in which drivers maneuver within the traffic stream is generally predictable, given prevailing driver attitudes, traffic conditions, roadway design, and immediate goals. This predictable maneuvering, expressed primarily in the form of travel lane selection, is interrupted when drivers approach a weaving area. In these areas, drivers alter their lane selection to pursue their own destination goals (to exit or to continue on the highway) and to accommodate traffic merging into or out of the traffic stream. The result is that the traffic stream lane distribution is altered from the one observed prior to the weaving area as the traffic seeks a new lane distribution downstream. Drew developed a method for predicting the change in lane distribution based on the Markov Chain Theory.

A Markov Chain is a system, which has a set S of states, changes randomly between these states in a sequence of discrete steps based on the probability of a change from one state to another. The length of time spent in each state is the "sojourn time" in that state, T . The transition between states is governed by the probability of transition, P . A future state S_j , is determined by applying the transition probability $P_{i,j}$ to the initial state S_i . Drew uses the approach to determine the lane distribution at various distances downstream from the disturbance. Drew substitutes a fixed distance for time for the discrete step. Drew's method is expressed in matrix form as follows: the final distribution matrix, $D(n)$, where n is the number of discrete steps that define the distance evaluated, is equal to the transition probability matrix T to the n power, $(T)^n$, times the initial distribution matrix, $D(0)$.

Manual on Uniform Traffic Control Devices (MUTCD), (FHWA, 2001).

The MUTCD Millennium Edition, published in 2001, introduces explicit definitions of preemption and priority at traffic signals. These definitions, combined with explicit instructions for phase transition, will reduce some of the existing institutional barriers by providing guidance that traffic engineers require to ensure safety and efficiency in operations.

Section 4A.02 "Definitions Relating to Highway Traffic Signals" provides the following definitions related to priority control systems:

- Emergency Vehicle Traffic Control Signal: A special traffic control signal that assigns the right-of-way to an authorized emergency vehicle. This type of signal is used where emergency vehicles must exit a station and gain the right-of-way to enter an arterial roadway.
- Preemption Control: Transferring normal operation of a traffic control signal to a special control mode of operation. This practice applies to standard traffic signals.
- Priority Control: A means by which the assignment of right-of-way is obtained or modified. This practice applies to standard traffic signals.

Section 4D.20 “Preemption and Priority Control of Traffic Control Signals” provides operational guidance for preemption and priority systems as follows:

Traffic control signals may be designed and operated to respond to certain classes of approaching vehicles by altering the normal signal timing and phasing plan(s) during the approach and passage of those vehicles. The alternative plan(s) may be as simple as extending a currently displayed green interval or as complex as replacing the entire set of signal phases and timing.

- Preemption control (see definition in Section 4A.02) is typically given to emergency vehicles and to vehicles such as boats and trains. Examples of preemption control include the following:
 - Prompt displaying of green signal indications at signalized locations ahead of fire vehicles, police cars, ambulances, and other official emergency vehicles.
 - A special sequence of signal phases and timing to provide additional clearance time for vehicles to clear the tracks prior to the arrival of a train.
 - A special sequence of signal phases to display a red indication to prohibit turning movements towards the tracks during the approach or passage of a train or transit vehicle.
- Priority control (see definition in Section 4A.02) is typically given to certain non-emergency vehicles such as buses and light-rail vehicles. Examples of priority control include the following:

Displaying early or extended green signal indications at an intersection to assist public transit vehicles in remaining on schedule.

Special phasing to assist public transit vehicles in entering the travel stream ahead of the platoon of traffic.

Section 4D.13 “Preemption and Priority Control of Traffic Control Signals” provides standards related to:

- Yellow change intervals;
- Red clearance intervals; and
- Pedestrian intervals when transitioning into and out of priority and preemption control.

The additional standards and guidance information related to traffic signal priority control in the latest edition of the MUTCD is a step forward, but there is little guidance for developing the green extension and early green recall strategies employed in the field.

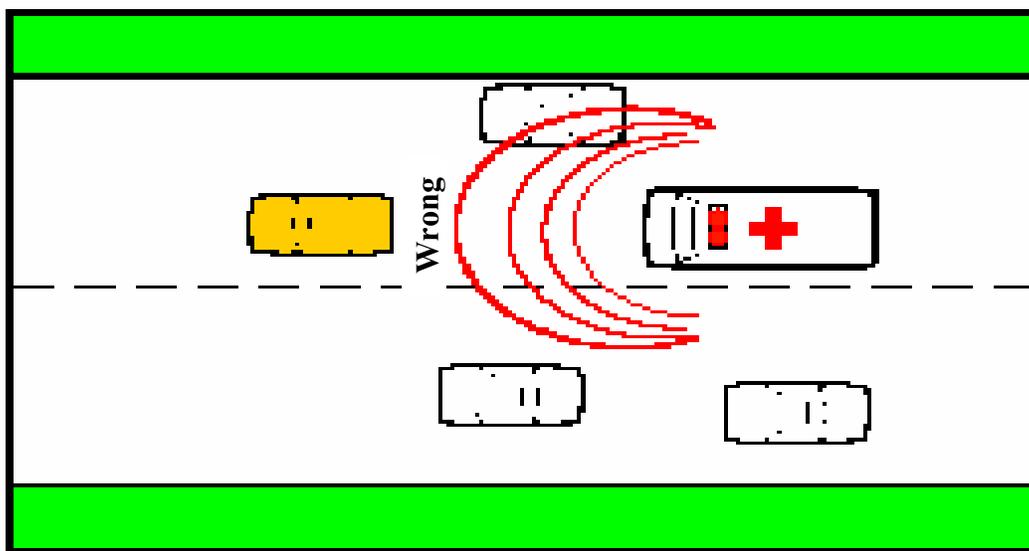
Virginia Driver’s Manual 2001-2002, (Virginia Department of Motor Vehicles, 2001).

The *Virginia Driver’s Manual* provides guidance for driver response to emergency vehicles that covers some, but not all, situations commonly seen in practice. The manual provides the following explicit guidance:

When police, fire, and rescue vehicles or ambulances approach you using a siren, flashing light or both, you must immediately yield the right-of-way. Pull over to the right edge of the road and stop until the emergency vehicle has passed. Don't follow any emergency vehicle any closer than 500 feet. Regardless of your direction, on an undivided highway, you must pull over to the edge of the road and allow an emergency vehicle to pass.

This statement is supplemented by the illustration shown in Figure 2.1. The issue with the current manual is that commonly observed situations are not addressed explicitly, which may leave room for confusion, or generate situations in which drivers must make snap decisions on the spot. Examples of such situations are:

- Opposing traffic on a divided highway is not required to pull over to the right edge of the road and stop. This may create a conflict when an auto is approaching an intersection and the emergency vehicle unexpectedly makes a left turn across the opposing lanes.
- Concurrent traffic stopped in a queue at a red signal must attempt to maneuver to create a pathway for an emergency vehicle approaching from behind, but there is little room to execute the required maneuvers.



Source: Virginia Driver's Manual, 2001.

Figure 2.1. Supplemental Guidance

2.5.2 *Equilibrium Principles in Driver Choice*

Congestion Theory and Transport Investment, *American Economic Review* (Vickrey, 1969).

Vickrey introduces a model that explains the stabilization of a driver's choice of a departure time, given estimates of travel time and all delay components particular to the chosen departure time. The principle is that commuters select their departure time in order to minimize a combination of travel time costs and schedule delay costs. Schedule delay costs occur because commuters who arrive too early or too late at the destination are penalized. Without any travel time cost, all commuters would depart at the same time, generating a large amount of congestion. Conversely, without any schedule delay cost, the departure distribution would be infinitely spread over time. Commuters face the following trade-off: Either they arrive on time and incur a maximum level of congestion, or they arrive very early (or very late) and incur no congestion. Vickrey states that the driver will choose the departure time that minimizes the cost of travel. At equilibrium, no driver can modify the departure time in order to decrease the travel cost. This definition is the natural extension of the user equilibrium introduced by Wardrop.

From W. Vickrey to Large-Scale Dynamic Traffic Models, (de Palma and Marchal, 1998).

This study examines the use of equilibrium principles in transportation as they pertain to traveler choice. In this study, traveler choice of destination, departure time, and route depend on a complex equilibrium across all three choices. The authors base their application of equilibrium principles upon the work of Vickrey (1969) and Wardrop (1952). De Palma's and Marchal's analysis establishes a comparison between Vickrey's model, developed for one *O-D* pair, and simulations performed for large-scale models that deal with many-to-many situations. In doing so, the authors use equilibrium principles in traveler choice to fill the gap between simple theoretical models using strong economic foundations. This work provides a foundation for a new class of dynamic traffic models designed to study current practical issues in urban transportation.

The Nash Equilibrium, (Kockesen and Ok, 1998).

Kockesen and Ok describe the actions of individuals in group problems in terms of strategic game theory. In iterative strategic game situations, individuals learn from each other. Learning occurs when individuals choose their actions based on their estimates of what the others will do and an assessment of the benefits associated with each possible action combination. In essence, an individual's decision boils down to solving the following problem:

$$\max_{x \in X} u(x, \theta)$$

where x is the vector of choice variables, or possible courses of action of the individual; X denotes the set of all possible courses of action available; θ denotes a vector of parameters outside the control of the individual, such as the actions of others; and u is the utility function for the individual.

This phenomenon is known as the Nash Equilibrium which is based on the premises that each individual acts rationally given one's beliefs about the other players' actions, and that these beliefs are correct. For any strategic game, a Nash Equilibrium outcome can be regarded as a steady state of a strategic interaction in which no one has an incentive to unilaterally deviate and take another action.

2.6 SIMULATION TOOLS

While traffic simulation models have proven to be useful in assessing benefits for emergency vehicles and the impacts for other roadway users, these models are unable to provide insight into the effects of driver behaviors on emergency vehicle safety and travel time due to the construction of key simulation algorithms, the fact that collisions are not permitted and limited variation in driver behaviors. Vehicles in microsimulations attempt to avoid collisions based on the car-following, gap acceptance, and traffic control algorithms employed. In continuous vehicle movement simulations such as CORSIM, if collisions do occur, they are treated as maximum decelerations that place the "following vehicle" in a car-following situation. In discrete vehicle movement simulations such as VISSIM and TRANSIMS, gap and closure comparisons force following vehicles to apply speed controls to avoid collisions and establish the car-following logic. In VISSIM and TRANSIMS, driver behaviors can be assigned, but they offer only minor excursions from a normal profile to induce some degree of randomness into the simulation.

These fundamentals prevent the use of microsimulations, in their present form, from realistically emulating the emergency vehicle response environment. FHWA is conducting research to improve CORSIM capabilities in this area, but true attempts to represent the driver behaviors in the presence of emergency vehicles have not been forthcoming. To further understand each of the three aforementioned simulations, the following summaries are offered as a compilation of various works, which are referenced where applicable.

2.6.1 CORSIM

CORSIM is a time-based microscopic tool with *stochastic* (random) simulation of individual vehicles in traffic-controlled urban networks and freeways. The CORSIM traffic flow logic performs a full range of controls on vehicles traveling within specific lanes and responding to any number of control devices, including fixed-time and actuated traffic signals, yield and stop signs, and ramp transitions. Vehicle flow is guided by car-following rules, lane-changing logic, and other driver decision-making processes (National Research Council, 2000).

The transportation network in CORSIM is made up of a set of nodes and links. The links are defined as the linear connection of two nodes with a specified length. Important link attributes include the number of lanes, lane alignment and lane connectivity descriptions, and the desired free-flow speed. The desired free-flow speed determines the speed vehicles strive to attain as they traverse the link—and is a key calibration factor in the model. Within the model, a lane is defined as a line with no width, and a vehicle may only be in one lane at any particular time (Halati, Lieu, and Walker, 1997).

Traffic control in CORSIM is determined by stop signs, yield signs, fixed time traffic signals, actuated traffic signals, and ramp meters. The traffic control logic used in CORSIM controls the movement of all vehicles at all intersections.

Fixed-time traffic signal control in CORSIM implements user-specified timing plans, where all control movements are identified by intersection approach and are assigned the timing interval as specified by the user. Multiple signal coordination along an arterial is accomplished by using cycle offsets. For traffic-actuated control, the user must specify more detailed information including yield points, force offs, permissive periods, and the type and location of traffic detectors to measure the presence or passage of a vehicle over a traffic control detector (Halati, Lieu, and Walker, 1997).

The movement of any particular vehicle in CORSIM depends on the status of the vehicle in terms of whether it is a leader, a follower, or an independent vehicle (Halati, Lieu, and Walker, 1997). A vehicle is a follower or a leader of another vehicle if it is within its area of influence, defined as a function of the vehicle separation distance and the speeds of each of the vehicles; otherwise the vehicle is defined as independent. For either a leader vehicle or an independent vehicle, barring impedances from traffic control devices, the vehicle seeks to attain a desired free-flow speed. When in car-following mode, vehicles strive to avoid collisions; however, due to the way vehicles are processed within CORSIM, sometimes “collisions” do occur. If a “collision” occurs, the vehicle is assigned the maximum deceleration rate and placed at the rear bumper of its leader vehicle. This method of treating “collisions” as maximum decelerations keeps vehicle crashes from occurring as a result of the vehicle movement logic (Halati, Lieu, and Walker, 1997). Vehicle acceleration is a function of several influencing factors within the model, including the desire to attain free-flow speed, maintain a safe car-following distance, change lanes, and comply with traffic control devices.

The CORSIM model supports two types of vehicle lane changing: mandatory and discretionary. Mandatory lane changes are designed so a vehicle can complete a turn at an intersection or must react to a lane closure or lane drop. Discretionary lane changes are designed to bypass a slower vehicle, join a shorter queue at an intersection, or bypass a bus station. For discretionary lane changes, the target lane for lane changing is selected based on the lane with the lowest impedance factor.

2.6.2 VISSIM

VISSIM is a relatively new microsimulation tool that overcomes many issues identified in CORSIM. VISSIM uses a discrete vehicle movement routine to allow for a range of driver behaviors in its main car-following algorithm. This microsimulation tool has provisions for selective response to traffic control devices by vehicle class, and its “lanes” have physical width dimensions that provide future capability for same-lane passing. VISSIM also contains provisions for priority treatment at traffic signals currently optimized for transit evaluation. This microsimulation tool provides the fundamentals required to execute an EV preemption routine in *before* and *after* conditions; however, it does require modification to incorporate special driver behavior algorithms and a situation-specific modification of vehicle longitudinal and lateral proximity preferences.

VISSIM (PTV Planung Transport Verkehr AG, 2000) is a stochastic microscopic simulation model capable of simulating traffic operations in urban areas with special emphasis on public transportation and/or multimodal transportation. VISSIM consists of two different programs: a traffic simulator and a signal state generator. The traffic simulator is a microscopic simulation model comprised of car-following logic and lane-changing logic. The car-following logic is based on the psycho-physical driver behavior model developed by Wiedemann (1974), which accounts for driver perception of closure and proximity. The discrete vehicle movement simulator is capable of simulating up to 10 times per second. It operates with reference to the signal state which polls detector information from the traffic simulator on a discrete time step basis. VISSIM simulates traffic flow in terms of "driver-vehicle units" to allow variation in driver behavior characteristics within a range applicable in normal driving conditions.

2.6.3 TRANSIMS

TRANSIMS is the emerging traffic transportation planning software suite being developed by the FHWA at Los Alamos National Laboratory. The TRANSIMS project is an aggressive effort to develop microscopic fidelity for use in evaluating regional transportation problems through an "agent-based" approach. This approach generates travelers with travel plans that emulate individuals in the real world. The travel plans are generated through processes that draw from census data, land-use data, vehicle ownership data, and traveler trip requirements data.

TRANSIMS generates all phases of a traveler's trip, including walking links, transit links, and auto links. The TRANSIMS traffic microsimulator executes all traveler movement. This module enables the TRANSIMS to simulate traveler movements and interactions in a metropolitan region's transportation system. Each link in the transportation network is divided into a finite number of cells and, at each time step each cell is examined for a vehicle occupant. When a vehicle is present in the cell, the vehicle may be advanced to another cell using a simple rule set which seeks to carry out the driver's trip plan while regarding traffic control devices, interference caused by other vehicles, and geometric conditions.

TRANSIMS provides a wide range of subjective driver qualities through a system that assigns driver attributes on a stochastic basis. These driver attributes, which define attitude, familiarity, and ability indexes, are used selectively in the algorithms that define car-following and lane-changing elements for the vehicle movement model. Traffic control devices and vehicle classes also have attributes that combine in algorithms to determine whether or not a certain class of vehicle will respond to a traffic control device, such as a signal.

The attribute system and a discrete time-step vehicle movement method allow TRANSIMS to more accurately model the actions of real drivers in real situations. Vehicles on the TRANSIMS network are assigned the attributes, which are then used in every time step to determine the cell-by-cell motion of the vehicle as each driver pursues the travel plan developed specifically for him/her. This flexibility is not without penalty; the computation requirements are tremendous in TRANSIMS requiring parallel processing of vehicle movements where small sections of the network are handled by each processor. When required, vehicles are handed off from one network section to another, complete with the attributes list that defines its tendencies (Los Alamos National Laboratory, 2002). In order to provide the traffic simulation, three basic steps are outlined in the TRANSIMS documentation:

- First, a representation of the transportation network is read in. This representation is very similar to a detailed street map and includes a number of lanes, turn pockets, merging lanes, turn signals, and so on. Vehicles traveling along streets in the road network are simulated in detail. In addition to the streets, accessories such as parking lots, activity locations, and transit stops; act like buffers for travelers who are not in a vehicle traveling on a street.
- Each vehicle's type and initial location are read in. Once this is complete, each traveler's plans are read in (as needed).
- Travelers are placed on the network and are allowed to travel from their point of origin to their final destination.

Vehicles move from one grid cell to another by using a system of movements from cell to cell according to the travel plan. Modifications in this approach support lane changing and plan following for each vehicle until it reaches the end of a link. At the end of the link, the vehicles wait for an acceptable gap in traffic or for protection from a signal before they move through the intersection onto the next link. This cycle continues until each vehicle reaches its destination, where it is removed from the network. Each roadway section is divided into grid cells, each of which is one lane wide and 7.5 meters long. As illustrated in Figure 2.2, each cell contains either a vehicle (or a part of one) or is empty.

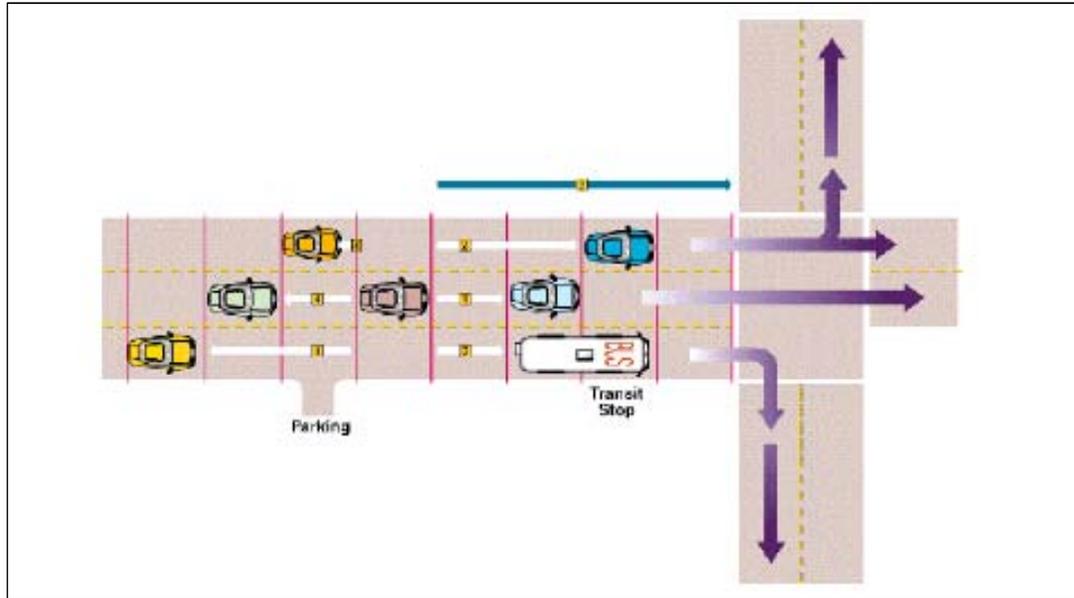
The lane-changing algorithm is presented here as an example of how decisions and movements on the network are based on the conditions in the immediate vicinity of each vehicle. The lane-changing algorithm uses a rule set (Los Alamos National Laboratory, 2002). The rules are applied after each applicable time step. Current network and vehicle position states are examined to make lane-changing decisions for every vehicle on the network. Lane changes to the right and left are considered on alternate time steps to reduce computational requirements. The algorithm for the passing lane changes are based on the following three gap calculations:

- The gap forward in the current lane;
- The gap forward in the new lane; and
- The gap backward in the new lane.

If these gaps satisfy the encoded constraints, a lane change is attempted under the following conditions:

- When a vehicle ahead in the current lane is preventing maintenance of the desired speed.
- When the gap in the neighboring lane is large enough to maintain the vehicle's current speed.
- If the lane change is made, there is no collision.

The TRANSIMS approach to vehicle movement presents the most promise in an effort to model the phenomena that takes place when emergency vehicles are present on the roadway. The method is capable of incorporating various driver behavior profiles. These behavior profiles can be characterized and represented in a rule format to allow drivers on the network to "react" to emergency vehicles with realism.



Source: From TRANSIMS Version 3.0 Documentation, Chapter 5, 23, May 2002.

Figure 2.2. Cellular Network Representation Used in TRANSIMS

2.7 CONCLUSIONS

The literature review conducted to support this research provides the necessary tools to address the research goals defined in Chapter 1. To support the goal of developing a holistic evaluation framework for preferential treatment, the literature review reveals the findings of others and establishes the basic variables and interactions, which must be considered and integrated. To support the goal of developing analytical methods to evaluate the safety and travel time benefits, the review of reveals the current state-of-the-art and documented limitations of evaluation methods for preemption and priority.

CHAPTER 3: EVALUATION OF PREFERENTIAL TREATMENT SYSTEMS

3.1 INTRODUCTION

Preferential treatment systems at signalized intersections have been deployed since the 1970s with very little change in the technologies and operating strategies. Many jurisdictions have deployed either EV preemption or transit priority, but very few have deployed both for a variety of reasons. More EV preemption-based systems have been deployed, most likely, because of the ability for fire and rescue officials to gain the attention of policy makers and to generate support due to the liability associated with emergency vehicle crashes and extended response times (Gifford et al., 2001). In some cases where EV preemption has been deployed, the selected technologies (such as siren-activated systems) did not support dual use deployment (Collura, et al., 2001). In other cases, lack of dual use is based on a lack of understanding as to how the two systems will perform when deployed together.

Stakeholders considering the planning, deployment, or operation of preferential treatment systems need an evaluation framework that examines both preemption and priority under the title of *preferential treatment*. This broader framework should support evaluation at the system level to better consider the major components and interactions involved. Such a tool would be useful to all stakeholders (policy makers, transportation planners, traffic engineers, fire and rescue planners, fire and rescue system operators, transit vehicle system planners, and transit vehicle system operators) across the entire preferential treatment deployment process.

3.2 PROBLEM STATEMENT

This dissertation addresses the need for an expanded evaluation framework to more fully address the issues faced by professionals involved in the preemption and priority deployment process. Current tools adequately address specific elements of this process; however, there currently is no end-to-end, holistic method by which preemption and priority deployment sites are identified, prioritized, selected, designed, and operated. This holistic approach is necessary to provide the highest overall benefit with the lowest level of interference between targeted beneficiaries at an acceptable level of impact to other user groups. A beginning step in meeting this need is to develop a framework to evaluate preferential treatment, which puts the factors involved in the evaluation process in terms consistent with those used in traditional aspects of transportation. Before describing the framework, it is necessary to identify the extent of the problem and to qualify the issues to be considered for any proposed framework.

There is a disparity between the deployment of preemption and priority as indicated in records of actual system deployments maintained by the U.S. Department of Transportation (USDOT). Each year since 1996, USDOT has conducted surveys to track the deployment of ITS infrastructure across the nation. Within these surveys, 78 metropolitan areas are selected for survey each year to assess the status of ITS deployment in nine key infrastructure areas. The results of the surveys are compiled and reported on the USDOT/JPO ITS Deployment Tracking website (USDOT/JPO FHWA). As of 2000, the cumulative results from the 1,750+ agencies surveyed indicate that 265 agencies had operational EV preemption systems installed on 17,116 emergency vehicles. Within the same survey population, there were 52 agencies with operational

transit priority systems installed on 895 fixed-route, fixed-schedule transit vehicles. Of the 78 metropolitan areas surveyed during 2000, 35 responded that they had deployed or planned to deploy either preemption or priority systems, or in some cases, both. For these 35 agencies, the 2000 survey indicated a total of 9,896 traffic signals under their control. Of these, 1,988 were equipped with EV preemption systems and only 10 were equipped with transit priority systems. The same 35 agencies indicated plans for 2005 call for an increase in the total number of traffic signals to 10,668; the number equipped with EV preemption should increase to 3,352; and the number equipped with transit priority should increase to 409.

These nationally compiled findings are supported by data collected in 1997 by the Virginia Department of Transportation (VDOT) (Asmussen, 1997). VDOT conducted a survey of all 50 states to determine the extent of EV preemption system deployment and to determine the maturity of deployment guidelines and operational procedures. Results of the VDOT survey indicated that 94% of the 50 agencies responded that they had deployed traffic signal preemption systems; however, in the jurisdictions with EV preemption, the systems were implemented on only a small percentage of their traffic signals.

In 2002 McHale (2003) completed research on EV preemption evaluations. McHale reviewed the VDOT survey and postulated that there are a number of issues with regard to EV preemption systems deployment and operation, such as:

- EV preemption is only needed at certain intersections, but no selection guidance exists.
- There may be an incomplete understanding of the potential benefits associated with EV preemption.
- There may be an incomplete understanding of the potential impacts associated with EV preemption.

In response to these issues, McHale proposed a framework for evaluation of emergency vehicles by outlining factors for consideration. He identified factors that define the need for preemption at a particular intersection, the potential magnitude of the emergency vehicle travel time benefit, the magnitude of the impact of preemption in terms of delay to non-emergency vehicle traffic, and the time required to reestablish traffic signal-timing plans.

In 2002, Chang (2003) examined the methods used for evaluating transit priority systems. As part of his research, Chang proposed a framework for evaluating transit vehicle priority to support and develop a set of measures of effectiveness. This new evaluation framework could provide policy makers, transit operators, and traffic operations engineers the means to evaluate the benefits and impacts of transit priority. Proposed measures included the reduction in transit run times on a particular route, the reduction in the variation of transit run times, and the increase in delay to side-street traffic.

While McHale and Chang addressed the need for evaluation frameworks to facilitate quantitative evaluation of preemption and priority, there are significant qualitative issues that have hindered deploying these technologies. These issues were examined by Gifford, Pelletiere, and Collura (2001) in a stakeholder requirements review conducted in the Washington D.C. area. These researchers interviewed stakeholders in Northern Virginia, Washington D.C., and Maryland in an effort to determine attitudes, issues, and barriers. The study identified three major stakeholder

groups: the fire and rescue community, the transit operations community, and the traffic operations community. In their review, the authors found that the relationship between the traffic operations and fire and rescue communities was more developed than the relationship between the traffic operations and transit operating communities. Further, the fire and rescue community was very concerned that integrated deployment of preemption and priority may reduce the effectiveness of preemption systems. The traffic operations community, while concerned about disruption to signal-timing plans and traffic flow by preemption, was more willing to allow preemption in the interest of public safety, than it was to put signal-timing plans and traffic flow at risk for priority.

This dissertation seeks to synthesize the contributions of the aforementioned researchers to formulate an evaluation framework that includes both EV preemption and transit priority. The referenced works are taken as a basis to address the following issues:

- There may be hesitancy for jurisdictions with preemption to add priority based on an incomplete understanding of how the two will interact when deployed on the same traffic signal control system and potentially the same traffic signals.
- There may be institutional barriers between the traffic operations, the fire and rescue, and the transit operations communities that prevent integrated deployments.

A holistic approach that facilitates multilateral examination of issues from the perspective of fire and rescue, transit, and traffic operations may provide a means to overcome barriers quicker than the 3- to 8-year period noted as the range for jurisdictions to zero in on deployment decisions and approaches by industry professionals attending a February 2003 ITS America transit priority workshop.

3.3 FRAMEWORK FOR EVALUATION OF PREFERENTIAL TREATMENT

This research approach will treat preemption and priority together as components of preferential treatment. The relationship between the preferential treatment components is based on shared use of the roadway and implementation hardware; interaction with the base traffic flow; integration of operational strategies; and the resulting interdependent performance. As such, the evaluation framework requires linkages between EV preemption and transit vehicle priority as illustrated in Figure 3.1.

Within the evaluation framework for preferential treatment, there is a need for evaluation plans to assess the performance of each specific components (preemption and priority) using concepts and analytical methods unique to each. Finally, to better assess the effectiveness of the overall preferential treatment deployment, the overarching evaluation framework must consider performance at the system level examining effectiveness of the integrating strategies and the interdependent performance of the overall system.

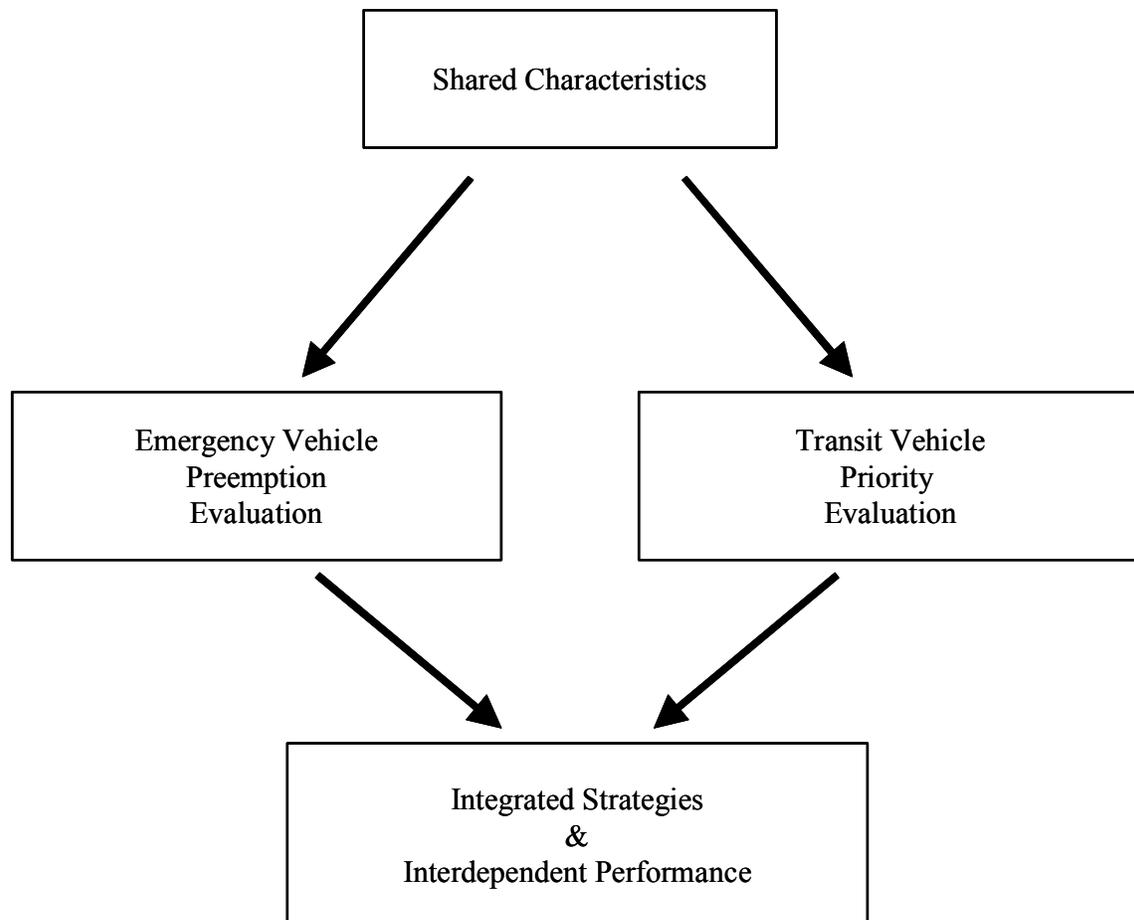


Figure 3.1. An Evaluation Framework for Preferential Treatment

3.4 EVALUATION OF EV PREEMPTION

An EV preemption evaluation plan, which is a component of the evaluation framework for preferential treatment, is illustrated in Figure 3.2. This evaluation plan consists of a 4-tiered approach, which will guide data collection, suggest evaluation concepts, define analytical requirements, and facilitate development of meaningful guidelines for local authorities to use in preemption deployment decisions and performance assessment.

3.4.1 *EV Preemption Corridor Study*

The EV preemption evaluation plan begins with a detailed corridor study regarding the field conditions. This top tier consists of three major elements:

- Roadway characteristics as they pertain to emergency vehicles, including: geometric properties; signal locations; distance between signals; signal-timing plans; pedestrian facilities; and impediments to line-of-sight at intersections.

- Traffic characteristics, including: traffic volumes along the segment of interest with particular attention to side-street volumes and the amount of green time dedicated to serve them; traffic speeds at peak volumes; intersection queue characteristics; and pedestrian activity.
- Emergency vehicle response characteristics with respect to the corridor segment of interest, including: the number of responses per hour per day; the origin of the responding vehicle; the response destination distribution; the type and number of response codes and the associated platoon response characteristics; the routes of choice for response to various zones; and the identification of key conflict and delay attributes of each intersection.

These three elements play a key role in understanding the problem and the environment for which the EV preemption solution is designed. The challenge is to determine what information is needed and how it translates into performance in order to guide the data collection effort to support evaluation. The remainder of the evaluation plan guides the data collection and analytical process.

3.4.2 *EV Preemption Transportation Planning*

The second tier of the emergency vehicle evaluation plan seeks to document the travel and traffic flow characteristics of emergency vehicles using the traditional 4-Step Travel Demand Forecasting Model to provide a familiar structure to aid in building an understanding of emergency vehicle travel patterns and emergency vehicle transportation needs. Each step is modified to accommodate the specific nature of emergency vehicle traffic and they provide a familiar structure to aid in building understanding regarding travel patterns and emergency vehicle needs. The four steps are summarized as follows:

- *Trip Generation* characteristics should be captured from response log data and from surveillance video of the arterial access point to determine trip generation patterns on an hourly and diurnal basis. In addition, the platoon characteristics of emergency vehicle travel should be captured in terms of platoon size, the frequency distribution of platoon sizes, and the time spacing between the first and last vehicle of each platoon response. The product of this step will be used in the *Trip Assignment* step to determine the traffic conditions most likely to be present during the highest response hours.
- *Trip Distribution* characteristics are determined from the response log data in order to establish travel patterns and to reveal the relative attraction characteristics of particular zones within the response area assigned to the fire and rescue station. In building the Origin/Destination (O/D) Matrix, it is important to include responses originating from “off station” locations. The product of this step will be used in the *Route Choice* step.
- *Route Choice* characteristics are determined to identify the primary response routes to the various zones. Route preference is based on the desire to make the quickest possible response, and without specific local conditions, should follow an algorithm that prefers travel on arterials over collectors over local streets. The product of this step is used in the *Trip Assignment* step to determine which intersections within the considered area should be considered for preemption and analyzed for benefits and impacts.
- *Trip Assignment* is the culminating activity in the process. In this step, the emergency vehicle flow characteristics (frequency, platoon characteristics, and intersection movement

requirements) are paired with the base traffic flow parameters (vehicles per hour, average speeds, and average queue lengths for each approach) for the corresponding time of day and day of the week. A resulting event data matrix provides the required inputs to the analysis tier of the EV preemption evaluation plan.

3.4.3 EV Preemption Analysis

The third tier of the EV preemption evaluation plan is the analytical process, where the emergency vehicle interaction with signalized intersections is analyzed to generate quantifiable estimates for the number and severity of emergency vehicle conflict points and the severity of delay likely to be encountered at red traffic signals. In addition, the impact of preemption to other traffic is determined in terms of increased control delay and queue lengths to Side Street and opposing traffic. (Methods for evaluating emergency vehicle safety and travel time benefits are presented in Chapters 4 and 5, respectively. A method for evaluation of the impact of preemption on side-street and opposing traffic delay and queue length is presented in related research conducted by Mittal [2002]). The product of this tier of the EV preemption evaluation plan is a quantifiable benefit and impact table that will allow stakeholders to analyze *before* and *after* cases in terms of the key measurement criteria.

3.4.4 EV Preemption Deployment Guidelines

The fourth tier of the framework incorporates the analytical results into engineering studies to serve as local guidelines, which are useful in the relative ranking of candidate corridors and intersections by potential benefit and impact measures.

3.5 EVALUATION OF TRANSIT PRIORITY

The evaluation plan for transit vehicle priority is illustrated in Figure 3.3. This process also uses a 4-tiered approach to guide data collection, suggest evaluation concepts, define analytical requirements, and facilitate development of local guidelines for priority deployment. While detailed development for each tier of a transit vehicle priority plan is beyond the scope of this dissertation, each tier can be developed in the same manner as those for the EV preemption evaluation plan.

The objective in developing each tier is to determine the operational relationships between the autos and the roadway and the transit vehicles and the roadway. These relationships and operating parameters serve as the input to techniques for assessing the benefits and impacts to transit vehicle priority. These benefits and impacts range from graphical evaluation of time-space diagrams to advanced simulation methods yielding specific benefit and impact estimates. (In related research, Deshpande [2003] uses this framework to develop a VISSIM-based analysis of transit priority.)

3.6 PERFORMANCE MEASURES

While the preferential treatment evaluation framework and associated preemption and priority evaluation plans facilitate high-level understanding of the phenomena in terms of performance, a

set of specific performance measures is ultimately required to support objective analysis of *before* and *after* cases and/or various operational strategies. In the domain of preemption and priority deployment evaluation, there is no accepted standard for performance measurement. ITS America published the *Overview of Transit Priority* (Baker, 2002), which addresses most high-level issues, including institutional and some performance issues. The white paper is valuable given the current state of maturity in evaluation of preferential treatment; however, as researchers increase the understanding of details regarding performance measurement, an update will become necessary.

A standardized measurement structure is one way to provide better support for future research and performance. This research offers a candidate measurement structure that spans a downward cascade from a high-level premise, down through a set of hypotheses, down through objective statements, to actual performance measures, and data collection requirements. Such a product will facilitate cross-cutting deployment-to-deployment comparison. Besides supporting benchmark comparison, a generalized, structured approach helps project managers avoid a common tendency in ITS projects for stakeholders migrate too quickly from conceptual design to component selection, deployment, and activation. The structure supports efforts to complete intermediate systems engineering steps, including functional requirement definition, identification of required system interfaces, and detailed design of the logical architecture.

Performance measure development begins by formulating objective statements derived from a premise and hypotheses. The following premise is the basis for the hypotheses, objectives, and measures presented in this dissertation:

Emergency and transit vehicles will benefit from *preferential treatment strategies* with minimum negative impact on other users. Further, the degree of benefit and impact is directly dependent on the operational environment, which is defined as the interaction of the geometric properties of the roadway, the signal strategies, and the characteristics and flow of the primary user classes (emergency vehicles, other traffic, and pedestrians).

The following hypotheses, derived from the previously stated premise, are the basis for the objective statements developed in this research:

- For *EV preemption*, benefits accrue in the form of reduced crash potential for emergency vehicles crossing a signalized intersection, and in the form of reduced travel time for emergency vehicles approaching and passing signalized intersections.
- For *transit vehicle priority*, benefits accrue in the form of reduced travel times over a measured segment, and in the form of reduced variation in travel time.
- For *other users*, the impact accrues in the form of increased control delay for side streets and opposite direction traffic.

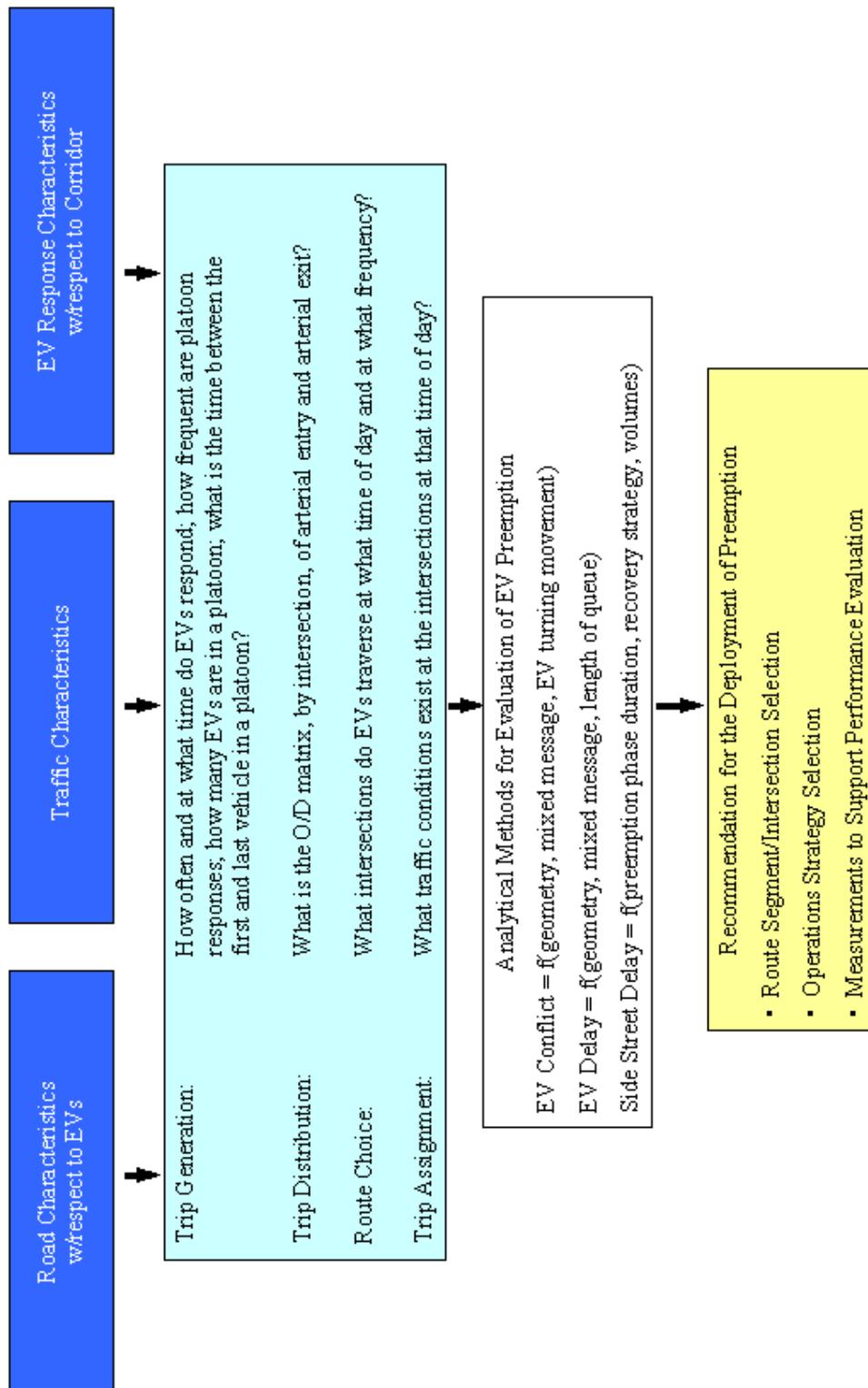


Figure 3.2. An Evaluation Plan for EV Preemption

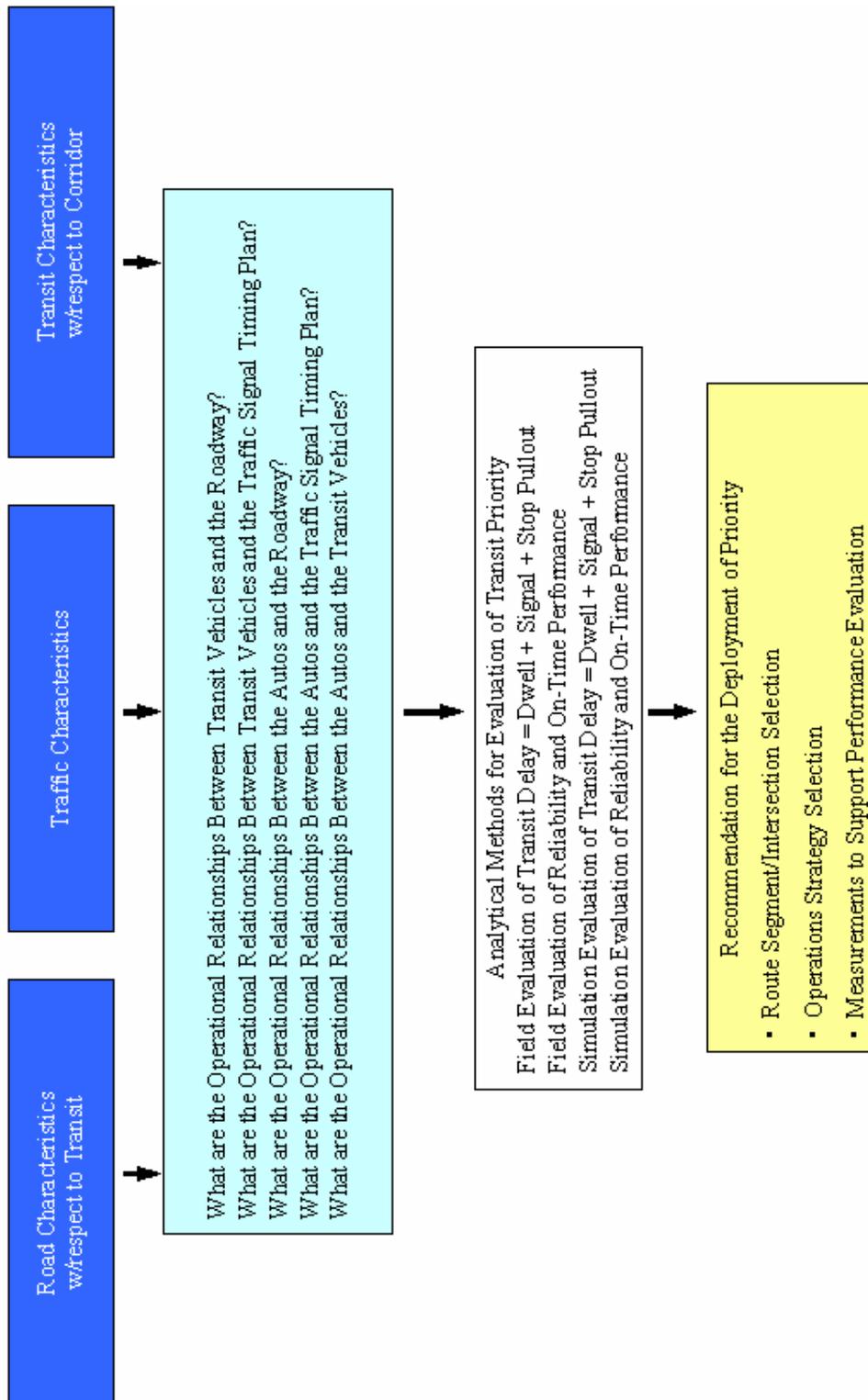


Figure 3.3. An Evaluation Plan for Transit Priority

Candidate objective statements for each system user class include the following:

- For Emergency Vehicles: Reduce the number and severity of active conflict points and reduce delay experienced in penetrating queues associated with red signal displays.
- For Transit Vehicles: Reduce total travel time and the variation in travel time along the treated segment of the corridor.
- For Other Users: Minimize delay while providing preferential treatment to emergency and transit vehicle through effective preemption, priority and recovery strategies.

These objective statements lead to performance measures, which are derived from the simulation-based work of other researchers. This effort furthers previous research by incorporating lessons learned in a FOT. Four broad categories of performance measures are:

- Base Traffic Performance: Provides an understanding of the interrelationship between traffic flow (including vehicles on the mainline and on the side streets within the normal traffic stream), the signal-timing plan, and the roadway.
- Emergency Vehicle Performance: Provides an understanding of the interrelationship between emergency vehicle flow characteristics, base traffic flow, the signal-timing plan, and the roadway.
- Transit Vehicle Performance: Provides an understanding of the interrelationship between transit vehicle flow, base traffic flow, the signal-timing plan, and the roadway.
- System Performance Measures: Provides an understanding of the performance of the preferential treatment systems, such as the number and type of requests received and granted, the requesting vehicle identification, the compliance with deconfliction strategies, and the record of specific signal-timing parameters executed during the event, and the parameters associated with signal-timing plan transition.

To ensure the best possible understanding of the issues and problems under examination, data collection should be supplemented by interviews with emergency vehicle and transit vehicle operators in order to establish the important contextual elements.

3.6.1 *Base Traffic Measures*

- Measure 1: Mainline travel time and the number of automobile stops while operating in a platoon without a bus.

Method: Direct measurement on the measured course.

- Measure 2: Mainline travel time and the number of automobile stops while operating in a platoon with a bus.

Method: Direct measurement on the measured course.

- Measure 3: Cross street delay.

Method: Collect intersection field data on average queue lengths and control delay.

3.6.2 *EV Preemption Measures*

- Measure 1: Emergency vehicle-specific conflicts as the result of auto driver and emergency vehicle operator interactions with concurrent, perpendicular, and opposing traffic streams.
Method: Surveillance video and/or written summaries; graphic records; and video/still images from field observers.
- Measure 2: Emergency vehicle delay as a result auto driver and emergency vehicle operator interactions.
Method: Surveillance video and/or written summaries; graphic records; and video/still images from field observers.
- Measure 3: Queue buildup and delay to side streets and opposing traffic on the arterial due to preemption and signal-timing recovery strategies.
Method: Surveillance video and/or written summaries; graphic records; and video/still images from field observers looking at queue buildup and the number of cycles to return to normal operations.

3.6.3 *Transit Priority Measures*

- Measure 1: Total corridor travel time.
Method: Direct measurement on the measured course.
- Measure 2: On-time performance at scheduled stops.
Method: Direct measurement of arrival times at scheduled stops.
- Measure 3: Bus delay experienced at signalized intersections.
Method: Direct measurement on the measured course.
- Measure 4: Bus delay experienced at passenger stops (dwell time and traffic stream reentry delay at pullout bus stops).
Method: Direct measurement with a stopwatch on the measured course.
- Measure 5: Weighted passenger time in the corridor.
Method: Passenger counts, including stop exchange numbers on observed runs.
- Measure 6: Queue buildup and delay to side streets due to priority and signal-timing recovery strategies.
Method: Surveillance video and/or written summaries; graphic records; and video/still images from field observers looking at queue buildup and the number of cycles to return to normal operations.

3.6.4 *System Performance Measures*

- Measure 1: The number of preferential requests by vehicle class and vehicle identification code made over a time period of interest.

Method: Periodic download of signal control data and/or the preferential treatment control interface device.

- Measure 2: The percent of requests granted by vehicle class and vehicle identification code by day of week and time of day.

Method: Periodic download of signal control data and/or the preferential treatment control interface device.

- Measure 3: By reason code, the distribution of denied preferential requests for each vehicle class and each vehicle identification code.

Method: Periodic download of signal control data and/or the preferential treatment control interface device.

- Measure 4: By signal phase, the distribution of the timing of preferential requests relative to the signal-timing plan (cycle, phase, pedestrian phase, etc.) for each vehicle class and each vehicle identification code.

Method: Periodic download of signal control data and/or the preferential treatment control interface device.

- Measure 5: The duration of each granted preferential request and the number of vehicles by class and vehicle identification code passing during a preferential phase.

Method: Periodic download of signal control data and/or the preferential treatment control interface device.

- Measure 6: The number of signal cycles required to restore cycle length, phase splits, and offsets to the prevailing signal-timing plan.

Method: Periodic download of signal control data and/or the preferential treatment control interface device.

3.7 DATA REQUIREMENTS AND COLLECTION

Identifying data requirements and developing collection strategies are critical steps in generating a valid evaluation of EV preemption and transit priority. In general, data collection must cover four major areas of interest: roadway characteristics; traffic studies; emergency vehicle conflict studies; and emergency vehicle delay studies. As with performance measures, there is no standard approach designed specifically for preferential treatment studies. Therefore, each performance measure listed above includes a general measurement method, which may be modified based on the technologies available on test equipment. Where applicable, the data requirements and collection methods recommended are drawn from traditional study techniques such as those proposed in Federal Transit Administration publication, *Advanced Public Transportation Systems: Evaluation Guidelines* (Casey and Collura, 1993). The guide provides a proven approach to supporting transit performance studies outlining the criteria for data selection and providing suggested collection methods. Some of these measures are transferable to emergency vehicles but most require some contextual update. Originally published in 1994, the guide is comprehensive, but new technologies may enable broader and more efficient methods, which could lower the cost and increase the accuracy of future evaluations. For example, where

emergency vehicles and/or buses are equipped with vehicle-mounted video cameras, automatic vehicle location systems, automated passenger counters, and/or electronic payment systems, real-time data collections or daily data collections from on-board storage media may readily be merged with other relevant data, such as traffic signal logs, using a universal time stamp to ensure synchronization.

Data collection for the *before* and *after* cases generally follow the same structure and methods, except where new measurement capabilities become available in the *after* case. For example, the technologies employed to provide preemption and priority will have some event and vehicle identification logging capabilities, which may replace or supplement some field collection elements. However, until methods mature and automated methods become more widely available, a preferential treatment evaluation will require a significant collection of field measurements to support the analytical methods proposed in this dissertation. Field observation may also be required to validate the functionality of technologies under field conditions. This action ensures that no safety issues are overlooked, such as altering dilemma zone calculations or the inadvertent execution of a preemption or priority routine while the requesting vehicle is at rest within the request generation range.

3.8 CONCLUSIONS AND RECOMMENDATIONS

In the past, preferential treatment system deployment patterns often favored the fire and rescue community due to minimal institutional barriers that exist for that application, and because fire and rescue officials are generally impressed with the system performance based on feedback from emergency vehicle operators. Public acceptance of EV preemption is high, and traffic operations officials are willing to accept potential disturbances to the signal-timing plan for the life and property saving benefits. The main issue with EV preemption deployment is that there is relatively little known about actual system performance in the field in terms of benefits and impacts with respect to specific emergency vehicle, base traffic, and roadway characteristics. This issue leaves a willing jurisdiction short on information that can help make the most cost-effective decisions in terms of corridor and intersection selection allowing the appropriate supporters and stakeholders to differentiate between where the system *could* be deployed and where it *should* be deployed.

Transit vehicle priority deployment patterns indicate that the institutional issues are potentially more difficult to overcome; possibly, because it is difficult for supporters to respond to stakeholder concerns. This situation may be more pronounced where transit vehicle priority is proposed for corridors already equipped with preemption because of a gap in the ability to quantify and communicate the interactive characteristics of the two systems.

To overcome these knowledge gaps, stakeholders need access to data and lessons derived from FOTs. To ensure these tests produce the breadth and depth of knowledge required to support future decisions, a holistic evaluation framework such as the one proposed is required. This framework recognizes the shared operating environment, the unique operational strategies of each preferential class. It also recognizes the interdependence of system performance with respect to emergency vehicles, transit vehicles, and other travelers on the roadway, including pedestrians.

Recommendations for future research include the search for more automated means to gather data required to support this evaluation plan. Field data is expensive to gather and often only provides a limited number of data points, which are very specific to the local operating conditions. This tends to limit the ability to extend the results of studies to broader, system level evaluation. An effort that seeks to determine measurements most affected by variation in field conditions may lead to a database of expected values and variation that is useful in generating more accurate traffic microsimulation techniques. The database will increase the ability to conduct high-fidelity system level evaluations to support city- and region-wide deployments.

CHAPTER 4: A METHOD FOR EVALUATION OF EV SAFETY BENEFITS

4.1 INTRODUCTION

To date, ITS designers and traffic engineers deployed and evaluated many systems to provide preferential treatment for emergency vehicles at signalized intersections. Industry and transportation researchers have worked to determine the degree of benefit for the emergency vehicles and the impact to other roadway users. This has produced evaluation frameworks and performance measures that focus on tools and methods to define benefit in terms of reduction in emergency vehicle delay at signalized intersections and impact to side-street traffic in terms of increased delay at signalized intersections.

In field applications, transportation professionals and fire and rescue officials have often expressed a desire to include “reduction in emergency vehicle crashes” as a deployment objective (USDOT/FHWA, 1995). This objective is a response to the nationwide issue that a significant number of crashes involving emergency vehicles occur at signalized intersections each year. Reducing the potential for emergency vehicle crashes is beneficial to the jurisdiction. Emergency vehicle involvement in crashes causes property damage, potentially injuries, and possibly fatalities. Further, the victims at the original response location are put into further jeopardy because the call will have to be filled by another emergency unit, thereby increasing the response time.

To measure performance in terms of the safety objective, a statistically significant time period needs to be studied to determine the impact on crash histories for specific locations. The period required to generate the required crash histories is beyond the scope of most evaluations due to the overall very low frequency of emergency vehicle intersection crashes at any particular location. Therefore, there is a need to develop an evaluation method that examines EV preemption in terms of safety in such a way that unreasonably long evaluation periods are not required. Evaluation periods extending 5 to 10 years into the future may not produce valid results because of the dramatic changes in traffic volume and changes in control strategies that may take place. The research summarized in this dissertation seeks to use a conflict point evaluation method derived from the study of conflict points typical of traffic design.

The goal of this research is two-fold: 1) to characterize the conflict points associated with emergency vehicles passing through signalized intersections; and 2) to propose a method for measuring emergency vehicle specific conflict points in terms of severity. The effort examines data captured during a FOT of an EV preemption system. Analysis yields both quantitative and qualitative means to assess safety implications of EV preemption. The result is a set of inference rules that allows planners and engineers to estimate benefits and select appropriate EV preemption strategies.

4.2 PROBLEM STATEMENT

This dissertation addresses the problem faced by ITS professionals: How can the benefits of ITS be measured and quantified in order to support economic analysis of deployment options?

Previous research on EV preemption, including research conducted at Virginia Polytechnic Institute and State University, has produced evaluation frameworks useful in evaluating EV preemption systems in terms of delay to emergency vehicles and delay to side street autos. McHale (2002) used CORSIM with a run-time extension to evaluate the delay in an effort to enhance the IDAS methodology for economic evaluation of EV preemption projects. Obenberger and Collura (2001) reviewed the impacts of commonly used strategies for transition from preemption control back to the signal-timing plan. Both made valuable contributions to EV preemption assessment methodologies, but the issue of safety impacts, raised in deployment decision processes, remains unaddressed.

As an example, Arlington County, Virginia, is pursuing an EV preemption system deployment that will use a vehicle-based emitter to request preemption via a detector and processor located at the signal. During the July 2002 stakeholders' meeting, emergency vehicle crash reduction was proposed as an objective and as an element of the justification in funding decisions. Because there is no evaluation methodology other than traditional crash history analysis to support the objective, assessing benefits will be a challenge. This dissertation suggests a method based on the measurable reduction in conflict points that are specific to the flow of emergency vehicles through signalized intersections.

The methodology proposed in this dissertation includes conflict point analysis used in traditional design and operation of intersection traffic control devices. Garber and Hoel (1999) open the chapter on Traffic Control Devices with a discussion of conflict points at intersections. The authors determine that the primary design objective for a traffic control system at an intersection is to reduce the number of significant conflict points. They propose that engineers analyze the turning movements at intersections to determine the significant conflict points. They further suggest that crossing conflicts are the most severe and should be minimized. Additionally, they state that the severity of a conflict point is a function of the type of conflict (diverging, merging, or crossing), the number of vehicles involved, and the speed of the vehicles in the traffic stream.

Classic conflict point theory identifies conflict points as diverging, crossing, or merging for each approach and departure at an intersection. This characterization describes the phenomena associated with normal traffic flow, but does not adequately describe the phenomena as it relates to emergency vehicles. By their very presence on the roadway, emergency vehicles infer unique right-of-way rules and auto drivers' different behaviors in the presence of emergency vehicles. One fundamental way to reduce the number of active conflict points is to limit the simultaneous movements that are allowed. This is the basis for phase design in traffic signal control. Each state has different rules for phase design and sequencing to reduce conflict for normal traffic conditions, though all are based on behavior rules that make the phases work for normal traffic. This may leave emergency vehicle-specific conflict potential unaddressed. The next section of this dissertation introduces the findings from the field study.

4.3 EMERGENCY VEHICLE CRASHES AND CONFLICT POINTS

Each year, there are a significant number of crashes that involve emergency vehicles. At the national level, there are approximately 90 fatal crashes reported annually in the Fatality Analysis Reporting System (FARS, 2002). On average, 42 are intersection-related crashes, of which 23

occur at signalized intersections. Analysis of all the fatal crashes involving emergency vehicles at signalized intersections during the period 1994 to 2001 reveals the following crash type distribution: rear-end fatal crashes = 4; sideswipe (same direction) fatal crashes = 0; and angle fatal crashes = 155. This data indicates that the most severe crashes are the angle type, which conforms to conventional thinking on intersection crash severity. Table 4.1 illustrates the significant number of fatal emergency vehicle crashes that occur on a national level each year.

Table 4.1. Emergency Vehicle-Related Fatal Crashes

Year	Number of EV-Related Fatal Crashes	Number of EVs Involved
2000	90	92
1999	84	86
1998	95	97
1997	104	105
1996	99	99
1995	84	88
1995	100	104

Unfortunately, nonfatal crashes involving emergency vehicles are not categorically reported in the National Highway Traffic Safety Administration's annual Traffic Safety Facts Report, making it difficult to analyze injury and property damage crashes at the national level. Therefore, research supporting this dissertation included a detailed study of emergency vehicle crashes in Northern Virginia over the 10-year period from 1992 to 2001. Information taken from the VDOT crash database revealed that the four counties that comprise the region experienced a total of 653 crashes, of which 387 were property damage crashes, 264 were injury crashes, and 2 were fatal crashes. Data for Fairfax County, which has the highest traffic density per mile in the region, indicated that the county had 190 emergency vehicle crashes on primary roads. Of these, 62 were at un-signalized intersections and 70 were at signalized intersections. Table 4.2 provides a breakdown of the fatal crashes by collision type.

Table 4.2. Emergency Vehicle-Related Fatal Crash Analyses

Collision Type	2000	1999	1998	1997	1996	1995	1994	Total by Type
Not collision with motor in Transport	22	25	24	34	24	23	23	175
Rear end	0	4	6	8	8	6	5	37
Head on	8	14	13	16	9	9	8	77
Rear to rear	1	0	0	0	0	0	0	1
Angle	55	35	49	40	55	46	61	341
Sideswipe, same direction	1	1	2	2	0	0	2	8
Sideswipe, opposite direction	0	3	0	0	0	0	0	3
Unknown	0	1	0	0	0	0	0	1
Total per Year	87	83	94	100	96	84	99	643

For this study, emergency vehicle passage events through signalized intersections were analyzed using overhead video and ground-based observations in an effort to identify emergency vehicle-specific conflict points. Observations suggest that, similar to conventional conflict points, emergency vehicle-specific conflict points are characterized in severity by the angle between the emergency vehicle path and the interacting traffic stream. Three general classes of interaction are defined by the geometry of the interacting traffic stream: concurrent; perpendicular; and opposing. Figure 4.1 illustrates the three classifications. Following the figure, each case and the types of conflict associated with each are described.

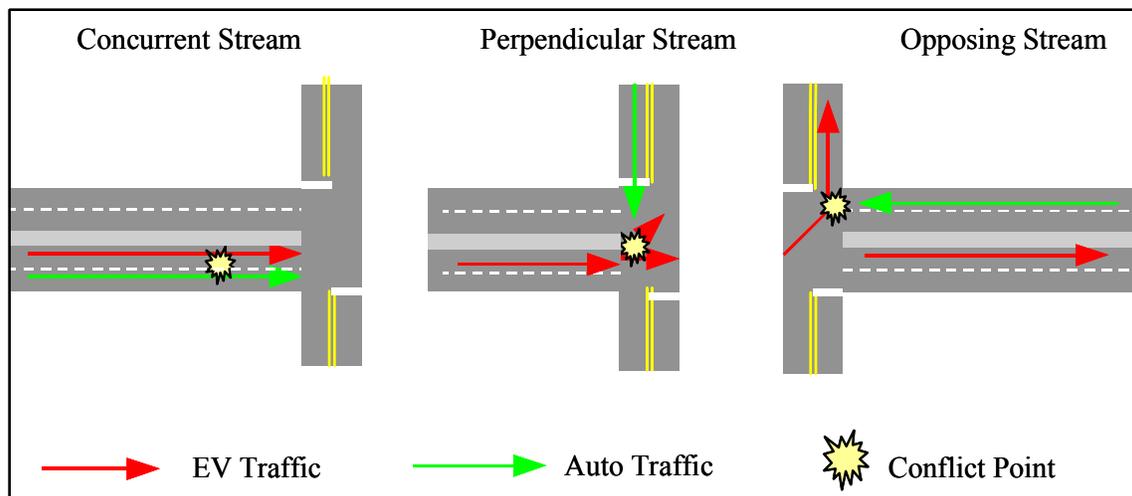


Figure 4.1. Emergency Vehicle-Specific Conflict Points

- Conflict with Concurrent Traffic Streams: Traffic flowing in the same direction as the emergency vehicle with shared use of the lanes and turn bays is characterized by the potential for low severity crashes (primarily rear-end and side-swipe [same direction] crashes). The number of interactions with concurrent traffic per event could be very high depending upon the traffic volume, and whether or not the traffic stream was free flowing and capable of moving to clear the path or stopped in multilane queues.
- Conflict with Perpendicular Traffic Streams: Traffic entering the intersection from a perpendicular approach is characterized by the potential for high severity crashes (primarily angle). The number of interactions was relatively low depending on whether or not the side street was in a red or green interval, and the presence of line-of-sight obstructions.
- Conflict with Opposing Traffic Streams: Traffic proceeding in the opposite direction on undivided and divided lane configurations exhibited two sets of characteristics depending upon whether or not the emergency vehicle proceeded through the intersection or turned left across opposing traffic. Two cases are described below:
 - Case 1: When the emergency vehicle proceeded through the intersection, it produced the potential for moderate severity crashes due to driver confusion. Some autos made sudden and abrupt stops at the stop line during the green interval and some proceeded through.

- Case 2: When the emergency vehicle made a left turn at the intersection, it produced the potential for very high severity crashes (angle or head-on) because of confusion by opposing stream auto drivers as to whether or not they should stop. The confusion is a product of both a green signal display to the opposing stream and the fact that emergency vehicles often make the left turn movement from the left through lane, surprising on-coming drivers.

4.4 DETERMINANTS OF CONFLICT SEVERITY

Early in the research, observations suggested potential structures to describe causality and severity regarding the conflict points. This resulted in identifying relevant dependent variable and independent variables. The dependent variable in this study is *conflict severity*. The emergent independent variables include: the geometric relationship of the traffic stream that interacts with the emergency vehicle; the degree to which messages to the auto drivers are mixed; and, the movement of the emergency vehicle (through or left turn). (See Appendix A for an explanation of the methods used to identify these relationships between variables.)

4.5 ANALYTICAL APPROACH

Each observed intersection passage event was reconstructed at a microscopic level, assigning emergency vehicle operator and auto driver actions down to the individual vehicle level. The reconstructed interactions were graphically documented to characterize the observed conflict and to assign a severity index. In addition to the graphic record, geometric conditions, signal displays, traffic volumes, and the vehicle movements were recorded using numerical codes to facilitate statistical analysis. This data was used to establish a macroscopic understanding of conflict potential and severity under various operating conditions.

The analytical approach used in this study attempts to identify: what were the guidance messages the auto driver received; how did the auto driver(s) respond to the guidance message; and how did the emergency vehicle operator navigate the intersection to minimize time delay while avoiding a collision? The goal is to present the quantitative input/output data in a meaningful inference rule set that allows transportation professionals to enter the key independent variables and derive a generalized dependent variable value. This variable value will help guide preemption deployment decisions and selection of signal displays best suited for preemption phases in traffic signal control.

The next section of this dissertation describes the analytical approach used to develop meaningful relationships between the data elements generated through observation and scoring.

4.6 DATA COLLECTION AND DATA STRUCTURE

The first step in the data collection was to determine the data required to examine all the applicable dimensions of the phenomena under study. Previously, the key independent variables were identified as the geometric relationship between the pathways of the interacting vehicles; the clarity of the guidance message provided to the auto drivers, and change in direction of the

emergency vehicle at the intersection. Because the operating characteristics of each intersection are unique, no single intersection could provide all the data to support the study. Therefore, several intersections were selected to support the study. Observation methods included overhead video, ground level video, and/or ground level observation by a research team member.

Intersections were picked to provide a variety of operating conditions, and they were required to possess certain similar characteristics. These characteristics included operational control under the Northern Virginia Smart Signal system, a minimum of two through lanes and a left turn bay, and either curbing or restricted shoulders. A total of 14 intersections were studied. The three contributing the most observations (177 of 210 total) are described here in terms of distinguishing characteristics:

- U.S. 1 and Southgate Drive, Fairfax County: This is the first intersection north of the emergency vehicle access point from a fire and rescue station. It operates on a 3-minute cycle time with a green percentage to the northbound arterial of approximately 84%. Emergency vehicles traverse this intersection on average 10 times per day with 2 runs during the AM peak. This intersection has a unique operating characteristic: a reduced northbound mainline flow during emergency vehicle passage due its location 250 feet north of an emergency entry signal at the emergency vehicle access point. The predominant emergency vehicle movement is through (87%), followed by a left turn (13%).
- U.S. 1 and South Kings Highway, Fairfax County: This is the second intersection north of the fire and rescue station located approximately 3,300 feet from the emergency entry signal. This intersection serves as a bottleneck to auto and emergency vehicle traffic flow due to the side street and arterial left turn volumes that reduce green time to the northbound arterial traffic. This signal also operates on a 3-minute cycle time with a green percentage to the northbound arterial of approximately 60%. The predominant emergency vehicle movement is through (90%), followed by a left turn (10%).
- Beauregard Street and Rayburn Drive, Fairfax County: This intersection has similar operating characteristics, including green-time distribution, to U.S. 1 and Southgate Drive, with the absence of a nearby emergency entry signal and without the affect it has on arterial flow. The predominant emergency vehicle movement is through (75%), followed by a right turn (25%).

Integral to the research effort was a training session to ensure inter-rater reliability. This included all participating scoring team members. The team used standardized forms and graphic documentation formats to review each interaction. Two evaluation teams were formed from a pool of three research associates. This ensured two team members were always involved in the review process and that at least one member was able to ensure continuity between evaluation sessions.

Following the training, all team members and the lead research associate participated in a scoring equivalency exercise using a sample of 30 interactions to verify scoring reliability. Both teams and the lead research associate reviewed the same 30 interactions independently. The three sets of results were then reviewed in a group session to reduce the potential for disparate scoring. As a final reliability review, all 210 interactions were reviewed jointly by the lead research associate and research team. Abnormalities in scoring were resolved using the graphic depictions, or reference to the video. The chart in Figure 4.2 illustrates the distribution of the total 210

observations with respect to the two most significant independent variables: interaction geometry and message clarity.

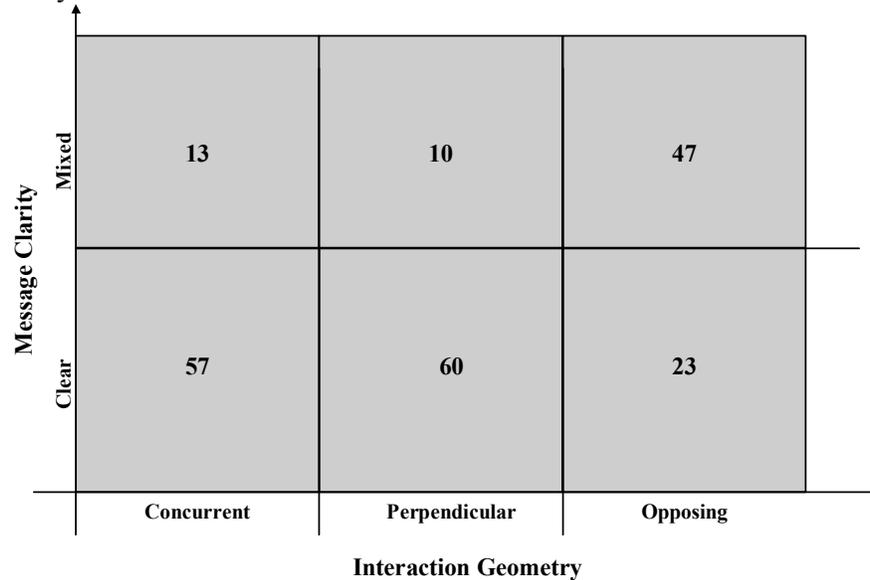


Figure 4.2. Distribution of Observations

4.7 PROPOSED CONFLICT EVALUATION METHOD

Evaluation methods for each emergency vehicle intersection passage followed a strict protocol designed to record and reconstruct the concurrent, perpendicular, and opposing elements. Each interaction geometry was evaluated along three dimensions—the degree to which mixed guidance messages were given to the driver, the number of non-emergency vehicles (referred to in the remainder of this dissertation as “autos”) involved in the interaction, and the degree to which emergency vehicle and auto pathways conflicted. Following the assessment, the reviewer assigned a conflict severity index based on criteria defined later in this dissertation. The severity indexes allow comparison and analysis with other events to identify trends and causal relationships. Prior to proceeding, it is necessary to establish definitions for the key components of the analytical method.

4.7.1 Mixed Message Definitions

Fundamentally, the existence of conflicts between emergency vehicles and autos is due to the message an auto driver receives. The *message*, which tells the driver to go, stop, or pull out of the emergency vehicle path, is a combination of two message elements: the signal display and the emergency vehicle siren and lights. When these two message elements are complementary, the number of conflict points is reduced and the potential for severe crashes is diminished. When these two message elements are non-complementary, conflict points are present. *Clear* and *mixed messages* are defined as follows for concurrent, perpendicular, and opposing flows.

- For concurrent flow, a *clear message* is present when the siren and lights convey to the autos to move out of the emergency vehicle path and yield the right-of-way, and a green signal

display at the intersection is complementary to allow autos to move as required to create a path for the emergency vehicle. A *mixed message* is present when the siren and lights convey to the auto to move out of the emergency vehicle path and yield the right-of-way, but a red signal display at the intersection is conflicting by telling the drivers to stop or hold their positions in the queue.

- For perpendicular flow, a *clear message* is present when the siren and lights approaching on the arterial convey to the auto on the perpendicular approach to stop or hold their positions in the queue, and a red signal display at the intersection is complementary. A *mixed message* is present when the siren and lights approaching on the arterial convey to the autos on the perpendicular approach to yield the right-of-way to the approaching emergency vehicle, but a green signal display at the intersection tells the autos to proceed.
- For opposing flow, a *clear message* is present when the siren and lights convey to the autos to yield the right-of-way to the approaching emergency vehicle, and a red signal display at the intersection is complementary, telling the autos to stop or hold their positions in the queue. A *mixed message* is present when the siren and lights convey to the auto to yield the right-of-way to the approaching emergency vehicle, but a green signal display at the intersection tells the autos to proceed.

Without EV preemption, the presence of a *clear* or *mixed message* at the time of emergency vehicle arrival is random depending on the signal-timing plan. With EV preemption, a green signal is displayed to the emergency vehicle approach for all movements and a red signal is displayed on all other approaches providing a *clear* message to all involved.

4.7.2 Conflict Definition

Previously, three emergency vehicle-specific conflict point types were identified based on the geometric relationship of the emergency vehicle path with the interacting traffic stream. Whether or not a crash occurs at any conflict point is a function of the auto driver and emergency vehicle operator maneuvers (direction and position) relative to each other. The research in Northern Virginia included a study of these interactions at the microscopic level. Initial research focused on establishing a common understanding about the types of pathway conflicts that occur and determining a relative degree of severity for each. A transportation research team used graphic renderings and video of 39 observed interactions to characterize the types of conflict.

Characterization included evaluating the interaction between the emergency vehicle and autos; the interaction between autos to create an emergency vehicle pathway; and the crossing angle and speed of the interacting traffic streams. A severity index was assigned based on the earlier presented national and local crash severity data in conjunction with inputs by emergency vehicle operators from the Fairfax County Fire and Rescue Station participating in the study. The results of the effort are fully described here along with the general distribution of conflict type across the range of severity indexes. (See Appendix B for a complete analysis of emergency vehicle crash data) Definitions and severity indexes for the eight general conflict situations are described following Figure 4.3. In general:

- Interaction with concurrent traffic streams produce conflicts in the lower portion of the severity index range due to low crossing angles and low closing velocities.

- Interaction with side-street approaches produce conflicts in the center of the severity index range due to higher crossing angles but lower closing velocities as emergency vehicles generally slow down when approaching green signals and are required by standard operating procedures to stop momentarily when approaching red signals.
- Interaction with opposing traffic streams produce lower range severity values for cases where the emergency vehicle proceeds on a through movement and produce very high severity values for cases when an emergency vehicle unexpectedly turns across the pathway of oncoming autos introducing the potential for crashes at high crossing angles with high closing velocities.

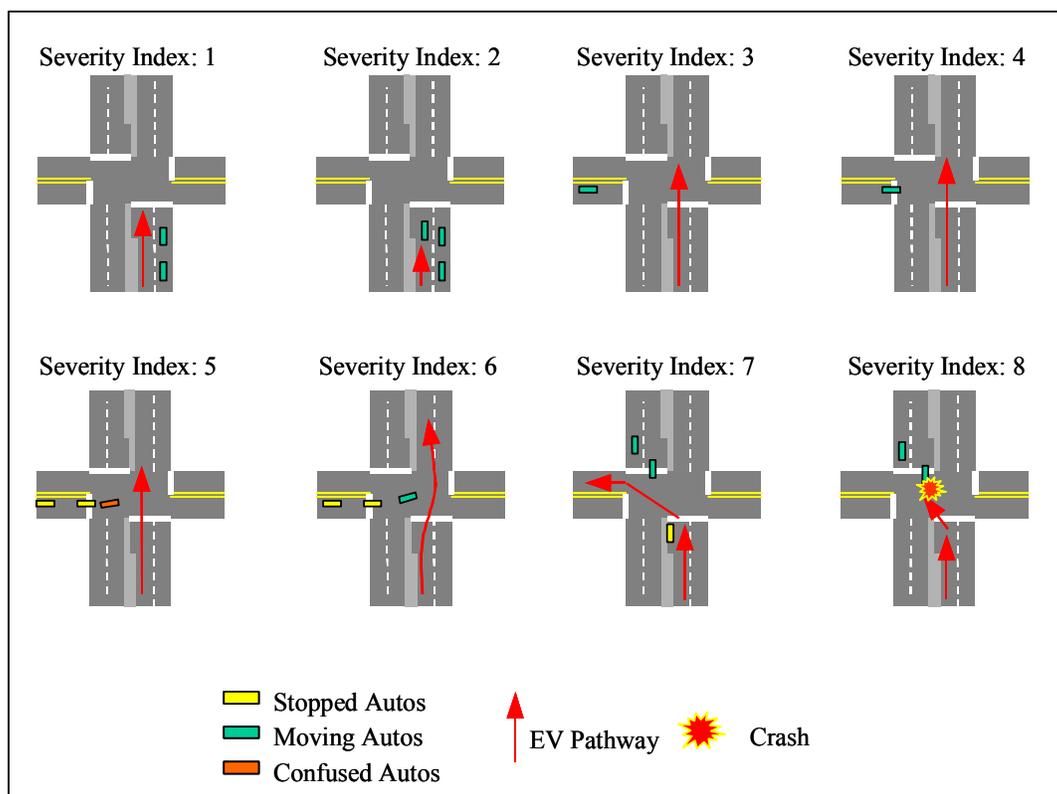


Figure 4.3. Conflict Severity Index by Situation

The eight situations depicted above are described as follows:

- Emergency Vehicle Unexpected Movement: Entry onto and travel down the roadway under response conditions, i.e., the attempt to achieve maximum practical travel speed consistent with standard operating procedures. Severity Index: 1.
- Emergency Vehicle Unexpected Movement in Relevant Proximity to Autos: Entry onto and travel down the roadway under response conditions, i.e., the attempt to achieve maximum practical travel speed consistent with standard operating procedures, while in close lateral and longitudinal proximity to autos. Severity Index: 2.
- Emergency Vehicle Conflicting Movement: The movement of an emergency vehicle within the traffic stream or at a signalized intersection, which requires the emergency vehicle to

unexpectedly cross the *potential* path of autos obeying roadway guidance and traffic control device cues. Severity Index: 3.

- Emergency Vehicle Conflicting Movement in Relevant Proximity to Autos: The movement of an emergency vehicle within the traffic stream or at a signalized intersection, which requires the emergency vehicle to unexpectedly cross the *actual* path of autos obeying roadway guidance and traffic control device cues. Severity Index: 4.
- Auto Displayed Confusion: The actions of the auto indicate that there was confusion in determining the appropriate reaction (stop, pull over, or continue). Severity Index: 5.
- Auto Unexpected, Conflicting Movement: The unexpected execution of a movement, which causes the emergency vehicle to alter its pathway. Severity Index: 6.
- Emergency Vehicle Highly Unexpected, Conflicting Movement: The highly unexpected execution of a movement that conflicts with the legal movement of autos. Severity Index: 7.
- Emergency Vehicle Crash: The contact of an emergency vehicle with autos as the result of unexpected and/or conflicting maneuvers taken during an interaction. Severity Index: 8.

4.8 DATA ANALYSIS AND RESULTS

The data was evaluated using the Classification and Regression Tree (CART) algorithm (StatSoft Corporation, 1984). For the independent variable, emergency vehicle conflict severity, the CART algorithm was used to produce a regression tree as depicted in Figure 4.4. The regression tree explains conflict severity as a function of mixed message, emergency vehicle movement, and interaction geometry. (See Appendix C for a complete explanation of the CART algorithm and a summary of its use in this research)

The inference from the analysis is that EV preemption reduces conflict potential by ensuring that a *clear* message is delivered to the auto drivers. Figure 4.5 compares the conflict potential for *clear* and *mixed* message cases. For the concurrent case, the conflict severity reduction is at a minimum. For the interaction geometries and emergency vehicle movements that present crossing conflicts (the perpendicular and opposing with an emergency vehicle left turn), the reduction in conflict severity is most pronounced.

The CART suggested hierarchal variable relationships could be used to form an inference rule set. This is facilitated if the conflict severity indexes are generalized (as shown in Figure 4.6) to reflect the range of consequences observed for a given set of antecedent conditions.

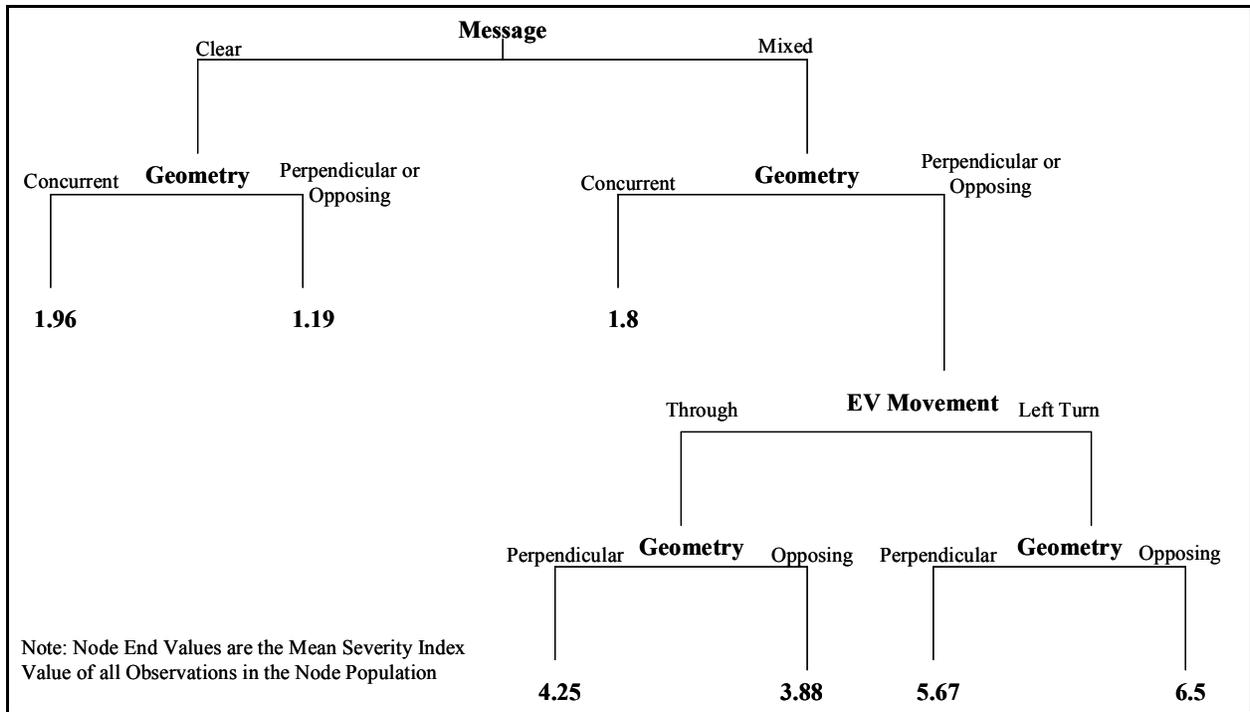


Figure 4.4. Classification and Regression Tree

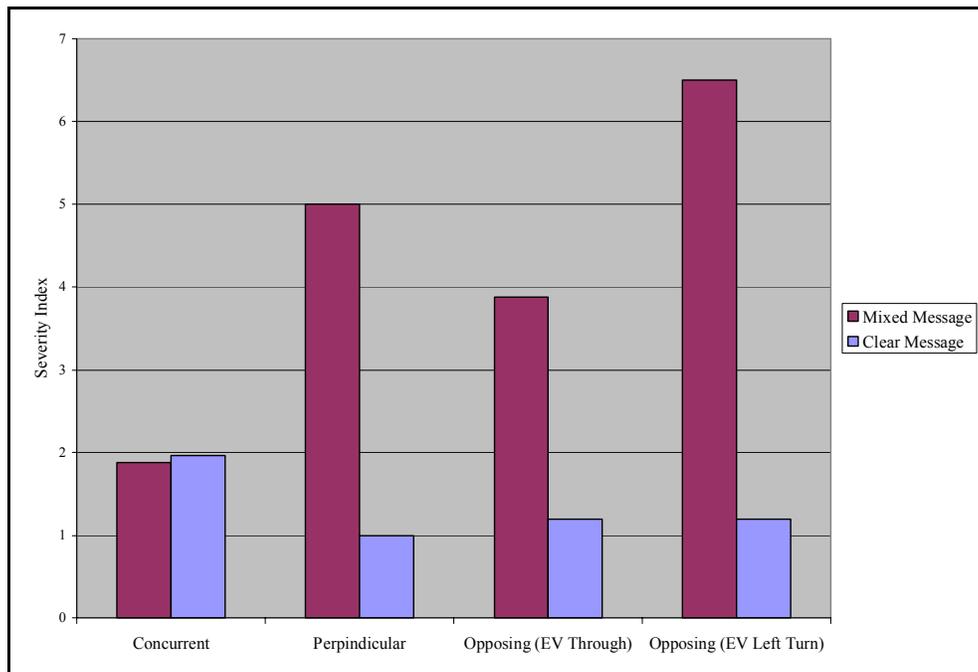


Figure 4.5. Conflict Severity by Message Type

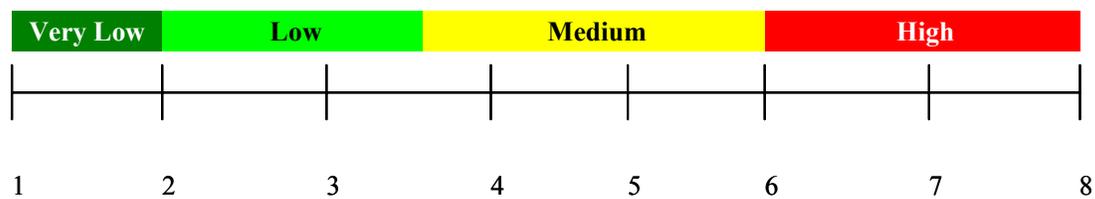


Figure 4.6. Generalized Conflict Severity Indexes

4.8.1 Concurrent Case

- Rule 1: If the message is *clear*, then the conflict severity is Low.
- Rule 2: If the message is *mixed*, then the conflict severity is Low.

4.8.2 Perpendicular Case

- Rule 1: If the message is *clear*, then the conflict severity is Very Low.
- Rule 2: If the message is *mixed*, then the conflict severity is Medium.

4.8.3 Opposing Case

- Rule 1: If the message is *clear* and the emergency vehicle movement is through, then the conflict severity is Very Low.
- Rule 2: If the message is *mixed* and the emergency vehicle movement is through, then the conflict severity is Medium.
- Rule 3: If the message is *clear* and the emergency vehicle movement is a left turn, then the conflict severity is Very Low.
- Rule 4: If the message is *mixed* and the emergency vehicle movement is a left turn, then the conflict severity is High.

These rules, which are based on the previously defined terms, provide a method for evaluating any signalized intersection before and after the deployment of EV preemption. The difference between the *before* and *after* case is that the *after* case contains only *clear* messages, dramatically reducing the potential for severe crashes associated with crossing conflicts.

4.9 AN ILLUSTRATIVE EXAMPLE

Figure 4.7 is the reconstruction of an event prior to deployment of EV preemption. The event took place at the intersection of U.S. 1 and Fairhaven Drive in Fairfax County, Virginia. The figure depicts a *mixed* message presented to the opposing traffic. The signal is in the green interval on both arterial approaches and, until the split second the emergency vehicle initiated the left turn, it appeared to be headed through in the left through lane. For a divided highway situation, the *Virginia Driver's Manual* (Virginia Department of Motor Vehicles, 2001) does not require opposing traffic to stop or pull over for approaching emergency vehicles. The opposing

traffic is only required to yield the right-of-way if the emergency vehicle requires it. In the case shown, the two auto drivers in the through lanes were taken by surprise as the emergency vehicle suddenly initiated a left turn. This caused confusion and required an abrupt stop from travel speeds of 45 mph.

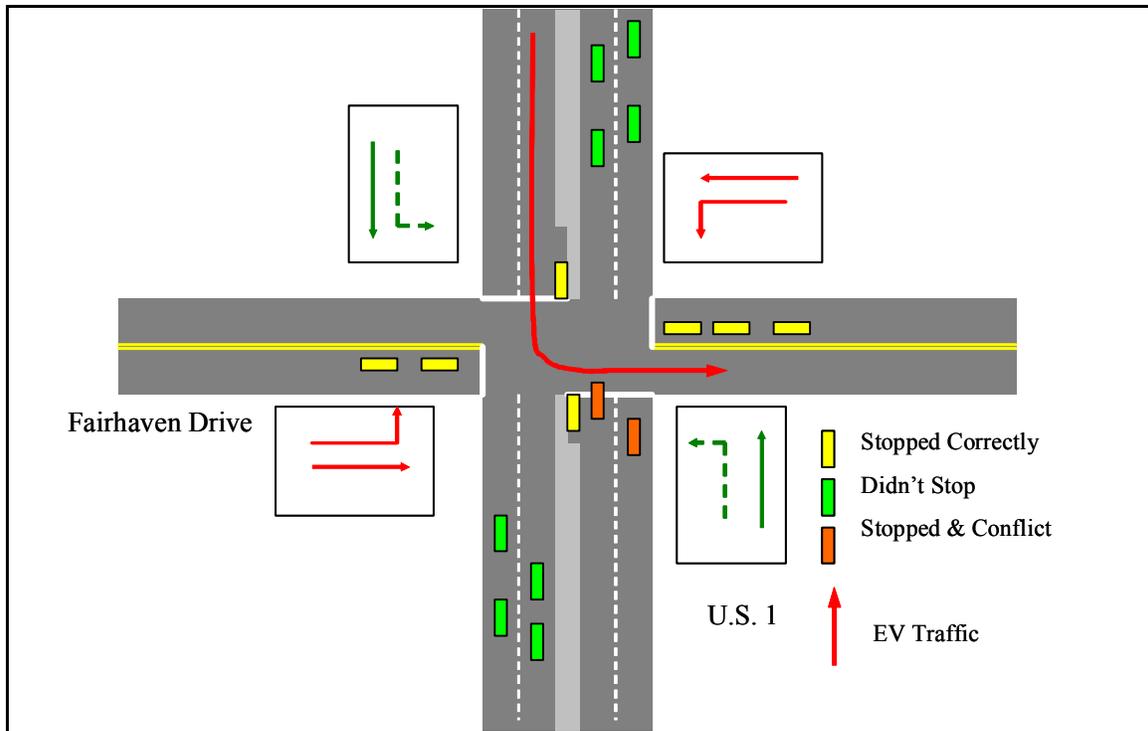


Figure 4.7. An Illustrative Example—Without Preemption

Based on the terms, definitions, and rules presented in this dissertation, the observer assigned conflict severity scores for this incident in Table 4.3. Had EV preemption been in place, the northbound autos would be given a 5-second amber interval, followed by a red interval, resulting in a conflict-free pathway for the emergency vehicle.

Table 4.3. Conflict Potential Scores for the Illustrative Example

Geometry of Interaction	EV Movement	Message Type	Number of Confused Autos	Conflict Score
Concurrent	N/A	Clear	N/A	Low
Perpendicular	N/A	Clear	0	Very Low
Opposing	Left Turn	Mixed	2	High

4.10 CONCLUSIONS AND RECOMMENDATIONS

Crash reduction is a bona-fide objective of EV preemption deployments. Emergency vehicle crash histories illustrate that there is a significant problem, and that a majority of the crashes are

intersection-related. Transportation planners and engineers need tools to determine EV preemption candidate intersections based on safety objectives, as well as emergency vehicle travel time reduction objectives.

This dissertation offers a methodology which links crash potential to emergency vehicle-specific conflict points at signalized intersections. Understanding this relationship allows transportation professionals to make estimates regarding the potential safety benefits of EV preemption without having to wait for the time required to generate a valid crash history. The Northern Virginia field study provided data indicating that the conflict points may decrease significantly in number and severity when EV preemption provides *clear* messages to the auto drivers. EV preemption phase displays that provide *clear* messages to all intersection approaches significantly reduce the number and severity of conflicts.

While the number of observations used to generate the inferences in this study is low compared to the thousands of data points available in other traffic and transportation areas, the methodology suggested is sound. The results correspond well with the traditional understanding of crashes, conflicts, and intersection control. This method, within a larger evaluation framework that examines the emergency vehicle travel time component, will be beneficial in providing a basis for decisions to deploy EV preemption.

CHAPTER 5: A METHOD FOR EVALUATION OF EV TRAVEL TIME BENEFITS

5.1 INTRODUCTION

To date, ITS designers and traffic engineers have deployed and evaluated many systems to provide preferential treatment for emergency vehicles at signalized intersections. Industry and transportation researchers have worked to develop performance evaluation methods to establish the degree of benefit for the emergency vehicles and the impact to other roadway users. This work has produced evaluation frameworks and performance measures that focus on simulation-based methods to define benefits in terms of reduction in emergency vehicle delay at signalized intersections and impact in terms of increased delay to side-street traffic.

Studies that support these frameworks often rely on traffic microsimulation tools, such as CORSIM, to perform evaluations of single intersections or sequential intersections on signalized arterials to determine the degree of benefit in the form of reduced emergency vehicle travel time. Although these studies provide valuable insights, the results are limited in their representation of actual emergency vehicle delay conditions at intersections where an emergency vehicle must penetrate static queues that build during a red traffic signal interval. The limitation is due to the manner in which the microsimulation tools move vehicles on the network using algorithms that control car following, lane changes, and interactive behaviors of drivers within a platoon. Limitations are due also to the manner in which the roadways and lane configurations are represented within the models.

To more accurately measure the emergency vehicle travel time benefit of preemption, microsimulation tools need to be updated with a special module designed specifically to evaluate emergency vehicle travel time in the vicinity of signalized intersections. Such a module, which may eventually be an element of the Next Generation Simulation (NGSIM) suite of algorithms, should allow evaluation of a range of operating conditions and preemption strategies. To develop such a module, there is a need to document the nature of the interactions taking place between emergency vehicles and other traffic within a framework that will facilitate future modeling efforts.

The goal of this chapter is three fold: 1) to characterize the phenomena that occurs when auto drivers in queue during a red traffic signal interval respond to an approaching emergency vehicle; 2) to translate the observed behaviors into special algorithms designed to generate a realistic response in terms of driver interaction within the queue; and 3) to demonstrate the utility of the algorithms by comparing the computed result with actual field observations recorded during a 2002 FOT of EV preemption in Northern Virginia. In breadth, the chapter will present an evaluation framework for emergency vehicle delay. In depth, the effort will define the algorithm requirements to reasonably emulate the phenomena. Analysis using the suite of algorithms will generate a forecast for emergency vehicle delay due to the existence of a given set of geometric conditions, traffic flow conditions, and traffic signal-timing plans. The result is a tool to allow engineers in the field to quickly assess the potential benefits of EV preemption.

5.2 PROBLEM STATEMENT

This chapter addresses the following problem faced by ITS professionals: How can the benefits of this specific intelligent transportation system, the combination of technology and strategy that comprise a preemption system, be measured and quantified in order to support decisions on whether or not to deploy the system? This question is significant when emergency vehicle response times are considered. Many jurisdictions now publish response times on publicly accessed websites as a key performance indicator the public safety department. The failure to reach a cardiac victim or to reach the scene of a fire within nationally recognized time criteria could present significant liability issues for local governments. Typical emergency vehicle response time standards are in the 4 to 7 minute range. As observed in one field observation during typical AM peak conditions, a 38-second delay at a single major intersection represents a significant deviation and puts lives and property at risk.

Before introducing the methods developed in this research effort, it will be useful to review current EV preemption evaluation methods and to examine the issue of emergency vehicle response times in detail.

5.2.1 *Current Evaluation Methods*

Recent research in the EV preemption arena, including research conducted at Virginia Polytechnic Institute and State University, has produced methods useful in evaluating EV preemption in terms of reducing delay to emergency vehicles. McHale (2003) used CORSIM with a run time extension to evaluate the delay along a 7-intersection corridor in which the center intersection was equipped with preemption. McHale's objective was to evaluate a specific preemption strategy across a variety of traffic flow conditions to develop enhancement recommendations for the IDAS methodology for economic evaluation of preemption.

Bullock (2003) used CORSIM with actual signal controller hardware-in-the-loop to evaluate the travel-time benefit, in part, to justify the installation of EV preemption systems at three intersections on approach to a new hospital and trauma center in the growing community of Landsdowne located in Loudon County, Virginia. In both reports, the authors noted the significant limitations of CORSIM to accurately emulate the delay an emergency vehicle encounters as it approaches an intersection on an approach with a static, multilane queue. CORSIM limitations include the following:

- Emergency vehicles obey the red signal and do not attempt to penetrate the queue since CORSIM does not have a selective signal compliance feature.
- Emergency vehicles do not attempt to pass within the same lane since CORSIM does not contain a provision for passing within the same lane.
- Autos in the queue do not attempt to change lanes to clear a pathway because there is no stimulus for lane change generated by the emergency vehicle.
- Autos in the queue do not attempt to offset laterally within a lane to create a pathway for the emergency vehicle because lanes within CORSIM do not have lateral dimensions for computational purposes.

McHale and Bullock recognized the limitations of CORSIM to microscopically evaluate the benefit of preemption at the individual intersection level. As a result, they conducted their evaluations at the corridor level using aggregated data to draw conclusions on network performance in terms of benefit to the emergency vehicles and impact to other traffic. Both made valuable contributions to the evaluation methods, which formed the basis for the research presented in this dissertation.

5.2.2 Fire and Rescue Response Time Standards

Determining a response time standard is the responsibility of each individual jurisdiction. It is a balance between the cost of service and the risk to life and property, which is largely influenced by the development density and type. Other considerations include such elements as the distance to the fire and rescue station and the nature of the roadways and congestion levels. In developing service plans, most jurisdictions generally consult accepted standards such as *flashover curves* as indicated by the National Fire Protection Association (NFPA, 2003) and survival rates from the American Heart Association (AHA, 2003). These standards outline activities that must be performed within certain time frames in order to have a better outcome for the buildings or persons involved.

For effective fire suppression, the NFPA states units must be able to apply water to a fire prior to the point of flashover, which, for most residential construction, occurs anywhere from 4 – 11 minutes after the fire begins (NFPA, 2003). A layman's definition of *flashover* is the point at which the room bursts into flame. The scientific definition of flashover states that it is caused by the radiation feedback of heat. Heat from the growing fire is absorbed into the upper walls and contents of the room, heating up the combustible gases and furnishings to their auto-ignition temperature. This buildup of heat in the room triggers *flashover*.

Effective rescue programs are generally based on a 2-tier life support response. Basic life support services provide cardiopulmonary resuscitation (CPR) to patients to stabilize their condition. The AHA studies show that CPR must begin immediately, and in all cases, no later than 4 – 6 minutes of a cardiac arrest. CPR must be followed by defibrillation in order to restore heart rhythm and prepare the patient for advanced life support (ALS) services. ALS may include treatments and medications by on-site emergency medical technicians working interactively with physicians over wireless data and voice connections. The combination of delayed CPR (more than 4 minutes) and delayed advanced life support (more than 12 minutes) is particularly lethal.

5.2.3 Public Reporting of Fire and Rescue Response Performance

A principal measure for service quality of public safety programs is the response times for fire and rescue services. Many jurisdictions set response time performance goals based on studies of fire flashover times and survival rates for persons suffering cardiac distress. Local conditions, including development density, help define the risk levels associated with a given resource level, apparatus inventory, and station locations. Of the four counties that comprise the Northern Virginia region, both Fairfax and Prince William Counties publish and report response time goals and performance on their public safety websites. Arlington county, has response time goals published, but does not post performance statistics on its website. Loudon county is currently developing response time performance goals. To date, Loudon County officials have measured

only “turnout time,” which is the time from receipt of a dispatch order at the station until the vehicle clears the garage doorway. (See Appendix C for a summary of the Northern Virginia county response time performance).

5.2.4 Fire and Rescue Response Times as Resource Planning Inputs

As previously cited, Loudon County, Virginia is in the process of evaluating its current approach to the provision of fire and rescue services. This evaluation is driven by the county’s rapid transition from a rural area to a mixed-use area, including high-density living areas and campus-style information technology centers. The influx of new population centers and the increase in congestion on the arterial roadways challenges the county’s ability to provide services at the standards adopted by neighboring Fairfax and Prince William Counties. This has led to several studies, including one published in January 2003 and posted on the Loudon County Public Service website (2003), which examines the future fire and rescue service plans. In this study, response time elements are defined and planning goals are established as follows:

- **Call Processing Time**: Time recorded from receipt of Emergency 9-1-1 call until units are dispatched. Standard: 1 minute.
- **Turnout Time**: Time recorded from dispatch until units are leaving the station. Standard: 1 minute.
- **Travel Time**: Time recorded from leaving the station until units arrive at the scene (variable according to station placement).
- **Set-Up Time**: Time recorded to gather equipment and proceed to the actual emergency site (variable depending on incident type; normally 1-3 minutes).

5.2.5 Analysis of Emergency Vehicle Delay

Analysis of the taxonomy of response times reveals that for a nominal 6-minute standard, 3 minutes are consumed by relatively fixed elements—dispatch time, turnout time, and setup time—leaving only 3 minutes for travel time. If an average emergency travel speed of 35 mph is achieved, a 3-minute travel time will yield an operating radius of less than 2 miles.

As growing congestion threatens the ability of fire and rescue services to meet the critical timelines, jurisdictions will need to evaluate options to maintain acceptable response times commensurate with risk and resources. EV preemption of traffic signals promises to minimize the impact of traffic signals on response times. Policy makers, traffic engineers, and fire and rescue professionals need a method to evaluate the potential benefit of preemption on an intersection-by-intersection basis. The research presented in this dissertation seeks to advance the state-of-the-art and close the current evaluation gap by suggesting a method to quantify the delay impact generated as the result of auto driver and emergency vehicle operator interactions in static, multilane queues. The method is based on field observations of the applicable behaviors in the field in Northern Virginia in 2002.

5.3 EMERGENCY VEHICLE DELAY AT SIGNALIZED INTERSECTIONS

When an emergency vehicle approaches an intersection, it must modify its speed profile to safely navigate the intersection environment. In cases where a signal is in the red interval, the autos in

the forming queue must maneuver within the geometric constraints of the roadway to generate a pathway for the emergency vehicle while honoring the red signal. In this case, the emergency vehicle speed profile will be significantly affected as the emergency vehicle often slows to a crawl (Figure 5.1), progressing at the rate that a pathway can be generated as the autos in the queue attempt to maneuver laterally (Figure 5.2).

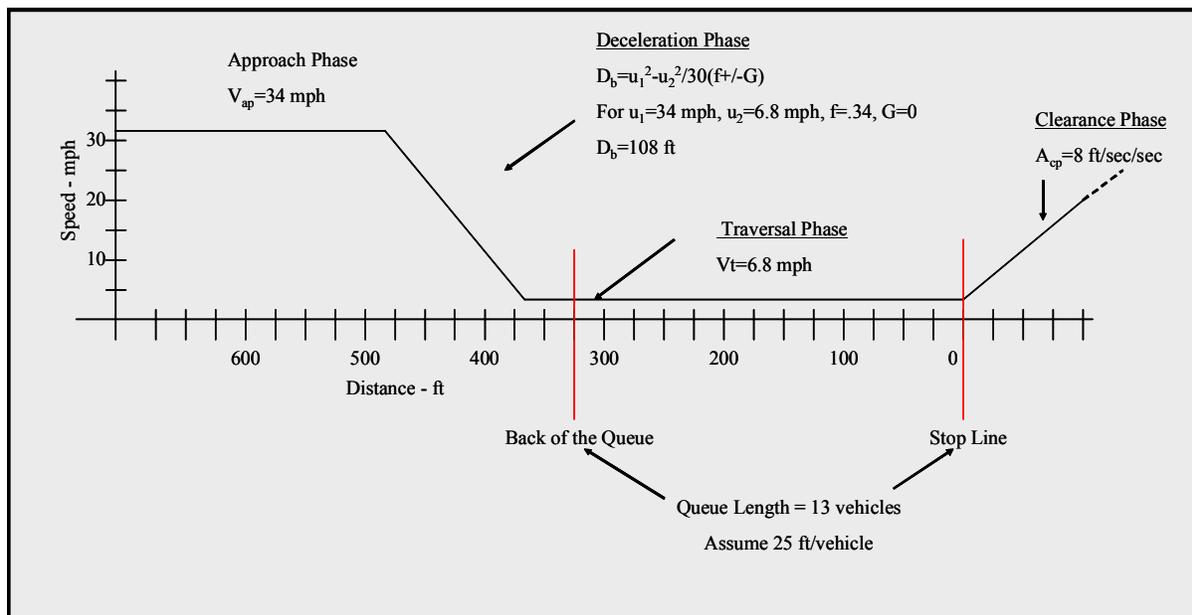


Figure 5.1. Speed Profile of an EV During a Red Interval

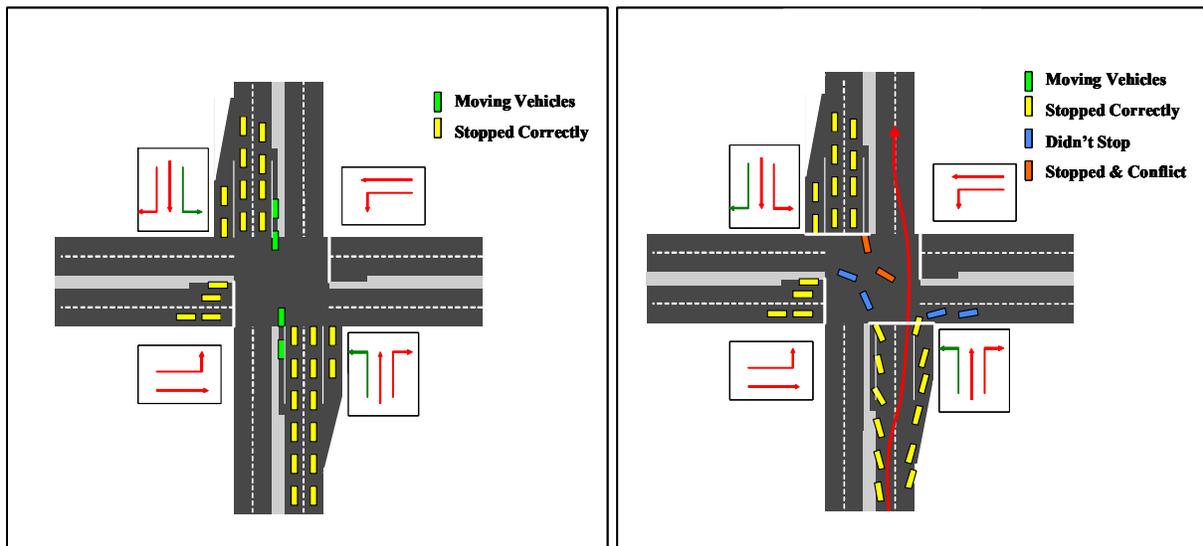


Figure 5.2. EV Traversal During a Red Interval

If the signal has been green long enough to allow the autos in the queue to begin to move, the emergency vehicle can maintain a more favorable speed profile (Figure 5.3). In this case, the platoon begins to disperse and the autos move into gaps in the right lane allowing the emergency vehicle to proceed in the left lane (Figure 5.4).

The worst case scenario occurs when the signal has been in the red interval long enough to form multi-lane, extended queues forming a barrier (especially if the roadway environment includes curbing). A very complex series of cooperative, interactive lateral and longitudinal maneuvers is required to create the passage for the emergency vehicle to proceed. The autos must execute “side-step” maneuvers, which take advantage of any excess lateral spacing, which may be available based on the number of lanes, the width of the lanes, and the width of the general vehicle population. The Northern Virginia FOT indicated that, for the typical AM and PM peak vehicle population (less than 5% heavy vehicles with no tractor trailer vehicles), a minimum of 36 ft of lateral space is required. This can be provided in the form of three 12 ft lanes (counting turn bays) or, can be provided with less/narrower lanes if there is access to a prepared shoulder (graded with gravel or paved).

Observations of this queue penetration phenomena revealed that success relied, not only on the availability of excess lateral space, but also on the ability of the drivers to perceive the need to move and to move cooperatively and interactively to create the required passage. This second factor, the requirement for cooperative, interactive maneuvering, is the one examined in depth in this research.

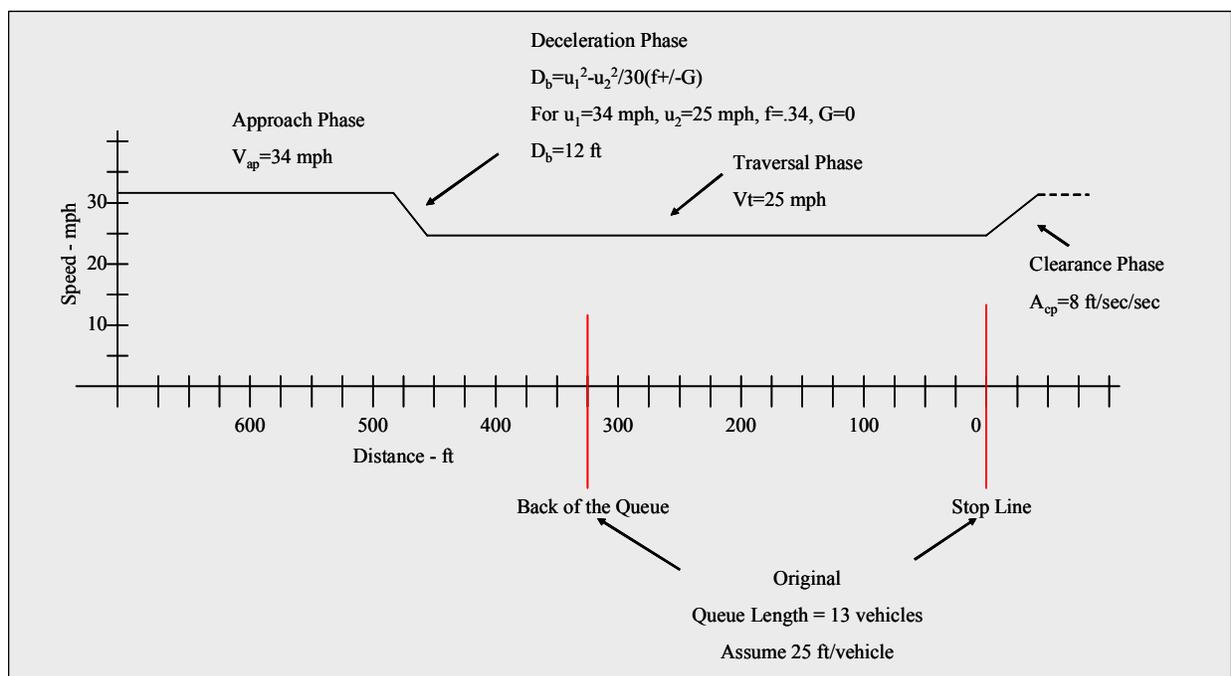


Figure 5.3. Speed Profile of an EV Following Transition to a Green Interval

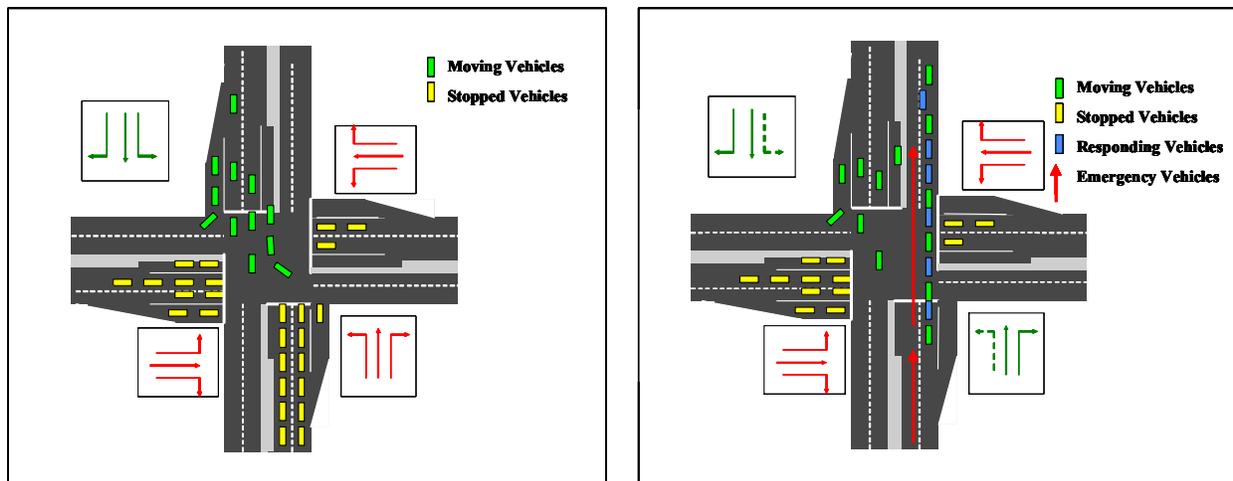


Figure 5.4. EV Traversal Following Transition to a Green Interval

Field observations from the Northern Virginia FOT were used to create a model of the actions the emergency vehicle and the queued autos. Observations indicated that most of the auto drivers executed favorable maneuvers. Those who did not generally corrected their maneuvers based on observing other members of the platoon. The result of this interactive learning was informally recorded in the following statement:

Once one person in the platoon does the right thing, more people start doing the right thing. The more people there are in the platoon doing the right, the more efficient the cooperative maneuvering becomes.

Based on the research recorded for this dissertation, following is an overview of the entire process:

The vehicles in the queue are stimulated to respond by the approach of an emergency vehicle operating its siren and lights. The vehicles in the queue respond by attempting to create a pathway by maneuvering cooperatively and interactively to create a pathway between two adjacent lanes. Each driver initiates a reaction based on individual ability to interpret the situation and skillfully maneuver the vehicles. Drivers with inferior abilities may learn by observing the actions of drivers who have selected superior responses. An artificial lane is generated as the auto drivers offset themselves laterally within the geometric limits afforded by the specific roadway and their own tolerance for lateral and longitudinal proximity. These actions allow the emergency vehicle to proceed at a reduced speed until the stop line is reached. Once at the stop line, the emergency vehicle waits for a gap in perpendicular traffic and then proceeds by accelerating to a maximum speed consistent with traffic conditions and standard operating procedures.

5.4 REVIEW OF CURRENT MODELS

Most microsimulations employ three algorithm sets that are central to the ability to evaluate emergency vehicle travel time through signalized intersections: car following; lane changing; and vehicle response to traffic control devices. These algorithms provide input to the vehicle displacement mechanism in order to update vehicle positions in each simulation time step. Before describing the emergency vehicle driver response model developed in this research, it is beneficial to examine methods currently used in vehicle movement in microsimulation tools such as CORSIM and to look at an example of emerging concepts developed to support TRANSIMS. Traditional car-following algorithms are developed on the basis of driver perception, decision, and response models that translate real-world observations into mathematical statements which can represent car following at various degrees of fidelity based on the complexity of the algorithms selected (Rothery, 1996). CORSIM uses very simple and rigid car-following algorithms. In CORSIM, vehicles operate as independents or in platoons. The difference determined by a set following distance commensurate with the desired free-flow speed set for the link.

When outside a set influence zone, the vehicles behave autonomously and maintain speed relative to the link and vehicle speed characteristics input to the model. Vehicles in platoons are either leaders or followers. Leaders behave like the independents. Followers are latched to the leader maintaining the leader's speed parameters and a fixed minimum following distance based on the assigned link and vehicle speed characteristics. When in the car-following mode, vehicles strive to avoid collisions; however, due to the way vehicles are processed within CORSIM, sometimes "collisions" do occur. If a "collision" occurs, the vehicle is assigned the maximum deceleration rate and placed at the rear bumper of its leader vehicle. This method of treating "collisions" as maximum decelerations keeps vehicle crashes from occurring as a result of the vehicle movement logic (Halati, Lieu, and Walker, 1997).

Besides car-following, lane-changing algorithms are the most influential elements of the vehicle movement process in microsimulation. In CORSIM, two types of lane changes are performed: mandatory and discretionary. *Mandatory* lane changes are made so that a vehicle can complete a turn at an intersection, or must react to a lane closure or lane drop. *Discretionary* lane changes are made to bypass a slower vehicle or join a shorter queue at an intersection (Halati, et al., 1997). For discretionary lane changes, the target lane for lane changing is selected based on the lane with the lowest impedance factor.

A third important element of microsimulation vehicle movement is vehicle response to traffic control devices. In CORSIM, all vehicles respond to traffic signal displays so, in the case of evaluation of emergency vehicle travel time, an emergency vehicle will stop to honor a red signal ignoring the real-world practices illustrated previously producing inaccuracies in the evaluation (Halati, et al., 1997).

Contrasting with the rigid methods in CORSIM, TRANSIMS provides a wide range of driver behaviors by using a system that assigns driver attributes on a stochastic basis. These driver attributes, which define attitude, familiarity, and ability indexes, are used selectively in the algorithms that define car-following and lane-changing elements of the vehicle movement

model. Traffic control devices and vehicle classes also have attributes that combine in algorithms to determine whether or not a certain class of vehicle will respond to a traffic control device such as a signal. Using this attribute system and a discrete time step vehicle movement method allows TRANSIMS to more accurately model the actions of real drivers in real situations. The vehicles on the TRANSIMS network are assigned the attributes, which are used in every time step to determine the cell-by-cell vehicle motion as each driver pursues the specifically designed travel plan developed. This flexibility is not without penalty; the computation requirements are tremendous in TRANSIMS and require parallel processing of vehicle movements, such that individual processors handle small network sections. When required, vehicles are handed off from one network section to another, complete with the attributes list that defines its tendencies (Los Alamos National Laboratory, 2003).

5.5 MODELING APPROACH

To develop the conceptual basis for an eventual model, functional requirements are identified based on the previous description of the phenomena that occurs when an emergency vehicle approaches a queue. The high-level requirements are: a means to generate vehicle movements, to describe auto responses based on driver behaviors, and to describe the interaction and learning that occurs between vehicles.

Based on these requirements, a high-level functional architecture for a Driver Response to Emergency Vehicle Approach Model (DREAM) is proposed as illustrated in Figure 5.5. The model's key component is the mechanism used to generate the auto displacements. This mechanism computes the spatial transitions of the autos in the queue over a measured time period based on: the drivers' ability to recognize the need to maneuver, driver behavior tendencies, and the drivers' ability to learn and update actions in real time. These three qualities simulate a real-world environment via modules that interface with the displacement mechanism in shaping the displacement process for maneuvering quality, and ultimately, the time required to maneuver.

The first module uses a stimulus-response process to explain how auto drivers respond to a stimulus, such as an approaching emergency vehicle. The module must consider a driver's perception of the need to move, the maneuver selection process, and adjustment of the driver's preferences for longitudinal and lateral vehicle separation. The second module focuses on driver behavior and incorporates a range of driver behavior characteristics that expressing expected attitudes and driving abilities in the population. It relates the driver behaviors to the quality of the actions being taken by the individual vehicles. The third module, the learning module, incorporates the concept that, by observing the other autos' maneuvers, each auto's interactive actions help create an emergency vehicle pathway.

5.6 DREAM COMPONENTS

The displacement mechanism seeks to emulate the stepwise spatial transitions observed in the field. From observing numerous field situations, the research team discovered a pattern. This pattern was used to develop a core simulation algorithm. The pattern of position transition, wherein the autos in the queue attempt to change their lateral position within a lane, is similar to

the patterns observed, on a larger spatial scale, in highway weaving areas. In weaving areas, a driver's behavior is a function of several factors, including traffic congestion levels, time to reach the desired exit, heavy vehicle presence, roadway geometrics, ability to maintain a desired speed, and the presence of on- and off-ramps.

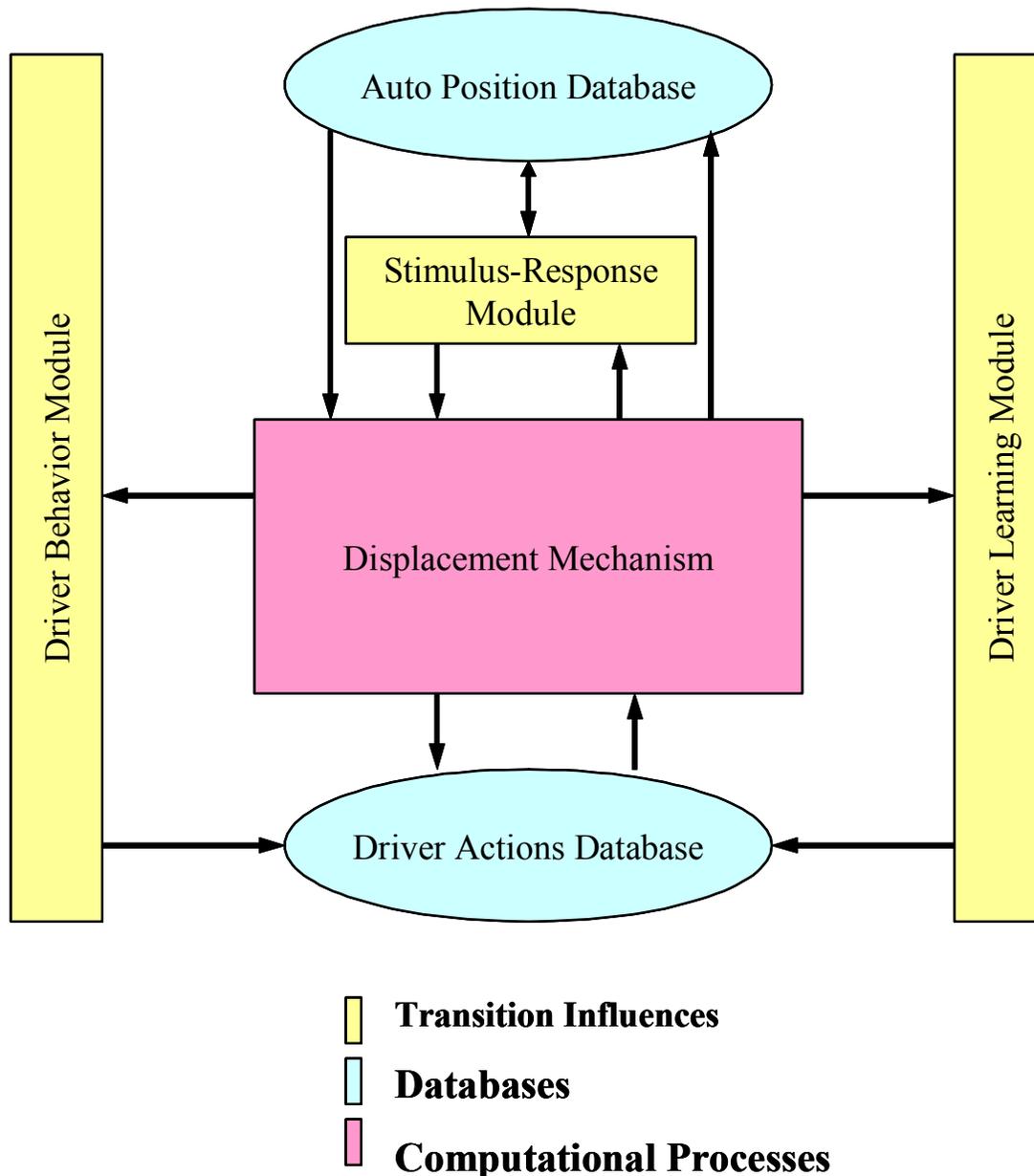


Figure 5.5. A High-Level Functional Architecture

Drew (1968) studied the actions of drivers in highway driving conditions and determined that for any given section of roadway, how drivers maneuvered within the traffic stream is generally predictable given prevailing driver attitudes, traffic conditions, roadway design, and immediate

goals. This predictable maneuvering, expressed primarily as travel lane selection, is interrupted when drivers approach a weaving area. In these areas, drivers alter their lane selection to pursue their own destination goals (to exit or to continue on the highway) and to accommodate traffic merging into or out of the traffic stream. The resulting traffic stream lane distribution is altered from the one observed prior to the weaving area as the traffic seeks a new lane distribution downstream.

Understanding the weaving area phenomenon is very important to highway designers and traffic engineers in determining the number of lanes required to serve a weaving area. This understanding leads to appropriate design for spacing weaving areas out along highway sections to reduce the crash potential associated with the lateral maneuvering that occurs. Drew developed a method, based on the Markov Chain theory, to predict lane changes in a weaving area. The method, illustrated in Figure 5.6 forms the basis for the displacement mechanism developed in this dissertation.

Essentially, the resting queue represents the initial position matrix where each vehicle in the queue is assigned a discrete position vector. The vector defines the auto position by column, lane, and lateral position within the lane. The vehicle at the back of a queue in the left-most lane (which may be a turn bay), positioned in the center of the lane is assigned a position vector Column 1, Lane 1, Position C (Figure 5.7).

To simplify the method developed in this research, all vehicles are assumed to begin the displacement from the center position within the lane. Field observations and emergency vehicle operator interviews indicate that emergency vehicles tend to approach multilane, blocking queues in the left-hand through lane, unless a right turn is planned for at the intersection. This approach tends to push autos in a left-turn bay to the left and autos in the through lanes to the right, thereby creating a pathway for the emergency vehicle that straddles the left through lane and the left turn bay. If the emergency vehicle wishes to turn right at the intersection, the mirror image approach is taken. In cases where a turn bay is open, the emergency vehicle pulls into it and uses it as a progression route to the stop line, where the appropriate movement (left turn, through, or right turn) is executed.

This research focuses on the approach observed in the majority of the field observations, where an emergency vehicle approaches a multilane blocking queue in the left through lane. Based on this assumption, an initial position and the desired position for each auto in the queue each vehicle can be defined. The two auto position states can be represented in matrix form; the columns reflect the queue position in terms of 1st, 2nd, 3rd, and on through the “nth” position as required numbered in ascending order from the back of the queue toward the stop line. The matrix row represents the lane number (from left-most to right-most) including turn bays. An L, C, or R that corresponds with left offset, center, and right offset, denotes an auto’s lateral lane position.

Solution for a Highway Weaving Problem

For a two-lane highway with an on-ramp, use Drew's method to determine the downstream lane distribution of the traffic entering the highway from the ramp at a rate of 300 vehicles per hour. Make the determination at points 500 and 1000 ft downstream of the weaving area given the following initial lane distribution and 500 ft transition probabilities.

Initial Lane Distribution:

Lane 1 (Inside Lane) – 300 vehicles per hour

Lane 2 (Outside Lane) – 0 vehicles per hour

Transition Probability Matrix (500 ft intervals)

To Lane	From Lane	
	Lane 1	Lane 2
Lane 1	a11 = .5	a12 = .4
Lane 2	a21 = .5	a22 = .6
Sum	1.0	1.0

Problem Solution Using Drew's Application of Markov Chains

$$D(2) = (T)^2 \times D(0)$$

$$(T)^2 = \begin{vmatrix} .5 & .4 \\ .5 & .4 \end{vmatrix} * \begin{vmatrix} .5 & .4 \\ .5 & .4 \end{vmatrix} = \begin{vmatrix} .45 & .44 \\ .55 & .56 \end{vmatrix}$$

$$(T)^2 \times D(0) = \begin{vmatrix} .45 & .44 \\ .55 & .56 \end{vmatrix} * \begin{vmatrix} 300 \\ 0 \end{vmatrix} = \begin{matrix} 135 \text{ vehicles per hour in lane 1} \\ 165 \text{ vehicles per hour in lane 2} \end{matrix}$$

Figure 5.6. Markov Chain Approach to a Highway Weaving Problem

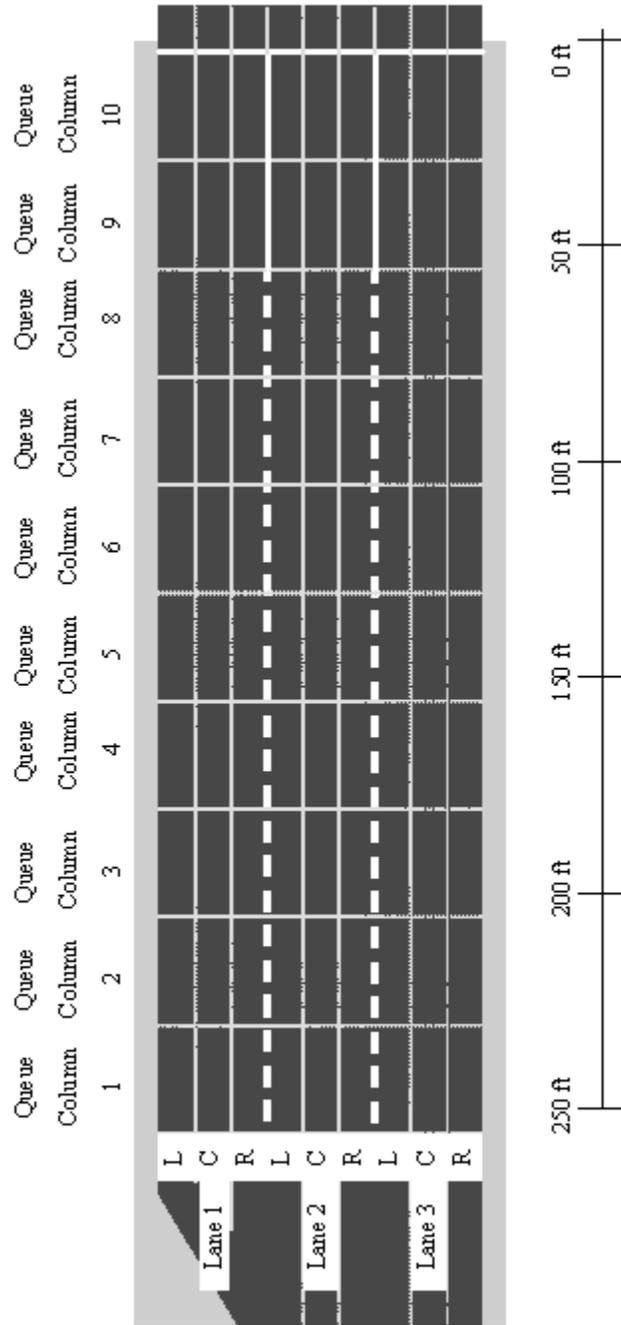


Figure 5.7. Position Reference on a Cellular Roadway Depiction

5.7 THE STIMULUS-RESPONSE MODULE

To operate a vehicle displacement module, a Stimulus-Response Module (SRM) is developed that contains the necessary elements to generate vehicle movements in a time-step sequence. Like TRANSIMS, the discrete vehicle displacement mechanism developed in this dissertation departs from traditional car-following theories and lane-changing rules used in continuous movement simulations. Each auto in the model is represented as an individual agent, possessing certain behavioral qualities that govern the vehicle movement in response to a particular stimulus. The SRM translates field observations of behaviors and actions into a process comprised of a series of perceptions, decisions, and actions. When combined with driver behavior and learning modules, the SRM drives the generation of a unique action for each auto considered in the simulation.

The SRM framework is patterned after the computational techniques used in the FHWA's emerging Interactive Highway Safety Design Model (IHSDM) (Levison, Simsek, and Bittner, 2001). The IHSDM uses a computational model to simulate the moment-to-moment actions of a single driver-vehicle unit. The central element in the IHSDM method is the driver performance model, which has six major computational functions: perception; speed decision; path decision; speed control; path control; and attention. Throughout the simulation period, the driver performance model generates control actions in response to the perceived situation at each simulation interval. The driver performance model design is based on the following assumptions: drivers are experienced in the driving task; drivers make appropriate decisions and take appropriate control actions when given good perceptual information; the driving environment is a relatively relaxed highway situation; and the driving task is limited to regulating vehicle speed and path.

The IHSDM model must be modified to reflect the required computations required in DREAM, which deals with driver response to *emergency and unexpected conditions*. Of the six IHSDM driver performance model computational requirements, only three need to be represented in the SRM module: driver development of situation awareness; driver perception/reaction; and path control. Speed decisions and speed control are not required—the vehicles involved begin from a resting position and maneuver at minimum speed to accomplish the maneuver required to generate the required lateral offset. In addition, a perception is not required as it is assumed that the driver's attention is captured when an emergency vehicle approaches from behind. Reaction begins when the emergency vehicle closes in within 2 to 4 car lengths from the subject vehicle. The SRM represents driver perception, path decision, and path control as a serial process illustrated in Figure 5.8.

SRM involves three phases: a situation awareness phase, the perception/reaction phase, and the path control phase. During the situation awareness phase, the auto driver interprets the developing situation and formulates possible courses of action. In the perception/reaction phase, the auto driver chooses an action to take at the point that the emergency vehicle enters the stimulus zone. In the path control phase, the auto driver makes an initial move forward followed by an offset maneuver.

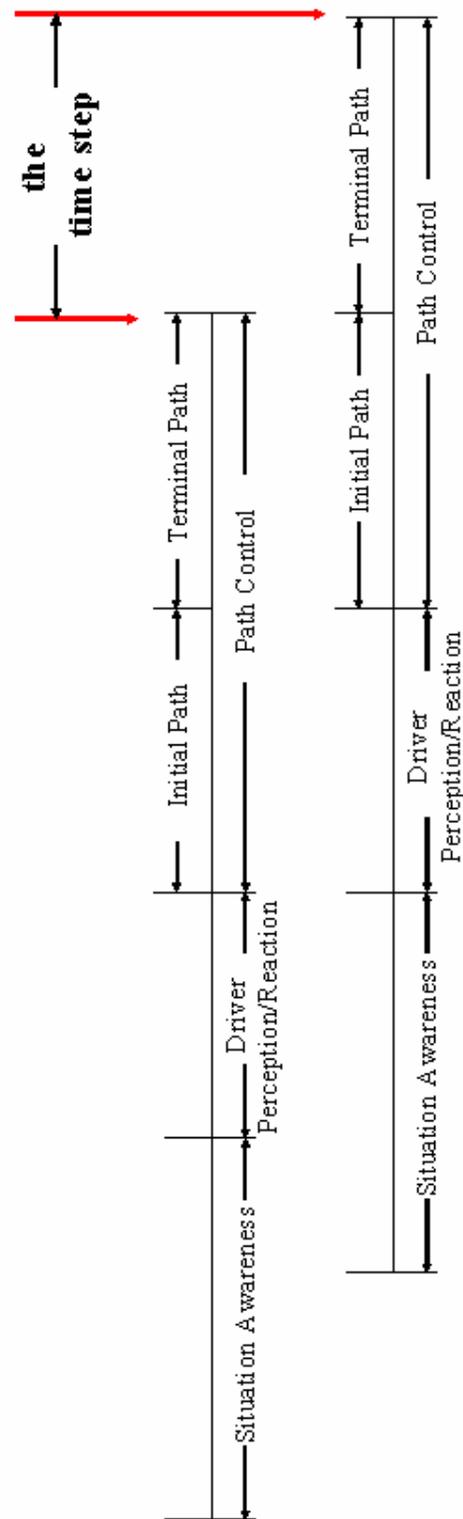


Figure 5.8. A Stimulus-Response Model

5.7.1 *The Driver Behavior Module*

The driver behavior module accounts for the affect drivers' attitudes and abilities have on successfully generating an emergency vehicle pathway. Driver attitudes can range from cooperative to antagonistic and ability to cope with the unexpected and the tight maneuvering requirements can range from those familiar to those unfamiliar with the situation. For this research, auto drivers are assumed to be cooperative in the case when an emergency vehicle is approaching. The issue of familiarity with how to act in these situations is handled stochastically. Each driver on the network is randomly assigned a behavior tendency, which represents the driver's ability to execute an offset maneuver. The driver population is divided into *familiar*, *neutral*, and *unfamiliar* population segments. This is accomplished by using user-selected frequency distributions to represent the real world. Behavior tendencies are generated within the model through Monte Carlo methods using a random number generator and a defined behavior distribution.

Three behavior tendencies are used in the Monte Carlo model to determine the transition probability which drives the displacement mechanism used in DREAM. The following driver behaviors are described as they relate to the reaction tendency of each vehicle:

- *Familiar* drivers will execute a *correct* offset maneuver that generates the most possible lateral offset contributing to the generation of a path for the emergency vehicle.
- *Neutral* drivers will execute a *minimal* offset maneuver which will not permit the emergency vehicle to pass unless. A *neutral* driver that observes the *correct* maneuvers of those in the same queue column, will update the quality of the offset maneuver in real time completing a *correct* maneuver. This is due to lateral learning among queue members. (Learning is described in a subsequent section)
- *Unfamiliar* drivers will balk or execute an *incorrect* offset maneuver (offset in the wrong direction) blocking the emergency vehicle path. A *unfamiliar* driver is not able to learn in real-time. These drivers must wait for the next simulation time step before learning can influence the quality of their actions. (Learning is described in a subsequent section)

So far, driver behaviors are described with reference as to how an individual in the queue will react. Individual drivers' actions are important to successfully generate an emergency vehicle pathway but, what determines whether or not an emergency vehicle can pass a particular column in the queue is the quality of the collective maneuvering of the vehicles in each column. One vehicle in the queue column that fails to make a *correct* maneuver will prevent the emergency vehicle from passing.

The quality of the collective maneuvering determines the transition probability in the Markov Chain method that was introduced when describing the DREAM displacement mechanism. In this model, transition from an initial position state to the subsequent position state is treated as a binary value, because there is only one subsequent state, which represents a "*pass*". This is the one in which the vehicles in the queue maneuver in the *correct* offset direction as shown in Figure 5.9. In this case, the emergency vehicle is allowed to progress. All other subsequent position states represent a "*fail*" as the emergency vehicle will not have the room to progress

(Figure 5.10). This principle, that transition probability is either 1.0 or 0.0 (*pass* or *fail*), help to simplify the DREAM displacement mechanism.

To develop a measure for collective behavior within a queue column, the first step is to assign a numerical value to each driver, which represents that driver's behavior tendency. For a *familiar* driver, a value of 3 is assigned. For a *neutral* driver, a value of 2 is assigned. For an *unfamiliar* driver, a value of 1 is assigned. The attachment of a behavior tendency value to any driver requires a random number generator and a lookup table that translates a driver behavior frequency distribution into a value for future computations. An example lookup table is developed as follows where RN represents the random number drawn for each driver in the problem.

In a default population that represents a largely experienced and familiar driver population, the driver behavior tendency distribution can be assumed as follows:

- 70 percent of the drivers are very skilled and experienced in similar situations, resulting in a *familiar* driver behavior tendency classification.
- 25 percent of drivers are cooperative and capable, but lack experience in similar situations, resulting in a *neutral* driver behavior tendency classification.
- 5 percent of drivers are either incapable of quickly processing unexpected situations, or have antagonistic attitudes preventing them from immediately contributing to a group solution, resulting in an *unfamiliar* driver behavior tendency classification.

This distribution can be expressed in the following default lookup table, where B_{ij} represents an assigned driver behavior tendency:

If $RN < .05$, then $B_{ij} = 1$ (Adverse)

If $RN \geq .05$ and $< .30$, then $B_{ij} = 2$ (Neutral)

If $RN \geq .30$, then $B_{ij} = 3$ (Favorable)

The behavior tendencies of all drivers within a problem can be expressed as a matrix, B_{ij} , which illustrates the spatial distribution behavior tendencies within a queue. Following is an example that represents a 3-lane road (represented by the matrix rows) with a 4-vehicle queue in each lane (represented by the matrix columns):

$$B_{ij} = \begin{vmatrix} 1 & 2 & 3 & 2 \\ 3 & 3 & 3 & 3 \\ 2 & 2 & 2 & 3 \end{vmatrix}$$

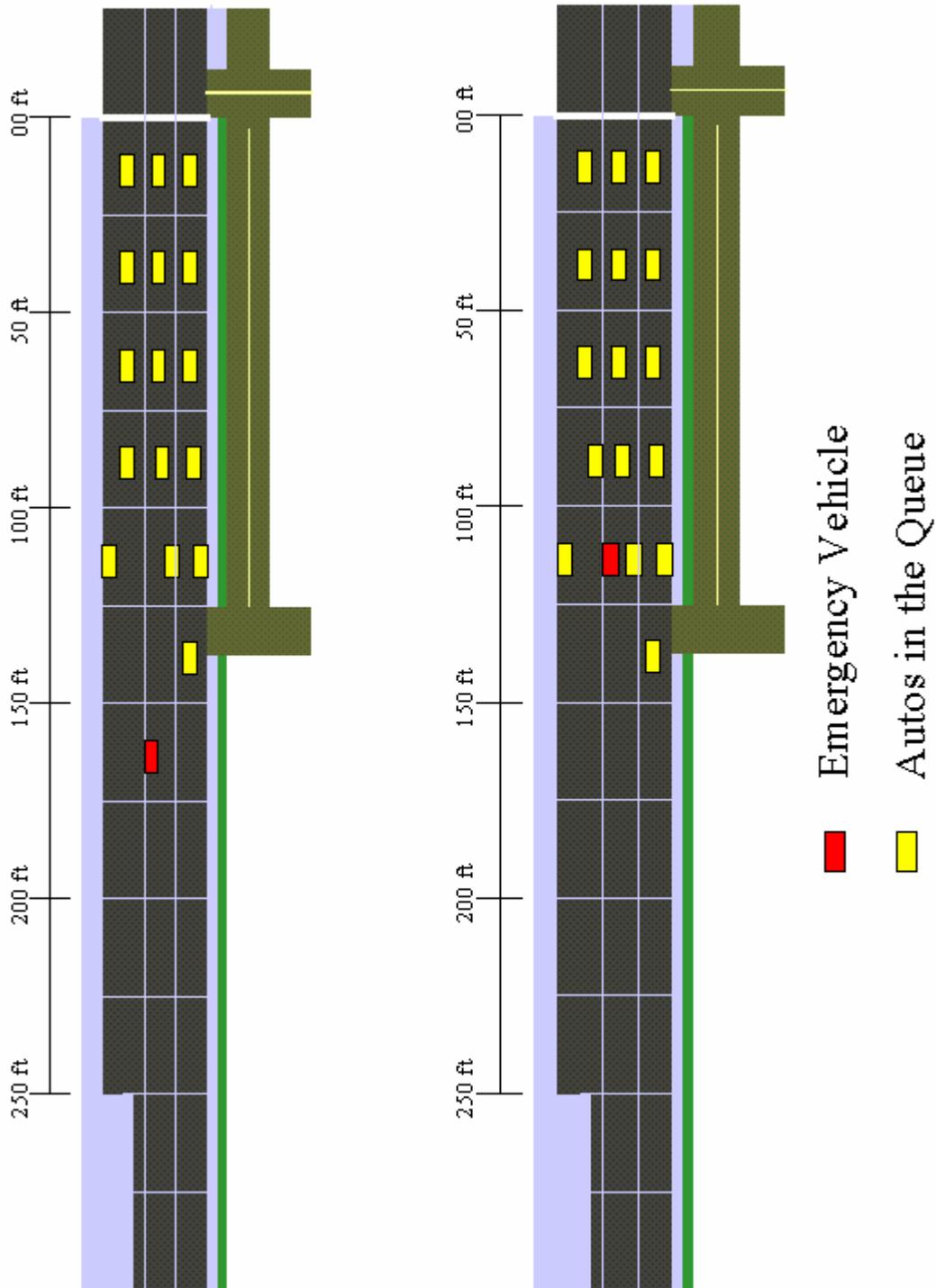


Figure 5.9. Autos Execute *Correct* Maneuvers

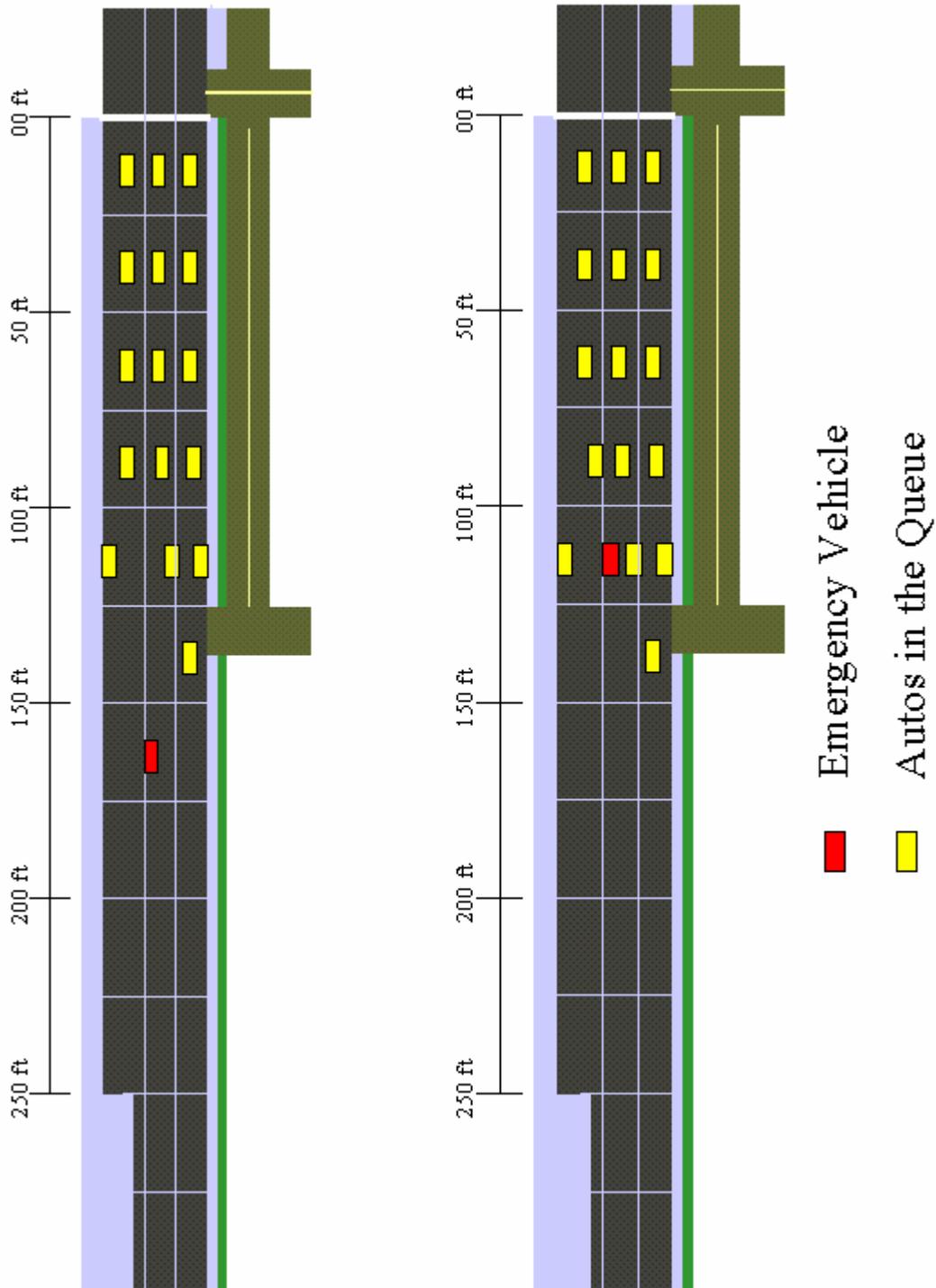


Figure 5.10. Autos Execute *Incorrect* Maneuvers

To determine the collective behavior index, BI_j , for a queue column, the values within the column are summed. In the preceding example, column 1 has a BI_j value of 6, Column 2 has a value of 7, and Columns 3 and 4 each have a value of 8.

Developing a transition probability for use with the Markov Chain method is based on using a binary transition probability to produce a simple rule set. The resulting rule set determines a pass or fail within the DREAM displacement mechanism. For example, a default rule set is expressed as follows:

Calculate the Column Behavior Index, BI_j

If $BI_j \geq 7$ and No Bij value =1, then the queue column trial is a Pass

If $BI_j < 7$ or and a Bij value =1, then the queue column trial is a Fail

5.7.2 The Driver Learning Module

Field observations of how auto drivers initially act, react, and interact indicates that a learning process takes place between drivers within the queue. Learning appears to take place along two dimensions. The first is *longitudinal* which takes place between the auto drivers in one queue column and the auto drivers in the subsequent queue column. This learning takes place in a serial fashion as a driver observes the correct reactions of the column immediately behind and updates their maneuver plan accordingly. The second is *lateral* learning, which takes place between auto drivers in the same queue column. Lateral learning takes place in real time as the drivers observe the maneuvers of those next to them and update their maneuver quality in response to observing superior maneuvers. Learning in this type of situation can be explained in terms of strategic game theory.

Strategic game theory can explain learning between members within an impromptu situation that requires a group solution (Kockesen and Ok, 2003). Individuals learn from each other when placed in strategic game situations as individuals (operating free of pre-negotiated agreements with other players) choose their actions based on their assessments of what the others will do and how benefits associated with each possible action pair affects them in return. In essence, individual decision-making efforts involve solving the following problem:

$$\max_{x \in X} u(x, \theta)$$

where x is the vector of choice variables, or possible courses of action, of the individual; X denotes the set of all possible courses of action available; θ denotes a vector of parameters that are outside the control of the individual such as the actions of others; and u is the utility function for the individual.

Kockesen and Ok comment on learned behavior in strategic games that causes closure toward equilibrium conditions. In cases where there is repetition of moves, a player's actions in subsequent moves are improved due to their increasing awareness concerning the likely moves

of others and the impact those selections will have on their ability to maximize their own utility function value. This brings the outcomes toward an equilibrium that represents the best outcome for the individual and the group. This phenomenon is known as the *Nash Equilibrium*. It is based on the premises that individuals act rationally given their beliefs about the other players' actions, and that these beliefs are correct. For any strategic game, a Nash Equilibrium outcome can be regarded as a steady state in which no one has an incentive to unilaterally deviate and take another action.

The queue response to an approaching emergency vehicle can be defined as a strategic game by defining the variables using the equation presented above. In the situation when an emergency vehicle urgently needs to pass through a static queue, x is the auto driver's choice of a *correct*, *minimal*, or *incorrect* offset path; X is the full range of actions ranging from a "do nothing" option to a crisply executed offset maneuver in the correct direction; θ is set of actions of the others may take; and u is the utility function which has the highest value when the chance to sustain auto damage is minimized and the chance for emergency vehicle progression is maximized. In the case where a driver executes a correct maneuver, the utility function is at its highest value. In the case where a driver executes an incorrect maneuver, the chance of vehicle damage is highest, and the emergency vehicle fails to progress. This case represents the lowest value of the utility function. In the case where a driver executes a minimal maneuver, vehicle damage is spared, but the emergency vehicle does not progress. In this case, the utility function is at an intermediate value.

Learning, based on these principles, is incorporated into DREAM with sub-routines which contain rule sets that check for learning opportunities and update driver behaviors accordingly. Longitudinal and Lateral Learning are described in the following sections.

5.7.3 Longitudinal Learning

The effect of longitudinal learning is computed for each queue column prior to executing the displacement routine. For queue column j , determine if the path control exhibited by queue column $j-1$ has a positive influence on queue column j 's behavior tendencies. Next, apply the following rule to calculate the effect of longitudinal learning.

Rule: If all members of queue column $j-1$ had a beginning behavior tendency value of 3 then, the behavior tendency of all members of queue column j are to be increased by 1 (to a maximum value of 3).

The following example represents a 3-lane road (indicated by the matrix rows) with a 4-vehicle queue in each lane (represented by the matrix columns):

		Queue Column											
		1	2	3	4								
$B_{ij} =$	<table style="border-collapse: collapse; width: 100%; text-align: center;"> <tr> <td style="border-right: 1px solid black; padding: 5px;">3</td> <td style="padding: 5px;">2</td> <td style="padding: 5px;">3</td> <td style="padding: 5px;">2</td> </tr> <tr> <td style="border-right: 1px solid black; padding: 5px;">3</td> <td style="padding: 5px;">3</td> <td style="padding: 5px;">3</td> <td style="padding: 5px;">3</td> </tr> <tr> <td style="border-right: 1px solid black; padding: 5px;">3</td> <td style="padding: 5px;">1</td> <td style="padding: 5px;">2</td> <td style="padding: 5px;">3</td> </tr> </table>	3	2	3	2	3	3	3	3	3	1	2	3
3	2	3	2										
3	3	3	3										
3	1	2	3										

Prior to executing the displacement routine, check for the effect of longitudinal learning. According to the rule, for queue column 2, a positive learning effect is indicated based on the behavior tendencies of queue column 1. Therefore, the behavior tendency for queue column 2 is adjusted prior to executing the displacement routine:

		Queue Column											
		1	2	3	4								
$B_{ij} =$	<table style="border-collapse: collapse; width: 100%; text-align: center;"> <tr> <td style="border-right: 1px solid black; padding: 5px;">3</td> <td style="padding: 5px;">2(3)</td> <td style="padding: 5px;">2</td> <td style="padding: 5px;">2</td> </tr> <tr> <td style="border-right: 1px solid black; padding: 5px;">3</td> <td style="padding: 5px;">3(3)</td> <td style="padding: 5px;">1</td> <td style="padding: 5px;">3</td> </tr> <tr> <td style="border-right: 1px solid black; padding: 5px;">3</td> <td style="padding: 5px;">1(2)</td> <td style="padding: 5px;">3</td> <td style="padding: 5px;">3</td> </tr> </table>	3	2(3)	2	2	3	3(3)	1	3	3	1(2)	3	3
3	2(3)	2	2										
3	3(3)	1	3										
3	1(2)	3	3										

The result of the longitudinal learning is the increased probability that queue column 2 will “pass” the displacement routine on the first try, thereby increasing the efficiency of the solution.

5.7.4 Lateral Learning

The effect of lateral learning is computed if a queue column displacement attempt results in a “fail”. In this case, the behavior tendency of each queue column member is increased based on the learning that took place after the failed attempt. For each queue column that fails a step in the displacement routine, apply the applicable rule from the following rule set to calculate the effect of lateral learning.

Rule 1: If $B_{ij} = 1$, Then $B'_{ij} = 2$

Rule 2: If $B_{ij} = 2$, Then $B'_{ij} = 3$

Rule 3: If $B_{ij} = 3$, Then $B'_{ij} = 3$

The following example represents a 3-lane road (indicated by the matrix rows) with a 4-vehicle queue in each lane (represented by the matrix columns):

		Queue Column															
		1	2	3	4												
$B_{ij} =$	<table style="border-collapse: collapse; width: 100%;"> <tr> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">2</td> <td style="padding: 5px 10px;">2</td> <td style="padding: 5px 10px;">2</td> </tr> <tr> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">1</td> <td style="padding: 5px 10px;">3</td> </tr> <tr> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">1</td> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">3</td> </tr> </table>	3	2	2	2	3	3	1	3	3	1	3	3				
3	2	2	2														
3	3	1	3														
3	1	3	3														

First compute the transition probability for queue column 3 using the rules for displacement developed in the Behavior Module.

Calculate the Column Behavior Index, BI_j . BI_j is determined by taking the sum of the individual BI_{ij} values within the queue column. Apply the following rules to test for the transition probability.

If $BI_j \geq 7$ and No B_{ij} value = 1, then the Column Move is a *pass*

If $BI_j < 7$ or a B_{ij} value = 1, then the Column Move is a *fail*

In this case, for queue column 3, $BI_j = 6$, therefore, the displacement step is a “*fail*”. Next, apply the lateral learning routine to determine the behavior tendency values for use in the displacement reattempt.

Rule 1: If $B_{ij} = 1$, Then $B'_{ij} = 2$

Rule 2: If $B_{ij} = 2$, Then $B'_{ij} = 3$

Rule 3: If $B_{ij} = 3$, Then $B'_{ij} = 3$

The updated behavior tendency vector for queue column 3 is shown as follows:

		Queue Column															
		1	2	3	4												
$B_{ij} =$	<table style="border-collapse: collapse; width: 100%;"> <tr> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">2</td> <td style="padding: 5px 10px;">2(3)</td> <td style="padding: 5px 10px;">2</td> </tr> <tr> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">1(2)</td> <td style="padding: 5px 10px;">3</td> </tr> <tr> <td style="padding: 5px 10px;">3</td> <td style="padding: 5px 10px;">1</td> <td style="padding: 5px 10px;">3(3)</td> <td style="padding: 5px 10px;">3</td> </tr> </table>	3	2	2(3)	2	3	3	1(2)	3	3	1	3(3)	3				
3	2	2(3)	2														
3	3	1(2)	3														
3	1	3(3)	3														

The result of the lateral learning is the increased probability that queue column 3 will “*pass*” the reattempted displacement routine. The net effect on the solution is a time penalty associated with the reattempt, but a solution is still possible.

5.7.5 *Longitudinal Constraints*

Repeated failures by a single queue column will impact the number of trials available to a subsequent column. During each trial, the autos move forward while attempting to perform the side-step maneuver, thereby using up the limited longitudinal maneuvering room available. In this situation, the autos can end up essentially bumper-to-bumper with no room to perform the side-step maneuver, and the emergency vehicle will remain blocked until the signal enters the green interval allowing the autos to move forward.

To represent this constraint, a longitudinal constraint is required. The longitudinal constraint states: If a column experiences two failures prior to achieving the required offset pattern (a total of three attempts – two failed and one passed), the subsequent column will be required to achieve a pass on the first attempt. If the subsequent column fails the first attempt, then there is no solution available. The emergency vehicle will be delayed until the signal enters the green interval and the queue can begin to disperse.

Rule: If the number of displacement trials required for queue column $j-1$ to achieve a *pass*, $N_{j-1} = 3$, then the limit of $N_j = 1$. If a *pass* for queue column j is not achieved within this limit, then end the process and record a “no solution”.

The probability of a “no solution” outcome is dependent on the random distribution of behavior tendencies within the queue. The probability requires the occurrence of a queue column of all *unfamiliar* drivers followed by a combination in the subsequent column that yields a failure on the first attempt. The chance of the occurrence in practice is dependent on the driver population used in the simulation.

5.8 PRESENTATION OF A SUITABLE ALGORITHM

Currently, there is no suitable algorithm available to examine the delay emergency vehicles experience when approaching traffic signals during the red interval. Existing microsimulation software such as CORSIM and VISSIM are not equipped to evaluate this phenomenon, and neither NGSIM nor TRANSIMS are currently forecast to include such a tool. The issue is that there has been relatively little research conducted to characterize and encode the range of auto driver behaviors that take place in the real world.

Closing this gap is the focal point of this section through the development of a simple algorithm that incorporates the various modules and mechanisms in DREAM. In the future, the algorithm can be incorporated into discrete movement microsimulations or it can be used to as a stand-alone tool for use in evaluation of emergency vehicle delay at traffic signals. The algorithm is presented in the same format as the algorithm presentations in the previously referenced TRANSIMS documentation. Eventually, this algorithm may be adapted into a worksheet evaluation tool, similar to the delay computation worksheets found in the Highway Capacity Manual.

The algorithm brings the elements of DREAM (the displacement mechanism, the stimulus-response module, the driver behavior module, and the learning module) into a rule-based, time-stepped method which will produce an estimate of the time required for an emergency vehicle to traverse a static, multilane queue. The method allows stakeholders in an EV preemption deployment decision to calculate the time required for the emergency vehicle to reach the stop line based the likely conditions that exist at a specific intersection at a specific time of day. The algorithm is presented as four separate routines linked logically according to the outcomes of each routine. The algorithm is explained in the following sections.

5.8.1 Initial Conditions Routine

Establish the Initial Position Matrix

Assume all vehicles are centered in the lane (i.e., position C). Create a position matrix P_{ij}

Example:

$$P_{ij} = \begin{vmatrix} C & C & C \\ C & C & C \\ C & C & C \end{vmatrix}$$

Establish the Initial Behavior Matrix

Use a random number generator to determine the behavior for each vehicle on the network based on the selected behavior distribution. As a default, use the following:

If $RN < .05$, then $B_{ij} = 1$ (*unfamiliar*)

If $RN \geq .05$ and $< .30$, then $B_{ij} = 2$ (*neutral*)

If $RN \geq .30$, then $B_{ij} = 3$ (*favorable*)

Example:

$$B_{ij} = \begin{vmatrix} 1 & 2 & 3 \\ 3 & 3 & 3 \\ 2 & 2 & 2 \end{vmatrix}$$

Set Time Step Value

Set the value for the initial move for each queue column to a user selected value. As a default value: $T_j = 2.5$ sec. Set the value for the adjustment move for each queue column to a user selected value. As a default value: $AT_{2,3,..n} = 2.0$ sec.

Set the Trial Record

Set value for the number of attempts for each queue column, N_j , to zero.

5.8.2 Longitudinal Learning/Longitudinal Constraint Routine

Check for Longitudinal Learning or Longitudinal Constraints

Step 1: Determine if the queue column under consideration benefits from the longitudinal learning principle. For each queue column (except queue column $j=0$) test using the following:

Rule: If all members of queue column $j-1$ had a beginning behavior tendency value of 3 (*familiar*) then, the behavior tendency of all members of queue column j are to be increased by 1 (to a maximum value of 3). Proceed to the Displacement Routine. Else, proceed to Step 2.

Step 2: Determine if excessive trials by queue column $j-1$ establish a constraint on the number of trials available to queue column j :

Rule: If the number of displacement trials required for queue column $j-1$ to achieve a *pass*, $N_{j-1} = 3$, then the limit of $N_j = 1$. Proceed to the Displacement Routine with the following constraint: If a *Pass* for queue column j is not achieved within this limit, then end the process and record a “no solution”. Else, proceed to the Displacement Routine without a longitudinal constraint.

5.8.3 Displacement Routine

Calculate the Time Required to Reposition

Step 1: Calculate the Column Behavior Index, BI_j

Rule 1: If $BI_j \geq 7$ and No B_{ij} value =1, then the queue column trial is a *pass*. Record the Time Step, T_j in the Time Keeper, record the number of trials, N_j and update the Position Matrix. Advance to queue column $j+1$ and proceed to Step 1 of the Displacement Routine.

Rule 2: If $BT_j < 7$ or and a B_{ij} value =1, then the queue column trial is a *fail*. Record the Time Step, T_j in the Time Keeper and record the number of trials, N_j . Proceed to Step 2.

Step 2: If a Trial outcome = *fail*, Calculate the Lateral Learning Effect. Update the behavior tendency for each member of the queue column according to the following rules:

Rule 1: If $B_{ij} = 1$, Then $B'_{ij} = 2$

Rule 2: If $B_{ij} = 2$, Then $B'_{ij} = 3$

Rule 3: If $B_{ij} = 3$, Then $B'_{ij} = 3$

Example:

$$B'_{ij} = \begin{vmatrix} 1(2) & 2 & 3 \\ (3) & 3 & 3 \\ 2(3) & 2 & 2 \end{vmatrix}$$

Step 3: Calculate the time required to execute an Adjustment Trial. Recalculate the Column Behavior Total, BI'_j .

Rule: If $BI'_j \geq 7$ and No B'_{ij} value = 1, then the queue column trial is a *pass*. Record the Adjustment Time Step, $AT_{2,3,..n}$ in the Time Keeper, update the trial record to reflect the total number of trials, N_j and update the Position Matrix. Advance to queue column $j+1$ and proceed to Step 1 in the Displacement Routine.

Rule: If $BI'_j < 7$, then the queue column trial is a *fail*. Record the Adjustment Time Step, $AT_{2,3,..n}$ in the Time Keeper and update the trial record to reflect the total number of trials, N_j and repeat Step 2 of the Displacement Routine.

5.9 AN ILLUSTRATIVE EXAMPLE

The first step in the procedure is to develop a cellular grid roadway representation for the intersection approach of interest. The cell width represents the lateral dimensions of the travel lanes, and the cell length represents the nominal storage distance for vehicles in a queue. For the discussion, the lane width is assumed to be 12 ft and the storage distance is assumed to be 25 ft per vehicle. To represent the lateral movements within each lane, the 12-ft cell is divided into three possible positions: left, center, and right. An example of a 5-vehicle queue, 2-lane approach with a 250-ft long left turn bay is shown in Figure 5.11. To solve for the emergency vehicle progression time, apply the algorithm presented in the previous section.

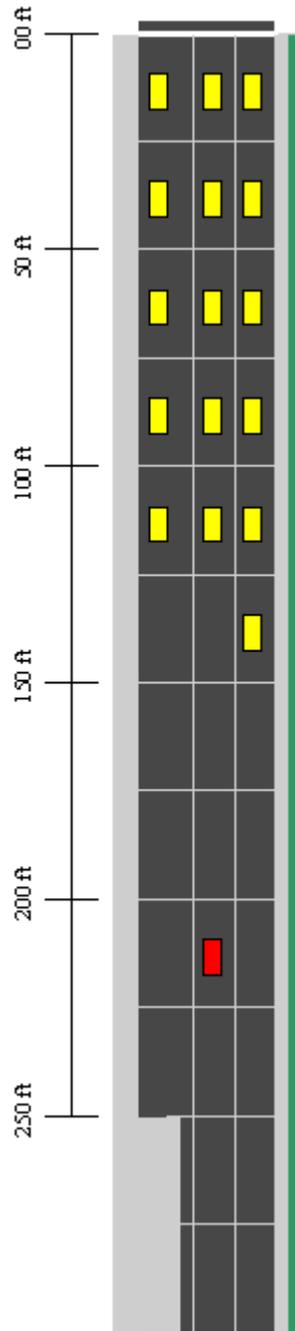


Figure 5.11. Illustrative Example Initial Conditions

5.9.1 Initial Conditions

Based on the conditions, the following position matrix is generated. Note that the asymmetric queue condition is resolved by beginning the computations at the point where the first blocking queue column can be established.

$$P_{ij} = \begin{vmatrix} C & C & C & C & C \\ C & C & C & C & C \\ C & C & C & C & C \end{vmatrix}$$

The second step of establishing the initial conditions is to generate the Behavior Tendency (BT) matrix using a random number generator and a user-selected Behavior Tendency distribution. For this example, assume a mid-day, weekday driver population that contains the following distribution:

- 50 percent of the drivers are very skilled and are experienced in similar situations, resulting in a *familiar* driver behavior tendency classification: $BT = 3$.
- 40 percent of drivers are cooperative and capable, but lack experience in similar situations, resulting in a *neutral* driver behavior tendency classification: $BT = 2$.
- 10 percent of drivers are either incapable of quickly processing unexpected situations, or not experienced in similar situations detracting their ability to contribute to a group solution, resulting in an *unfamiliar* driver behavior tendency classification: $BT = 1$.

The following random number matrix was generated for this problem:

$$RN_{ij} = \begin{vmatrix} .094 & .845 & .531 & .481 & .791 \\ .593 & .398 & .522 & .325 & .536 \\ .091 & .593 & .855 & .227 & .124 \end{vmatrix}$$

Using the distribution selected for this problem, the random numbers translate into a Behavior Tendency matrix as shown:

$$BT_{ij} = \begin{vmatrix} 1 & 3 & 3 & 3 & 3 \\ 3 & 2 & 3 & 2 & 3 \\ 1 & 3 & 3 & 2 & 2 \end{vmatrix}$$

The Time Step selection is next, and values for the initial trial and adjustment trials must be set. The values for the initial trial can range from 2 to 5 seconds, depending on the driver population, excess lane width available, and the vehicle class and size mixture. Values for the adjustment

trial can also range be 2 to 5 seconds. Values found to work well in emulating the activity observed during the Northern Virginia are: for initial trial, $T_1 = 2.5$ sec and for the adjustment trials, $AT_{2,3,...n} = 2.0$ sec. This selection considers the increase in efficiency as drivers take subsequent trials.

Lastly, the beginning value for the number of attempts for each queue column, N_j , is set to zero.

5.9.2 Execution of DREAM

Queue Column 1

$BT_{ij} =$	1	3	3	3	3
	3	2	3	2	3
	<u>1</u>	3	3	2	2

Determine BI_j 5

Trial Outcome F

Trial Record, N 1

Time Record, T 2.5

Consider lateral learning and reattempt:

$BT_{ij} =$	1(2)	3	3	3	3
	3(3)	2	3	2	3
	<u>1(2)</u>	3	3	2	2

Determine BI_j 5(7)

Trial Outcome F(P)

Trial Record, N 1(2)

Time Record, T 2.5(2.0)

Queue Column 2

Checking for longitudinal learning and longitudinal constraints reveals that there is no longitudinal learning effect, nor is there a longitudinal constraint.

$BT_{ij} =$	1(2)	3	3	3	3
	3(3)	2	3	2	3
	<u>1(2)</u>	<u>3</u>	3	2	2
Determine BI_j	5(7)	7			
Trial Outcome	F(P)	P			
Trial Record, N	1(2)	1			
Time Record, T	2.5(2.0)	2.5			

Queue Column 3

Checking for longitudinal learning and longitudinal constraints reveals that there is no longitudinal learning effect, nor is there a longitudinal constraint.

$BT_{ij} =$	1(2)	3	3	3	3
	3(3)	2	3	2	3
	<u>1(2)</u>	<u>3</u>	<u>3</u>	2	2
Determine BI_j	5(7)	7	9		
Trial Outcome	F(P)	P	P		
Trial Record, N	1(2)	1	1		

Queue Column 4

Checking for longitudinal learning and longitudinal constraints reveals that there is longitudinal learning, which increases the Behavior Tendency for each member of Queue Column 4 by an increment of 1 up to the limit 3. There is no longitudinal constraint.

$BT_{ij} =$	1(2)	3	3	3[3]	3
	3(3)	2	3	2[3]	3
	<u>1(2)</u>	<u>3</u>	<u>3</u>	<u>2[3]</u>	2
Determine BI_j	5(7)	7	9	[9]	
Trial Outcome	F(P)	P	P	P	
Trial Record, N	1(2)	1	1	1	
Time Record, T	2.5(2.0)	2.5	2.5	2.5	

Queue Column 5

Checking for longitudinal learning and longitudinal constraints reveals that there is no longitudinal learning effect because the initial values of queue column $j-1$ Behavior Tendencies are the ones used in the determination. There is no longitudinal constraint.

$BT_{ij} =$	1(2)	3	3	3[3]	3
	3(3)	2	3	2[3]	3
	<u>1(2)</u>	<u>3</u>	<u>3</u>	<u>2[3]</u>	<u>2</u>
Determine BI_j	5(7)	7	9	[9]	7
Trial Outcome	F(P)	P	P	P	P
Trial Record, N	1(2)	1	1	1	1
Time Record, T	2.5(2.0)	2.5	2.5	2.5	2.5

Example Summary: For this problem, the 5-vehicle queue required six total trial attempts to create a pathway for the emergency vehicle. Only one failure was recorded in queue column 1 due to the presence of a driver with an Adverse Behavior Tendency. The total time required for the emergency vehicle to advance

the length of the symmetric portion of the queue was $T = 14.5$ seconds. This corresponds to a queue penetration speed of 8.6 ft/sec or 5.8 mph.

5.10 EVALUATION OF MODEL RESULTS

Evaluating the model determines its capability to provide an estimate of emergency vehicle progression time through a static queue of a given length, and provides researchers an opportunity to become familiar with how the model behaves relative to input variable selection. Evaluating model behaviors includes analysis of output values and the variation in those values, as well as measures of interaction that occur between variables within the model. The credibility of the model output combined with credibility of the driver interaction indications determines the suitability of the model for further research. To conduct the evaluation, the key input variables must be selected and assigned a value range, within which, assessments can be conducted regarding the model's final output and internal functionality.

5.10.1 *Selecting Input Variables*

The first step is to select the input variables for variation within the experiment. The four input values that can be selected include: the internal time step values for the initial and adjustment trials; the distribution of the three behavior tendencies; selective application and/or modification of the rules that determine the effect of longitudinal and lateral learning; and application and/or modification of rules representing the longitudinal constraint. For this dissertation, the time steps, learning rules, and constraint rules are fixed at the values presented in the algorithm and the illustrative example.

The second step in constructing the model evaluation is to establish a set of population profiles reflecting a range of behavior tendency distributions. The population profiles provide insight into the model response. Any variation in these parameters (which represent varying levels of the driver population's ability to solve the problem efficiently) reveals the model's ability to replicate the nonlinear nature of variation in driver behavior and performance under unexpected conditions.

Four population profiles, reflecting unique distributions of driver behavior tendencies, are constructed to determine the effect different population demographics have on the outcomes of participant interactions and the final results. The four population profiles used represent populations that range from highly *familiar* as reflected in Profile 1 to *unfamiliar* as reflected in Profile 4.

In constructing the profiles for the experiment, the desire is to use a range of profiles that will expose the potential lower and upper boundaries of *unfamiliar* behavior tendency percentages. These boundaries are defined as the points where the variation in outcomes is reduced to a point that suggests convergence toward uniformity in model results. Holding the percentage of *neutral* tendencies constant across the profiles, results in a one-for-one exchange of *unfamiliar* for *familiar* participants as the profiles advance from Profile 1 to Profile 4. The profiles used are defined as follows:

- Population Profile 1: 5 percent Adverse, 30 percent Neutral, and 65 percent Favorable
- Population Profile 2: 10 percent Adverse, 30 percent Neutral, and 60 percent Favorable
- Population Profile 3: 20 percent Adverse, 30 percent Neutral, and 50 percent Favorable
- Population Profile 4: 30 percent Adverse, 30 percent Neutral, and 40 percent Favorable

5.10.2 Establishing the Problem Dimensions

The next major element in development of the evaluation is to select values for the dimensions that establish the problem size in terms of the number of participants and their arrangement in rows (representing the number of lanes) and columns (representing the number of vehicles in the queue). The dimensions selected should force the model to perform over the range of interactive rules and constraints.

For this Beta-level testing, two queue lengths are used: 5 and 10 vehicles. A 5-vehicle queue represents a case in which the emergency vehicle approaches the intersection shortly after the beginning of the red interval. During the AM rush hour in Northern Virginia, a 5-vehicle queue builds on arterials in the first 10 – 15 seconds of the red interval, leaving nearly 45 – 50 seconds until the signal transitions to a green interval. In a typical 5-vehicle queue situation, the emergency vehicle is able to penetrate the entire queue prior to the transition to the green interval.

A 10-vehicle queue represents a case in which the emergency vehicle arrives late in the first half of the red interval, approximately 20 – 25 seconds into a typical 60-second red interval. At solution time values of 25 – 35 seconds, depending on queue column failure rates, the emergency vehicle will just reach the stop line prior to transition to the green interval. This point is the limit for application of this model, as driver behaviors change in response to the green signal when the queue begins to disperse.

The second dimension of the problem is the number of lanes. The method is valid for any number of lanes (including turn bays) greater than three based on the typical lane and vehicle widths observed during the Northern Virginia FOT. Because this is a Beta-level evaluation, taken prior to encoding the model into a computer program, a 3-lane situation is evaluated for simplicity in calculation.

With the key evaluation parameters selected, the evaluation proceeds by iteratively solving the 5- and 10- vehicle queue problems across each of the population profiles using a new randomly generated behavior tendency matrix for each iteration. Table 5.1 summarizes the experimental design and identifies the input variable values under examination. Eight iterations are run for each problem across each population profile to develop output measures that will demonstrate model output and how the model behaves internally.

Table 5.1. Summary of Experiment Design

Number of Vehicles in the Queue	Number of Lanes	Time Step Initial Trial/ Adjustment Trial (sec)	Population Profile	Longitudinal Learning Rules	Lateral Learning Rules	Longitudinal Constraint
5	3	2.5 / 2.0	1 thru 4	Default	Default	Default
10	3	2.5 / 2.0	1 thru 4	Default	Default	Default

5.10.3 Selecting Output Measures

A Beta-level analysis determines if the model design, in fact, effectively approximates the types of driver behaviors and interactions that were previously described in this dissertation. The following list identifies functional requirements to be examined and the measures used to determine the model's ability to perform each function.

- **Functional Requirement:** Provide an estimate of the time required for the emergency vehicle to traverse a blocking queue of a given length (expressed in the number of vehicles) and width (expressed in the number of available lanes).

Measurement: The total estimated traversal time.

- **Functional Requirement:** Provide an estimate of the variation in traversal time as a result of different random seed values for determining driver behavior tendencies within a given population profile.

Measurement: The standard deviation in estimated traversal time.

- **Functional Requirement:** Provide an estimate of the number of longitudinal learning opportunities presented and utilized within a given problem for a given random seed value set for determining driver behavior tendencies.

Measurement: Record the number of opportunities presented (i.e., the occurrence of queue columns with all members possessing a *Favorable* behavior tendency) and record the number of opportunities utilized by the successive queue column to avoid a first trial failure.

- **Functional Requirement:** Provide an estimate of the number of lateral learning opportunities utilized to ensure second trial passes.

Measurement: Record the number of trials in which a mixture of *neutral* and *familiar* queue column members succeed in the first trial.

- **Functional Requirement:** Provide an estimate of the number of times that successive failures in a problem reach the longitudinal constraint causing a *No Solution*.

Measurement: Record the number of times a problem reaches the longitudinal constraint limit.

Table 5.2 summarizes the experimental design indicating the output variables to be examined.

Table 5.2. Key Measures for Evaluation of Model Performance

Number of Vehicles in the Queue	Progression Time / Variation	Number of Longitudinal Learning Opportunities Presented/Utilized	Number of Lateral Learning Benefits	Number of Times Longitudinal Constraints Exceeded
5				
10				

5.10.4 Analysis of the Test Data

The first step in model analysis is to verify that the *actual* driver behavior distributions generated for the evaluation correlate with the *expected* driver behavior distributions within each of the design population profiles. Problems were manually solved for both the 5- and 10-vehicle queue lengths on a 3-lane road. In total, 56 problems were solved. Within this sample, 1,320 participants were generated to form 440 queue columns. Each participant was randomly assigned behavior tendencies using a Monte Carlo method and the appropriate population profile definitions. The number of problem solutions was increased until the actual distribution of behavior tendencies began to converge on the expected values.

The analysis in Tables 5.3 and 5.4 show the comparison of the actual to expected distributions for each of the population profiles used in the 5- and 10-vehicle queue cases. The results of correlation tests comparing the actual and expected distributions are summarized in Table 5.5.

Table 5.3. 5-Vehicle Queue Length Driver Behavior Distributions

Population Profile	Expected Incidence of Adverse Behavior	Actual Incidence of Adverse Behavior	Expected Incidence of Neutral Behavior	Actual Incidence of Neutral Behavior	Expected Incidence of Favorable Behavior	Number of Times Longitudinal Constraints Exceeded
1	5%	8%	30%	32%	65%	60%
2	10%	9%	30%	33%	60%	58%
3	20%	19%	30%	34%	50%	47%
4	30%	30%	30%	30%	40%	40%

Table 5.4. 10-Vehicle Queue Length Driver Behavior Distributions

Population Profile	Expected Incidence of Adverse Behavior	Actual Incidence of Adverse Behavior	Expected Incidence of Neutral Behavior	Actual Incidence of Neutral Behavior	Expected Incidence of Favorable Behavior	Actual Incidence of Favorable Behavior
1	5%	5%	30%	24%	65%	71%
2	10%	8%	30%	28%	60%	64%
3	20%	15%	30%	35%	50%	50%
4	30%	23%	30%	36%	40%	41%

Table 5.5. Correlation of Actual Distribution to the Expected Distribution

Vehicles in the Queue	Population Profile 1	Population Profile 2	Population Profile 3	Population Profile 4
5	.998	.990	.973	1.00
10	.989	.998	.981	.714

For the 5-vehicle queue problem, there was at least a 97% correlation in all four population profiles. For the 10-vehicle queue problem, the correlation was above 98% for population profiles 1, 2, and 3. The correlation in population profile 4 was 71%, suggesting that the number of samples needs to be increased in order to make definitive assertions about the behavior of population profile 4 in the 10-vehicle queue case. For the purpose of evaluating model development functionality, this level of correlation is deemed acceptable. Once the Beta version is accepted, coding a computer program for future research will enable the appropriate numbers of runs required to be generated to reach higher correlation levels across all population profiles.

5.10.4.1 Measure One: Traversal Time

Emergency vehicle traversal time estimates were generated for the 5- and 10-vehicle queue cases. The results shown in Figure 5.12 indicate that the estimated progression time increases as the percent of drivers with an *unfamiliar* behavior tendency increases.

The mean value for the 5-vehicle queue case for population profile one is 13.83 seconds, compared to 14.83, 18.17, and 20.17 seconds for population profiles 2, 3, and 4, respectively. For the 10-vehicle queue case, population profile 1 yields a mean value of 27.25 seconds, compared with 28.25, 31.5, and 35.75 for population profiles 2, 3, and 4, respectively. The model appears to respond appropriately to the increase in the percent of drivers with an *Adverse* behavior tendency.

5.10.4.2 Measure Two: Variation in Traversal Time

The standard deviation was computed for all the runs in each population profile in both the 5 and 10 vehicle queue cases. The results, shown in Figure 5.13, indicate that the standard deviation is lowest at the population profiles representing the extremes. For the 5-vehicle queue case, population profiles one, two, and four exhibited very low standard deviations in estimated traversal times. This suggests that, for a 5-vehicle queue problem, very experienced and very inexperienced populations will generate very predictable results. Population profile three introduces enough drivers with *unfamiliar* tendencies to generate variation. For the 10-vehicle queue case, population profiles one and two produced the highest standard deviations and the standard deviations were much higher than those in the 5-vehicle queue problems. This is due to

larger number interactions and the increased probability that the *unfamiliar* drivers will influence the outcome. In the 10-vehicle queue case, the standard deviations for population profiles three and four fall off dramatically suggesting that there is a critical percent of *unfamiliar* drivers, that when present, will make trial attempt failures predictable.

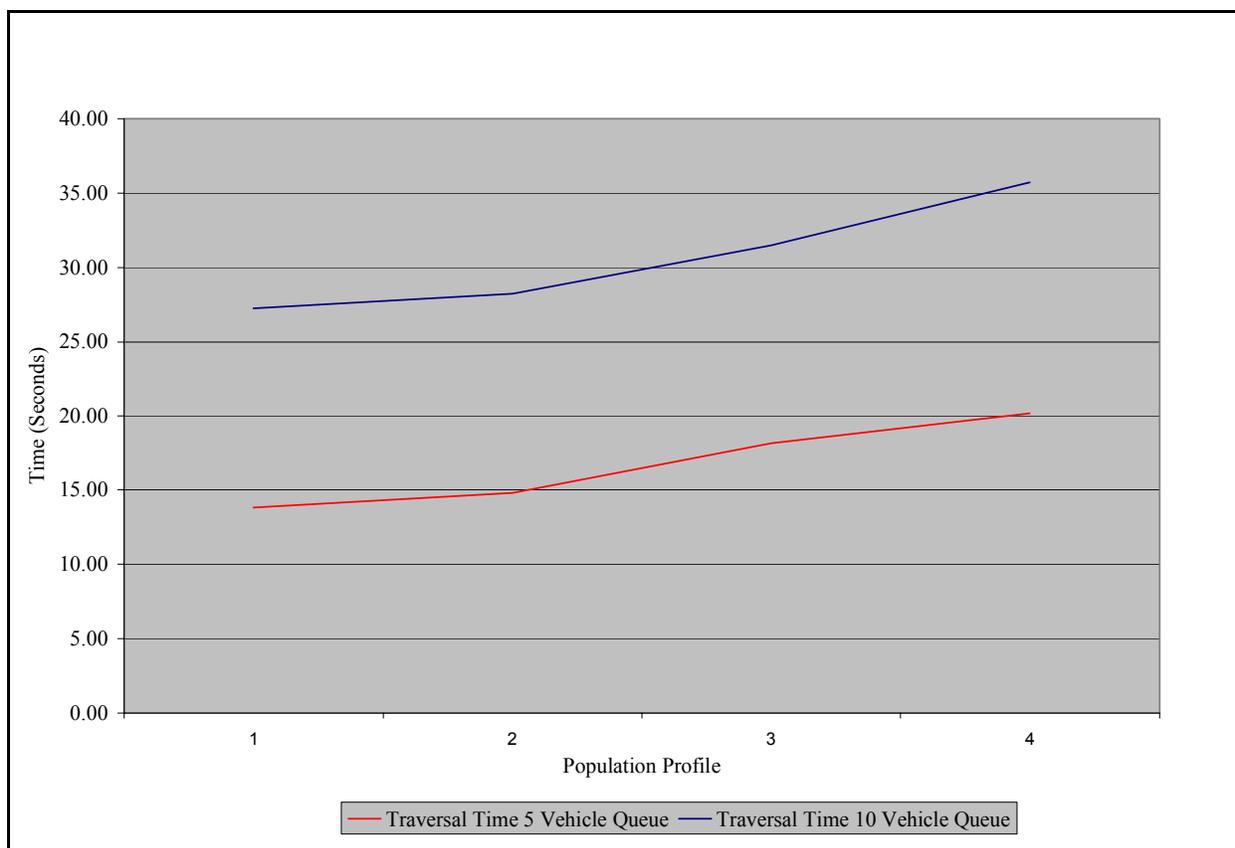


Figure 5.12. Traversal Time for 5- and 10-Vehicle Queues

Figure 5.13 illustrates the mean number of failures per problem for 5- and 10-vehicle queues, with respect to changes in population profile. As the data suggest, for the 5-vehicle queue problem, the mean number of failures increases across all four population profiles. For the 10-vehicle queue, the mean number of failures stabilizes once a critical value of *Adverse* drivers is present in the population. Analysis of the standard deviations and the occurrence of failures relative to population profiles and problem size support the credibility of the model.

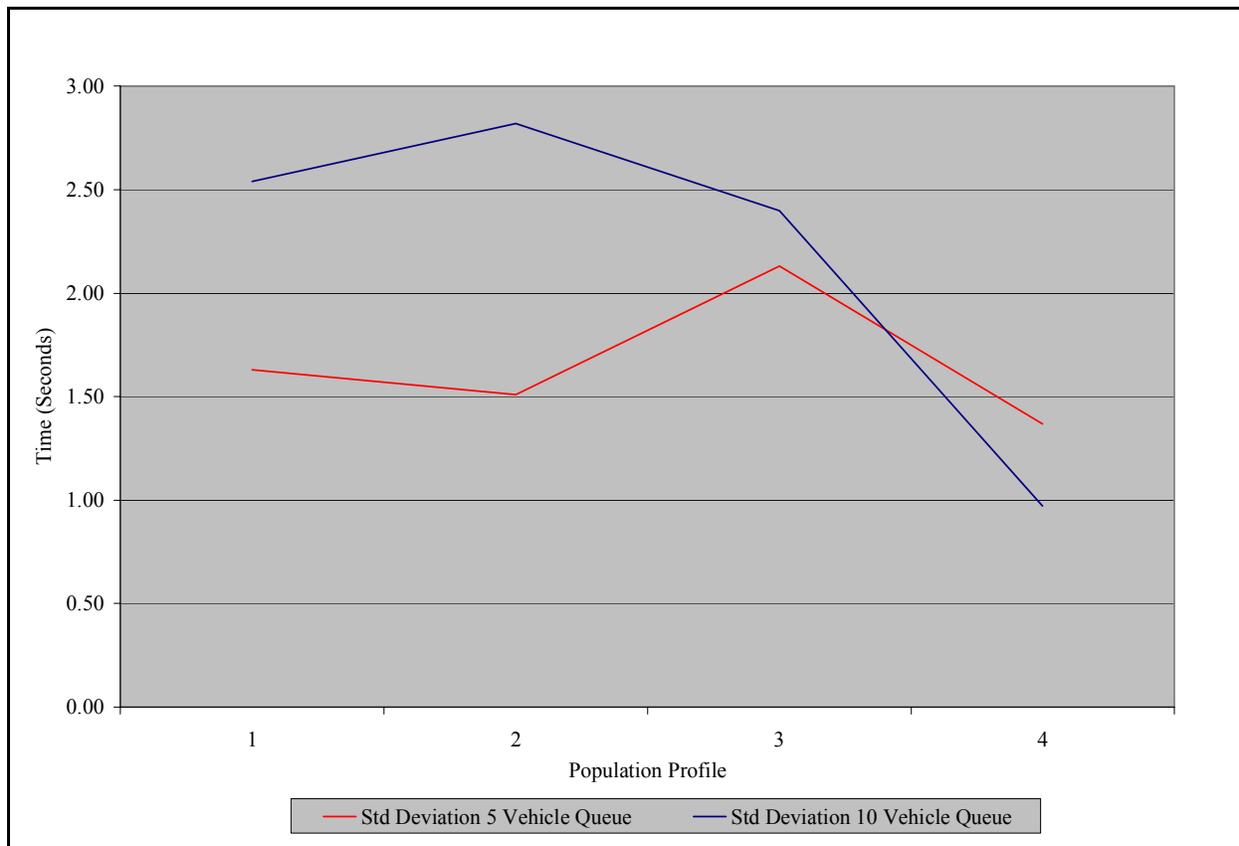


Figure 5.13. Standard Deviation in Traversal Time for 5- and 10-Vehicle Queues

5.10.4.3 Measure Three: Occurrence of Longitudinal Learning

Figure 5.14 illustrates the number of longitudinal learning opportunities presented by population profile and the number of those opportunities utilized to benefit the successive queue column. A longitudinal learning opportunity is only presented when all members of a queue column possess *favorable* tendencies. The longitudinal learning opportunity can only be utilized by a successive queue column if the successive queue column contains at least one members with an *unfamiliar* behaviors tendency. For the 5-vehicle queue, the number of opportunities decreased as the percent of *unfamiliar* drivers increased. In the 10-vehicle queue case, the number of opportunities per problem is significantly higher than in the 5-vehicle queue case, and it appears to drop as the population profile becomes less *familiar*. These results are as expected.

Results of the number of opportunities utilized do not indicate clear patterns. This is a function of the random occurrence of the very specific queue column behavior tendency composition required. This is as expected. A strong pattern in utilization longitudinal learning opportunities would counter the modeling intention which is to present these as rare occurrences dependent on the specific population present in the problem.

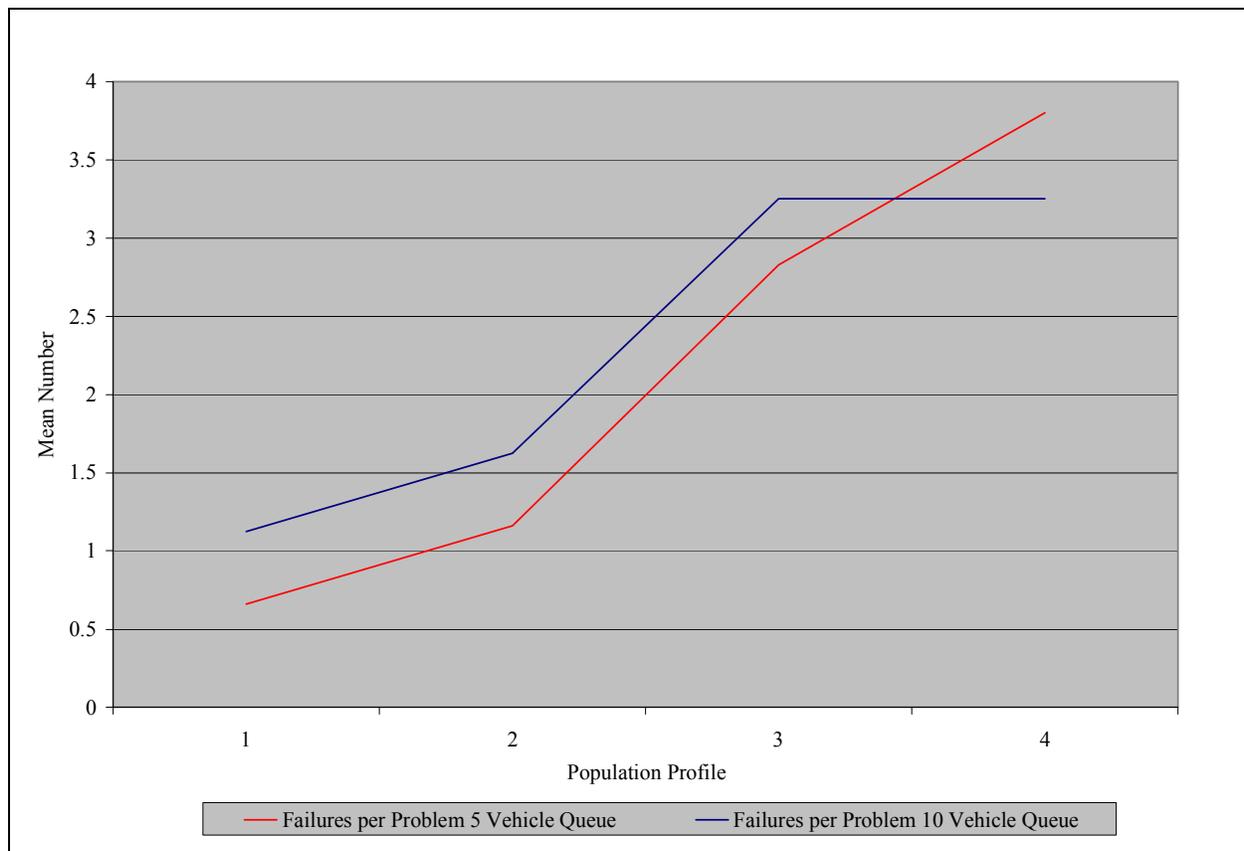


Figure 5.14. Mean Failures per Problem for 5- and 10-Vehicle Queues

5.10.4.4 Measure Four: Occurrence of Lateral Learning

Lateral learning is the primary learning mechanism built into the model. Its occurrence in the evaluation problems is shown in Table 5.9. Lateral learning requires a moderately specific queue column driver behavior composition. The composition must contain at least one *familiar* driver and no *unfamiliar* drivers. The rate of occurrence of lateral learning is sensitive to increases in the percent of *unfamiliar* tendencies and/or decreases in the percent of *familiar* tendencies. In this evaluation, the population profile designs required a one-for-one exchange between the *unfamiliar* and *familiar* sub-sets of the overall population. For the 5-vehicle queue case, the mean number of lateral learning occurrences is constant for population profiles one and two and decreases as the percent of *unfamiliar* drivers increases through population profile three and four. For the 10-vehicle queue case, the mean increases from profile one to two and then decreases through profile three and four. These results are as expected. They indicate the key role of lateral learning in the more experienced population profiles and the decreasing likelihood of lateral learning as the percent of *unfamiliar* drivers increases and the percent of *familiar* drivers decreases resulting in higher first trial failure rates and extended emergency vehicle traversal times.

5.10.4.5 Measure Five: Occurrence of Longitudinal Constraints

The longitudinal constraint was not invoked in any of the evaluation problems. This is because the only queue column driver behavior tendency composition which can experience two failures (required to enable the constraint) is one in which all members are of an *unfamiliar* tendency. The probability of this occurring is dependent on the population profile selected. For one in which 10 percent are Adverse, the probability of all three queue column members being adverse is 1 in 1000. Once the longitudinal constraint is enabled, it is only enacted when the successive queue column experiences a failure on the first trial. The queue column failure rate observed in population profile two was only 23 percent in the 5 vehicle queue problems and only 16 percent in the 10 vehicle queue problems solved for this analysis. The model intention is that the enactment of the longitudinal constraint would be extremely rare, but no field data was available to generate the characteristics of this phenomenon.

5.10.5 Analysis Summary

The model analysis indicates that the modeling qualities that were designed into the algorithm are functional. The principal model output, emergency vehicle traversal time is reasonable when compared to field observations. The comparison presented in Figure 5.15 is for illustrative purposes only. It compares the results of the four tested population profiles to a limited number of field data points available. In addition, there is a comparison with a baseline population profile, Population Profile 0, (which is comprised only of drivers that are *familiar*. Trend lines in the chart represent a least squares approach to establishing a linear relationship between queue length and progression time for the given population profile and the available field data. In order to aid in determination of the benefit of EV preemption, a “with EV preemption” trend line is shown computed at using an emergency vehicle speed of 25 mph through the intersection environment. The chart indicates that the benefit increases as the expected queue length increases and that the benefit for a specific queue length increases as the experience and ability of the driver population are reduced.

5.11 CONCLUSIONS AND RECOMMENDATIONS

The purpose of the research, documented in this chapter, is to identify the state-of-the-art in the evaluation of the travel time benefits of EV preemption. In particular, this chapter examines the reduction in emergency vehicle delay at signalized intersections. Current research methods have used microsimulation tools to estimate benefits in single- and multiple-intersection cases. The problem noted by previous researchers is that the algorithms used in most programs do not account for the unique driver behaviors that take place when an emergency vehicle approaches a queue held at a red traffic signal. The impact of the inaccuracies introduced has been deemed acceptable when the focus of the evaluation is at the network level but; for a jurisdiction facing the need to address emergency vehicle response times in areas of rapid growth and increasing congestion, a tool capable of high fidelity estimates at the intersection level is required.

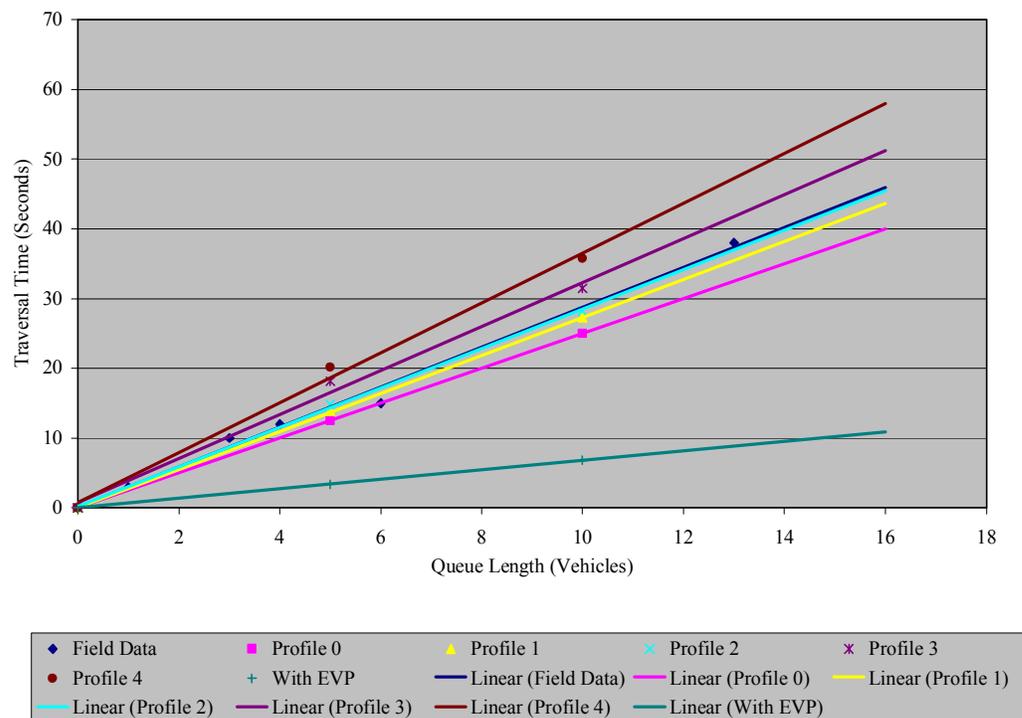


Figure 5.15. Forecast EV Traversal Time by Queue Length for All Population Profiles

This research is a significant first step in meeting this need. Field observations provided the basic understanding of how drivers react when emergency vehicles approach static queues from behind. Drivers appear to want to help create a pathway for the emergency vehicle by executing side-step maneuvers and reducing their normal lateral and longitudinal clearance preferences. Drivers maneuver in an interactive and collective manner that can be modeled as demonstrated by DREAM, the algorithm developed as part of this dissertation. DREAM adapts the key components found in state-of-the-art microsimulations and techniques under development for advance simulation tools in development by FHWA. DREAM operates on the equilibrium principle that drivers wish to maximize the potential for the emergency vehicle to get through while minimizing the potential to be involved in a crash. Key elements of the model include a displacement mechanism that is governed by the distribution of driver familiarity with such situations within the subject driver population. DREAM uniquely defines driver behaviors and the rule sets by which they influence the probability of drivers executing maneuvers that benefit the group. Preliminary analysis of DREAM indicates that the model captures the random occurrence of driver behaviors and offers a baseline for continued development.

Analysis indicates that providing a special green interval on the emergency vehicle approach will translate into significant time savings for first responders. For a heavily traveled arterial in Northern Virginia, the delay encountered at a single intersection can be as much as 38 seconds. EV preemption would conservatively allow the emergency vehicle to traverse the same distance in approximately 9 seconds – a savings at one intersection of nearly 30 seconds.

While the analysis of DREAM involved a relatively low number of data points, initial indications are promising. Advancing the research by development of a computer program version is warranted and will prove to be cost effective in providing actionable information to policy makers, fire and rescue personnel, and traffic operations agencies. The 10 significant field observations used to support this study were gathered over an 8-month period involving over 400 man-hours in the field and 720 hours of surveillance video at key intersections. DREAM allowed analysis of 56 problems in approximately 10 hours of manual problem solution.

CHAPTER 6: CONCLUSIONS, AND RECOMMENDATIONS

The research conducted for this dissertation focused on the subject of evaluation of *preferential treatments* in the form of EV preemption and transit vehicle priority at signalized intersections. The objective of the research, in breadth, was to integrate previous research on the evaluation frameworks and methods which have addressed each of these preferential treatments in isolation of one another. In depth, this research sought to improve the ability to quantify the safety and travel time benefits associated with EV preemption by examining the interaction of auto traffic with emergency vehicles during the approach, crossing, and clearing of signalized intersections. As a result of observations made during a FOT in Northern Virginia, basic methods for evaluating each of these elements to benefit areas were developed in an effort to fill a gap in current evaluation methods and to provide a basis for development of safety- and delay-based warrants for site selection and operation of EV preemption.

Current preemption evaluation methods rely almost exclusively on microsimulation, which satisfies planning level needs, but falls short of operational level evaluation requirements due to the inability to model driver behavior in the presence of emergency vehicles. This leaves the safety benefits element largely unstudied and introduces significant inaccuracy in evaluation of emergency vehicle travel time benefits at the intersection level. This research closes these gaps in evaluation methods by characterizing these driver behaviors and presenting methods that will form the basis for future research and, eventually result in accurate, easy to use evaluation tools.

6.1 ASSESSMENT OF THE EVALUATION FRAMEWORK

The overall research approach, based on the need to develop a holistic framework for evaluation of EV preemption and transit vehicle priority, is sound. Current evaluation frameworks and methods focus on one of the strategies or another, but the reality is that an increasing number of jurisdictions are deploying both strategies on the same corridors. The holistic framework for evaluation is a cost-effective approach because it allows the jurisdictions and the stakeholders to share the capital cost of the signal system devices. Further, for those jurisdictions where attainment of federal clean air standards is in jeopardy, a funding strategy that seeks federal funds to subsidize the capital costs can increase the number of intersections covered. In addition to clean air concerns, congestion management is an issue for both fire and rescue and transit communities. The same congestion levels that cause problems for emergency vehicles are the same that reduce transit-operating efficiencies. Finally, regions that need to develop Homeland Security-related evacuation and first response plans may benefit from the deployment of preferential treatment systems on corridors serving as regional response and evacuation routes.

The framework presented in Chapter 3 will provide a planning and assessment template for all stakeholders to use for developing options for the deployment of preferential treatment systems. The framework acknowledges the shared roadway use and the need to perform traffic corridor studies, through which the particular operational variables and relationships that affect preemption and priority system design and operation will be revealed. While certain distinctive components of the study needs are identified in previous research, this effort has tied them together using the terms and measurement methods employed in traditional transportation planning and traffic operations evaluation. Beyond this, the framework introduces a key element

of evaluation that is often neglected and that is the need to have measures to evaluate the performance of the system with respect the execution of the operational strategies and the impacts to the other roadway users including pedestrians. Often times, evaluation has focused on the individual concepts and strategies or on hardware and component performance. This research introduces the system level evaluation concept that will produce the information necessary to allay stakeholder concerns and bias within the various stakeholder groups, which prevents joint deployment of preemption and priority in many cases.

6.2 ASSESSMENT OF THE EVALUATION OF SAFETY BENEFITS

The *safety benefits* of EV preemption are often cited as justification used by deployment advocates; however, very little research has been done in this area due to the difficulty in gathering data and the lack of a structured evaluation approach. Emergency vehicle crash records are not compiled and analyzed as part of the General Estimate System, which forms the basis for the National Highway Transportation Safety Agency's annual traffic safety report. Emergency vehicle crashes are reported in the Fatality Analysis Reporting System, but the number of fatal crashes is low, less than 2 percent of the annual total. This makes the problem virtually invisible at the levels that would traditionally fund studies and research. At the local level, however, emergency vehicle crashes have significant impact in terms of liability, public perception, and levels of service as damaged apparatus may be out of commission for months.

This research forwards a method that uses conflict analysis as a surrogate for crash analysis in much the same way that the Federal Aviation Administration uses analysis of near-misses as a means to prevent mid-air collisions. The problem, to date, is that there is no published literature on how to analyze conflicts for emergency vehicles, given that the normal right-of-way rules and traffic control device rules, are changed in the presence of a responding emergency vehicle. This research involved analysis of hundreds of auto and emergency vehicle interactions under a wide variety of roadway geometries, traffic flow levels, and signal-timing plans to produce a classification of conflicts by type and severity. The specific classifications were related to readily measurable input variables that dictate the type and severity of conflict that will exist under a given set of conditions. This method of relating geometric, operating, and signal-timing plan conditions to conflict will serve as the basis for prioritization of intersections for EV preemption deployment.

6.3 ASSESSMENT OF THE EVALUATION OF TRAVEL TIME

Current methods to assess emergency vehicle *travel time benefits* are primarily based on microsimulation. Therefore, high-fidelity evaluation of the time savings potential at the intersection level has been difficult to achieve based on the vehicle displacement algorithms employed. Continuous simulation tools such as CORSIM must treat emergency vehicles the same as all other vehicles on the network. Discrete movement simulation tools have greater flexibility, and some, such as VISSIM, already have methods for adjusting driver behaviors, lane-changing logic, traffic control device adherence rules, and rules that govern the ability to pass in the same lane. Other tools, such as TRANSIMS, provide for individual selection of many different driver attributes and could readily adapt to alternative car-following, lane-changing, and passing algorithms for use in special cases such as the approach of emergency vehicles. The

problem thus far, has been a lack of documentation of the nature of driver behaviors and the resulting actions that are associated with emergency vehicles in the traffic stream.

This research has documented the behaviors and classified them in order to provide a relationship between the real-world and simulation algorithm requirements in terms of attitudes towards cooperation, maneuver selection, and maneuver execution. Further, this research has introduced a method for evaluating the problems observed in the real world when emergency vehicles approach queues at during the red interval. The method allows generalized evaluation based on easily obtained measures of geometric, traffic flow, and traffic signal-timing plan conditions specific to an intersection. Using the model forecast traversal time for various queue conditions compared with traversal times possible with EV preemption, stakeholders can quantitatively assess benefit intersection-by-intersection and corridor-by-corridor.

6.4 ABILITY TO GENERALIZE RESULTS

The results of this research are limited to the scenarios evaluated, which were selected to be representative of the type commonly encountered. Significant effort has been taken in the research to relate the observed and modeled phenomena to basic parameters, which can be measured in the field and input as the entry values. Both the conflict severity forecasting method and the travel time benefit determination method incorporate this quality. The limitation of the results of this research lies primarily in the size of the samples of calibration data, which leads to recommendations for further research and suggestions for implementation.

6.5 RECOMMENDATIONS FOR FURTHER RESEARCH

This research introduced methods to overcome a key barrier in EV preemption evaluation. These methods established baseline understandings of emergency vehicle-specific conflict points and the impact of driver behaviors on emergency vehicle progression through static queues. Both of these contributions are of value, but they need to be incorporated into a larger context, which seeks to develop guidelines and warrants. In order to support closure on this long-range goal, further research needs to be done in three key areas: calibration and validation; generalization; and incorporation of the probabilistic elements associated with deriving benefit from these systems.

6.5.1 Calibration and Validation

Research to calibrate and validate the results of this research should be conducted using video imaging systems to capture a large enough sample to establish statistical measures of confidence. Using the framework provided in Chapter 3, intersections and corridors should be selected for instrumentation. An extensive effort should be made to capture the interactions at a high enough resolution to allow frame-by-frame analysis of actions with a maximum time step of 1 second. The video used in this research used a 4-second time lapse between images, which was adequate for initial characterization but will prove to be of poor quality in working towards a characterization, which will eventually yield real-time visualization techniques in simulation.

6.5.2 Generalization

Beyond calibration and validation, a study is necessary to assess the utility of the methods in different regions of the country in order to compare the driver behaviors and the effect of different geometric standards and traffic operations practices (such as the Michigan left turn). Like the Interactive Highway Safety Design Model under development by FHWA, an eventual set of guidelines and warrants may incorporate state-by-state adjustment factors.

6.5.3 Incorporation of Probabilistic Elements

At this point, the methods presented in this research provide an absolute value of the benefit in terms of conflict point severity and emergency vehicle traversal time through intersections. These are the foundations of assessment that will eventually need to incorporate the probability of events, such as emergency vehicle left-turn movements at an intersection or the probability of emergency vehicle arrival during a red interval with various queue conditions. Extending the evaluation to include this aspect will provide the basis for cost effectiveness evaluation of investment on a particular intersection or corridor.

6.6 FINAL SUMMARY

This research centered on the following premise:

Emergency and transit vehicles will benefit from *preferential treatment strategies* with minimum negative impact on other users. Further, the degree of benefit and impact is directly dependent on the operational environment, which is defined as the interaction of the geometric properties of the roadway, the signal strategies, and the characteristics and flow of the primary user classes (emergency vehicles, other traffic, and pedestrians).

It followed an experimental design seeking to prove or disprove the following hypotheses:

- For *EV preemption*, benefits accrue in the reduction of crash potential when emergency vehicles cross a signalized intersection, and in the reduction in delay caused when emergency vehicles approach and pass through signalized intersections during a red interval.
- For *transit vehicle priority*, the benefits accrue in the reduction of travel time over a measured route segment, and in the reduction in the variation in travel time.
- For *other users*, the impact is increased control delay on the mainline and the side streets.

The methods developed and the results of analysis prove the first two hypotheses subject to the previously identified limitations. The third hypothesis was not examined in this research, but was examined in parallel research conducted by others working within the same FOT. It is included for the sake of completeness.

Proof of the hypotheses is only one measure of merit for this research. Another, probably more important, is the development of a holistic framework for conducting evaluation of preferential treatment strategies on the system level. A third measure is the development of methods that begin to describe the effect of driver behavior in the presence of emergency vehicles in terms of safety and emergency vehicle travel time. Lack of fidelity in the treatment of emergency vehicles

in evaluation methods has been the largest limitation identified in research sponsored from the federal level down to the local level. Completion of this research and documentation of its findings in this area will be beneficial to others as the stakeholders in preferential treatment deployment decisions seek methods to support decisions and practices.

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APPENDIX A: USE OF THE CART ALGORITHM

Introduction

The Classification and Regression Tree (CART) was selected for use in development of the analytical method for safety benefits because of its ability to predict the value of a categorical dependent variable based on the value of one or more predictor variables. The method has much in common with traditional methods such as Discriminate Analysis, Cluster Analysis, and Nonlinear Estimation, but CART was selected over these methods because of the ability for the analyst to tailor the final explanation with expert judgment, the ability to generate very easy to understand graphical representations of the hierarchal relationship between variables, and CART's inherent suitability for exploratory analysis of previously undefined phenomena.

A Description of CART

Development of the CART methodology is generally attributed to Breiman, Friedman, Olshen, and Stone (1984). In the explanation of the method, the authors offer an example of the analysis of the risk of heart attacks based on three independent variables: blood pressure; age; and the presence of sinus Tachycardia. In the example, the independent variable values guide the decision maker to separate patients into high- or low-risk categories. Traditional linear discriminate analysis would have assigned coefficients to the variable values in a method that simultaneously considered each of the variables. Brieman et al., found that the resulting linear regression formulas reflected low explanatory values for each variable when considered simultaneously, and found that linear regression methods produced coefficients and signs that did not make sense.

The CART method, on the other hand, produced a tree in which the influence of a variable was assessed in a hierarchal manner. The method results in the development of a tree in which a branch is followed based on the value of the first variable. The decision maker works down the branches of the tree towards a terminal node, which represents the risk level associated with the values of all three variables considered independently in a hierarchal manner. CART ensures that the influence of each variable is determined independently bounded by the outcome of the evaluation of the variable above it in the hierarchy (if any)

The size of a tree developed with CART is an important issue, since an unreasonably big tree can only make the interpretation of results more difficult. Generally, a tree should be sufficient to account for the known facts, but it should be kept as simple as possible in order to facilitate understanding and trust by decision makers. The tree should exploit information that increases predictive accuracy and ignore information that does not. Ultimately, the tree's purpose is to generate greater understanding of the phenomena it describes. Once tree is "grown", pruning it, or right-sizing it, is accomplished in one of two ways. The first is the one used in this research – the participation of subject matter experts in selecting the final explanatory variables and limitation of the number of terminal nodes based on prior research, or even intuition. A second method can employ cross-validation techniques using a validation data set and a series of formal processes developed by Brieman, et al., for that purpose.

The Flexibility of CART

One of the key features of CART is the analyst's participation in the process to determine the final tree. In building the tree, the analyst selects two parameters that define the ability of the algorithm to split a node developing additional branches and new nodes. These first of these parameters involves the minimum number of samples in a node to allow splitting and the minimum number of samples allowed in a terminal node. This splitting constraint based on node sample size, works interactively with a constraint, which defines the minimum deviance value in terminal nodes. CART uses a measure of the difference in behaviors (deviance) allowed within each node by establishing a minimum deviance value as a percentage (normally .010) of the total deviance observed within the data set. The analyst establishes and sets the "minimum" size factor for the following elements: splitting; terminal node size; and deviance as a means to control tree development. In an extreme case, minimum node sizes and a zero value of deviance can result in a separate branch for every case contained in the data set.

A second key feature is that tree methods are nonparametric and nonlinear. The final results of using tree methods for classification or regression can be summarized in a series of logical "if-then" conditions. Therefore, there is no assumption that the underlying relationships between the predictor variables and the dependent variable are linear. This quality facilitates eventual development of expert systems and/or fuzzy logic systems that can be incorporated into computerized decisions support systems.

A third key feature is that tree methods are particularly well suited for data mining tasks, such as the phenomena examined in this research in which there is little *a priori* knowledge and no existing theories or predictions regarding which variables are related and how. Tree methods help researchers reveal simple relationships between variables that may have been unnoticed using other analytic techniques.

Application of Cart in Evaluation of Safety Benefits

CART was used to determine the relationship between a wide range of independent variables measured in the field and the independent variable CONFLICT.SCORE. The value of the CONFLICT.SCORE was determined using the methods and scoring samples developed in Appendix A. Because there was no existing knowledge base on emergency vehicle-specific conflict points, the research team established values for many of the factors that could be contributory in anticipation of using CART to help in the determination of causality. The following is the results of a series of runs made using the S-PLUS software package. Two machine-developed trees are presented to illustrate the tree growing and pruning process using the governing parameters explained above. The final tree is the result of the machine processes and expert judgment.

Regression Tree: InitialTree Growing Parameters:

In this run, the tree was grown to its full extent by setting the minimum node size constraints and the deviation to the minimum possible values. The formula used was:

EV.CONFLICT.SCORE ~ EV.LEFT.TURN + INTERACTION.GEOMETRY + EVP.IN + MESSAGE.TYPE + SIGHT.DISTANCE + EV.THROUGH

Data = Sorting.Copy.No.Va.Complete.Scores.and.Data

Node Split Parameters: mincut = 1, minsize = 2, mindev = 0)

Results:

- Number of terminal nodes: 20
-
- Residual mean deviance: $1.083 = 203.7 / 188$
-

Node Summary: node), split, n, deviance, yval, * denotes terminal node

- 1) root 208 687.4000 2.274
- 2) MESSAGE.TYPE<0.5 138 130.4000 1.471
 - 4) INTERACTION.GEOMETRY<1.5 50 49.9200 1.960
 - 8) EVP.IN<0.5 31 44.7100 2.097
 - 16) EV.LEFT.TURN<0.5 26 44.6500 2.115 *
 - 17) EV.LEFT.TURN>0.5 5 0.0000 2.000 *
 - 9) EVP.IN>0.5 19 3.6840 1.737 *
 - 5) INTERACTION.GEOMETRY>1.5 88 61.7200 1.193
 - 10) INTERACTION.GEOMETRY<2.5 52 0.0000 1.000 *
 - 11) INTERACTION.GEOMETRY>2.5 36 56.9700 1.472
 - 22) EVP.IN<0.5 17 0.0000 1.000 *
 - 23) EVP.IN>0.5 19 49.7900 1.895
 - 46) EV.THROUGH<0.5 4 10.7500 2.250
 - 92) EV.LEFT.TURN<0.5 3 10.6700 2.333 *
 - 93) EV.LEFT.TURN>0.5 1 0.0000 2.000 *
 - 47) EV.THROUGH>0.5 15 38.4000 1.800 *
 - 3) MESSAGE.TYPE>0.5 70 292.6000 3.857
 - 6) INTERACTION.GEOMETRY<1.5 20 7.2000 1.800
 - 12) EV.THROUGH<0.5 9 2.0000 2.000
 - 24) EV.LEFT.TURN<0.5 1 0.0000 2.000 *
 - 25) EV.LEFT.TURN>0.5 8 2.0000 2.000
 - 50) EV.LEFT.TURN<1.5 7 2.0000 2.000 *
 - 51) EV.LEFT.TURN>1.5 1 0.0000 2.000 *
 - 13) EV.THROUGH>0.5 11 4.5450 1.636 *
 - 7) INTERACTION.GEOMETRY>1.5 50 166.9000 4.680

14) EV.THROUGH<0.5 17 9.7650 6.118
 28) EV.LEFT.TURN<0.5 1 0.0000 5.000 *
 29) EV.LEFT.TURN>0.5 16 8.4380 6.188
 58) INTERACTION.GEOMETRY<2.5 8 0.8750 5.875
 116) SIGHT.DISTANCE<0.5 2 0.5000 5.500 *
 117) SIGHT.DISTANCE>0.5 6 0.0000 6.000 *
 59) INTERACTION.GEOMETRY>2.5 8 6.0000 6.500 *
 15) EV.THROUGH>0.5 33 103.9000 3.939
 30) SIGHT.DISTANCE<0.5 30 93.3700 3.767
 60) INTERACTION.GEOMETRY<2.5 6 13.5000 3.500
 120) EV.LEFT.TURN<0.5 5 13.2000 3.400 *
 121) EV.LEFT.TURN>0.5 1 0.0000 4.000 *
 61) INTERACTION.GEOMETRY>2.5 24 79.3300 3.833 *
 31) SIGHT.DISTANCE>0.5 3 0.6667 5.667 *

The initial tree produced is shown below in three views. The first, Figure A.1, shows the mean Conflict Score value in each of the terminal nodes. The second, Figure A.2, shows the number of observations in each terminal node. The third, Figure A.3, shows the deviance within each of the terminal nodes.

Comments on the Initial Tree:

While this tree is fully explanatory as indicated by the low residual deviance, the high number of terminal nodes will make it difficult for incorporation into simple inference systems. Many of these terminal nodes are inconsequential, since the number of observations they contain are so low. In order to improve upon the tree, the pruning process is accomplished within CART using a new set of node splitting constraint parameters and a revised independent variable list.

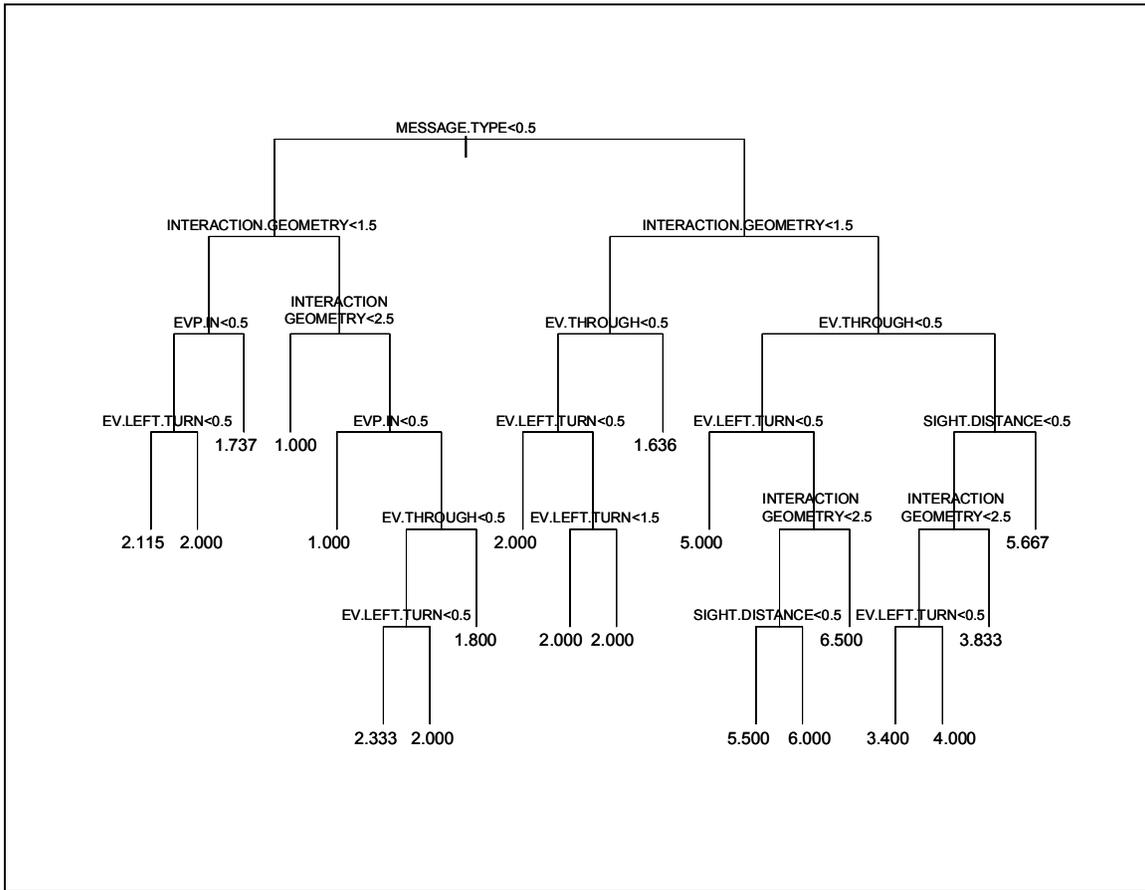


Figure A.1. Initial CART Tree (Mean Conflict Scores)

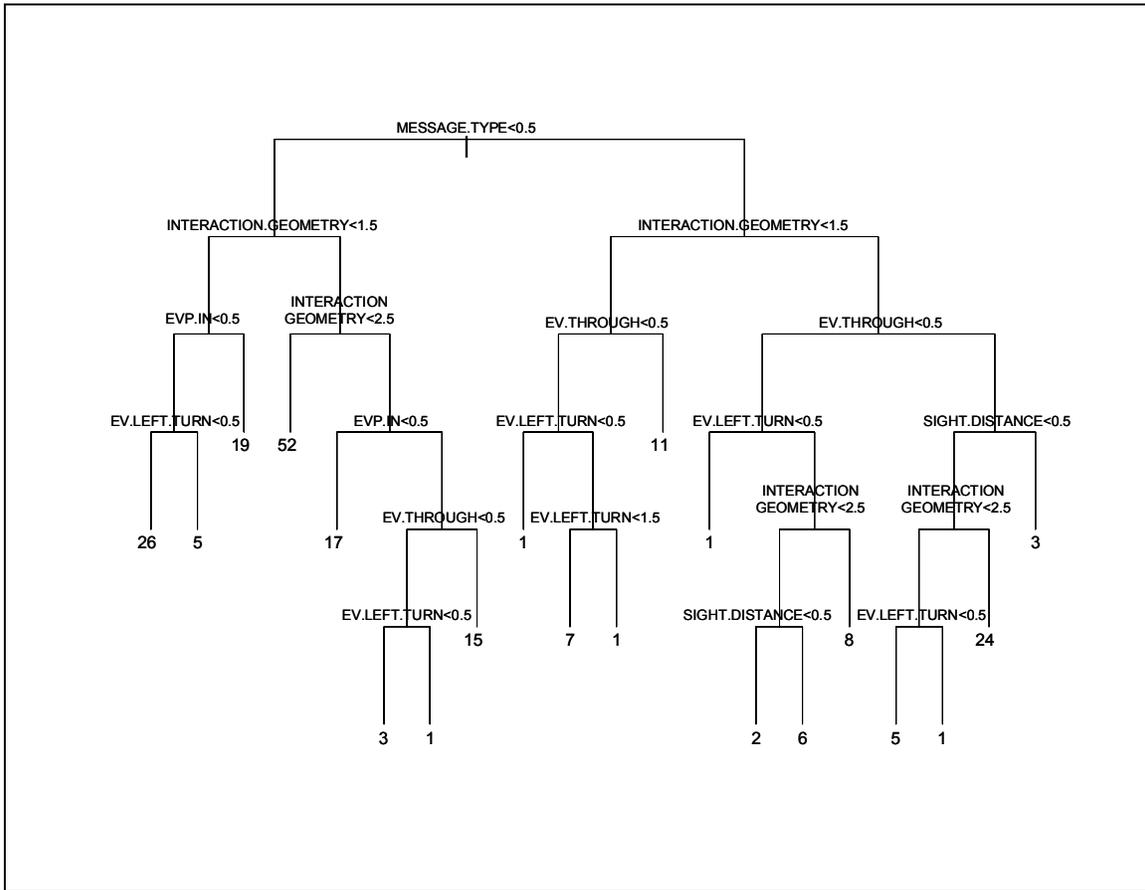


Figure A.2. Initial CART Tree (Sample Size)

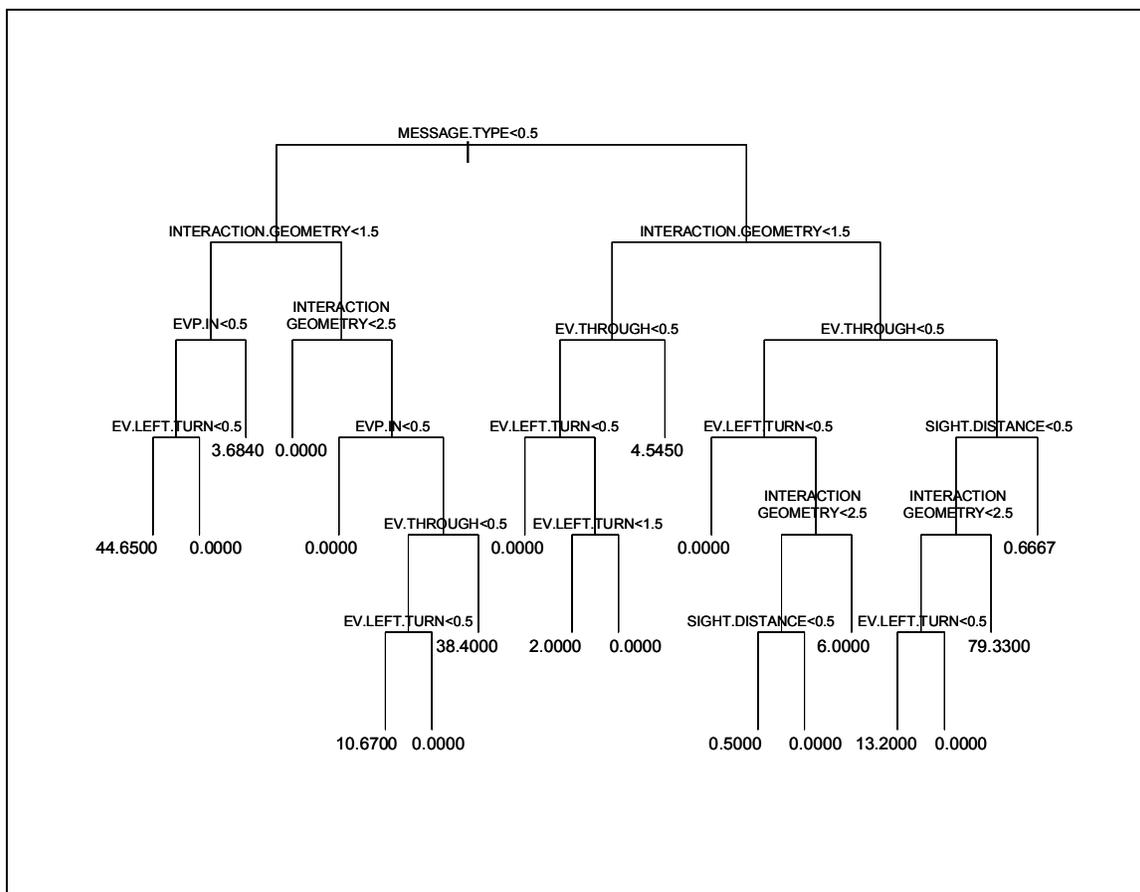


Figure A.3. Initial CART Tree (Deviance)

Regression Tree: Semi-Final

In this run, the tree was pruned using CART. The list of independent variables was reduced by eliminating those that caused splits which were duplicative or added little to the explanation of the phenomena as indicated by the applicable terminal node sizes and deviance values. To complement the reduction in the number of variables, the node splitting constraints were also modified. The mincut and minsize parameters were doubled to 2 and 4, respectively, requiring larger nodes to split and larger terminal nodes. In addition, the deviance within terminal nodes was raised to 0.01 from 0.00. The result was a more manageable tree. The formula used was:

$$EV.CONFLICT.SCORE \sim INTERACTION.GEOMETRY + MESSAGE.TYPE + EV.LEFT.TURN$$

Data = Sorting.Copy.No.Va.Complete.Scores.and.Data

Node Split Parameters: mincut = 2, minsize = 4, mindev = 0.01

Results:

- Number of terminal nodes: 11
-
- Residual mean deviance: $1.148 = 226.1 / 197$
-

Node Summary: node), split, n, deviance, yval, * denotes terminal node

- 1) root 208 687.4000 2.274
- 2) MESSAGE.TYPE<0.5 138 130.4000 1.471
 - 4) INTERACTION.GEOMETRY<1.5 50 49.9200 1.960
 - 8) EV.LEFT.TURN<0.5 45 49.9100 1.956 *
 - 9) EV.LEFT.TURN>0.5 5 0.0000 2.000 *
 - 5) INTERACTION.GEOMETRY>1.5 88 61.7200 1.193
 - 10) INTERACTION.GEOMETRY<2.5 52 0.0000 1.000 *
 - 11) INTERACTION.GEOMETRY>2.5 36 56.9700 1.472
 - 22) EV.LEFT.TURN<0.5 27 54.5200 1.593 *
 - 23) EV.LEFT.TURN>0.5 9 0.8889 1.111 *
- 3) MESSAGE.TYPE>0.5 70 292.6000 3.857
 - 6) INTERACTION.GEOMETRY<1.5 20 7.2000 1.800
 - 12) EV.LEFT.TURN<0.5 12 4.6670 1.667 *
 - 13) EV.LEFT.TURN>0.5 8 2.0000 2.000 *
 - 7) INTERACTION.GEOMETRY>1.5 50 166.9000 4.680
 - 14) EV.LEFT.TURN<0.5 33 105.0000 3.970
 - 28) INTERACTION.GEOMETRY<2.5 8 23.5000 4.250 *
 - 29) INTERACTION.GEOMETRY>2.5 25 80.6400 3.880 *
 - 15) EV.LEFT.TURN>0.5 17 12.9400 6.059
 - 30) INTERACTION.GEOMETRY<2.5 9 4.0000 5.667 *
 - 31) INTERACTION.GEOMETRY>2.5 8 6.0000 6.500 *

The semi-final tree produced is shown below in three views. The first, Figure A.4, shows the mean Conflict Score value in each of the terminal nodes. The second, Figure A.5, shows the number of observations in each terminal node. The third, Figure A.6, shows the deviance within each of the terminal nodes.

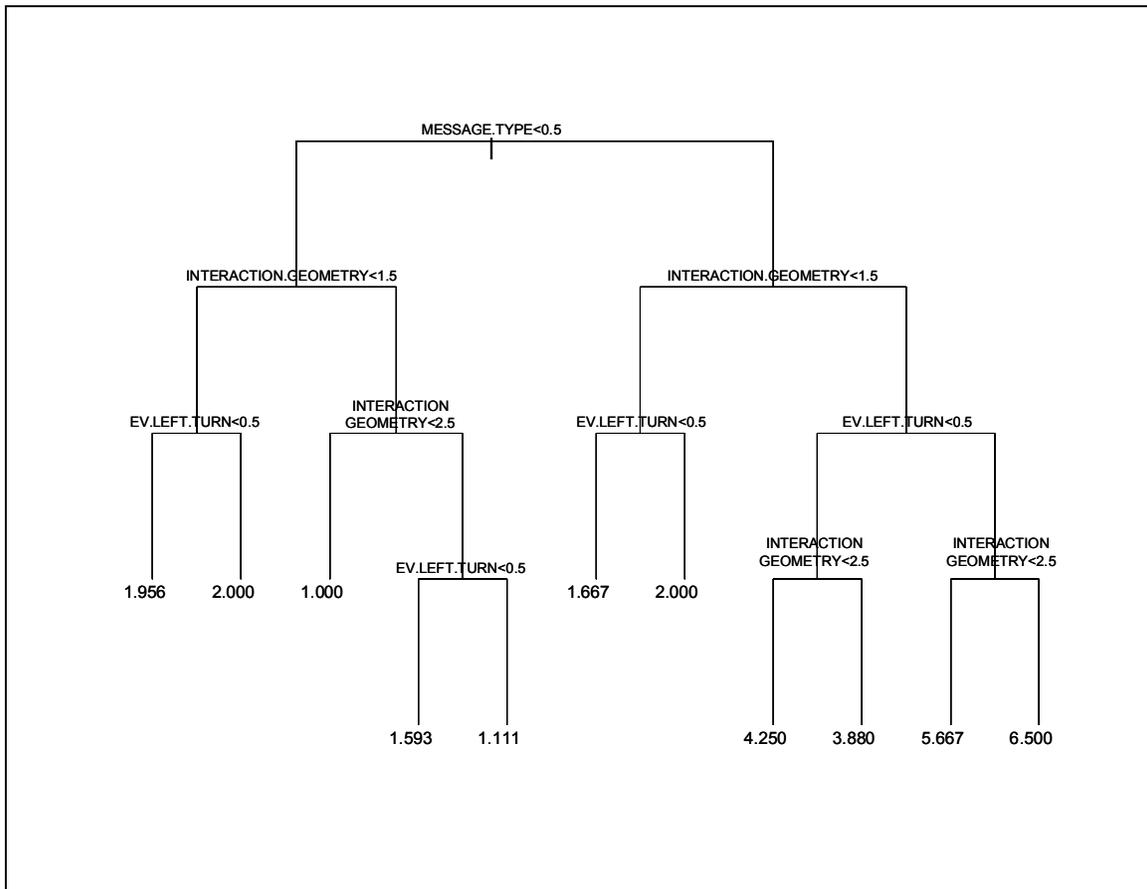


Figure A.4. Semi-Final CART Tree (Mean Conflict Scores)

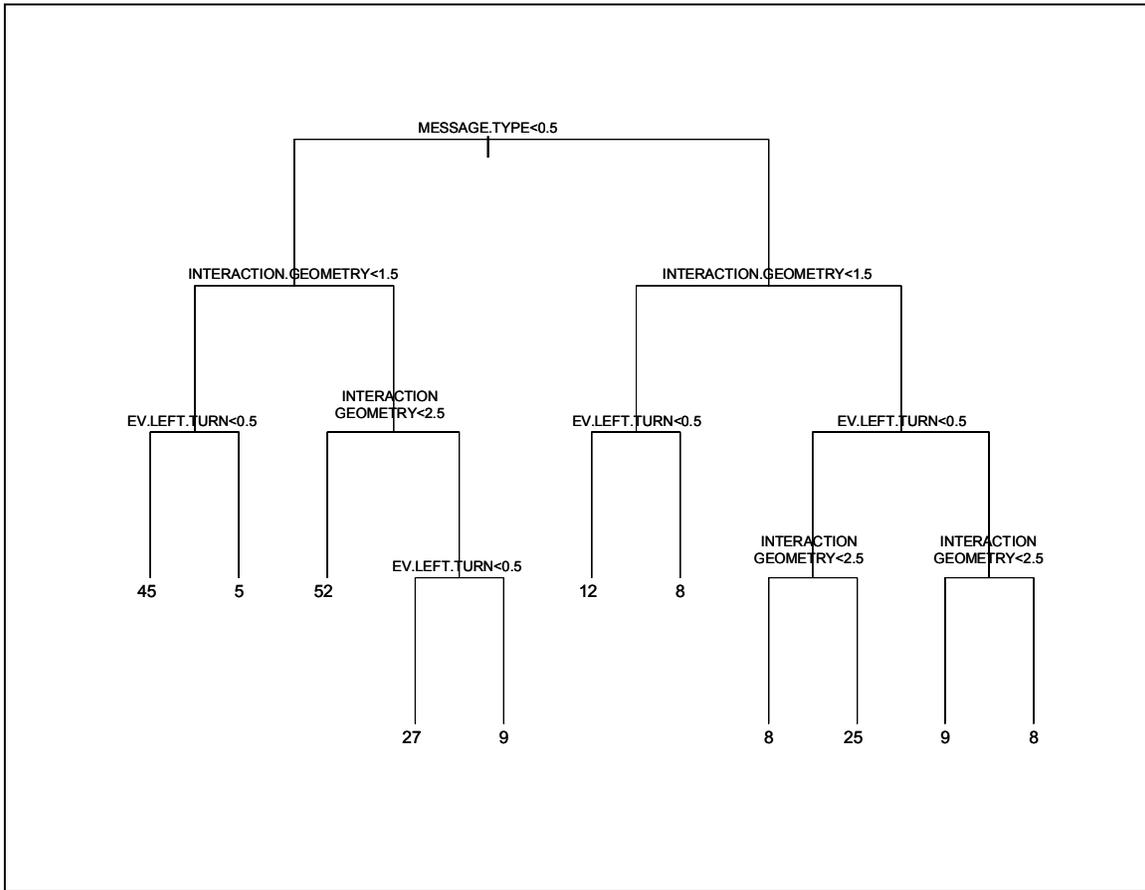


Figure A.5. Semi-Final CART Tree (Sample Size)

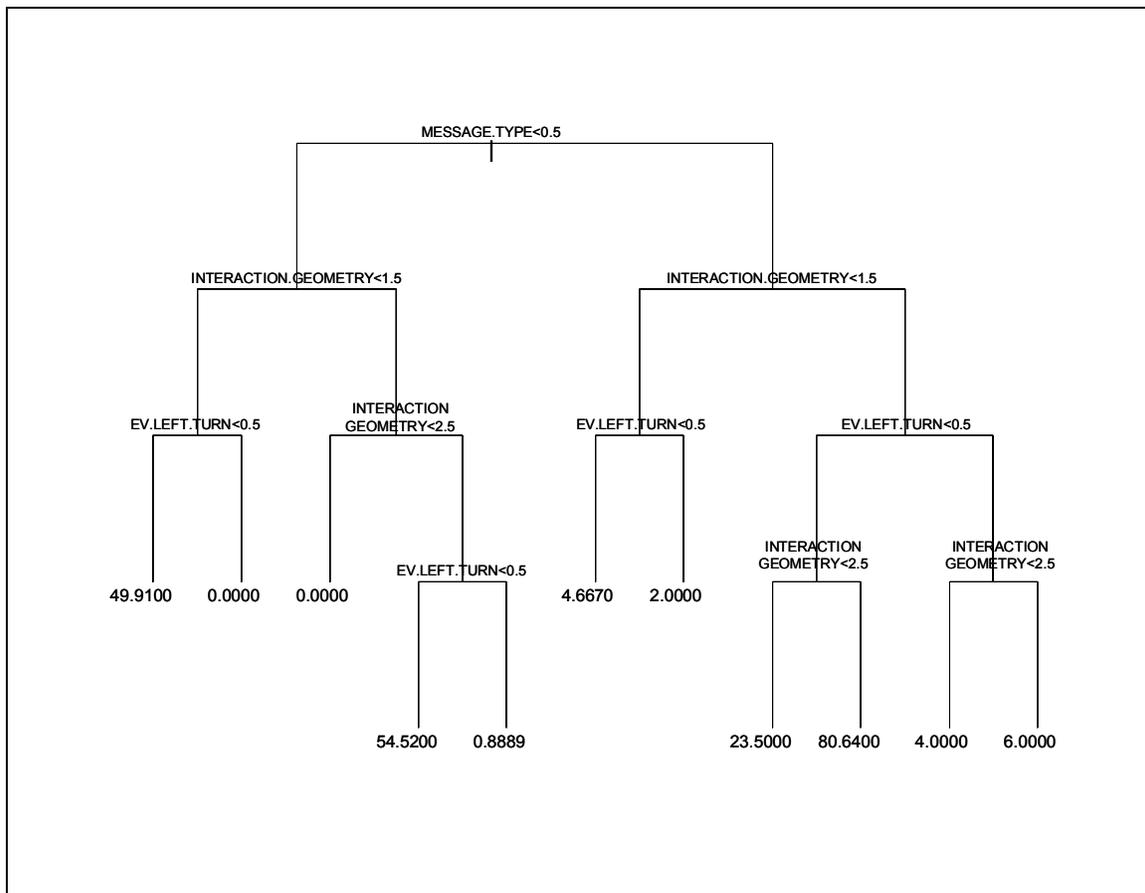


Figure A.6. Semi-Final CART Tree (Deviance)

Comments on the Semi-Final Tree:

The semi-final tree is much simpler. It provides an easily traced causality chain, which can lead to development of a simple set of rules forming an inference system. The residual deviance is very low indicating a good explanatory value and, the number of terminal nodes was reduced from 20 to 11. This tree is satisfactory, but examination reveals that the terminal nodes circled in Figure A.7 are good candidates for pruning based on expert knowledge and the guidelines for pruning. All of these terminal nodes have either a very low number of observations within them or have very low internal deviances. Experience suggests that the terminal nodes within the circles can be collapsed into single nodes containing the samples within each.

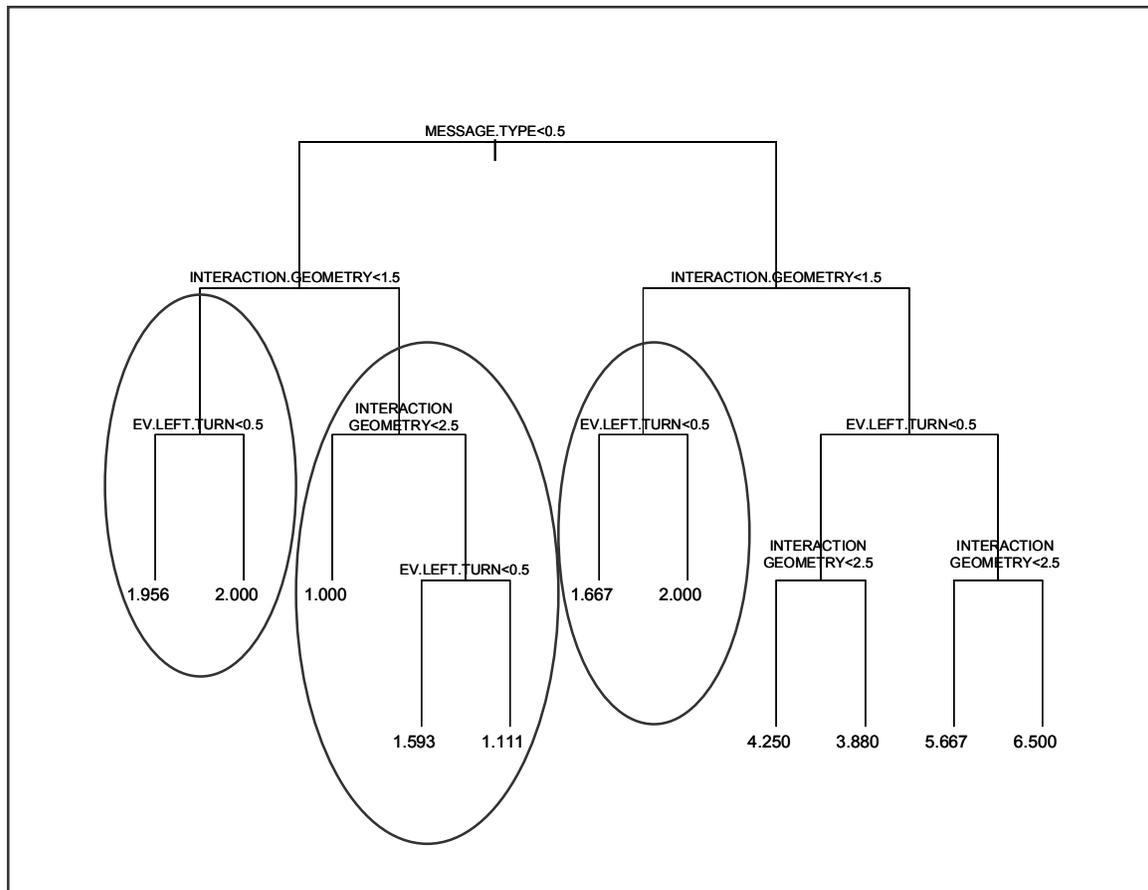


Figure A.7. Final CART Tree (Mean Conflict Scores)

CART Summary

The result of the tree growing and tree pruning process is shown in Chapter 4 as Figure 4.4. This tree represents a very clear explanation of the relationship between CONFLICT.SCORE and only three independent variables, which can be readily assessed at any operational intersection located on an emergency vehicle response route. The surviving independent variables are INTERACTION.GEOMETRY, MESSAGE.TYPE, and EV.LEFT.TURN. A tree of this reduced complexity facilitates development of a simple rule set that provides stakeholders in an EV preemption deployment decision an analytical method to estimate the safety benefit using a conflict analysis method. In the future, the variable relationships developed in this research may lead to development of expert systems or fuzzy logic systems that will form a core element of future warrants for deployment based on the reduction of emergency vehicle crash potential.

APPENDIX B: ANALYSIS OF EMERGENCY VEHICLE CRASHES

Introduction

The study of emergency vehicle crashes to determine the causes and potential remedies is not widely practiced. This is due to several reasons. First, emergency vehicle crashes are not reported in a separate category in the NHTSA Annual Traffic Safety Report. They are reported in FARS, so there is visibility into the fatal crashes—but this only provides national level visibility into only a small number of crashes (approximately 80 per year). The second reason for the low amount of research into emergency vehicle crashes is the low number of crashes any one jurisdiction may experience in a year or even 3 years (periods often associated with normal traffic crash analysis). A study of emergency vehicle crashes at the local level may require a 5- or 10-year study period. Study periods of this length are difficult for use in engineering decisions because of the wide range of changes in the operations environment, which may take place and the need for feedback on the return on investment of an EV preemption deployment. A third reason is that even in an extended study period, there may be very low frequencies associated with specific locations making it difficult to determine appropriate roadway or operational remedies.

Conflict Analysis

One of the objectives of this research is to develop a conflict analysis method specific to emergency vehicle conflict points that occur at signalized intersections. Traditional conflict analysis suggests that the severity of a particular conflict point at an intersection is a function several factors: roadway geometry (including the existence of line-of-sight problems and excessive skew angles); the type of traffic control device in-place and its operations strategy (including the number of phases that allow simultaneous conflicting movements); the speed of vehicles entering the intersection; and the angle between the vehicle pathways allowed to move at the same time.

The problem is that the conventional understanding of conflict points breaks down while an emergency vehicle is present. This is due to the precedence of the emergency vehicle over the traffic control device in determination of right-of-way. The result of the presence of an emergency vehicle in the traffic stream, at an intersection can be confusion or driver errors which present conflict points unique to the operation of emergency vehicles at signalized intersections. The purpose of this appendix is to present data used in development of the definitions of conflict points and the assignment of severity codes to each classification. The intention is that the emergency vehicle conflict points developed in this research will provide transportation professionals a tool to analyze the safety impacts of EV preemption using the reduction in the number and severity of conflict points in *before* and *after* cases as a surrogate for the before and after crash analysis that may not be feasible due to the lack of crash data for a specific location.

Crash Analysis – The National Level

Total Annual Fatal Emergency Vehicle Crashes

As mentioned previously, emergency vehicle crashes are not categorically reported in the Traffic Safety Facts annual report published by NHTSA. Therefore, the only source of national level data is FARS. This limits the visibility into the size and scope of the problem but meaningful information gain be gained by examining the fatal crashes reported in FARS. Over the 8-year period (1994-2001), there were 724 fatal crashes involving EVs—an average of 90 fatal crashes per year.

Intersection Related Emergency Vehicle Crashes

The first level of analysis conducted within this study, was to determine the number of intersection-related crashes. As the data show, nearly 50 percent of the crashes take place in intersection environments. A total of 336 crashes occurred within or in immediate proximity to intersections—both signalized and non-signalized.

Of the 336 intersection-related fatal emergency vehicle crashes, 182 took place at or in immediate proximity to signalized intersections. This indicates that significant conflict points exist at intersections in spite of the fact that emergency vehicles operating a siren and lights are to be given the right-of-way in spite of right-of-way assignment by the signal displays (Figure B.1). On average, there are 42 intersection related emergency crash fatalities per year, of which 23 per year occur at signalized intersections.

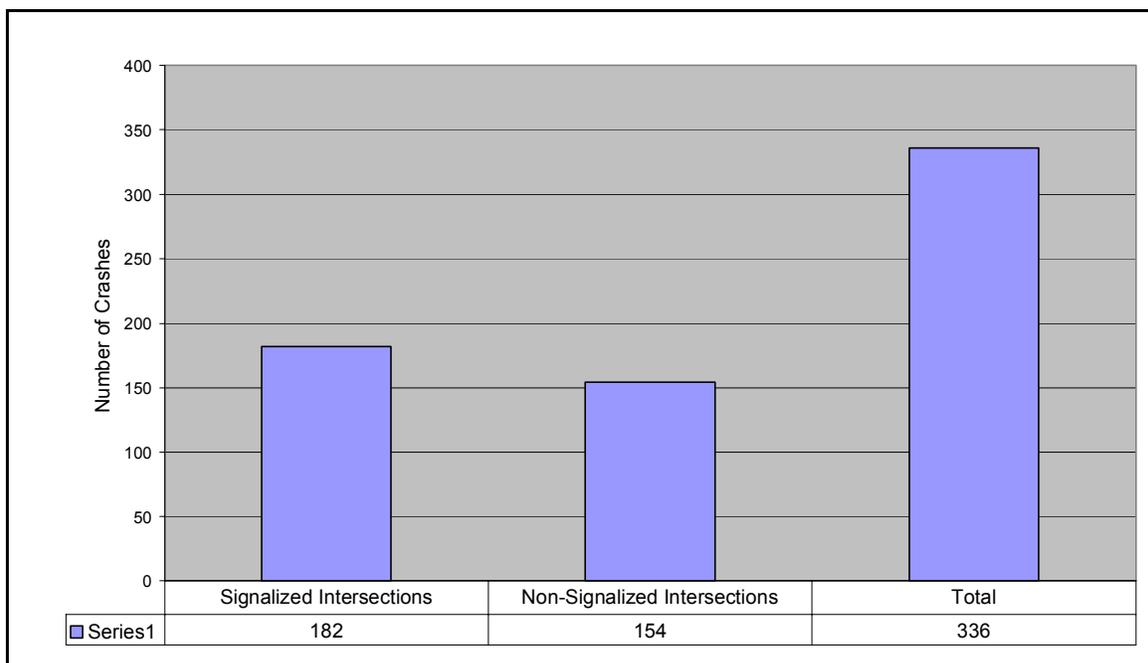


Figure B.1. Fatal Emergency Vehicle Crashes at Intersections

Analysis of the emergency vehicle fatal crashes at signalized intersections over the period from 1994 through 2001 revealed that the highest number of fatalities (155 of 182 occur during angle

collisions (Figure B.2). This finding is consistent with analysis of crashes at signalized intersections under normal traffic conditions.

Although these findings are important, they do not provide a complete picture due to the lack of visibility into the number of property damage and injury crashes. Therefore, this study went beyond the national level data and examined emergency vehicle crash data at the local level. The purpose of continuing the analysis at the local level was to reveal a more complete understanding of crash types with respect to intersections and signals and the relative proportions of crash severity.

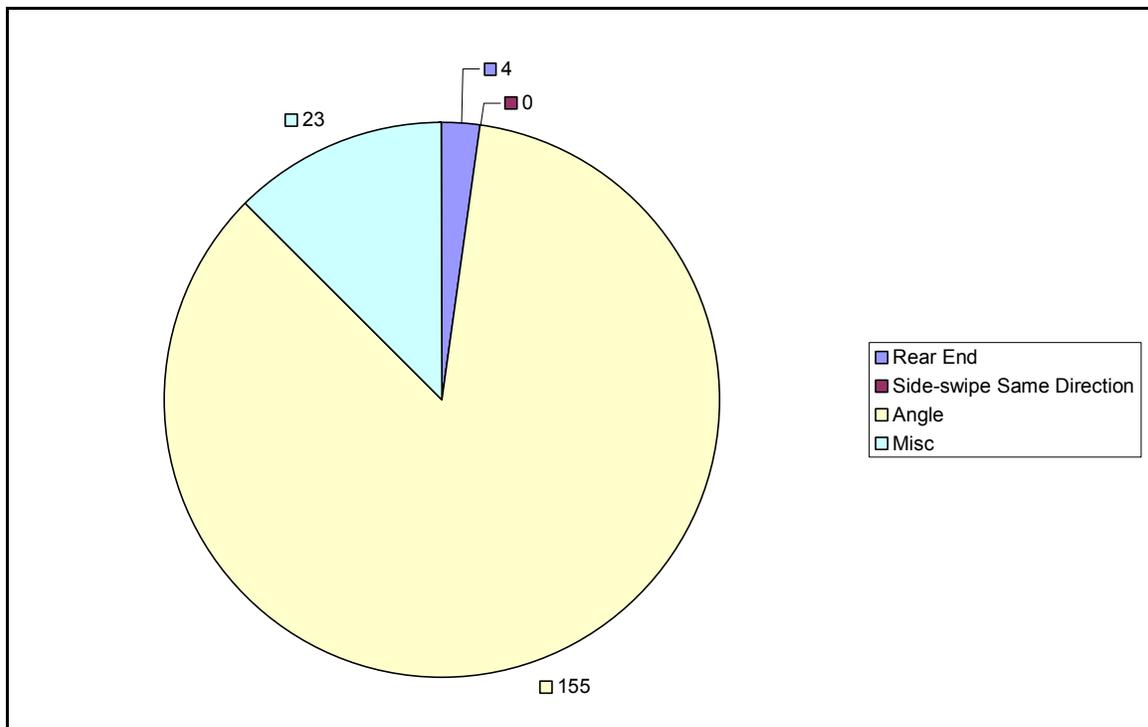


Figure B.2. Fatal Emergency Vehicle Crashes at Signalized Intersections

Crash Analysis—The Local Level

The second tier of the emergency vehicle crash study examined the phenomena at the regional level in Northern Virginia. The Northern Virginia region, for the purpose of this study, is comprised of four counties: Fairfax, Arlington, Prince William, and Loudon. This study included examination of the 10-year emergency vehicle crash history for the Primary Roads in each of these counties for the period 1992 through 2001.

The local level analysis begins with a breakdown of emergency vehicle intersection crashes by county and by crash severity: property damage, injury, and fatality (Figure B.3). The counties are shown, from left to right, by decreasing number of emergency vehicle crashes. This order follows the VDOT ranking of the counties by density in terms of annual vehicle miles per roadway mile. Fairfax County, which has the highest primary road traffic density in the region,

had the highest number of emergency vehicle crashes (190 crashes in the 10-year period). Because of this relationship, the highest number of emergency vehicle crashes and the highest traffic density, Fairfax County Primary Roads were examined in detail.

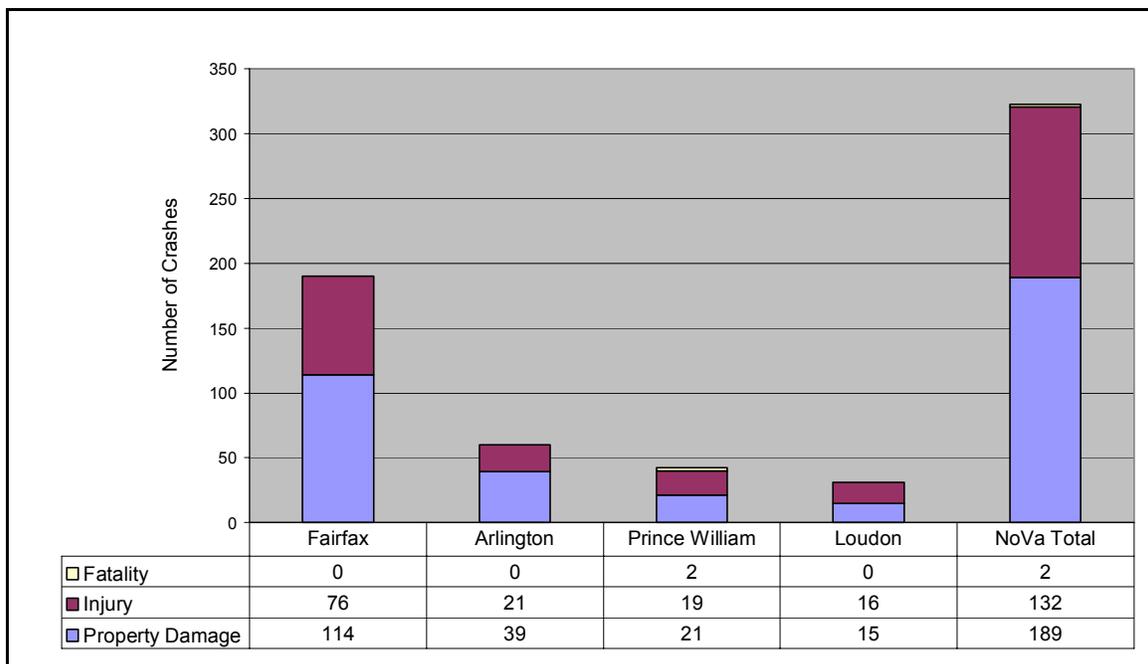


Figure B.3. Northern Virginia Emergency Vehicle Crashes

Like the national data, the county data (Figure B.4) shows that there are a significant number of intersection-related crashes. For the county, intersection crashes data represent nearly two-thirds of the total, which is different from the national data. The difference may result in part that the national data is blind to the number of property damage and injury crashes.

The particular interest for this study is crashes at signalized intersections. For Fairfax County, 70 of 132 intersection-related emergency vehicle crashes occurred at signalized intersections (Figure B.5). Like the national data, the split is nearly even between signalized and un-signalized intersections, averaging 7 emergency vehicle crashes per year at signalized intersections on primary roads. Figure B.6 provides a breakdown of the Fairfax County signalized intersection emergency vehicle crashes by collision type. The emergency vehicle crash characteristics of specific roadways are examined in Figure B.7, along with the distribution of property damage and injury crashes by collision type. This data clearly shows that emergency vehicle crashes involve a wide range of interaction geometries, and the crash severity is related to the interaction geometry and closing velocity of the emergency vehicle. In cases where closing velocities are low (sideswipe same direction), crashes are primarily property damage only. In cases where closing velocities are high (rear-end and angle crashes), 35 to 50% of crashes are injury crashes.

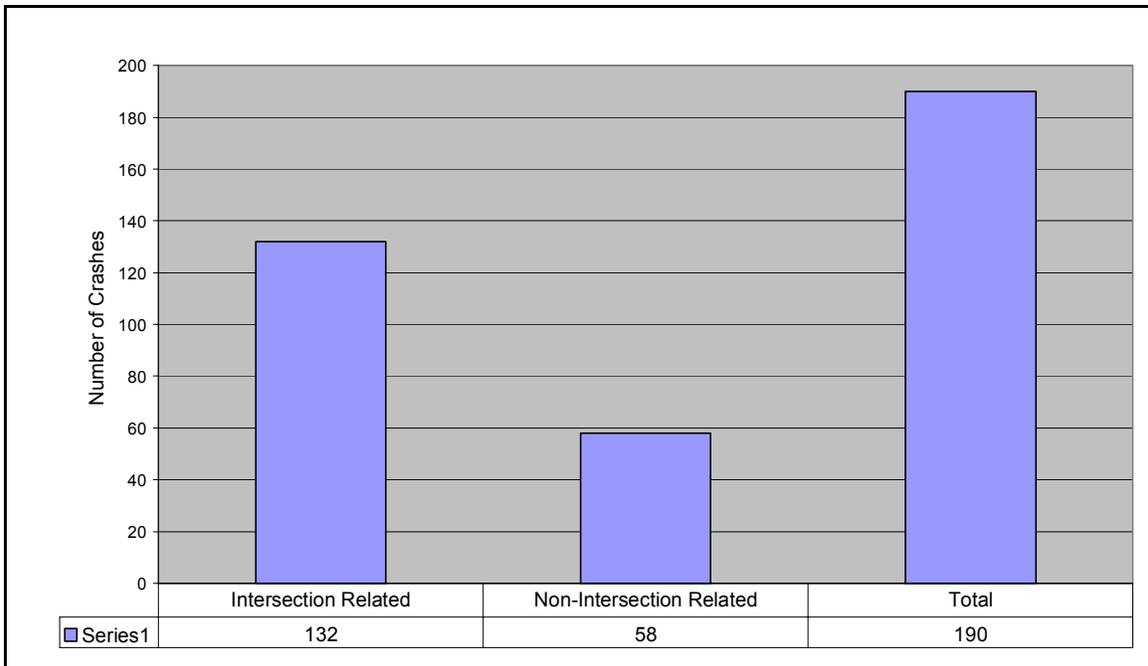


Figure B.4. Emergency Vehicle Crashes on Fairfax County Primary Roads

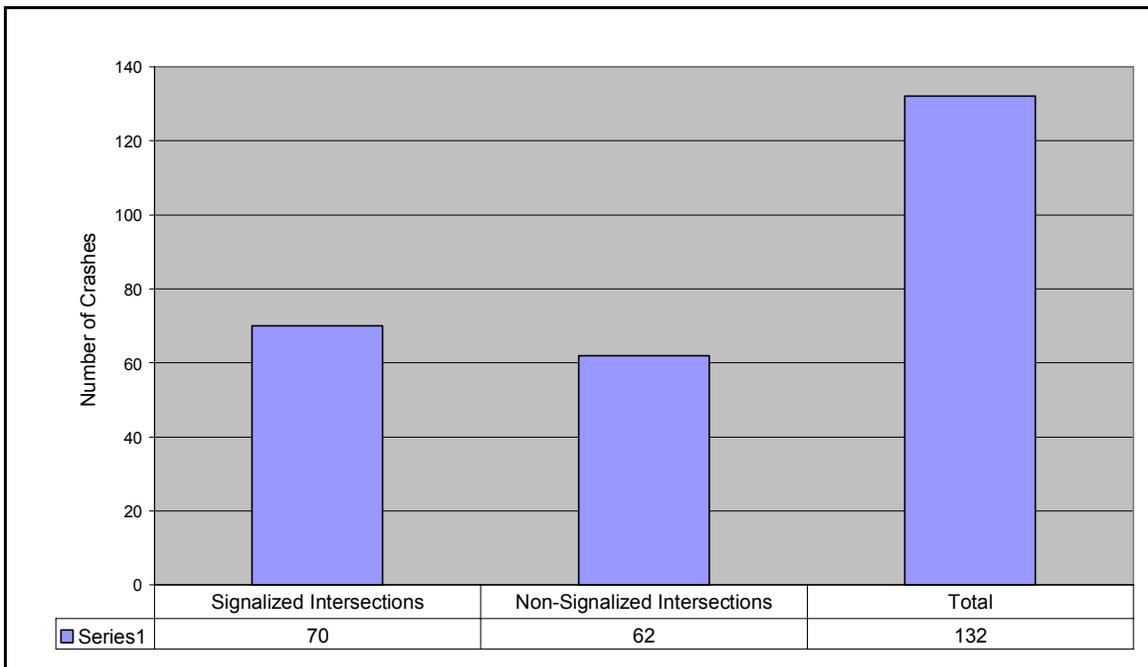


Figure B.5: Emergency Vehicle Crashes at Fairfax County Intersections

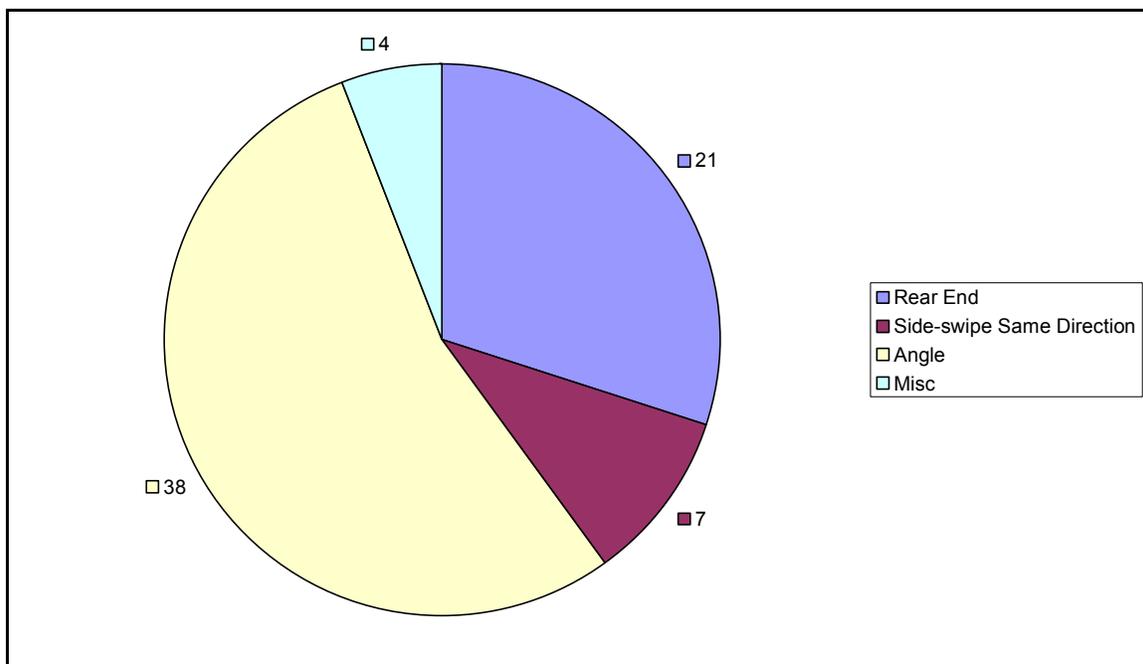


Figure B.6. Emergency Vehicle Crashes by Type on Fairfax County Primary Roads

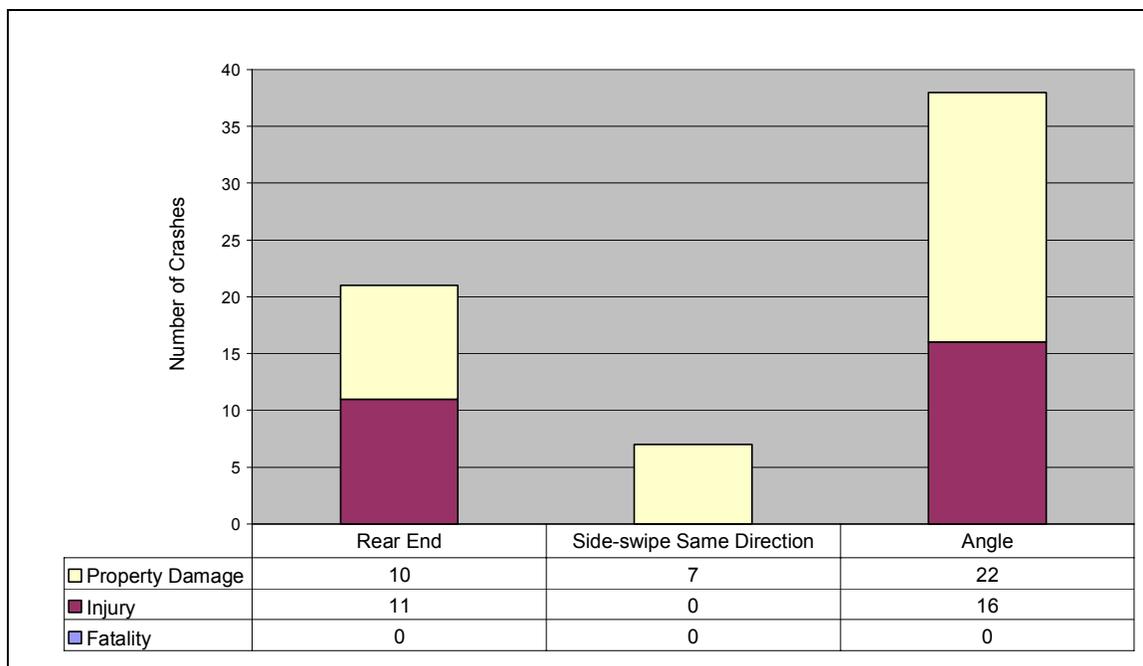


Figure B.7. Emergency Vehicle Crashes by Type at Fairfax County Intersections

Figure B.8 presents data for Primary Roads in Fairfax County. The three with the highest number of crashes are U.S. 1, S.R. 7, and S.R. 123. These roads are characterized by both urban and rural settings. Lane widths in urban areas are narrow and shoulders are generally not available. In rural

areas, lane widths are adequate and shoulders generally exist although, they often are often adjacent to ditches and roadside obstacles such as trees and poles. All three have very high volumes, and the number of signals/mile is very high. On U.S. 1, for instance AM peak volumes in the test corridor are as high as 3,000 vph. U.S. 1 signal density is 39 signals on the 14-mile section from the Prince William County line to the Alexandria City line. The route with the least number of crashes also experiences high peak volumes, but it runs primarily through rural areas. On S.R. 28, the lane widths are wide, shoulder areas are good, and the number of signals per mile is low due to a combination of access control and low number of side streets per mile.

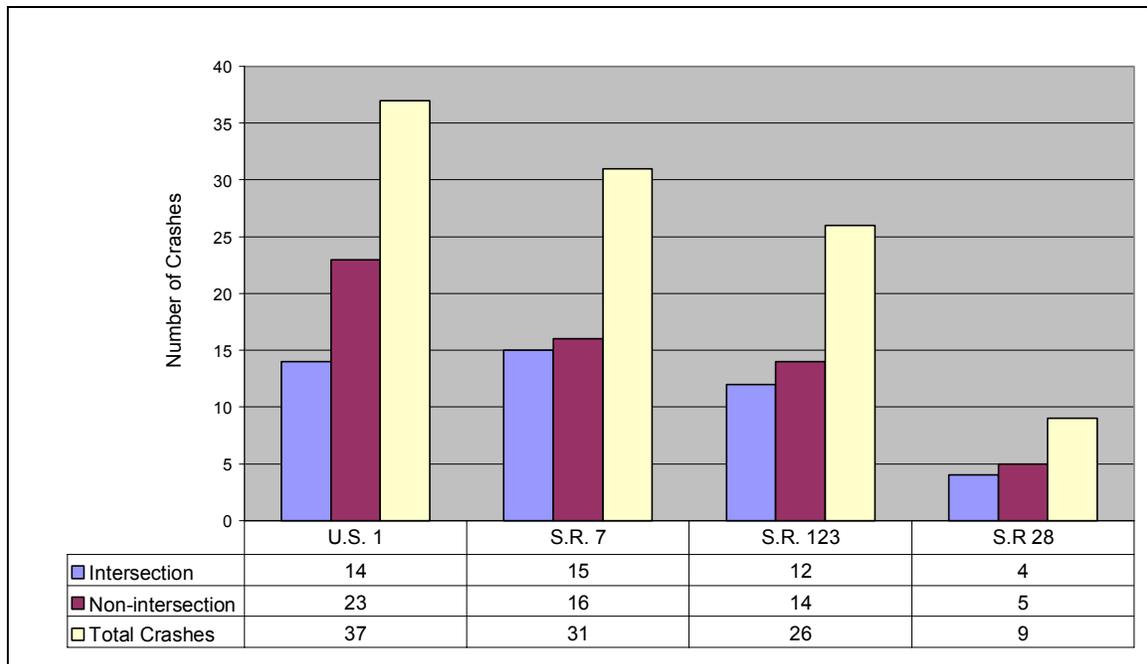


Figure B.8. Emergency Vehicle Crash Analysis by Route for Fairfax County

For each of the roadways examined in Figure B.8, an analysis of the number of crash sites (intersection and non-intersection) was conducted to gain insight into the roadway performance. Further, an analysis was conducted to determine if there were any sites with multiple emergency vehicle crashes over the study period. All sites with multiple crashes in the 10-year period were intersection sites. The results of the roadway and site analysis are shown in Figure B.9 for each of the three roadways examined in the previous discussion.

Conflict Point Severity

To support this research, national and local emergency vehicle crash data was used to generate a relative severity scale by collision type. To accomplish this, crash data was examined for each collision type. The percentage of crashes for each severity and collision type were computed based on the local level crash data presented previously. Having normalized the number of crashes by severity and collision type, a weighted value was computed for each using the following weights. Property damage crashes were assigned a value of 1, injury crashes were

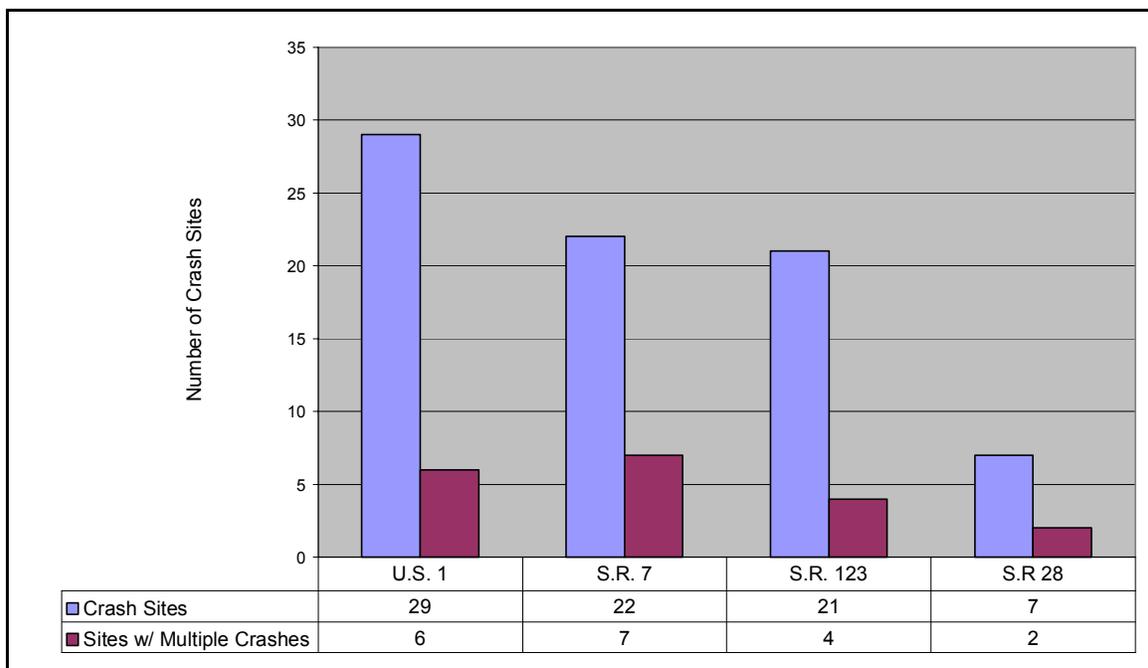


Figure B.9. Emergency Vehicle Crash Sites on Fairfax County Primary Roads

assigned a value of 2, and fatal crashes were assigned a value of 5. Table B.1 presents the results of this computation. The result of this analysis is a ranking as follows from least severe crashes to most severe using scores from 1 to 8, where 8 represents the occurrence of a crash. The spectrum (Figure B.10) ranges from the lowest score assigned to sideswipe (same direction) conflicts, through rear-end conflicts, to angle conflicts. Within angle conflicts, the severity score varies according to the likely velocity of the emergency vehicle and the conflicting auto at the potential time of impact based on initial velocities and stopping distance available at the time the auto indicated awareness. To complete the relative severity score range determined by crash history, the research team incorporated a driver interaction descriptor to account for auto drivers who display confusion during the approach and passage of the emergency vehicle. The “confused driver” was assigned a value of 5 out of 8 based on the input emergency vehicle operators. Complete definitions for each conflict are offered in Section 4.7.2. of this dissertation.

Table B.1. Weighted Values of Crash Severity by Collision Type

Severity (Weight)	Collision Type			Total Number
	Sideswipe Same Direction	Rear-End	Angle	
Property Damage (1)	.18	.26	.56	39
Injury (2)	.00	.41	.59	27
Fatal (5)	.00	.03	.97	159
Weighted Value	.18	1.23	6.59	

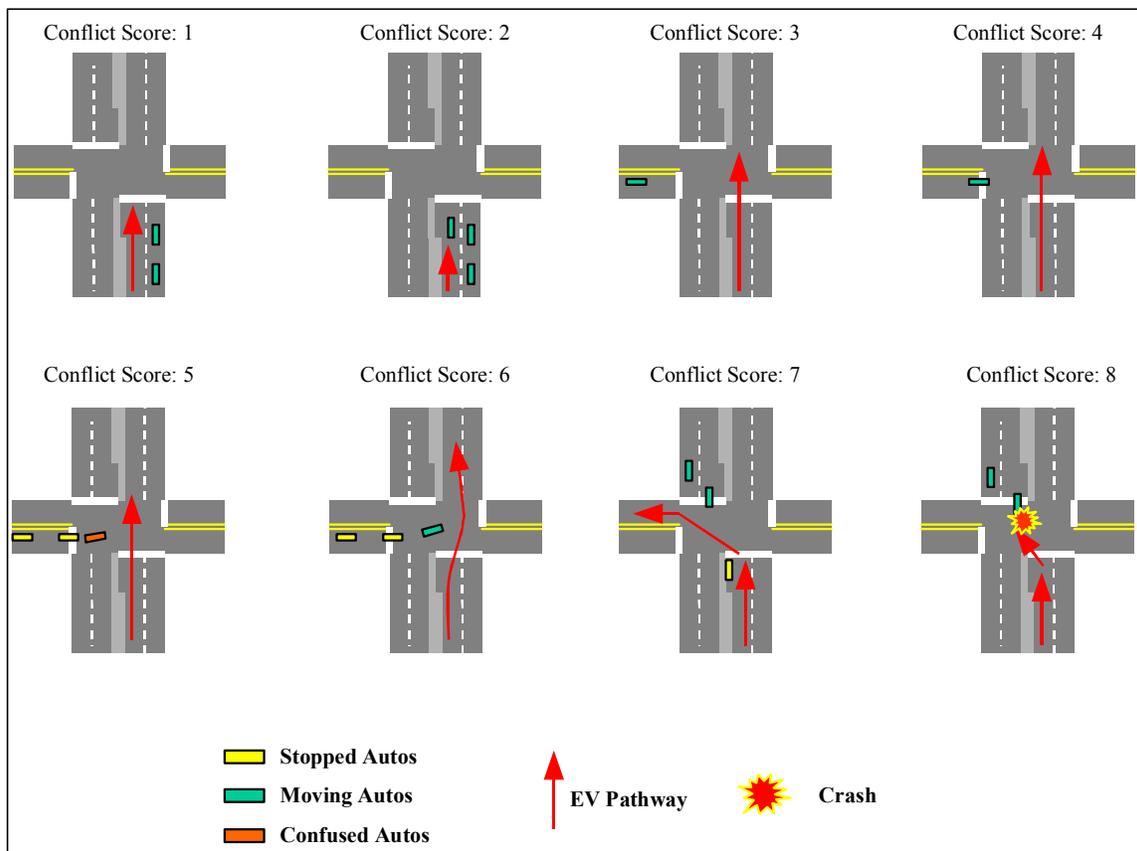


Figure B.10. Conflict Severity Index

APPENDIX C: FIRE AND RESCUE RESPONSE GOALS

The following tables summarize the fire and rescue response time goals and performance for FY 2002 as reported on the individual county websites (Fairfax County Department of Public Safety, 2003), (Prince William County Department of Public Safety, 2003), (Arlington County Department of Public Safety, 2003), (Loudon County Department of Public Safety, 2003)

Table C.1. Fire Suppression Services Response Times

Jurisdiction	Fire Suppression Response Goal (min)/% Achieved		
	High Density	Medium Density	Low Density
Fairfax Co	6 / 55%		
Prince William Co	6.5 / 78%	8.0 / 77%	11.0 / 88%
Arlington Co	4 / Actual Times Not Publicly Posted		
Loudon Co	Only Turnout Times Posted		

Table C.2. Basic Life Support Services Response Times

Jurisdiction	Rescue Services Basic Life Support (BLS) Response Goal (min) / % Achieved		
	High Density	Medium Density	Low Density
Fairfax Co	All Units Dispatched for Cardiac Patients are ALS Capable		
Prince William Co	6.5 / 87%	8.0 / 88%	11.0 / 92%
Arlington Co	5 / Actual Times Not Publicly Posted		
Loudon Co	Only Turnout Times Posted		

Table C.3. Advanced Life Support Services Response Times

Rescue Services			
Advanced Life Support (ALS)			
Response Goal (min) / % Achieved			
Jurisdiction	High Density	Med Density	Low Density
Fairfax Co	5 / 78%		
Prince William Co	6.5 / 81%	8.0 / 82%	11.0 / 60%
Arlington Co	5 / Actual Times Not Publicly Posted		
Loudon Co	Only Turnout Times Posted		

VITA

William C. Louisell

William C. (Chuck) Louisell was born in Annapolis Maryland on December 24th, 1957. Raised in an Army family, he lived in many locations but considers Virginia his home. He attended Virginia Polytechnic Institute and State University where he completed the two-year ROTC program. After graduating with a B.S. in Agricultural Engineering in June of 1980, he attended pilot training in October at Vance AFB, OK and received his Air Force pilot's wings in October 1981.

After pilot training, Chuck served in many flying assignments in the F-16 and F-15. He also completed staff assignments including Flying Safety, International Affairs, and Strategic Plans and Policy. Chuck commanded the 60th Fighter Squadron which participated in operations in the Persian Gulf and in the Air Defense of Iceland. Following squadron command, Chuck served as a member of the Secretary of Defense Strategic Studies Group examining the impact of advanced information technology on organizational and operational change. He subsequently commanded the Air Force's largest flying training operation as the Operations Group Commander, 56 Operations Group, Luke AFB AZ. Besides the flying training mission, the group served as part of the civil air traffic control structure serving the Phoenix, AZ terminal control area.

Chuck is a graduate of Air Command and Staff College and the Air War College. He has an M.S. in Administration from Central Michigan University (1987) and an M.S. in Systems Engineering from Virginia Polytechnic Institute and State University (1999).

Having retired from the Air Force in 2002, Chuck is now employed by Science Applications International Corporation in the Transportation Research Division supporting the Federal Highway Administration, Intelligent Transportation System, Joint Program Office.

Chuck is married to the former Melissa Ray of Charleston, South Carolina. They have one daughter, Chandler Marissa.